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EXPERIMENTAL MANIPULATIONS OF PHYTOPLANKTON IN EAU GALLE RESERVOIR

by

John W. Barko, Andrew R. Klemer,
Dwilette G. McFarland, M. Susan Hennington

Environmental Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631

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Poor water quality in Eau Galle reservoir, located in west-central Wisconsin, has been associated historically with an overabundance of nuisance planktonic algae (phytoplankton) during the summer months. In an attempt to improve water quality, a variety of experiments was conducted over a 2-year period in large (10-m-diameter) enclosed water columns. Specific objectives of these experiments were to reduce phytoplankton standing crop and to promote

(Continued)

20. ABSTRACT (Continued).

favorable changes in species composition, i.e., away from nuisance algae (cyanophytes and dinoflagellates) towards more desirable algae (diatoms and chlorophytes). Experimental treatments, implemented singly and in combination, included destratification by mixing, addition of soluble silica, sediment sealing with sand, and precipitation of phosphorus with block aluminum sulfate. Mixing, alone or in combination with silica addition, extended the presence of vernal diatom populations into the summer in one investigation. In contrast, addition of silica to the water column without mixing had no effect on diatom production. In general, mixing stimulated phytoplankton production by increasing phosphorus availability. However, phosphorus inactivation with block aluminum sulfate suspended in the water was sufficient to overcome this effect. Individual effects of phosphorus precipitation and sediment sealing were similar; both decreased phytoplankton standing crop in association with decreased total phosphorus concentrations. Since most of the phosphorus contributed to the phytoplankton in Eau Galle reservoir derives from the sediment, complexation of sediment phosphorus is recommended to improve water quality.

Preface

The studies reported herein were sponsored by the Department of the Army, Office of the Chief of Engineers (OCE) Directorate of Civil Works (DAEN-CW), through the US Army Corps of Engineers (CE) Environmental and Water Quality Operational Studies Research Program (EWQOS). The EWQOS is managed by the US Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss. Technical Monitors for OCE were Dr. John Bushman, Mr. Earl Eiker, and Mr. James L. Gottesman.

Principal investigators for these studies were Drs. John W. Barko and Andrew R. Klemer, Environmental Laboratory (EL), WES. Ms. Dwilette G. Hardin and Ms. M. Susan Hennington identified and enumerated the phytoplankton. Assistance in sediment chemistry was provided by Dr. Rex L. Chen. Martha Albritton provided extensive computer assistance. Critical reviews were provided by Drs. Gordon L. Godshalk and Thomas Hart. This report was edited by Ms. Jamie W. Leach, and graphics prepared by Lamar D. Scott, Jr., of the WES Information Products Division.

This investigation was performed under the general supervision of Dr. John Harrison, Chief, EL, and Mr. Donald L. Robey, Chief, Ecosystem Research and Simulation Division, and the direct supervision of Dr. Hart, Chief, Aquatic Processes and Effects Group. The EWQOS was managed by Dr. Jerome L. Mahloch.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

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Contents

EXPERIMENTAL MANIPULATIONS OF PHYTOPLANKTON IN EAU GALLE RESERVOIR

Introduction

1. Dense algal populations occur in many Corps of Engineers impoundments with documented regularity. The excessive growth of algae is frequently associated with an advanced state of eutrophication and is symptomatic of a variety of limnological conditions favoring high algal population densities (Wetzel 1983). In addition to obvious reductions in the aesthetic quality of reservoirs supporting excessive algal biomass, the decomposition of algae can result in reductions in dissolved oxygen and the formation of potentially toxic organic residues (Henning and Kohl 1981). Algae-related water quality problems are a source of considerable public concern related to the use of reservoir resources.

2. Many lakes and most reservoirs receive nutrients from nonpoint and other sources that are not readily amenable to control. In such systems it is not feasible to regulate algal standing crop by modifying nutrient loadings. Thus, in-lake approaches to algal management, perhaps involving changes in species composition (i.e., from nuisance species to more desirable species), need to be developed. Towards this end enclosure experiments have been conducted in attempts to manipulate both the standing crop and species composition of the planktonic algae (phytoplankton) of Eau Galle reservoir, a classically eutrophic system located in west-central Wisconsin. Results of these experiments are reported for initial consideration in formulating a management plan specific to algal problems in Eau Galle. The data presented here represent only a portion of an extensive database developed for Eau Galle in an effort to improve current understanding of reservoir processes (Kennedy 1985, 1986).

