Lake and Reservoir Management 18(3):227-238, 2002

Development of a Total Phosphorus Concentration Goal in the TMDL Process for Lake Okeechobee, Florida (USA)

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ABSTRACT

Havens, K. E. and W. W. Walker, Jr. 2002. Development of a total phosphorus concentration goal in the TDML process for Lake Okeechobee, Florida (USA). Lake and Reserv. Manage. 18(3):227-238.

This paper describes the approach used to establish an in-lake concentration goal for total phosphorus in the total maximum daily load (TMDL) process carried out by the Florida Department of Environmental Protection (FDEP) for Lake Okeechobee. In order to specify the in-lake phosphorus goal, the first consideration was to identify the most suitable indicator of "imbalance in flora or fauna" pursuant to Subsection 62-302.530(48)(b) of the Florida Administrative Code (FAC). Blooms of cyanobacteria (blue-green algae) were previously identified as one of the most serious symptoms of cultural eutrophication in this lake, and there existed a large data set relating total phosphorus to chlorophyll a, which can be used to index the occurrence of blooms. We evaluated the occurrence of samples with chlorophyll a in excess of 40 $\mu g \cdot L^{-1}$ (moderate bloom) and 60 $\mu g \cdot L^{-1}$ (severe bloom) as a function of total phosphorus concentrations in order to specify the lake phosphorus goal. A cross-tabulation procedure was used to identify a range of total phosphorus corresponding to a rapid increase in bloom frequency. Near-shore and pelagic data sets were sorted by total phosphorus and each was sub-divided into ten intervals of approximately equal sample size. When total phosphorus averaged below 30 $\mu g \cdot L^{-1}$, the probability of moderate blooms was below 3% and the probability of severe blooms was near 1% in the near-shore region. When total phosphorus averaged between 35 and 45 $\mu g \cdot L^{-1}$, frequencies were between 15 and 35% for moderate blooms and between 2 and 5% for severe blooms, respectively. Pelagic bloom frequencies also increased with increasing phosphorus, but the response was considerably muted relative to that observed in the near-shore area. To ensure an acceptable level of risk in terms of algal bloom occurrence, a total phosphorus goal of 40 $\mu g \cdot L^{-1}$ was selected by the FDEP. Mass-balance modeling results (Walker 2000) indicate that an average external phosphorus load of 140 metric tons y^{1} (compared to a 1973 to 1999 mean of 498 metric tons y^{1}) would provide a long-term average phosphorus concentration in the lake's pelagic zone of 40 $\mu g \cdot L^{-1}$. Based on our empirical model relating bloom frequencies to total phosphorus, it is predicted that under these TMDL loading conditions, bloom frequencies in the near-shore region would be 2 to 9%, as compared to 5 to 33% under present conditions. Successful implementation of the TDML should significantly reduce near-shore bloom frequencies in Lake Okeechobee.

Key Words: total maximum daily load, total phosphorus, algal blooms, chlorophyll a.

Section 303(d) of the Federal Clean Water Act requires that each state develop total maximum daily loads (TMDL) for chemical constituents identified as pollutants in impaired water bodies by the United States Environmental Protection Agency. The State of Florida submitted a list of impaired waters in 1998, which included Lake Okeechobee. Phosphorus (along with elevated levels of un-ionized ammonia, chloride, fecal coliform bacteria, iron, and low levels of dissolved oxygen) was identified as a priority pollutant. Further, the State of Florida concluded that phosphorus is the "predominant reason for impairment" of the lake (FDEP 2000) and began the process of developing a total phosphorus TMDL in spring 2000. Consistent with the Clean Water Act (CWA), the TMDL is being developed to ensure that the lake can meet applicable water quality standards for its designated uses. This takes into consideration a "margin of safety" to ensure protection of the resource (USEPA 1999). Because Lake Okeechobee is a Class I water body (potable water supply), the standard for use impairment is that concentration of phosphorus that does not "cause an imbalance in natural populations of aquatic flora or fauna" (FAC 62-302.530(48)(b).

