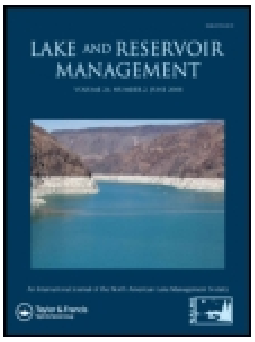

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Summer Fluctuations in Planktonic Chlorophyll a Concentrations in Lake Okeechobee, Florida: The Influence of Lake Levels

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ABSTRACT

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During summer (May-October), a positive relationship was evident between lake water levels and chlorophyll *a* concentrations in littoral and littoral:pelagic interface regions of Lake Okeechobee. High water levels in synergy with the large size (1830 km^2), shallow depth (Z_x = 2.7 m), and unique bottom configuration of Lake Okeechobee appeared to facilitate greater horizontal mixing and circulation which resulted in higher phosphorus concentrations in a portion of the littoral zone. In shallow littoral regions where light penetration was sufficient, an empirical link between phosphorus and chlorophyll *a* was evident. East-to-west and north-to-south gradients of phosphorus extended from hard-bottom littoral regions to the open-water pelagic zone located over soft, phosphorus-laden flocculent muds, and these gradients were more pronounced at low lake levels. Phosphorus loading from tributaries only affected algal concentrations in a small portion of the lake. A higher water level regulation schedule was implemented in 1978 to augment water supplies and this increased lake levels when precipitation was sufficient. A slightly lower lake level regulation schedule might reduce the frequency of hypereutrophic algal blooms in nearshore and littoral areas.

Key Words: hypereutrophic, wind, phosphorus, chlorophyll *a*, algae, lake levels.

Lake Okeechobee (26°58′ N, 80°50′ W) is the second largest lake within the continental United States and represents a valuable natural resource to the region. The lake serves as the primary drinking water supply for 75,000 inhabitants, and the sport and commercial fishery is valued at $28 million (Bell 1987). The lake serves as a secondary source of water for the southeast urban coast of Florida (population 4,500,000) during drought as water can be delivered to recharge local aquifers via an extensive series of canals and pump stations. In addition, water from Lake Okeechobee is used to irrigate crops in a 300,000 ha region south of the lake. During heavy precipitation, water from surrounding lands can be back-pumped against gravity into the lake to alleviate local flooding.

Interest in the cultural eutrophication of Lake Okeechobee has increased as total phosphorus (TP) concentrations rose from 50 mg/m^3 in the early 1970s to 120 mg/m^3 in 1988 (Janus et al. 1990). Phosphorus loading rates are considerably higher than natural levels due to agricultural runoff and averaged between 156 and 480 mg TP/m^2/yr from 1974 and 1987 (Janus et al. 1990). The South Florida Water Management District (SFWMD 1989) attributed higher TP concentrations to excessive anthropogenic loading and is attempting to decrease external phosphorus loading by 40%.

Conflicting interpretations were expressed concerning attempts to reduce phosphorus loading into Lake Okeechobee and subsequent impact on algal biomass (Canfield and Hoyer 1988, Schelske 1989). In August 1986 a 300 km^2 blue-green algal bloom comprised of primarily *Anabaena circinalis* caused invertebrate mortality due to oxygen depletion and release of ammonia, but no fish kills were observed (Jones 1987). This event accelerated efforts to explain phytoplankton dynamics and the highly variable trophic conditions that, at times, ranged from oligotrophy (<3 mg chlorophyll *a*/m^3) to extreme hypereutrophy (>90 mg chlorophyll *a*/m^3). For example, on June 2, 1988, chlorophyll *a* concentrations were 5 and 185 mg/m^3 at two sampling stations that were only 6 km apart.

The objective of this paper was to determine factors related to the wide spatial and temporal variation observed in planktonic chlorophyll *a* concentrations during summer months (May-October) in Lake Okeechobee.

Description of Lake Okeechobee

The morphometry of Lake Okeechobee is unique to North America because of the lake's large size (1830 km^2), shallow water depth (Z_x = 2.7 m), and a north-south and east-west fetch of 54 and 47 km, respectively (Fig. 1). A levee was built around the lake for flood control, and with the exception of one creek, all inflows and outflows are controlled by structures. Improvements were made to the levee over time to allow for greater release of water from the lake during wet periods. Between 1972 and 1978, minimum and maximum regulation levels were established at 4.3 and 4.7 m above mean sea level (msl), respectively. In 1978, the regulation schedule was increased to a 4.7 m msl minimum and a 5.3 m msl maximum to provide greater water supply. Between 1974 and 1989, lake levels fluctuated 2.6 m during extreme wet and dry periods (Fig. 2). This fluctuation resulted in a 50 and 160% difference in lake surface area and volume, respectively.

Aquatic macrophytes cover about 23% of the lake area at the regulated minimum pool elevation of 4.7 m or higher. Flocculent, unconsolidated muds comprise 44% of the bottom of the deeper portions of the lake and highest concentrations of sediment phosphorus are found in this region (Reddy and Graetz 1989). Maceina and Soballe (1990) found wind resuspension of mud-bottom sediments was an important determinant of seasonal and average annual limnological conditions in the pelagic zone of the lake. The remaining lake bottom is composed of sand, limestone, shell, and peat. A limestone outcropping exists in the southern pelagic region extending 8-12 km offshore between stations L6 and L7 (Fig. 1).

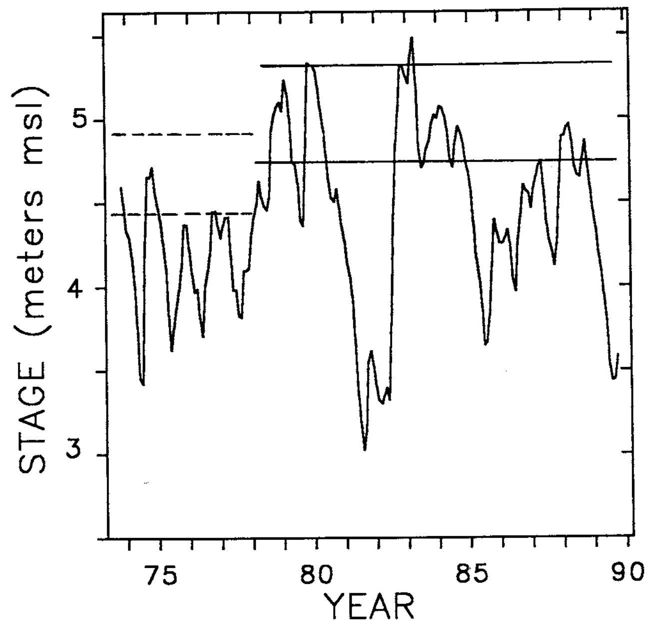

Figure 2.—Mean monthly lake stage (m msl) in Lake Okeechobee from 1974 to 1989. Dashed lines indicate the minimum and maximum regulation schedule from 1973 to April 1978. The lake level regulation schedule was raised after April 1978 (solid lines).