Site Description

3. Eau Galle reservoir is a small (0.6 km^2), shallow (3-m mean depth), moderately alkaline (2 to 4 meq ℓ^{-1}) dimictic impoundment (Figure 1). It has one major and two minor tributaries, which deliver nutrients from cattle lots and associated agricultural lands, and a single outflow, which receives water from both surface and bottom withdrawal points. Major water exchange and

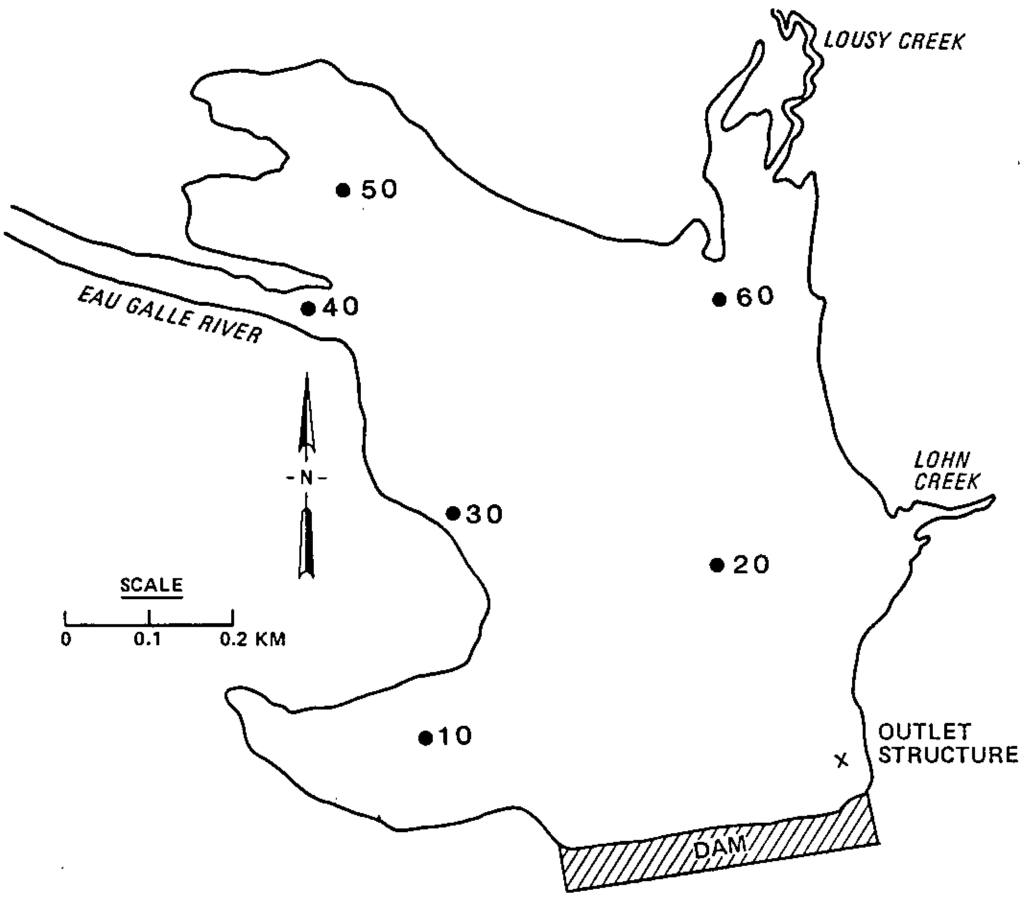

Figure 1. Map of Eau Galle reservoir indicating locations of sampling stations

external nutrient loading occur during spring thaw, when as much as half of the reservoir volume is replaced within a period of several days. Throughout the remainder of the year, hydraulic exchange is relatively minor. During the summer, bottom withdrawal of water in combination with wind-driven mixing processes promote hypolimnetic warming (Gaugush 1984), which accelerates mineralization rates and enhances nutrient cycling. Historically, algal blooms in Eau Galle reservoir have been severe.

4. The seasonal succession of phytoplankton in Eau Galle, characterized at six sampling stations in 1981 (Figure 2), is fundamentally similar to that described for many temperate eutrophic lakes (Wetzel 1983). Eau Galle is dominated by Bacillariophyta (diatoms) during spring and fall periods of

destratification, and codominated by Cyanophyta (blue-green algae) and Pyrrhophyta (dinoflagellates) during summer stratification. Three species (*Stephanodiscus hantzschii* Grun., *Aphanizomenon flos-aquae* (L.) Ralfs, and *Ceratium hirundinella* (O.F.M.) Schrank) typically contribute 50 percent or more of total annual phytoplankton biomass (Barko et al. 1984). Depressed epilimnetic silica concentrations occur during spring and fall periods of diatom growth. The development of nitrogen-fixing cyanophyte populations during the summer reflects reduced inorganic nitrogen availability. The combination of changes in thermal conditions, water column stability, silica, and nitrogen concentrations that occurs seasonally is related to major changes in the phytoplankton composition of Eau Galle (cf. Barko et al. 1984).

Approach

5. Experiments were conducted in situ during 1983 and 1984 in water columns enclosed within 10-mil polyethylene tubes. The tubes were 10 m in diameter, 3.6 m in length, and extended to the sediment surface. They were fabricated with pockets at the top and bottom to accommodate steel-conduit and styrofoam flotation rings, and gravel-filled polyethylene archor rings, respectively.