A proposed TMDL was developed by the Florida Department of Environmental Protection (FDEP 2000) based on input from a group of lake and watershed experts (TMDL Technical Advisory Committee) and other interested parties who attended a series of public meetings during the process. Identification of a total phosphorus TMDL included: (a) selection of an indicator for ecological imbalance; (b) identification of a lake water phosphorus concentration that prevents this imbalance; and (c) identification of the phosphorus loading rate necessary to achieve the concentration, taking into consideration natural variability of the system. In this paper we describe the process for items (a) and (b), which resulted in the proposed lake water total phosphorus goal. The documentation of modeling related to item (c) may be obtained at www2.shore.net/~wwwalker or by contacting Dr. Walker.

Site Description

Lake Okeechobee is a large (1,800 km^2), shallow (mean depth ~2.7 m), multi-function ecosystem located in Florida, USA at 27°00' N Latitude and 80°50' W Longitude (Fig. 1). It is the center of the inter-connected Florida Everglades ecosystem, and it also is a central feature of a regional flood control project constructed in the mid-1900s by the US Army Corp of Engineers. Lake Okeechobee includes a large western marsh region within its diked perimeter; the open water area (the focus of this paper) includes a central pelagic region and a near-shore region. The open water area of Lake Okeechobee is considered highly eutrophic based on its concentrations of total phosphorus, which average approximately 100 µg·L^{-1}, and its low Secchi disk transparencies, which average near 0.3 m (James et al. 1995). Filamentous cyanobacteria dominate the phytoplankton (Havens et al. 1998) and large-scale surface blooms have occurred (Jones 1987). The rate of eutrophication increased dramatically in the last 30 years, and this is largely attributed to high inputs of phosphorus from agricultural sources in the watershed (Steinman et al. 1999). Total phosphorus concentrations in the lake more than doubled between the 1970s and 1990s. This trend may have been facilitated by increased lake stage that occurred during that same period (Canfield and Hoyer 1988, Havens 1997).

A number of ecological changes have been linked with the accelerated eutrophication of Lake Okeechobee (Havens et al. 1996a). These include: an increase in the frequency and intensity of algal blooms (Havens et al. 1995); a shift in the benthic invertebrate community towards pollutant tolerant taxa (Warren et al. 1995); and a spread of cattail along the western lakeshore (Richardson and Harris 1995). The lake sediments have accumulated a large quantity (in excess of 30,000 metric tons) of phosphorus, and as a result of resuspension, diffusion, and bioturbation, the internal phosphorus recycling rates now equal in magnitude the external loads (Olila and Reddy 1993, Moore et al. 1998).

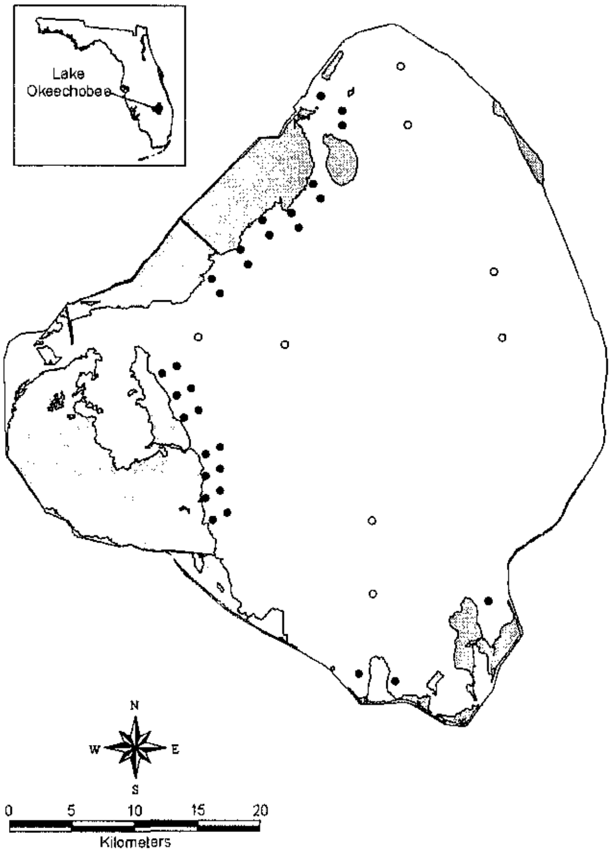

Figure 1.–Map of Lake Okeechobee showing the locations of water quality sampling sites in the pelagic (open circles) and near-shore (closed circles) regions. The shaded area is littoral wetland.