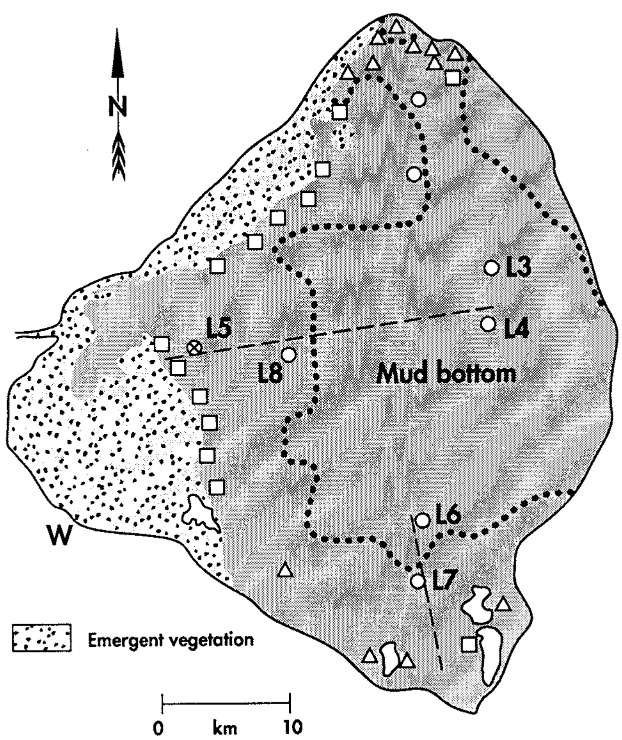

Figure 1.—Map of Lake Okeechobee showing the location of limnological stations and the weather station (W). Open circles represent the open-water pelagic region (○), and the circle with the x represents the nearshore pelagic zone (⊗). Squares (□) and triangles (Δ) represent littoral stations with the squares indicating where triplicate samples were taken. Dashed lines indicate locations of west-to-east and south-to-north transects. The dotted line delineates hard bottom from mud bottom.

Methods

Surface water samples (0.5 m) were collected from eight stations in the pelagic zone usually once per month between September 1974 and September 1989 as part of a monitoring program conducted by the SFWMD (Fig. 1). Samples were not taken during all months and chlorophyll *a* concentrations (CHLA) were not determined from 1977 to 1979. In August 1986, the SFWMD initiated a sampling program at the littoral:pelagic zone interface (now defined as the littoral zone) in the northern, western, and southern regions of the lake (Fig. 1). Subsurface water samples (0.5 m) from the littoral zone were collected twice a month between May and October from 36 to 46 stations.

Water samples were analyzed for TP, soluble reactive phosphorus (SRP), and turbidity. Water was filtered through a 0.45 μm membrane filter immediately upon collection to determine SRP. Color and phosphorus species concentrations were determined colormetrically (APHA 1971, U.S. EPA 1979). This change in techniques in 1979 specified a change in reagents to determine TP which resulted in a small increase (7%) in TP concentrations (D. E. Canfield, Univ. Florida, pers. commun., 1990). The discrepancy was not considered in this analysis. Turbidity was determined from 1974 to April 1978 with a Jackson Turbidimeter (JTU). After that, turbidity was recorded using a nephelometer (NTU). JTU values were converted to NTUs (Maceina and Soballe 1990). Specific conductance was measured in the field with a Hydrolab Surveyor II.

For CHLA determinations, water was filtered onto a Whatman GF/C glass fiber filter (1.2 μm) and neutralized with a $MgCO_3$ solution. Filters were frozen, then homogenized for 1-2 min, and chlorophyll extracted with 90% acetone. Chlorophyll extracts were centrifuged for 15 min and supernatants placed in 1 cm cuvetts for absorption measurements with a spectrophotometer. CHLA was corrected for phaeophytin using the equations of Parsons and Strickland (1963).

Monthly wind speeds were obtained from the NOAA (1974-89) at a site near the southeast perimeter of the lake (Fig. 1). Stage was measured by the U.S. Army Corps of Engineers from three stations and water budget data were collected from all major (N = 27) inflows and outflows from the lake (Federico et al. 1981). Monthly nutrient loads were calculated from daily inflow and from monthly or biweekly measurements of TP. Federico et al. (1981) estimated that 98% of the phosphorus load entering the lake was measured.

From previous work (Shireman et al. 1990, Maceina and Soballe 1990) and personal observation, I speculated that high levels of nonalgal turbidity may limit algal growth in the pelagic zone by restricting light penetration. Concentrations of nonalgal turbidity were computed by subtracting algal turbidity from turbidity using the procedures of Maceina and Soballe (1989). Algal turbidity (ALGTURB) was computed from the equation:

$$\text{ALGTURB} = 0.0125(\text{CHLA}) + 0.000696(\text{CHLA})^2 \quad (r^2 = 0.94) \quad (1)$$

By using previous studies (Federico et al. 1981, Schelske 1989) and inspection of mean annual limnological concentrations, I divided Lake Okeechobee into five distinct limnological regions: 1) open-water pelagic, 2) nearshore pelagic, 3) north littoral, 4) west littoral, and 5) south littoral (Fig. 1). Between May and October, hypereutrophic algal blooms (CHLA > 40 mg/m³) were observed (Maceina and Soballe 1988, 1989) which corresponded to warmer water temperatures and lower wind speeds (Maceina and Soballe 1990). In addition, 63% of the tributary inflow (hence nutrient loading) occurred between May and October. Thus, only limnological data collected during these months were analyzed.