6. The principal treatments during 1983 consisted of mixing and enrichment with silica (as sodium metasilicate): each treatment alone, in combination, and a control (Table 1). The rationale for silica enrichment as

Table 1

Experimental Treatments in 1983

Column Number	Treatment
1	Silica* + mixed
2	Mixed
3	Silica
4	Control

* Silica was applied continuously as $Na_2SiO_3 \cdot 9H_2O$ at an approximate rate of 20 g SiO_2 per cubic metre per month.

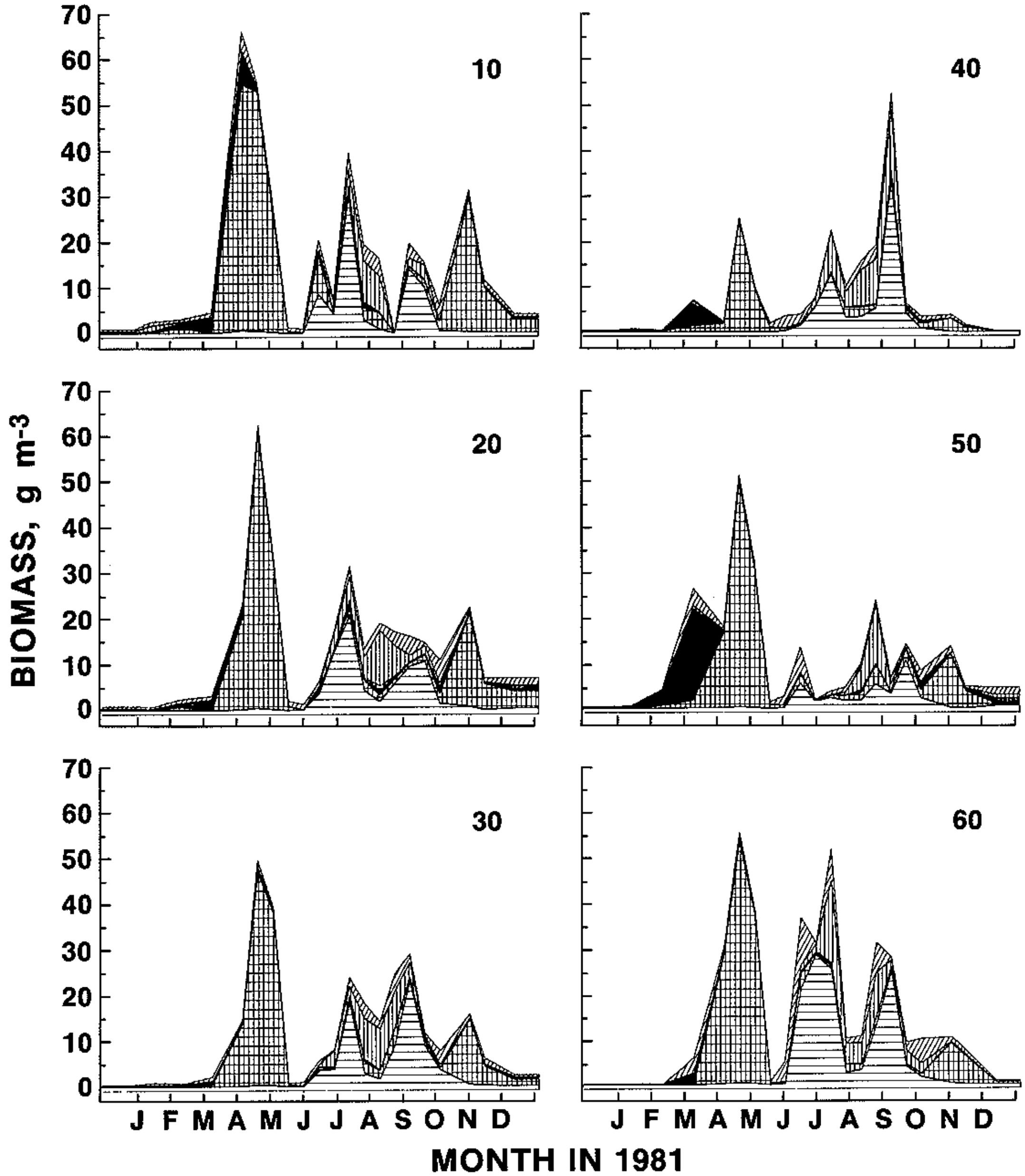

Figure 2. Seasonal succession and biomass of phytoplankton in the epilimnion at six stations during 1981. Stations are identified by number in subfigures. Separately designated Divisions include Cyanophyta (▤), Bacillariophyta (⊞), Chrysophyta (■), and Pyrrhophyta (▥). Separately indistinguishable Divisions are grouped in "Other" (▨). Month identifiers designate first day of each month

a means of influencing phytoplankton composition is based on the firmly established link between silica depletion and the waning of diatom populations (Lund 1950, 1964), and on the hypothesis that nutrient loading stimulates silica use by diatoms at a rate exceeding that at which silica can be replenished. Artificial destratification (mixing) was combined with silica enrichment because water column stability during summer stratification promotes the loss by sedimentation of diatoms and other desirable phytoplankton while favoring dinoflagellates and those cyanophytes capable of buoyancy regulation and effective vertical migration. Mixing was provided by axial-flow pumps driven by 1/4-hp (186-watt) electric motors (Quintero and Garton 1973). Thus, these experiments were intended to encourage diatoms principally, and unicellular chlorophytes (green algae) at the expense of cyanophytes and dinoflagellates.

