Relating Algal Bloom Frequencies to Phosphorus Concentrations in Lake Okeechobee

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ABSTRACT

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Empirical relationships were developed between algal bloom frequencies and total phosphorus concentrations for three distinct regions of Lake Okeechobee, and hypotheses were derived to explain observed spatial variation in those relationships. The analyses were based on water quality monitoring data collected monthly between 1986 and 1993, at 10 open-water stations, 12 north littoral stations, and 14 south littoral stations. Using a cross-tabulation procedure, phosphorus/bloom-frequency relationships were developed for bloom criteria of 10, 20, 30, 40, 50, and 60 μg L^{-1} chlorophyll *a*. For bloom criteria in the range of 40 to 60 μg L^{-1} chlorophyll *a*, blooms were not detected when phosphorus was less than 30 μg L^{-1}. During the 1986-1993 monitoring period, this threshold phosphorus concentration was exceeded 3% of the time in the open lake, 25% of the time in the north littoral, and 48% of the time in the south littoral. When phosphorus concentrations were between 30 and 60 μg L^{-1} in the littoral regions, frequency or risk of an algal bloom increased with phosphorus concentration. The maximum risk of an algal bloom generally occurred when phosphorus exceeded 60 μg L^{-1}. This condition was observed 70% of the time in the open lake, 29% of the time in the north littoral, and 15% of the time in the south littoral. When phosphorus concentrations exceeded 60 μg L^{-1}, risk of a 40 μg L^{-1} bloom was 19% in the open lake, 28% in the north littoral, and 60% in the south littoral. Regional variations in the relationship between phosphorus and bloom frequency may be due to variations in nitrogen availability. Highest total nitrogen concentrations were found in the south littoral zone, where bloom frequencies at a given phosphorus concentration were also highest. Reductions in lake water phosphorus concentrations can be expected to cause reductions in bloom frequencies in the littoral zones, but have little impact on the open lake. This result has positive implications for lake users, because the more responsive littoral region is also the location of the most frequent algal blooms.

Key Words: algal blooms, chlorophyll *a*, phosphorus, algae, eutrophication management.

Successful management of eutrophication requires an understanding of factors that regulate the composition, biomass, and bloom potential of algal assemblages. In large lakes, those factors may vary horizontally within the water mass. In elongated reservoirs, there is often a transition from a turbid, nutrient rich, light limited, low algal biomass riverine zone to a more transparent, nutrient deficient, lower algal biomass lacustrine zone. Often, a nutrient replete transitional zone of high algal biomass occurs between the two extremes (Lind et al. 1993). In large lakes, there may likewise be spatial variation due to differences in sediment composition, water depth, and location relative to external nutrient inputs. This is the case in large sub-tropical Lake Okeechobee, Florida, where a recent investigation (Philips et al. 1993) documented four distinct pelagic ecological zones, whose water chemistries and limiting nutrient status (Aldridge et al. 1994, Havens 1994a) were linked closely to the composition of underlying sediments. Most importantly, the lake often displayed light-limited algal production in a large central region overlying unconsolidated muds. Algal blooms appear to be spatially and temporally regulated by light availability, and they generally occur along the western and southern edges of the lake, where sand and peat sediments occur. When nutrient limitation does occur, it is almost always by nitrogen, at least at open-water sites where bioassays have been performed.

In Lake Okeechobee, and in lake ecosystems where water quality management efforts are underway, it is important that managers be able to detect responses to successful actions. An important attribute of "recovery," in terms of use impairment, is the frequency of algal bloom events. It is necessary to define these phenomena based on some quantitative measure, and to make predictions about their frequency in the context of documented spatial variation. Some regions may be insensitive to changes in nutrient concentrations, while others may show very early signs of recovery. This information is critical.

Our objective was to develop empirical relationships between algal bloom frequencies and total phosphorus concentrations for three distinct regions of Lake Okeechobee (pelagic, northwest littoral, and southwest littoral), and to provide hypotheses to explain any observed spatial variation in the relationships. Phosphorus was considered because ongoing management strategies have targeted that element, and there have been significant declines in external loads from agricultural basins (Flaig and Havens 1995). However, there have not been corresponding declines in lake water total phosphorus, and there has been a concern that even if declines do occur, algal blooms will not correspondingly decrease because nitrogen-limited conditions predominate. In this analysis, we examine the historical data from 36 lake-wide water quality monitoring stations, and address that concern.