Effects of tributary inflow and nutrients on limnological characteristics were examined. From 1974 to 1987, phosphorus inflow into the lake averaged 205 mg/m³ (Maceina, unpubl.) and was higher than ambient lake water (Table 1). Since specific load data were not available from the SFWMD after September 1987, precise tributary nutrient loading effects on CHLA in the littoral regions could not be addressed. However, over the period of record (1974-1987), flow-weighted phosphorus loads (mg P/m³) remained relatively consistent over time and the correlation between inflow and phosphorus load was greater than 0.9. Thus, mean monthly tributary inflow was assumed to be indicative of phosphorus loading. The influence of total tributary inflow entering the lake on TP in the open-water pelagic region was assessed. Tributary inflow from specific structures was assigned to the limnological regions that were located in close proximity, and potential effects on regional limnological conditions were examined. Further detail of the location, description, hydrologic, and chemical characteristics of water entering the lake can be found in Federico et al. (1981).

To assess potential horizontal phosphorus movement throughout the lake, two gradients or transects were examined to determine the impact of wind, stage, and tributary inflow on TP (Fig. 1). 1) A west-to-east transect was designated from a) four western littoral stations, b) the nearshore pelagic station (L5), c) an open-water pelagic station near the

Table 1.—Mean values for chlorophyll *a* (CHLA, mg/m³), total phosphorus (TP, mg/m³), soluble reactive phosphorus (SRP, mg/m³), specific conductance (COND, μS/cm), nonalgal turbidity (NTU), and color (Pt-Co units) in five regions of Lake Okeechobee during the summer (May-October) from August 1986 to September 1989. N = sample size. Mean values in rows followed by the same letter were not significantly (P > 0.05) different.

Parameter	Region: Open-water pelagic	Nearshore pelagic	North littoral	West littoral	South littoral
CHLA	28[a]	32[a]	36[a]	29[a]	29[a]
TP	90[a]	52[b]	81[a]	56[b]	52[b]
SRP	24[a]	9[c]	19[b]	8[c]	10[c]
COND	571[b]	556[b]	493[c]	568[b]	613[a]
Non-algal turbidity	18[a]	9[b]	7[bc]	5[c]	5[c]
Color	33[c]	32[c]	50[a]	45[ab]	42[b]
N	215	30	374	734	187

center of the lake (L8), and d) two open-water pelagic stations (L3, L4) located on the eastern edge of the lake. 2) A south-to-north transect was assigned from a) south littoral stations, b) an open-water pelagic station (L7), and c) an open-water pelagic station (L6) north of L7.

Since water quality stations were permanent and sampled over time, a repeated measures split-plot analysis of variance design (Steel and Torrie 1960) was used to test for spatial and temporal differences in limnological variables. Chi-square analysis was used to test for homogeneity of various algal conditions among different regions. To describe CHLA:TP relationships, data were transformed to $\log_{10}$ values and correlations computed. Linear and multiple regression equations, and correlation coefficients were computed to describe relationships among variables. Covariate analysis was used to detect differences in slope and intercept values among simple linear regression equations.

Results

Spatial Distribution of Limnological Parameters

During the summer months between 1986 and 1989 when the period of record was comparable among regions, average CHLA concentrations did not vary ($P > 0.10$) among regions (Table 1). However, significant heterogeneity ($X^2 = 27.27$, $P < 0.01$) in the frequency of algal concentrations representing oligotrophy to eutrophy (CHLA <40 mg/m^3), hypereutrophy (CHLA 40-90 mg/m^3), and extreme hypereutrophy (CHLA >90 mg/m^3) was observed among regions (Table 2). The lake-wide frequency of hypereutrophic CHLA concentrations was 27% and was highest in the north littoral region (32%) and lowest in the open-water pelagic zone (17%).

Although average CHLA concentrations did not vary among regions, differences in other limnological variables were evident (Table 1). At the nearshore pelagic, west, and south littoral regions, TP and SRP concentrations were less than those observed in the open-pelagic and north littoral regions. In the north littoral zone, lower conductivity and higher phosphorus concentrations were due, in part, to tributary inflow and anthropogenic loading as 60% of the phosphorus inflow to the lake entered from the northern basins. In the open-water pelagic region, higher phosphorus concentrations were associated with greater levels of nonalgal turbidity due to wind resuspension of soft flocculent bottom muds (Maceina and Soballe 1990).

Chlorophyll:Phosphorus Relationships

Maceina and Soballe (1988, 1989) found that in regions where phosphorus and nitrogen were correlated to CHLA, phosphorus appeared as the limiting nutrient. In addition, total nitrogen-to-total phosphorus ratios usually exceeded 17 in Lake Okeechobee (Maceina and Soballe 1988, 1989) which suggested phosphorus limitation to algal growth (Sakamoto 1966).

In the open-water pelagic region, no relationship ($r = 0.10$) was evident between algal biomass and TP. The lack of an empirical relationship between CHLA and TP in the open-water pelagic region was likely due to light limitation (Shireman et al. 1990). In this region, wind resuspension of flocculent, soft-bottom sediments readily occurred when wind speeds exceeded 20 km/hour (Maceina unpubl.). This increased nonalgal turbidity and phosphorus (Table 1) in the water column, but lowered light penetration compared to other regions of the lake.

In the north littoral region, a weak, but significant ($P < 0.01$) relationship ($r = 0.36$) was evident between CHLA and TP (Fig. 3). Ample supplies of SRP were available to algae (Table 1) and the minimum detection level (<4 mg/m^3) for SRP was only observed for 23% of the samples. Although water clarity conditions in the summer at the north littoral region were similar to the nearshore pelagic region, phosphorus levels were only weakly linked to differences in algal biomass in this region, suggesting that this nutrient was not limiting algal biomass. Primary source of this phosphorus was tributary inflow as average monthly TP and SRP in this region were correlated to total monthly inflow ($r = 0.56$, $P < 0.01$) and not to nonalgal turbidity (r

Table 2.—Frequency of occurrence for various chlorophyll *a* concentrations (CHLA) observed in Lake Okeechobee at five different limnological regions during the summer. Data are from August 1986 to September 1989. N = 1536.