7. The principal treatments during 1984 consisted of sediment sealing with silica sand and phosphorus precipitation with alum (Table 2). Each treatment was implemented alone and in combination with mixing, as described above for 1983 experiments. Principal treatments were intended to reduce phytoplankton standing crop by diminishing phosphorus availability. Mixing was combined with principal treatments to modify phytoplankton species composition at reduced levels of phytoplankton standing crop.

Table 2

Experimental Treatments in 1984

Column Number	Treatment
1	Sediment seal* + mixed
2	Alum** + mixed
3	Sediment seal
4	Alum

* Sediment was "sealed" with 5 cm of washed silica sand. Total mass added was 8 tons (7,257 kg) per column.

** $Al_2(SO_4)_3 \cdot 14H_2O$ (55%) was added in block form. Blocks were continuously added to keep pace with dissolution rate.

8. On a weekly basis, temperature, oxygen, pH, and conductivity were monitored with a Hydrolab Digital 4041; transparency was measured with a Secchi disk; and two integrated samples (0-3 m) were taken from each enclosed water column and the open water. Separate aliquots of each sample were analyzed for alkalinity, chlorophyll a content corrected for phaeopigments (American Public Health Association (APHA) 1980), total phosphorus, total soluble phosphorus, total nitrogen, total soluble nitrogen (Raveh and Avnimelch 1979 for nitrogen and phosphorus), and dissolved silica (automated molybdosilicate method; APHA 1980). Aliquots for algal counts and cell volume determinations were fixed in Lugol's iodine; subsamples of 1.0 to 50 ml were transferred to sedimentation chambers and examined with a Wild M-40 inverted microscope following the technique of Lund, Kipling, and LeCren (1958). Algal biomass determinations were made in accordance with techniques described by Barko et al. (1984).

Results

Phytoplankton response in 1983

9. The 1983 investigation had three phases. During the first phase (9 May to 13 June), columns #1 and #2 were mixed continuously and silica was added to columns #1 and #3 (Table 1). Silica enrichment continued through the second phase (13 June to 19 July), but mixing was intermittent due to storm-related power failures on three occasions: 13 June, 28-29 June, and 3-6 July. During the final period (19 July to 16 August), a secondary treatment (addition of liquid alum) was implemented in column #1, silica enrichment continued in columns #1 and #3 until 22 July, and mixing in columns #1 and #2 until 9 August.

10. Both phytoplankton biomass and community composition varied among study periods (Figure 3). Diatoms and cryptophytes were most abundant during the first period of investigation. Diatom biomass during the first period was much greater in the mixed columns than in either the unmixed columns or the open water. Conversely, cryptophyte biomass was greatest in the unmixed columns.

11. During the second phase of investigation total phytoplankton biomass increased significantly in the open water and in all columns except #2. Increased biomass during this period was due almost entirely to the