Characteristics of the Lake

Lake Okeechobee is large (1,730 km^2), shallow (mean depth = 2.7 m), naturally eutrophic (Stoermer et al. 1992), and located in south Florida, USA, at 27° 00' N Latitude and 80° 50' W Longitude (Fig. 1). The lake has a large littoral zone of emergent and submerged vegetation along its south and west margins; this zone is an important habitat for spawning of economically important fish, and a nesting and feeding site for waterfowl. Lake Okeechobee has a natural origin (Gleason and Stone 1975), and prior to human development, it had few natural outlets. When water level exceeded the height of a natural levee at the south shore, water flowed in a 40 km wide, shallow river into the Florida Everglades (Gleason 1984). To improve flood control and water supply, a dike was constructed around the lake between the 1930s and 1960s, creating what is today essentially a reservoir. All inflows (except Fisheating Creek to the west) and outflows are regulated by structures. Since the mid 1900s, the lake also has been impacted by nutrient discharges from agriculture in the watershed, predominantly phosphorus from dairy and beef cattle operations to the north, and nitrogen from sugar cane and vegetable farms to the south. However, both nitrogen and phosphorus loadings to the lake have declined in the last decade, coincident with agricultural BMPs and other watershed programs (Flaig and Havens 1995, James et al. 1995).

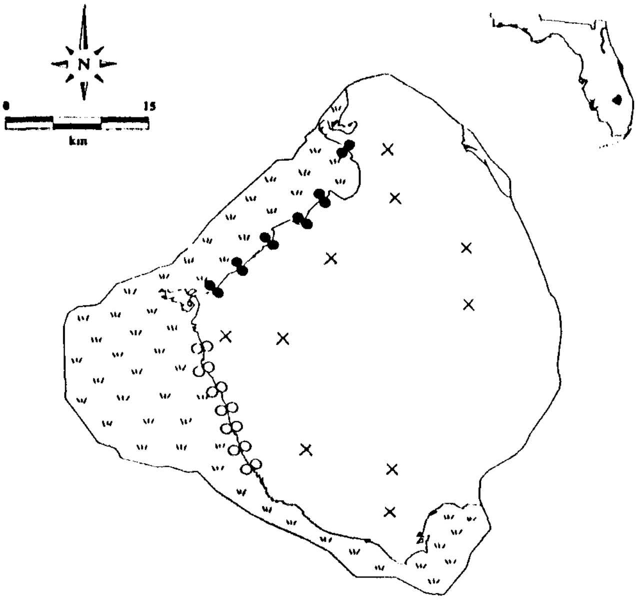

Figure 1.—Map of Lake Okeechobee, showing the location of the 10 open-water, 12 north littoral and 14 south littoral stations sampled monthly between 1986 and 1993. The inset map shows the location in Florida, USA.

Data Set

Lake Okeechobee water quality has routinely been monitored by the South Florida Water Management District (SFWMD), at least monthly since 1973. However, prior to 1986, only eight pelagic stations (Fig. 1) were sampled. Since 1986, additional pelagic stations, as well as 26 near-littoral stations, have been sampled on a monthly or more frequent basis. We considered this 34-station data set for the period November 1986 to October 1993 in this comparative analysis of chlorophyll/phosphorus relationships.

All sample collections (near-surface) and analyses were done according to consistent standard protocols and the SFWMD QA/QC plan. Chlorophyll *a* was determined spectrophotometrically according to Strickland and Parsons (1968), after filtering samples onto glass fiber filters, grinding in a tissue grinder, and overnight acetone extraction. Total phosphorus was determined colorometrically after persulfate digestion in an autoclave (USEPA 1979), and total nitrogen was analyzed using standard nitrogen methodology for flow-injection autoanalyzers (USEPA 1987).

Background and Analytical Methods

Empirical models relating chlorophyll *a* to total phosphorus are typically derived from regression analyses of temporally-averaged measurements collected in populations of lakes or lake stations. Monitoring data are averaged over depth (typically within the mixed layer) and time (typically within the growing season or summer) to generate chlorophyll *a* / total phosphorus pairs used in regression (Dillon and Rigler 1974, Carlson 1977). This approach is most useful to extract generalized models from large data sets representing lakes with a wide range of trophic states.