CHLA level (mg/m³)	Region: Open pelagic	Nearshore pelagic	North littoral	West littoral	South littoral	Average frequency
<40	0.828	0.767	0.678	0.726	0.738	0.731
40-90	0.167	0.233	0.297	0.238	0.219	0.241
>90	0.005	0.000	0.024	0.035	0.043	0.028

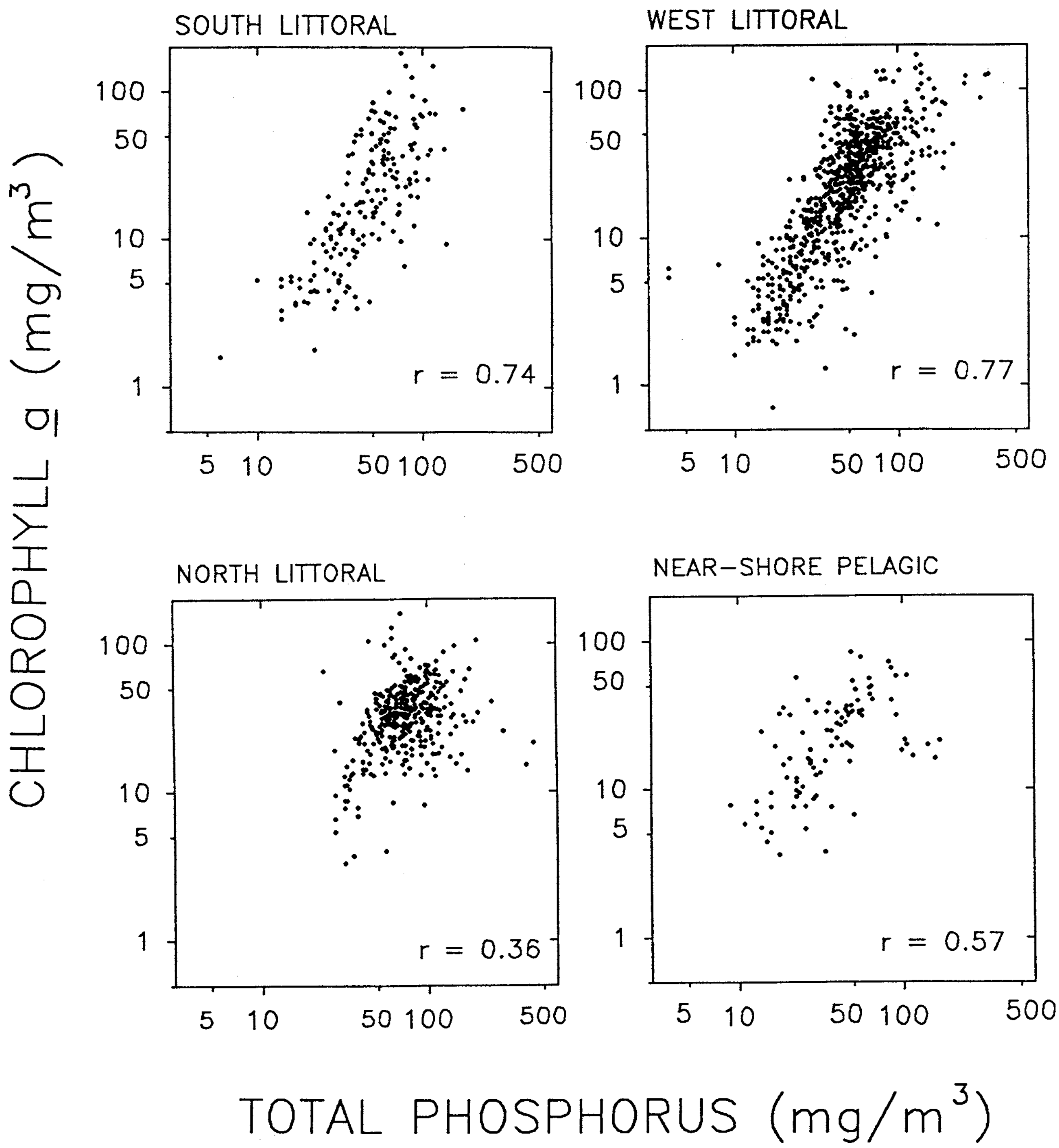

Figure 3.—Log_{10}-log_{10} plots of chlorophyll *a* vs. total phosphorus during the summer (May-October) from four limnological regions in Lake Okeechobee.

= –0.07 and –0.23, P >0.5). Tributary inflow from the northern basins was high in phosphorus and likely contributed to the highest frequency of hypereutrophic algal conditions in the north littoral measured in the lake (Table 2).

In the nearshore pelagic region located 12 km from phosphorus-rich mud sediments, TP was positively correlated (r = 0.57, P <0.01) to CHLA (Fig. 3). Improved light conditions existed as nonalgal turbidity was much lower compared to the open-water region (Table 1). In the south and west littoral regions, relationships (r = 0.74 to 0.77, P <0.01) were evident between CHLA and TP (Fig. 3). Lowest levels of nonalgal turbidity were observed in the west and south littoral regions and were associated with greater light penetration in the water column. The strongest correlative links between CHLA and TP were evident in these two regions in summer (Fig. 3). Detection levels of SRP were observed for 50-71% of water samples collected from these three littoral and nearshore regions suggesting greater algal uptake and/or SRP lower concentrations.

Thus, a gradient was observed in Lake Okeechobee as the empirical link between CHLA and TP increased from the open-pelagic region, westward and southward, to the littoral regions. This corresponded to a reduction in nonalgal turbidity and phosphorus concentrations, but improved light conditions for algal growth nearer to the littoral regions located over firm bottom.

Temporal Variation in Algal Biomass

Although average CHLA concentrations did not vary between regions, temporal fluctuations in algal biomass were observed in four of five regions (Fig. 4). In the littoral regions, hypereutrophic conditions were prevalent in 1988 as average monthly CHLA exceeded 40 mg/m^3. Variation in CHLA was greatest in the southern and western littoral regions from 1986-87 to 1989 as mean monthly CHLA ranged from 7 to 76 and 9 to 55 mg/m^3, respectively. Among years, mean summer CHLA levels were significantly ($P < 0.05$) different, and were highest in 1988 and lowest in 1989 in these two littoral regions. In 1988, hypereutrophic algal conditions were observed for 49% of the samples collected in these two regions compared to only 6% in 1989. Temporal variation in CHLA was more homogeneous in the north littoral region as mean monthly CHLA varied from 21 to 51 mg/m^3. Annual frequency of occurrence of hypereutrophic algal levels ranged from 23 to 42%. CHLA concentrations were significantly ($P < 0.05$) higher in the summers of 1986 and 1988 compared to 1989 in the north littoral region.