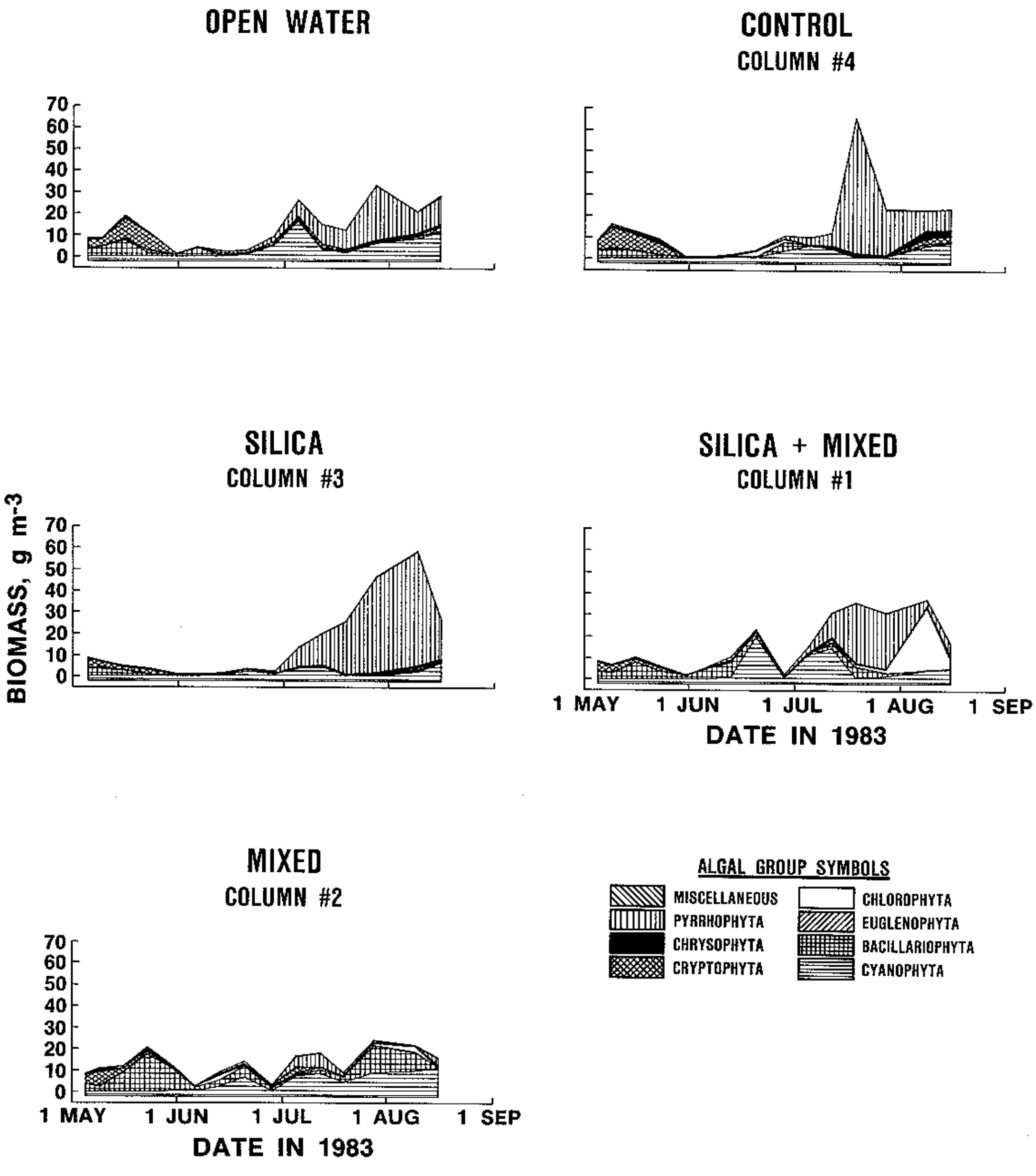

Figure 3. Contributions of various algal groups (taxonomic Divisions) to total phytoplankton biomass in the open water and in experimentally enclosed water columns during the summer of 1983

development of cyanophyte and dinoflagellate blooms as populations of diatoms and cryptophytes waned. Significantly, however, the proportion of diatom biomass to total phytoplankton biomass remained greater in the mixed than in the unmixed columns or the open water during this period.

12. Total phytoplankton biomass reached maximum levels during the third period of investigation. At that time dinoflagellates assumed nearly complete dominance in both unmixed columns and the open water. In contrast, diatoms and cyanophytes codominated column #2, and chlorophytes dominated column #1.

Phytoplankton response in 1984

13. The 1984 investigation was continuous, with no interruptions in mixing. Phytoplankton biomass in 1984, with the exception of that in column #1, was about half the biomass in 1983 (contrast Figures 1 and 2). Greater biomass in column #1 than elsewhere was due solely to the development of a massive chlorophyte population (principally the filamentous species, *Mougeotia*) during mid through late summer (Figure 4).

14. Dinoflagellates peaked in the open water and in all columns except #3 during June of 1984, approximately 1 month earlier than in the previous year. These peaks corresponded with the waning of relatively minor diatom and chrysophyte populations. During mid-July cyanophytes assumed dominance over dinoflagellates. Biomass in all columns except #1 at that time was exceptionally low, but comparable to that in the open water. Throughout the remainder of the study cyanophytes continued to dominate all columns and the open water. Dominance in column #1, however, was shared by chlorophytes.

Physical and chemical effects on phytoplankton

15. Additions of silica to the water column in 1983 significantly increased silica concentrations, up to threefold greater than in the open water, but this treatment alone had no effect on diatom biomass. Diatom production was stimulated by addition of silica in combination with mixing (column #1), but to a lesser extent than mixing alone. Dissolved SiO_2 concentrations in 1984 increased progressively from <3 mg ℓ^{-1} to 9 mg ℓ^{-1} throughout the study, did not vary among treatment columns or the open water, and were unrelated to diatom abundance.

16. Total nitrogen concentrations were essentially unaffected by the various treatments in either investigation. In contrast, total phosphorus was higher and ratios of total nitrogen to total phosphorus were lower in mixed columns and the open water than in unmixed columns, particularly in 1984