However, averaging masks temporal variance, which is typically large. In summarizing data from five large lake and reservoir data sets, Smeltzer et al. (1991) showed that within-year coefficients of variation are typically in the range of 25-30% for phosphorus and 40-60% for chlorophyll *a*. Depending upon sampling frequency, temporal variance may introduce considerable error into the chlorophyll/phosphorus pair values used in regression.

Another limitation of temporally-averaged chlorophyll/phosphorus models is that averaging masks extreme events (blooms) which may be of considerable management significance. Walmsley (1984) introduced the concept that impairment of lake uses is more sensitive to the frequency and severity of algal blooms than to "average" conditions. This concept apples to surface water-quality measures such as chlorophyll *a* or transparency, but not to integral measures such as hypolimnetic dissolved oxygen. Bloom frequency can be approximately quantified from typical monitoring data sets as the percent of the time that chlorophyll *a* exceeds a regionally-defined bloom criterion, expressed as an instantaneous chlorophyll *a* concentration. For example, based upon correlations of user surveys with reservoir monitoring data, Walmsley (1984) found that chlorophyll *a* concentrations exceeding 20 µg L^{-1} were associated with "algal nuisance conditions" and concentrations exceeding 30 µg L^{-1} were associated with "severe algal nuisance conditions" in South African reservoirs. Heiskary and Walker (1988) calibrated and applied this concept to lakes and lake users in developing regional phosphorus criteria for Minnesota lakes. They found that lake users generally classified lakes as "swimming impaired" when chlorophyll *a* concentrations were between 20 and 60 µg L^{-1}; the median concentration of this category of use impairment was 40 µg L^{-1}. Lower limits for the categories "no swimming" and "high algae" were also near 40 µg L^{-1}.

In the present study, relationships between phosphorus concentrations and algal bloom frequencies were examined using an algorithm similar to that applied by Heiskary and Walker (1988) to Minnesota lakes and by Walker (1987) to Lake Champlain. A bloom criterion of 40 µg L^{-1} chlorophyll a is generally considered to be appropriate for Lake Okeechobee (Havens 1994b), and it has been adopted by the Florida Department of Environmental Protection. However, this value has not been tested against lake user survey data. Therefore, as part of a sensitivity analysis, phosphorus/bloom-frequency relationships are developed for bloom criteria of 10, 20, 30, 40 , 50, and 60 µg L^{-1}chlorophyl *a*.

As distinct from the traditional regression approach, the present analyses make no assumptions about the shape or functional form of the relationship between phosphorus concentrations and bloom frequencies. Data reduction involved cross-tabulation of phosphorus and chlorophyll *a* measurements as follows:

1. Data were compiled by station, date, and depth for all records containing non-missing values for both total phosphorus and chlorophyll *a*;
2. Station samples were averaged by date, because in some cases multiple depth samples were collected within the generally well-mixed water column;
3. Records were divided into ten equal-sized intervals based upon total phosphorus concentrations; this resulted in between 90 and 116 samples per interval per lake region;
4. Mean values for total phosphorus and chlorophyll *a* were calculated for each phosphorus interval;
5. Algal bloom frequencies were calculated as the percent of samples exceeding 10, 20, 30, 40, 50, and 60 µg L^{-1} in each phosphorus interval;
6. A Chi-square test for association between phosphorus interval and bloom frequency was applied for each bloom criterion (Snedecor & Cochran, 1989).

This analysis was repeated for each of three lake regions identified in Fig. 1. Average total nitrogen concentrations also are calculated in each phosphorus interval to provide supplementary information on potential nitrogen limitation. The standard error of measured bloom frequency in a given phosphorus interval can be estimated using the binomial distribution (Snedecor & Cochran, 1989):

$$SE_f = [\ f\ (\ 1\text{-}f\ )\ /\ n\ ]^{.5}$$

where f is the estimated frequency, expressed as a fraction, and n is the number of samples.

For a typical sample size of 100, standard errors are as follows:

Estimated Frequency:	5.0%	10%	25%	50%	75%	90%	95%
Standard Error:	2.2%	3.0%	4.3%	5.0%	4.3%	3.0%	2.2%

Results and Discussion

There is a statistically significant ($p < 0.01$) association between phosphorus intervals and algal bloom frequencies for all three lake regions, except for the open lake with bloom criteria of 10 and 60 µg L^{-1}.