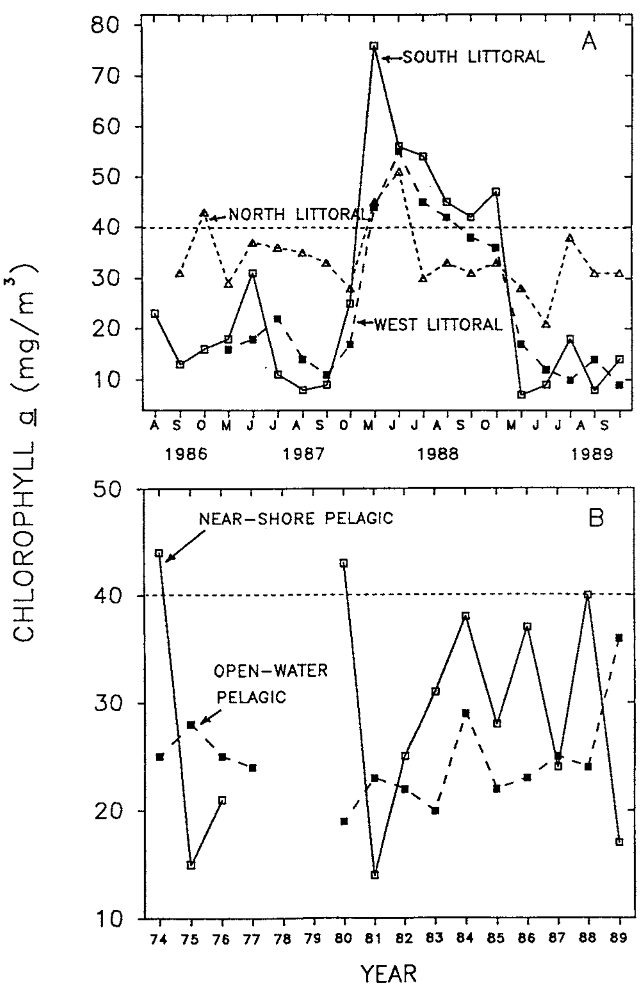

Figure 4.—Mean monthly chlorophyll *a* concentrations at three littoral regions (A) during summer (May-October). Data were collected from August 1986 to September 1989. Mean seasonal chlorophyll *a* concentrations taken at two pelagic regions (B) during summer (May-October). Data were collected from 1974 to 1989.

At the nearshore pelagic region approximately 2.5 km from the western littoral region, average CHLA exceeded 40 mg/m^3 in 1974, 1980, and 1988 (Fig. 4). Mean CHLA as low as 14 mg/m^3 was measured in summer 1981, and significant ($P < 0.05$) year-to-year differences occurred. In the open-water pelagic region, average summer levels of CHLA ranged from 19 to 36 mg/m^3, but no significant ($P > 0.10$) annual differences were evident.

Factors Related to the Temporal Variation in Algal Biomass During Summer

Extreme variation in CHLA concentrations that occurred at the western and southern littoral regions between 1986 and 1989 was associated with fluctuations in lake level. At these regions, mean monthly lake stage during the summer was positively correlated ($r = 0.65$ to 0.78, $P < 0.01$) to average CHLA levels (Fig. 5). Wind speed was also positively correlated to mean monthly CHLA and TP ($r = 0.43$ to 0.65, $P < 0.10$) in these two regions. However, monthly wind speed and stage were also positively correlated ($r = 0.60$, $P < 0.01$), multicolinearity existed among variables.

To isolate effects of wind from stage on limnological variables, three discrete lake stages were chosen: 1) low <3.95 m msl, 2) medium 3.96-4.49 m msl, and 3) high >4.50 m msl. Between 1986 and 1989 for all three lake stage groups, average annual TP levels did not vary ($P < 0.10$) in the eastern open-water pelagic region (Fig. 6). At high lake stages, the coefficient of determination for the regression between TP and distance from the edge of the littoral zone (0 km) to the eastern pelagic zone (32 km offshore) decreased. The intercept and slope coefficients were significantly ($P < 0.05$) higher and lower at high lake levels, respectively, than those values computed at the low and medium stages. This indicated greater homogeneity of TP along this transect at high water levels (Fig. 6).

Along this west-to-east gradient at low lake

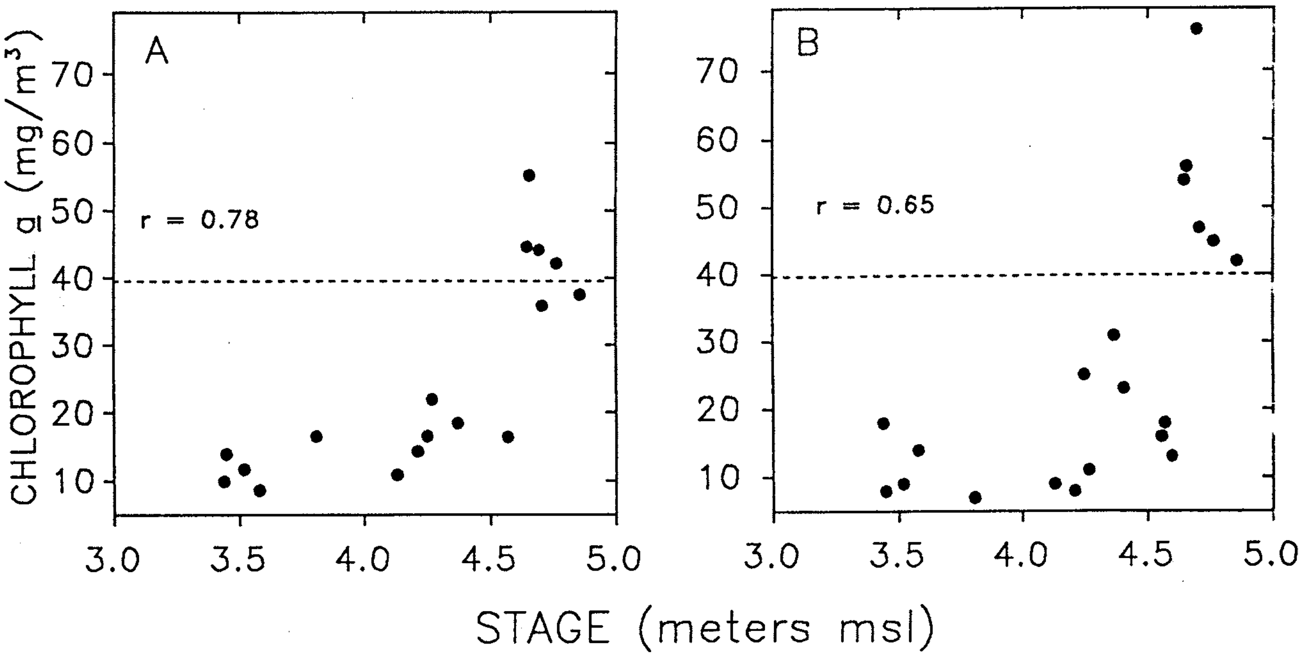

Figure 5.—Mean monthly chlorophyll *a*-to-lake stage level relationships during summer (May-October) from west (A) and south (B) littoral regions in Lake Okeechobee.