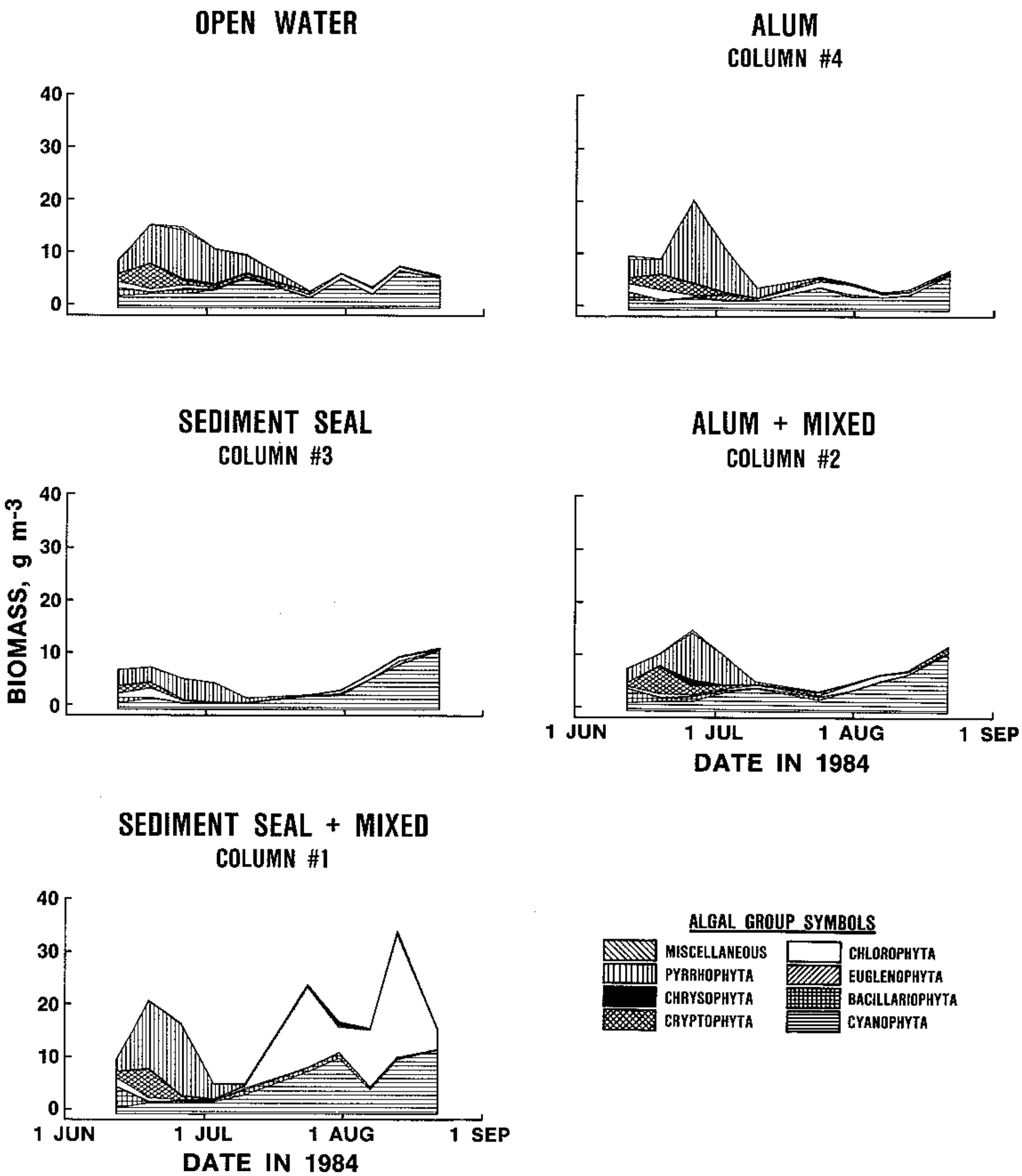

Figure 4. Contributions of various algal groups (taxonomic Divisions) to total phytoplankton biomass in the open water and in experimentally enclosed water columns during the summer of 1984

(Figure 5). Part of this effect was due to reductions in phosphorus associated with sediment sealing (1984 column #3) and addition of alum (1984 column #4). However, the same trend in 1983 with no experimental reductions in phosphorus indicates that mixing did elevate total phosphorus levels. In both investigations there were strong associations between high total phosphorus concentrations, low nitrogen-to-phosphorus ratios, and high cyanophyte biomass. Conversely, low total phosphorus and high ratios of total nitrogen to total phosphorus were associated with high dinoflagellate biomass.

17. Concentrations of total phosphorus were significantly correlated positively with total phytoplankton biomass ($r > 0.55$, $p < 0.01$) and negatively with Secchi depth ($r < -0.73$, $p < 0.01$) during both study years. Secchi depth decreased in these investigations proportionately with increasing phytoplankton biomass and was further depressed periodically in mixed columns due to turbidity caused by sediment resuspension. Mixing increased the rate of phosphorus flux from sediment interstitial water into the overlying water (Table 3). Notably, however, sediment sealing reduced the rate of phosphorus flux to less than half that determined under unsealed conditions. All experimental water columns remained aerobic from surface to sediment surface; thus, differences in phosphorus flux were probably not determined by differences in redox potential.

Table 3

Flux Rates (at 15°C) of Orthophosphate From Sediments Within Selected Experimental Columns during the 1984 Investigation

Treatment Condition	Flux rate, mg m^{-2} day^{-1}*
Sediment sealed	14.4
Sediment sealed + mixed	20.6
Sediment unsealed	32.9

* Calculated using a modification of Fick's equation from vertical profiles of orthophosphate concentration measured in sediments.