Selection of an Indicator for Ecological Imbalance

As noted above, there have been a number of ecological changes in Lake Okeechobee during recent decades and any one or a number of these might indicate an imbalance. The ecological indicators that could potentially be used to set the TMDL for Lake

Okeechobee must answer two key questions: (1) Is the observed change a response to increased phosphorus inputs? (2) Are the available data sufficient to allow one to establish a quantitative relationship between the indicator and total phosphorus, so that a concentration standard can be identified for the TMDL? Only in the case of algal blooms were both answers affirmative (Table 1).

The occurrence of algal blooms in Lake Okeechobee has been evaluated previously (e.g., Havens et al. 1994, Havens et al. 1995, Walker and Havens 1995) based on the frequency of chlorophyll a concentrations in excess of 40 μg · L-1. This chlorophyll a concentration has a history of reflecting impaired use in other lakes and reservoirs. Heiskary and Walker (1988), for example, found that Minnesota lakes were considered "swimming impaired" by users when chlorophyll a concentrations were between 20 and 60 μg · L-1. The median concentration in this category of impairment was 40 μg · L-1. The lower limits of categories "no swimming" and "high algae" also were near 40 mg · L-1. The South Florida Water Management District (SFWMD) has collected chlorophyll a data in the pelagic region of Lake Okeechobee since the early 1970s, along with data on total phosphorus and other water quality parameters (James et al. 1995). There are over 6,300 paired chlorophyll a and total phosphorus observations available for developing quantitative relationships, as well as evidence that in high-use areas of the lake (for both humans and wildlife), these attributes are strongly correlated (Walker and Havens 1995). Hence, it is possible to establish a quantitative relationship between algal blooms and total phosphorus, something that cannot be done for any of the other ecological indicators. Algal blooms also reflect very clearly an ecological imbalance in the system because their proliferation and subsequent die-off have been shown to cause macro-invertebrate kills in the near-shore area of this lake (Jones 1987) and a myriad of harmful ecological impacts in other lake ecosystems (Paerl 1988). For these reasons, it was determined that algal blooms represented the best indicator of use impairment upon which to base a total phosphorus TMDL for Lake Okeechobee.

Table 1.–Changes in Lake Okeechobee possibly linked to phosphorus enrichment, and their potential for goal setting in the TMDL process.

Change	Response to Nutrients?	Quantitative Data?	Utility in Setting TMDL
Increased occurrence of *Typha* (cattail) along lakeward edge of littoral zone, where community is exposed to nutrient-rich water (Richardson et al. 1995).	Yes, consistent with effects of phosphorus enrichment observed in Florida Everglades (Newman et al. 1996).	No site-specific data are available.	Suggest a nutrient effect but cannot be used to set a specific numeric goal. Might be related in part to water depth.
Increased dominance of pollution-tolerant oligochaetes in lake sediments and loss of diversity (Warren et al. 1995).	Yes, consistent with effects of cultural eutrophication documented in other lakes (Brinkhurst 1974).	Yes, but only from widely separated times during eutrophication period (1970, 73, 91).	Indicate a nutrient effect but cannot be used to set a goal due to lack of consistent historic data.
Large-scale loss of submerged plant beds during late 1990s (Havens et al. 2001).	This ecological change is linked to a prolonged period of high lake stage. However, blooms may contribute to the problem by attenuating light.	n/a	Not useful for setting a phosphorus TMDL because primary driving variable is light availability.
Shift from diatom to cyanobacteria (blue-green algae) dominance in the phytoplankton (Havens et al. 1996).	Typical response of lakes to enrichment with phosphorus and development of low total nitrogen to phosphorus ratio (Smith 1983).	Yes, but only from late 1970s and post-1988.	Results indicate a nutrient enrichment effect, but cannot be used to set a numeric goal due to lack of consistent historical data.
Increased frequency of high chlorophyll concentrations and algal blooms (Jones 1987, Havens et al. 1994).	Typical response of lakes to enrichment with phosphorus (Schindler 1977).	Yes, monthly or more frequent data from a large number of sites since 1970s. Quantitative models exist linking blooms with phosphorus.	At this time these data are the most applicable for setting a phosphorus goal.