Figure 2a plots bloom frequencies against mean total phosphorus concentrations for the open lake stations. Vertical lines indicate the 10%, 50%, and 90% intervals, which in this data set, occur at concentrations of 42, 77, and 137 µg L^{-1}, respectively). Based upon 40 and 60 µg L^{-1} chlorophyll *a* criteria, bloom frequencies in the open lake were 20% and 6%, respectively, summed over all phosphorus intervals. The apparent weak correlation between phosphorus and bloom frequency is consistent with the notion of a high phosphorus content in abiotic particles (resuspended sediments) and the importance of nitrogen and light as factors controlling algal production (Phlips et al. 1993, Aldridge et al. 1995, Havens 1994a) in the relatively deep, turbid region of the open lake. The enhanced degree of light limitation in cases where both sediment resuspension and total phosphorus are maximal (Phlips et al. 1993) is evidenced by the declining trend in bloom frequencies over the 100 to 160 µg L^{-1} phosphorus range. This area of the lake is unlikely to respond in a noticeable manner to reductions of external phosphorus loads, because internal processes (wind-driven sediment resuspension) largely drive both nutrient content, light climate, and algal biomass. Canfield and Hoyer (1988) reached a similar conclusion, but, in our opinion, they incorrectly (see below) inferred that the relationship applied to the entire lake.

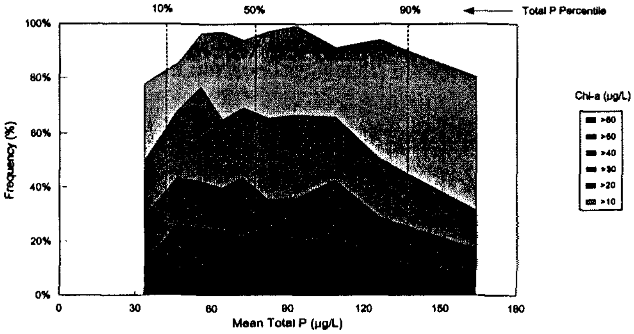

Figure 2a.—Chlorophyll *a* interval frequencies versus total phosphorus concentrations at the open lake stations. This figure generally indicates the "risk" of various intensities of algal blooms at given total phosphorus concentrations.

Results from the north littoral stations are plotted in Fig. 2b. Phosphorus concentrations in this region are characterized by 10%, 50%, and 90% values of 21, 47, and 92 µg L^{-1}, respectively. Integrated frequencies of 40 and 60 µg L^{-1} chlorophyll *a* concentrations were 13% and 3%, respectively. In contrast to the open lake, bloom frequencies in this region are strongly correlated with total phosphorus, although a plateau in this relationship is evident. At phosphorus concentrations below 35 µg L^{-1} (the 0 to 30th percentiles), chlorophyll *a* exceeded 40 µg L^{-1}in less than 1% of the samples. Between 35 and 92 µg L^{-1} (the 30th to 90th percentiles), bloom frequencies increased from below 1% to near 35%. In the highest phosphorus interval (above 92 µg L^{-1}), the 40 µg L^{-1}bloom frequency decreased from 35 to 25%. As in the open water region, some factor other than phosphorus appears to limit maximal algal biomass and bloom frequencies at high total phosphorus concentrations in the north littoral. Light penetration is generally high in this region, relative to the open lake (Phlips et al. 1993), suggesting that light limitation is not the controlling factor. Our data (see below) suggest that nitrogen limitation may be involved.

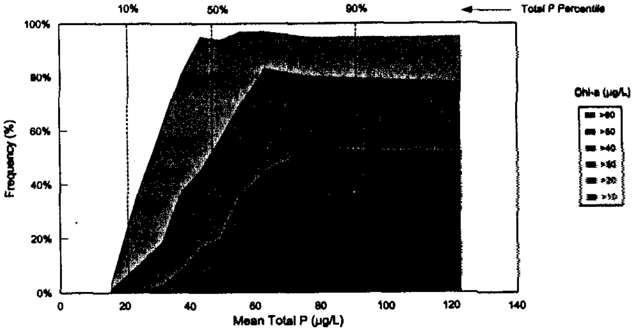

Figure 2b.—Chlorophyll *a* interval frequencies versus total phosphorus concentrations at the north littoral stations. This figure generally indicates the "risk" of various intensities of algal blooms at given total phosphorus concentrations.