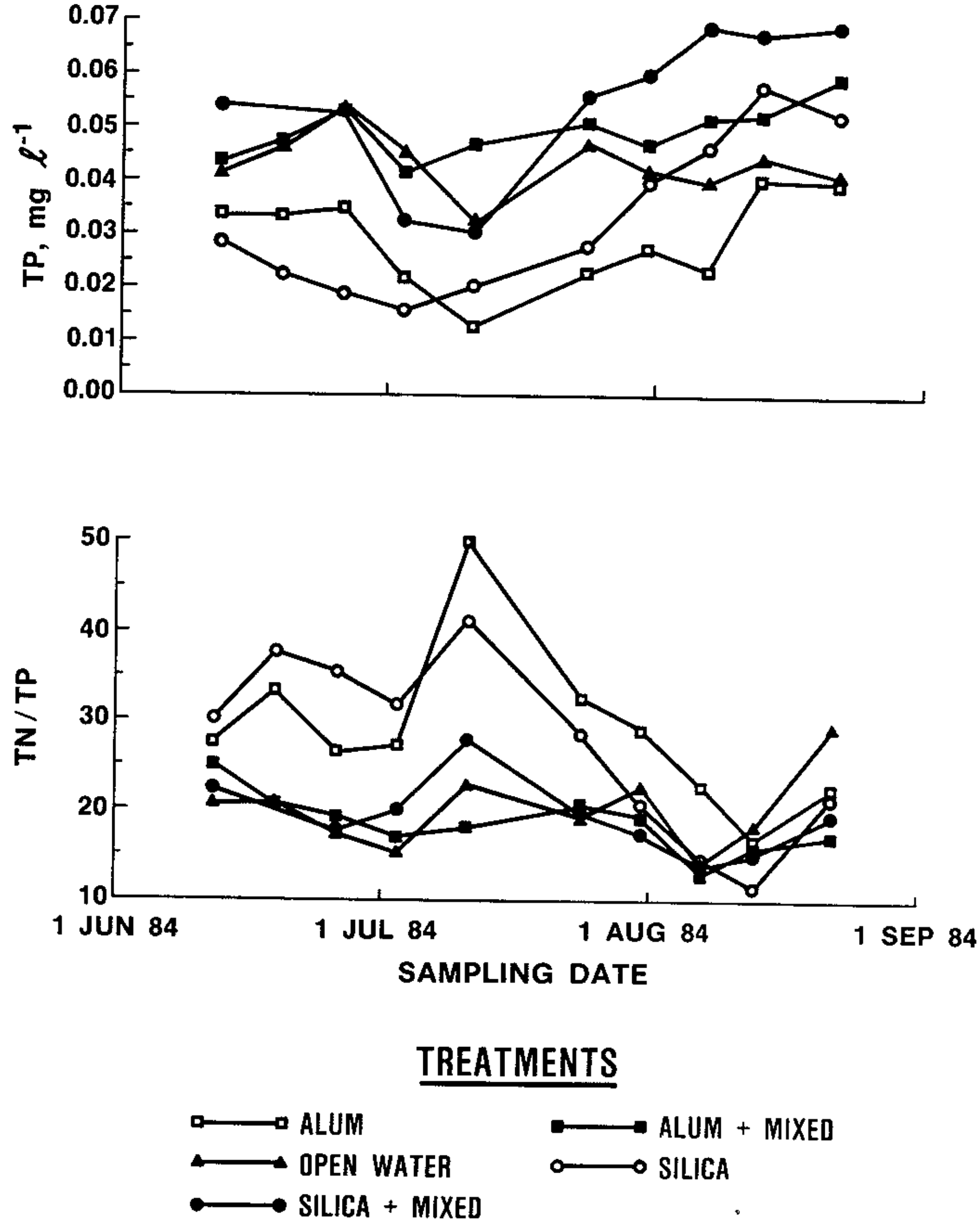

Figure 5. Total phosphorus (TP) concentrations and ratios of total nitrogen to total phosphorus (TN/TP) in the open water and in experimentally enclosed water columns during the summer of 1984

Discussion

18. Certainly silica concentration was not the sole factor controlling diatom population dynamics in the enclosures. Diatom populations in the silica-enriched column in 1983 were as sparse in the spring as those in the control column, and by mid-July diatoms were virtually absent from these unmixed columns despite relatively high concentrations of SiO_2 (>3.0 mg ℓ^{-1}). In the open water as well as in the unmixed columns, diatoms began declining in mid-May as water column stability (i.e., resistance to mixing) increased. Diatoms, because they are relatively dense and lack the ability to maintain position within the water column, are particularly disadvantaged in hydraulically stable environments (Hutchinson 1967). Destratification by mixing in 1983 facilitated the extension of spring diatom populations into the summer, but this effect was not enhanced by silica additions. Thus, diatom population dynamics in Eau Galle appear to be more responsive to hydraulic conditions than to the availability of silica.

19. Unlike conditions in 1983, experiments in 1984 were initiated a full month following the collapse of vernal diatom populations (Barko, unpublished), and in contrast to the previous year's results, diatom production in 1984 was not encouraged by mixing. Apparently, mixing in Eau Galle is only effective in maintaining vernal diatom populations when initiated prior to diatom collapse (see also Nicholls, Kennedy, and Hammett 1980).