stages, partial regression coefficients indicated that wind speed was a negligible variable explaining spatial differences in TP (Table 3). At lake stages >3.95 m msl, wind speed was a significant regressor of TP concentrations along the gradient and the predominant variable at higher lake stages. For these analyses, monthly inflow, and inflow lagged 1, 2, and 3 months, did not affect (P >0.25) TP concentrations (Table 3) or CHLA at different lake stages along the gradient.

Table 3.—Multiple regression equations predicting mean monthly total phosphorus concentrations (TP) from tributary inflow (Q), wind speed (WIND), and the distance between the edge of the littoral zone and the open-water pelagic zone (DISTANCE) along west-to-east and south-to-north transects. See Figs. 6 and 7.

Transect	Water level (m msl)	Total model R^2	Independent variable[a]	Partial R^2	Probability
West-to-east	<3.95	0.71	DISTANCE	65	<0.01
			WIND	4	0.11
			Q	2	0.28
	3.95-4.49	0.75	DISTANCE	41	<0.01
			WIND	33	0.04
			Q	1	0.48
	>4.50	0.41	DISTANCE	16	0.02
			WIND	24	<0.01
			Q	1	0.52
South-to-north	<3.95	0.89	DISTANCE	84	<0.01
			WIND	5	0.06
			Q	<1	0.68
	3.95-4.49	0.77	DISTANCE	66	<0.01
			WIND	9	0.13
			Q	2	0.34
	>4.50	0.59	DISTANCE	29	<0.01
			WIND	27	<0.01
			Q	3	0.24

[a]DISTANCE and WIND demonstrated positive (P <0.10) slopes as regressors of TP except along the north-to-south transect at water levels <3.95 m msl when wind demonstrated a negative slope coefficient due to covariation among independent variables.

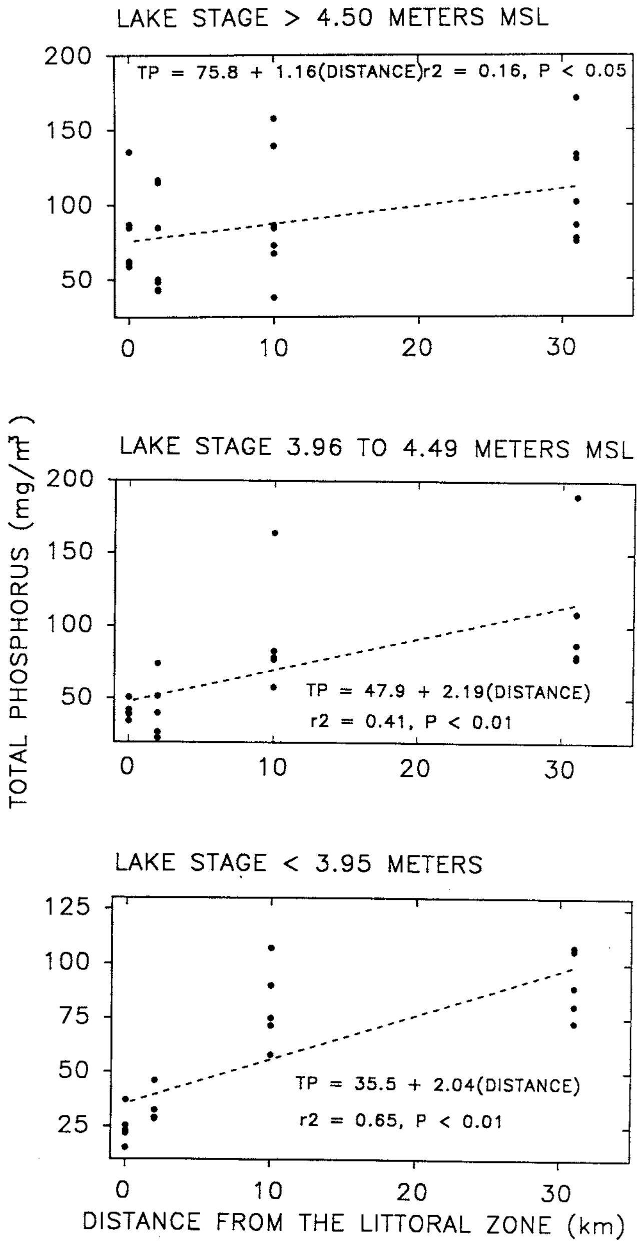

Figure 6.—Mean monthly summer total phosphorus concentrations along a west-to-east (left to right) gradient at three different lake stages.

Similar results were observed along a south-to-north gradient that extended 12 km offshore (Fig. 7). At all three lake stages, a positive relationship between TP and the distance from the littoral to pelagic zone existed. However, this relationship weakened at increased water levels as TP concentrations were greater in the south littoral region at high lake stages than at low lake levels. When lake levels were high, wind speed and distance each explained an equal proportion of the variation in mean monthly TP concentrations along the south-to-north gradient (Table 3). At low stages, wind was a negligible variable accounting for differences in TP. Tributary inflow to the south end and inflow lagged 1, 2, and 3 months were not related ($P > 0.24$) to TP concentrations in this region.