Results for the south littoral station are shown in Fig. 2c. Phosphorus concentrations in this region are characterized by 10%, 50%, and 90% values of 17, 31, and 70 µg L^{-1}, respectively. Integrated frequencies of the 40 and 60 µg L^{-1} chlorophyll *a* concentrations were 18% and 7%, respectively. Of the three regions examined, bloom frequencies were most sensitive to phosphorus in the south littoral. At phosphorus concentrations below 31 µg L^{-1} (the 0 to 50th percentiles), chlorophyll *a* exceeded 40 µg L^{-1} in less

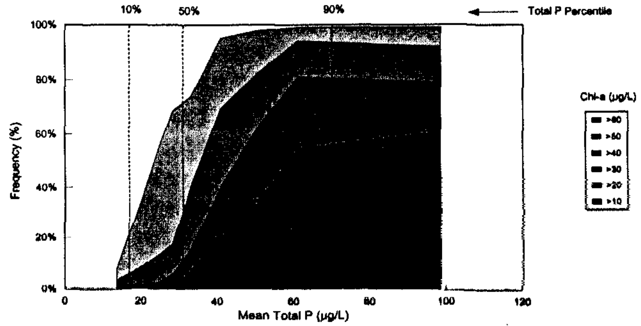

Figure 2c.—Chlorophyll *a* interval frequencies versus total phosphorus concentrations at the south littoral stations. This figure generally indicates the "risk" of various intensities of algal blooms at given total phosphorus concentrations.