20. This study was partially successful in maintaining preferred algae (diatoms) by mixing, but not at the expense of nuisance algae (cyanophytes and dinoflagellates). In general, the growth of cyanophytes was stimulated by mixing, while that of dinoflagellates was either depressed somewhat or unaffected under the same conditions. The growth of chlorophytes, principally filamentous *Mougeotia*, which is not a desirable species, was also stimulated under some circumstances by mixing--in combination with alum treatment in 1983 and sediment sealing in 1984. Chlorophytes were essentially absent from columns in which mixing was implemented alone.

21. Trimbee and Harris (1984) suggested that the most notable effect of periodic natural mixing episodes on phytoplankton was a shift in dominance from nonnitrogen-fixing to nitrogen-fixing species. In our investigations, nitrogen-fixing cyanophytes dominated at times under both mixed and unmixed conditions, but were generally more abundant in mixed columns. The most

prominent cyanophyte taxa in mixed columns were *Anabaena* and *Aphanizomenon* species, both of which readily fix nitrogen. Nitrogen fixation has been viewed as a response to stoichiometric imbalance between nitrogen and phosphorus availability (Schindler 1977). Accordingly, relatively low ratios of total nitrogen to total phosphorus, as in our mixed columns, tend to favor nitrogen-fixing cyanophytes (Smith 1983).

22. Dinoflagellates, principally *Ceratium*, were dominant in the absence of mixing during mid through late summer in 1983. However, in 1984 mixing had no obvious effect on dinoflagellates, which achieved dominance in all columns and in the open water during the early summer. An interesting observation applicable to both years of investigation is that dinoflagellates generally fared best where cyanophytes fared poorest. On the whole, 1983 was dominated by dinoflagellates while in 1984 cyanophytes dominated. There may be an antagonistic interaction that accounts for the apparent inverse relationship between dinoflagellate and cyanophyte population development (Vance 1965; Dottne-Lindgren and Ekbohm 1975; Nicholls, Kennedy, and Hammett 1980), but causal mechanisms have not been satisfactorily explained.

23. In general, the production of phytoplankton biomass was stimulated by mixing, and this effect was most pronounced in 1983. This response is attributed to increased phosphorus availability caused by sediment resuspension and enhanced phosphorus diffusion from sediments under mixed conditions. Notably, phosphorus inactivation with block aluminum sulfate under these conditions was sufficient to overcome stimulated biomass production. Although these results are strictly applicable only to relatively shallow regions (less than about 3 m) of Eau Galle, they do underscore the important influence of sediments on phosphorus availability and resultant phytoplankton production.

24. The sediment is the major source of phosphorus in Eau Galle during the summer months, when inflows account for no more than a few percent of the total phosphorus budget (James, Kennedy, and Gaugush 1986). During this period phosphorus in concentrations >2,000 $\mu g\ \ell^{-1}$ in the anoxic hypolimnion is made available to the phytoplankton by periodic weather-related mixing events (Gaugush 1984). Mixing in Eau Galle is facilitated by relatively low water column stability due to the effects of bottom withdrawal of water on the thermal regime. Similar effects of weather-induced mixing on phosphorus dynamics have been reported for Shagawa Lake, Minnesota, another relatively shallow

basin located within the same climatic setting as Eau Galle (Stauffer and Armstrong 1984).

25. Sediment sealing with sand in the absence of mixing was fairly effective in reducing total phosphorus release from sediments under ambient aerobic conditions, but would probably have had a lesser effect under anaerobic conditions due to enhanced phosphorus availability at low redox potentials (Wetzel 1983, p 261). Mixing largely negated the effect of sediment sealing on phosphorus release, indicating that the advantage gained by increasing the diffusion distance between sediment surface and overlying water was minor. Addition of alum in the 1984 investigation decreased total phosphorus concentrations in an unmixed water column, and thus was effective in precipitating a portion of the phosphorus released from underlying sediment.

Conclusions and Recommendations

26. Improved water quality in Eau Galle with consequent reductions in phytoplankton densities will require a reduction in phosphorus release from sediments during the summer months. We recommend that this can be accomplished by administering aluminum sulfate (alum) directly onto the sediment surface within the profundal region (i.e., >3 m depth) according to procedures described in Kennedy and Cooke (1982). The advantage to using alum as opposed to an inert sediment seal is that the former selectively complexes phosphorus in chemical forms that are unaffected by changes in redox potential. Prerequisite to the successful application of this approach is the knowledge (which we have) that internal loading of phosphorus from sediments dominates the midsummer phosphorus budget. Alum treatment of sediments in natural lakes to control phytoplankton production has been generally quite successful (Cooke and Kennedy 1981), but has not been applied to a reservoir system. We recommend that treatment of sediments in Eau Galle be followed by a minimum 4-year period of intensive limnological monitoring, in order to assess longevity of treatment effects.

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