In addition, the same phenomena was evident for the long-term data base (1974-1989) as phosphorus concentrations were more homogeneous at high water from western (station L5) to eastern (stations L3, L4; see Fig. 1) portions of the lake. Higher phosphorus concentrations occurred in the eastern open-water pelagic zone compared to the nearshore pelagic region. A negative relationship ($r = -0.70$, $P < 0.01$) was evident between the percent difference in average TP concentrations between the eastern pelagic and nearshore pelagic regions and lake

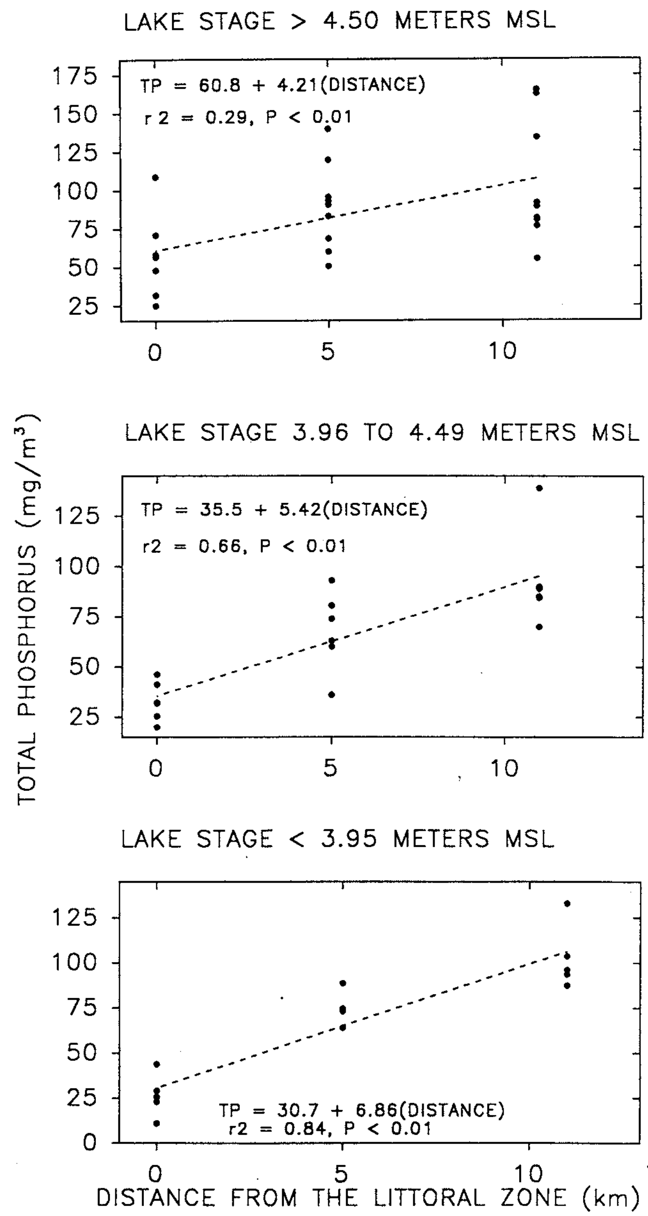

Figure 7.—Mean monthly summer total phosphorus concentrations along a south-to-north (left to right) gradient at three different lake stages.

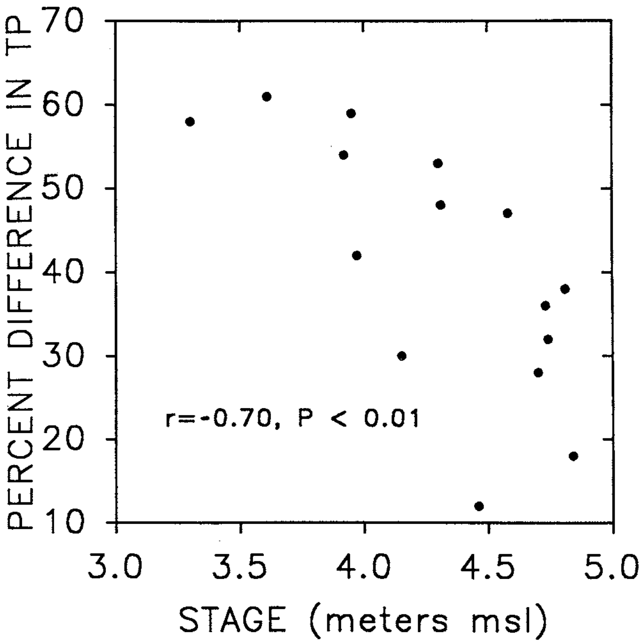

Figure 8.—Percent difference in mean summer total phosphorus (TP) concentrations between the eastern pelagic region and the nearshore pelagic region as a function of lake stage.

level (Fig. 8). Lake stages below 3.9 m msl resulted in a TP difference of greater than 50% between the two areas. These regions were separated by a hard sand bottom that extended eastward from the littoral zone. For 16 summer mean values, tributary inflow from the western watershed was not related (r = 0.33, P = 0.20) to TP at the nearshore pelagic region.

Consonant to the west and south littoral regions, a positive correlation (r = 0.80, P <0.01) was computed between lake stage and mean summer CHLA concentrations at the nearshore pelagic region. Lake stages >4.5 m msl during the summer in 1974, 1980, 1984, and 1988 were associated with average CHLA concentrations exceeding or approximating 40 mg/m³ (Fig. 9). With improved light conditions in this region, TP was correlated to CHLA and higher TP concentrations occurred in this region when lake levels were greater.

Assessment

In a vast portion of the open-water pelagic zone that overlies profundal muds in Lake Okeechobee, algal levels did not vary with phosphorus concentrations. Possibly, high levels of wind resuspended non-algal turbidity restricted algal productivity in this region during the summer due to light limitation. Similar phenomena were observed by Hoyer and Jones (1983) and Macias and Lind (1990) in other waterbodies as high levels of inorganic suspended solids were associated with elevated phosphorus levels, decreased light, and lower algal biomass. Schelske (1989) reported SRP was available and not utilized by algae in the pelagic zone of Lake Okeechobee indicating that phosphorus was not limiting to algal production. Canfield and Hoyer (1988) found that although phosphorus concentrations increased in the lake over time, algal biomass remained relatively constant in the pelagic zone.

High tributary inflow supplied ample phosphorus to the north littoral region which weakened the relationship between CHLA and TP. In order to achieve a 40% reduction in phosphorus loading, the SFWMD (1989) proposed a maximum allowable flow-weighted concentration of 180 mg P/m³ at all structures by 1993. This reduction would be primarily achieved in the northern basins as three structures provided 8% of inflow to the lake, but 35% of the tributary phosphorus. The greatest frequency of hypereutrophic algal concentrations occurred in the northern littoral region. Thus, a reduction in phosphorus loading could potentially reduce algal concentrations in this region.