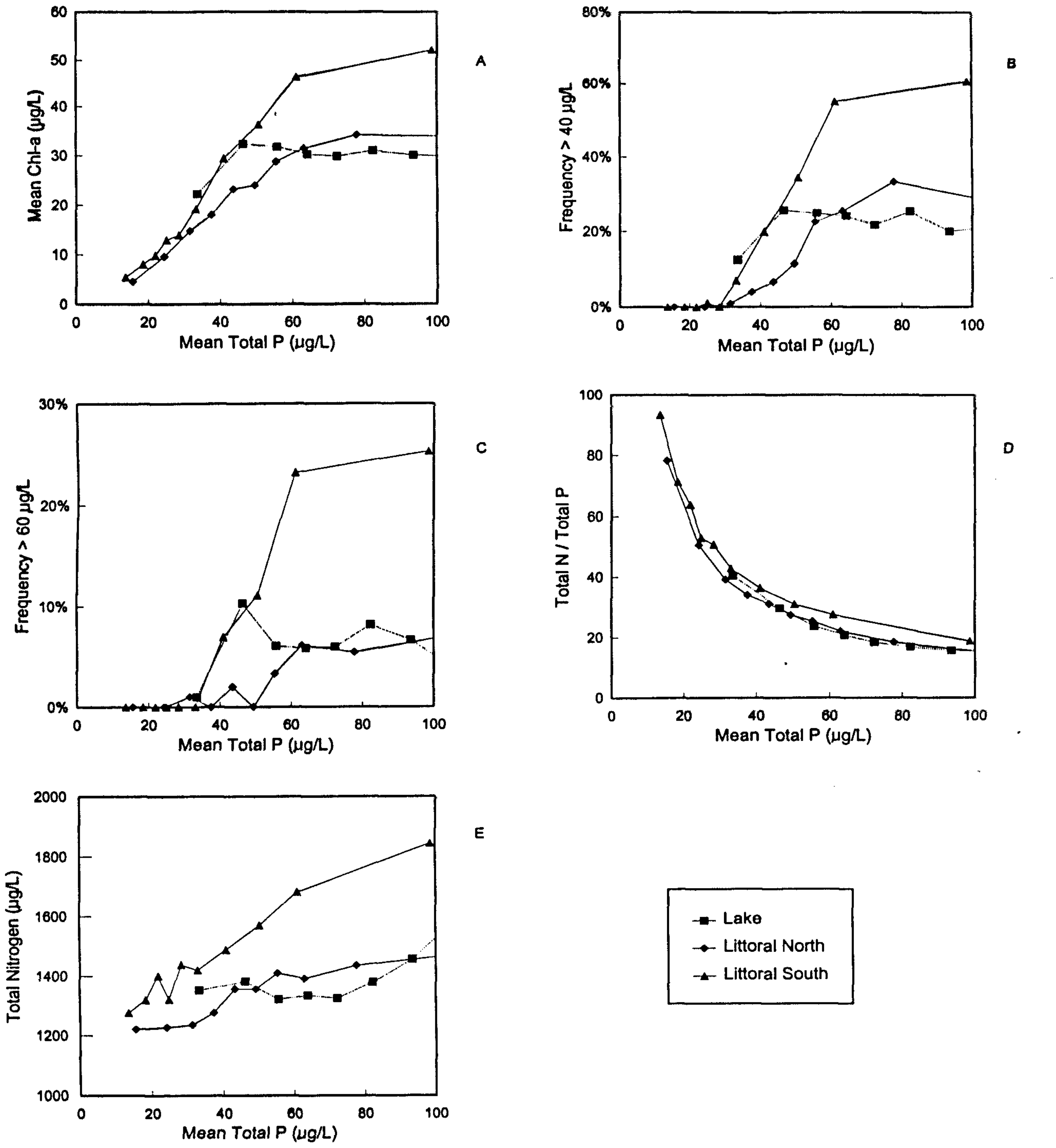

Figure 3.—The effects of station location on relationships between chlorophyll *a* and total phosphorus concentrations (A), the frequency of >40µg L^{-1} blooms and total phosphorus concentrations (B), the frequency of >60µg L^{-1} blooms and total phosphorus concentrations (C), total nitrogen/phosphorus ratios and total phosphorus concentrations (D), and total nitrogen and total phosphorus concentrations (E).

than 1% of the observations. At higher phosphorus levels, frequencies exceeding both the 40 and 60 µg L^{-1} thresholds increased to 60% and 25%, respectively. Further increases in bloom frequency were not apparent at phosphorus concentrations exceeding 60 µg L^{-1}.

Comparison of Regional Responses

Mean chlorophyll *a* concentrations, frequencies of chlorophyll a events exceeding 30, 40, and 60 µg L^{-1}, total nitrogen concentrations, and total nitrogen/

phosphorus ratios were plotted against total phosphorus in order to better illustrate inter-regional variation, and to elucidate possible controlling factors.

Regional variation in the response of bloom frequencies to phosphorus are evident (Fig. 3a-c). At phosphorus concentrations exceeding 60 μg L^{-1}, the frequency or risk of a 40 μg L^{-1} algal bloom averages 19% in the open lake, 28% in the north littoral region, and 60% in the south littoral region. In the same phosphorus range, the risk of a 60 μg L^{-1} bloom averaged 5%, 7%, and 27%, respectively.

The phosphorus intercept (the concentration below which blooms were not detected), was on the order of 30 to 35 μg L^{-1} at the littoral sites for 40 to 60 μg L^{-1} bloom criteria. The intercept was not definable for the lake stations because of their higher phosphorus range.

Regional differences in bloom response to phosphorus may be related to variations in nitrogen, particularly in the higher phosphorus range. In a given phosphorus interval, both the total nitrogen concentrations and total nitrogen/phosphorus ratios were consistently higher in the south littoral zone (Fig. 3d-e), where the highest bloom frequencies also were observed. At phosphorus concentrations exceeding 60 μg L^{-1}, nitrogen values averaged 300-400 μg L^{-1} higher in the south. Assuming a chlorophyll a/nitrogen ratio of 7 in algal cells (Bowie et al. 1985), this excess nitrogen could account for an additional 43-57 μg L^{-1} of chlorophyll *a* if all of it were incorporated into biomass.

In the 0 to 100 μg L^{-1} phosphorus range, the total nitrogen/phosphorus ratio decreased with increasing phosphorus concentration, but remained above 15 in all three lake regions (Fig 3d). In the highest phosphorus interval (90th to 100th percentiles), total nitrogen/phosphorus ratios averaged 13 at the lake stations, 12 in the north littoral, and 19 in the south littoral zone.