Spatial Variation in the Chlorophyll-Phosphorus Relationship

There is considerable spatial variation in chlorophyll-phosphorus relationships in Lake Okeechobee (Phlips et al. 1993a). The major difference occurs between a mud-bottomed central region and a sand and peat-bottomed near-shore region located just offshore of the littoral marsh. In the pelagic region, high concentrations of re-suspended sediments result in high total phosphorus concentrations, but there is a low biomass of phytoplankton due to light limitation. In the near-shore region, light limitation occurs at times, but during much of the year there is an adequate amount of underwater irradiance for net growth of phytoplankton, and nutrients are limiting to growth. Most often the primary limiting nutrient is nitrogen, but co-limitation by nitrogen and phosphorus also is observed, especially when phosphorus concentrations are relatively low (Aldridge et al. 1995, Phlips et al. 1997). As a result of this spatial variation, the relationship between algal bloom frequencies and total phosphorus is much stronger in the near-shore region than in the central pelagic zone, although that area does display a muted response. The setting of a total phosphorus concentration goal is focused primarily on the near-shore area, which corresponds to the area most heavily used by fish, wildlife, and society. Modeling results (see below) indicate that substantial reductions in phosphorus concentrations resulting from TMDL implementation will drive the system towards an increasingly phosphorus-limited state.

Phosphorus Goal Setting

In order to investigate relationships between algal bloom frequencies and total phosphorus concentrations in the central pelagic and near-shore zones, we used a cross-tabulation procedure similar to that applied by Heiskary and Walker (1988) and described in detail by Walker and Havens (1995). Chlorophyll *a* concentrations exceeding 40 and 60 $\mu g \cdot L^{-1}$ were used as bloom criteria. In contrast to traditional regression models, the cross-tabulation procedure makes no assumptions about the shape or functional form of the relationship between phosphorus concentrations and bloom frequencies. Data from the near-shore (30 stations) and pelagic (8 stations) regions were analyzed separately using the procedure described below. For the pelagic region, the period of record was 1973 to 1999, while for the near-shore region the period was 1987 to 1999. We considered using the same period of record data for both regions, but rejected that approach (i.e., omitting the pre-1986 pelagic data) because the lack of variation in pelagic total phosphorus since 1986 precluded finding the underlying relationship between phosphorus and blooms. The following reflects our sequential data analysis procedure.

(1) All samples (identified by station, date, and depth) with non-missing values for both total phosphorus and chlorophyll a were compiled.

(2) Data from each station were averaged by date because samples were taken occasionally at multiple depths from the generally well-mixed water column.

(3) The resulting data set was sorted by total phosphorus and divided into ten intervals of approximately equal sample sizes. To focus on phosphorus concentrations that are in the potentially growth-limiting range most relevant for development of a phosphorus goal, intervals with mean TP concentrations exceeding 100 $\mu g \cdot L^{-1}$ were excluded from the analysis. This removed approximately 10% of the observations from the analysis, and also eliminated a large amount of variation in bloom frequencies not associated with phosphorus.

(4)The mean concentration of total phosphorus was calculated for each interval, and frequencies were calculated for each interval as the percent of samples with chlorophyll *a* concentrations in excess of 40 and 60 $\mu g \cdot L^{-1}$.

(5)Mean ratios of total nitrogen to total phosphorus also were calculated for each interval, in order to provide supplementary information in support of the selected total phosphorus standard.

In considering the entire near-shore zone (30 stations) as a unit, compared to separate north and south regions, we obscure some of the variability in bloom risk that occurs in that part of the lake (Walker and Havens 1995). The data analysis carried out here gives rise to a bloom vs. phosphorus relationship that is intermediate to that observed in the north near-shore (less sensitive) and south littoral (more sensitive), but in general, provides an unbiased representation of that lake region.

Results and Discussion

In the near-shore region of Lake Okeechobee, total phosphorus concentration (1986 to 1999) ranged from <4 to 330 $\mu g \cdot L^{-1}$, with a median of 48 $\mu g \cdot L^{-1}$ and a mean of 56 $\mu g \cdot L^{-1}$. Chlorophyll *a* concentration ranged from <1 to 185 $\mu g \cdot L^{-1}$, with a median of 22 $\mu g \cdot L^{-1}$ and a mean of 26 $\mu g \cdot L^{-1}$. The data set includes

3,615 observations of total phosphorus and chlorophyll a. In the pelagic region, total phosphorus (1973 to 1999) ranged from 15 to 265 μg · L^{-1}, with a median concentration of 77 μg · L^{-1} and a mean of 87 μg · L^{-1}. Chlorophyll *a* ranged from <1 to 187 μg · L^{-1}, with a median concentration of 21 μg · L^{-1} and a mean of 25 μg · L^{-1}. The pelagic data set includes 2,720 observations.