My analyses suggested that the transport of phosphorus-laden water from the offshore open-water pelagic region to the southern and western littoral zones was the dominant factor affecting algal concentrations in these areas. In limnological regions located over firm bottom where light penetration in the water column was greater, empirical relationships between CHLA and phosphorus were evident. Higher lake stages occurred in Lake Okeechobee since 1978 and this, in conjunction with greater TP and SRP concentrations after 1979, probably resulted in higher algal levels at the west and south littoral regions. At high water levels,

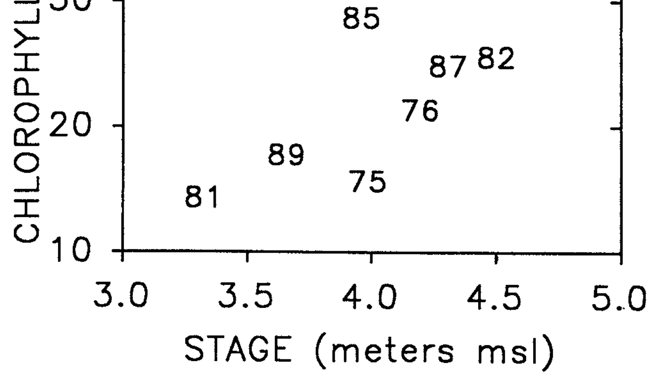

Figure 9.—Mean summer chlorophyll *a* and lake stage values for the nearshore pelagic region (L5). Numeric values represent years.

hypereutrophic CHLA concentrations were recorded at the nearshore pelagic region in 1974 and 1980. Although CHLA concentrations were not measured in the littoral zone prior to 1986, the nearshore pelagic region displayed limnological characteristics intermediate between the open-water pelagic and the west-south littoral regions. At lake levels greater than 4.5 m msl, the probability of exceeding 40 mg CHLA/m^3 increased in these three regions.

Based on average annual data, Canfield and Hoyer (1988) and Janus et al. (1990) speculated that higher lake stages may influence P levels via trophic upsurge by reflooding the littoral zone which remineralized and transported phosphorus to the pelagic zone. Thus, this form of internal phosphorus loading may promote algal growth in the clearer waters of the littoral:pelagic interface instead of internal loading from offshore wind-resuspended phosphorus. However, Maceina and Soballe (1990) found that higher wind speeds were associated with greater precipitation and tributary inflow and these latter two variables increased lake levels. Wind speed was a better predictor of average annual TP concentrations than stage. Partial regression coefficients indicated stage was not a significant predictor of TP after accounting for the variation in TP associated with wind.

Specific mechanisms to explain this lake stage-to-algal biomass relationship could not be addressed with monitoring data collected by the SFWMD. I hypothesized, however, the hard sand bottom:mud bottom interface located 4-12 km from the eastern edge of the west littoral zone (Fig. 1) formed a greater impediment to movement of wind-driven suspended particles containing phosphorus at low stages compared to high stages. Similarly, at the south end of the lake at lower lake levels, the limestone outcropping also appeared to obstruct phosphorus movement between the open-water pelagic and the south littoral region during summer.

At deeper water depths in Lake Okeechobee, greater wave heights, lengths, and velocity would be expected in this lake with a long fetch (Thijsse 1952, Hutchinson 1957), and this could promote the transport of phosphorus into the west and south littoral regions. Thus, elevated algal levels would be expected if light was sufficient. In support of this, wind speed affected and accounted for some of the variation in the TP-to-distance relationships along the east-to-west and the north-to-south gradients at higher lake stages (>4.5 m msl), but not when lake levels were low (<3.96 m msl).

The Lake Okeechobee regulation schedule developed by the U.S. Army Corps of Engineers in 1972 (Trimble and Marban 1988) maintained summer lake levels below 4.5 m msl (Fig. 10). Hence, this earlier schedule potentially reduced the frequency and magnitude of hypereutrophic algal conditions in the west and south littoral regions. Under the current regulation schedule, a minimum elevation of 4.73 is allowed by June 1 which can rise over time to 5.34 m msl by October 1 (Fig. 10). If the regulation schedule is not achieved, then releases are only made for irrigation, drinking water, and maintenance of salinity in the St. Lucie estuary on the Atlantic east coast.

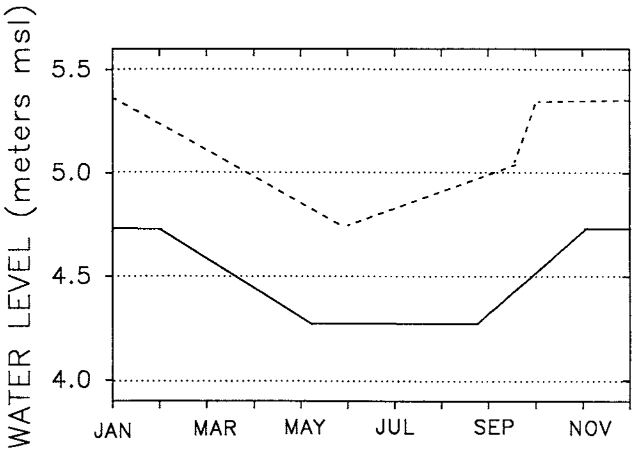

Figure 10.—Lake level regulations schedules for Lake Okeechobee in 1972 (solid line) and 1978 (dashed line). Elevations are in m above mean sea level (msl).

A General Design Memorandum (U.S. ACE 1954) predicted future human and agricultural growth in the region and proposed raising the lake to meet water supply demands. The current 4.73-5.34 m msl schedule was proposed in 1954 and this report ultimately recommended a 5.95-6.55 m msl lake level after improvements were made to the levee and maximum outflow capacity increased. If such water levels were attained, this analysis suggests that algal levels would rise and hypereutrophic conditions would more likely occur compared to when the lake is less than 4.5 m msl. In addition, high water levels could reduce macrophyte abundance due to flooding and light limitation. Protection of the 40,000 ha vegetated littoral zone is a goal of the SFWMD (1989) for maintenance of fish and wildlife populations.

In conclusion, unless the 40% reduction in phosphorus loading results in lower phosphorus levels in the water column, then current maintenance of regulation water levels will likely result in a greater frequency of hypereutrophic algal levels when water input to the lake is sufficient. Future research efforts should focus on water and nutrient movement and wind-resuspension in relation to lake level to provide a mechanistic explanation for my observations. If the objective of the SFWMD is to prevent hypereutrophic conditions from occurring in Lake Okeechobee, then a lower regulation schedule should be considered and alternative water supplies identified or water conservation promoted. Certainly, any increase in lake levels from the current regulation schedule should be approached with caution.

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