Effects of nitrogen limitation on chlorophyll *a* response to phosphorus have been observed in northern lakes and United States reservoirs at total nitrogen/phosphorus ratios below 12 (Dillon and Rigler 1974, Walker 1984, 1985a). In samples containing less than 5 μg L^{-1} chlorophyll *a*, organic nitrogen concentrations averaged 1,310 μg L^{-1} in the open lake, 1,230 μg L^{-1} in the north littoral zone, and 1,310 μg L^{-1} in the south littoral zone. It is possible that this portion of the total nitrogen pool is largely associated with humic material and is unavailable to algae. This unavailability might cause nitrogen limitation of algal growth at higher total nitrogen/phosphorus ratios than would otherwise occur. Walker (1985b) identified an analogous "nitrogen intercept" of 150 μg L^{-1} while developing empirical models for predicting chlorophyll *a* as a function of phosphorus and nitrogen in U.S.A. Corps of Engineer reservoirs. It is possible that the higher nitrogen intercept for Lake Okeechobee (near 1,300 μg L^{-1}) reflects a greater importance of nitrogen associated with humic materials.

The role of nitrogen is further complicated by the potential for nitrogen fixation by blue-green algae; higher total nitrogen values may reflect more nitrogen fixation, as well as higher external nitrogen inputs. Presently, nitrogen fixation is estimated to account for up to 30% of daily nitrogen inputs to the lake from all sources, including tributary discharges and precipitation (Phlips and Ihnat, 1995). Although the management significance of nitrogen is unclear, variations in nitrogen concentrations and total nitrogen/phosphorus ratios may partially explain the observed spatial variations in chlorophyll a response to phosphorus.

Management Significance

The data support the view (Canfield and Hoyer 1988) that conditions in the open water zone of Lake Okeechobee are insensitive to reductions in phosphorus concentrations, although a pronounced sensitivity is indicated for the littoral region, especially the south, where SFWMD monitoring data recently have documented intense algal blooms. In this region, which is also one of the most intensively utilized for recreational fishing, reductions in bloom frequencies likely would occur in response to reductions in lake water phosphorus concentrations.

Nonpoint-source pollution control programs in the Lake Okeechobee watershed have focused on phosphorus reduction. To the extent that nitrogen is important in the littoral zone, incidental reductions in nitrogen loads might seem to provide additional benefits. However, that strategy should be approached with caution. If the effect is a greater reduction in nitrogen concentrations relative to phosphorus, there might be a resulting increase in relative abundance of nitrogen-fixing cyanobacteria (Smith et al. 1995). Because of the importance of internal cycling and transport processes, additional modeling efforts are needed to predict responses of phosphorus, nitrogen, and bloom frequencies to reductions in external loads.

References

Aldridge, F. J., E. J. Phlips, and C. L. Schelske. 1995. The use of nutrient enrichment bioassays to test for spatial and temporal distribution of limiting factors affecting phytoplankton dynamics in Lake Okeechobee, Florida. Arch. Hydrobiol. Beih. Ergebn. Limnol. 45:177-190.

Bowie, G. L., W. B. Mills, D. P. Porcella, C. L. Campbell, J. R. Pagenkopf, G. L. Rupp, K. L. Johnson, P. W. H. Chan, S. A. Gherini and C. E. Chamberlin. 1985. Rates, constants, and kinetics formulations in surface water modeling. EPA/600/3-85/040 US Environmental Protection Agency. Athens, Georgia.

Canfield, D. E. and M. V. Hoyer. 1988. The eutrophication of Lake Okeechobee. Lake Reserv. Manage. 4:91-99.

Carlson, R. E. 1977. A trophic state index for lakes. Limnol. Oceanogr. 22:361-369.

Dillon, R. J. and F. H. Rigler. 1974. The phosphorus-chlorophyll relationship in lakes. Limnol. Oceanogr. 19: 767-773.

Flaig, E. G. and K. E. Havens. 1995. Historical trends in the Lake Okeechobee ecosystem. I. Land use and nutrient loading. Arch. Hydrobiol. Suppl. 107: 1-24.

Gleason, P.J. 1984. Environments of South Florida present and past. Miami Geographical Society, Coral Gables, FL, USA.