Near-shore bloom frequencies (Fig. 2) increased with total phosphorus concentrations up to a certain point (approximately 60 μg · L^{-1} total phosphorus), beyond which a plateau in bloom frequencies was evident. We suspect that nitrogen and light limitation are the reasons for this plateau. A standard plot of chlorophyll a vs. total phosphorus in the near-shore region has this same tendency (Havens et al. 1999), and it is typical of what is observed in multi-lake data sets (Prairie et al. 1989, Mazumder and Havens 1999, Brown et al. 2000). Canfield (1983) showed that in Florida lakes, much of the residual variation can be explained by introducing nitrogen as a second variable in the regression model (Canfield 1983). In Lake Okeechobee, multivariate models with phosphorus and nitrogen provide only a small amount of additional predictive power (Mazumder and Havens 1999), suggesting that light limitation may be the more important factor. This is consistent with results of nutrient-addition bioassay studies carried out under different light levels (Phlips et al. 1997). Often when very high phosphorus concentrations occur, they are associated with high concentrations of abiotic seston particles (high total and non-volatile suspended solids), poor light conditions, and light limitation of phytoplankton. Where this occurs, the yield of chlorophyll *a* per unit of phosphorus is lower than expected based on the regression model derived from the larger population.

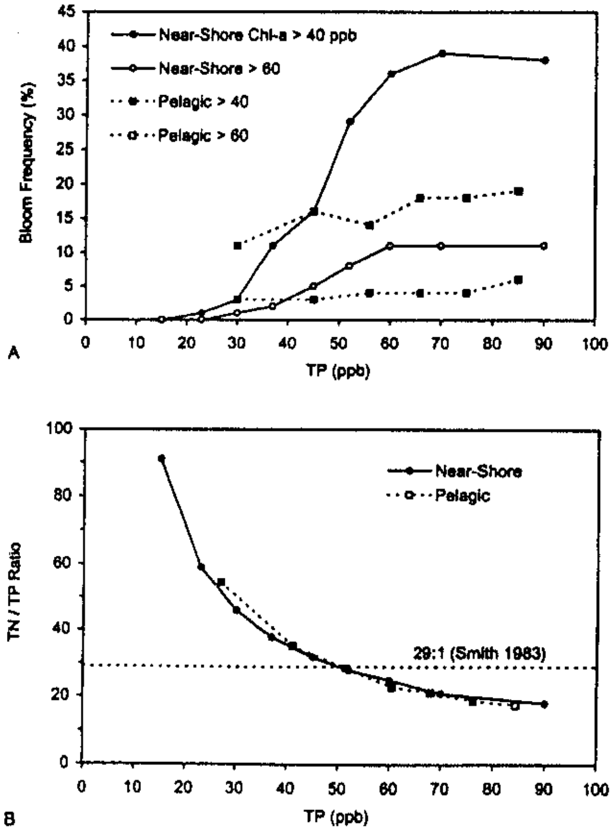

Figure 2.–Bloom frequencies versus total phosphorus concentrations, indicating the "risk" of algal blooms (chlorophyll a > 40 μg · L^{-1}) and extreme algal blooms (chlorophyll a > 60 μg · L^{-1}) at given total phosphorus concentrations in the near-shore and pelagic zones.

In the present study, at phosphorus concentrations of 30 μg · L^{-1} or below, chlorophyll *a* at near-shore stations exceeded the 40 μg · L^{-1} criterion in 3% of the samples and it exceeded 60 μg · L^{-1} in just 1% of samples; i.e., the "risk" of blooms was very low. An increasing frequency of blooms occurred in the total phosphorus interval between ca. 35 and 45 μg · L^{-1} with the most pronounced increase occurring between total phosphorus means of ca. 45 and 50 μg · L^{-1}. The maximal bloom frequency of 40% occurred in the interval with mean total phosphorus = 70 μg · L^{-1}. Bloom frequencies based on the 60 μg · L^{-1} chlorophyll criterion displayed a similar pattern in relation to total phosphorus, but only reached a maximum frequency of 10%. In the pelagic region the frequency of moderate and severe blooms also increased with increasing total phosphorus, but the response was very muted (note also that there are no <30 μg · L^{-1} total phosphorus intervals for this more eutrophic lake region). As indicated previously, the pelagic region is characterized by a frequent surplus of phosphorus and limitation by light.