Gleason, P. J. and P. A. Stone. 1975. Prehistoric trophic level status and possible cultural influences on the enrichment of Lake Okeechobee. Report, Central and Southern Florida Flood Control District, West Palm Beach, Florida.

Havens, K. E. 1994a. Seasonal and spatial variation in nutrient limitation in a shallow sub-tropical lake (Lake Okeechobee, Florida, USA) as evidenced by trophic state index deviations. Arch. Hydrobiol. 131: 39-53.

Havens, K. E. 1994b. Relationships of annual chlorophyll *a* means, maxima and algal bloom frequencies in a shallow eutrophic lake (Lake Okeechobee, Florida, USA). Lake Reserv. Manage. 10: 133-138.

Heiskary, S. and W. W. Walker. 1988. Developing phosphorus criteria for Minnesota lakes. Lake Reserv. Manage. 4:1-10.

James, R. T., B. I. Jones and V. H. Smith. 1995. Historical trends in the Lake Okeechobee ecosystem. II. nutrient budgets. Arch. Hydrobiol. Suppl. 107: 25-47.

Lind. O. T., T. T. Terrell, and B. L. Kimmel. 1993. Problems in reservoir trophic state classification and implications for reservoir management. p. 57-67. *In* J. G. Tundisi, and A. Duncan (eds). Comparative Reservoir Limnology and Water Quality Management, Kluwer Academic Publ., The Netherlands.

Philips, E.J., F.J. Aldridge, P. Hansen, P. V. Zimba, J. Ihnat, M. Conroy and P. Ritter. 1993. Spatial and temporal variability of trophic state parameters in a shallow subtropical lake (Lake Okeechobee, Florida, USA). Arch. Hydrobiol. 128:437-458.

Philips, E. J. and J. Ihnat. 1995. Planktonic nitrogen fixation in a shallow subtropical lake (Lake Okeechobee, Florida, USA). Arch. Hydrobiol. Beih. Ergebn. Limnol. 45: 191-202.

Smeltzer, E., W. W. Walker, and V. Garrison. 1989. Eleven years of lake eutrophication monitoring in Vermont: a critical evaluation. Enhancing States Lake Manage. Prog., U.S. Environmental Protection Agency and North American Lake Management Society, p. 53-62.

Smith, V., B. L. Jones, R.T. James and K. E. Havens. 1995. Historical trends in the Lake Okeechobee ecosystem. IV. Nitrogen:phosphorus ratios, cyanobacterial dominance, and nitrogen fixation potential. Arch. Hydrobiol. Suppl. 107: 71.88.

Stoermer, E. F., N. A. Andersen and C. L. Schelske. 1992. Diatom succession in the recent sediments of Lake Okeechobee, Florida, USA. Diatom Res. 7:367-386.

Snedecor, G. W. and W. G. Cochran. 1989. Statistical methods (8th ed.). Iowa State University Press, Ames, Iowa.

Strickland, J. D. H. and T. R. Parsons. 1968. A practical handbook of sea water analysis. Fisheries Research Board of Canada.

U.S.E.P.A. 1979. Methods for chemical analysis of water and wastes. United States Environmental Protection Agency, Washington, DC.

U.S.E.P.A. 1987. Handbook of methods for acid deposition studies. United States Environmental Protection Agency, Washington, D.C.

Walker, W. W. 1984. Empirical prediction of chlorophyll in reservoirs. Lake Reserv. Manage., Proceedings of Third Annual Conference, North American Lake Managment Society, Knoxville, Tennessee, p. 292-297.

Walker, W. W. 1985a. Empirical methods for predicting eutrophication in impoundments, report 3, model refinements. USAE Waterways Experiment Station, Vicksburg, Mississippi, Technical Report E-81-9.

Walker, W. W. 1985b. Statistical bases for mean chlorophyll *a* criteria. Lake Reserv. Manage., Proceedings of Fourth Annual Conference, North American Lake Management Society, McAfee, New Jersey, p. 57-62.

Walker, W. W. 1987. Cross-tabulation as a tool for analyzing large monitoring data bases. Monitoring, Modeling, and Mediating Water Quality. Proc. American Water Resources Association Conference, Syracuse, New York.

Walmsley, R. D. 1984. A chlorophyll *a* trophic status classification system for South African reservoirs. J. Environ. Quality 13: 97-104.