Based upon the near-shore results, we can select a total phosphorus goal that will maintain a probability of moderate algal blooms (chlorophyll *a* < 40 μg · L^{-1}) below some specified level. The key question is: "What frequency of blooms constitutes an ecological imbalance?" Given that Lake Okeechobee always may have been somewhat eutrophic (Gleason and Stone 1975), it is not reasonable to specify a bloom frequency of zero as the goal. At some frequency, algal blooms may be a natural feature of the lake. The difficulty is in determining the natural frequency, since there were no quantitative data on phosphorus or chlorophyll *a* concentrations prior to the early 1970s. We restrict our analysis to finding the lowest *observed* frequency of blooms using existing data (1973 to 2000).

In a detailed analysis of chlorophyll *a* data from Lake Okeechobee, Havens et al. (1995) documented minimal bloom frequencies of 15 to 25% (based on the 40 μg · L^{-1} chlorophyll criterion) at two long-term monitoring stations located in the proximity of the near-shore region. Those frequencies were observed during

1980-82, and contrasted with maximal frequencies of 31 to 33% at the same locations in the 1990s. Based on our bloom frequency model, the historic low frequency of 15% corresponds to a total phosphorus concentration between 37 and 45 μg·L^{-1} (Fig. 2). The frequency of 25% corresponds to total phosphorus between 45 and 52 μg·L^{-1}. Hence, the identified range of total phosphorus corresponding with the lowest observed bloom frequencies in the near-shore zone is 37 to 52 μg·L^{-1}. Based on these results, and evidence that the lake was experiencing symptoms of cultural eutrophication prior to the early 1980s (FDA 1976), the FDEP identified a total phosphorus concentration of 40 μg · L^{-1} as the near-shore goal for preventing a "imbalance in flora or fauna."

Lake-Wide Phosphorus Goal

TMDL development involves modeling the response of lake phosphorus concentration in critical locations and seasons to variations in external phosphorus loads and other controlling factors. While the phosphorus goal is based primarily upon data from the near-shore region, existing mass-balance models predict average phosphorus concentrations in the pelagic zone (James et al. 1997, Pollman 2000, Walker 2000). In order to apply these models in the TMDL process, the relationship between pelagic and near-shore phosphorus concentrations must be considered.

As discussed by Maceina (1993) and Havens (1997), lake stage has an influence on spatial variability of phosphorus concentrations in the lake (Fig. 3A-B). When considering temporally paired data, near-shore phosphorus concentrations are below pelagic values at all stages. Phosphorus increases with stage in the near-shore region, but not in the pelagic region. The difference in total phosphorus between near-shore and pelagic regions varies from as much as 50-60 μg·L^{-1} when stage is low (near 12 ft NGVD) to as little as 20 μg·L^{-1} when stage is high (greater than 16 ft).

At least two mechanisms may explain these patterns. First, the bottom topography of the lake may limit horizontal transport of nutrients under low stage conditions. Along the south and west perimeter of the pelagic zone, approximately 10 km offshore, there is a reef of rock at a higher elevation than the surrounding lake bottom. When stage is less than ~14 ft NGVD, there may be relatively little mixing of water between the pelagic (the location of high internal phosphorus recycling) and near-shore regions. In contrast, this mixing may be enhanced at high stage, when the rock reef no longer serves as an effective barrier to water and nutrient transport. This hypothesis is supported both by empirical data (Maceina 1993) and modeling results (Sheng 1993). Another factor that may be important at low stage is uptake of phosphorus in the near-shore region by vascular plants and their attached epiphyton. Phlips et al. (1993b) observed an inverse relationship between the abundance of vascular plants and both water depth and plankton chlorophyll a in that region. Havens et al. (1996b) documented that planktonic and attached algae are limited by the same nutrients, and Hwang et al. (1998) documented high rates of phosphorus uptake by epiphyton under low stage, high irradiance conditions.

Because near-shore phosphorus concentrations

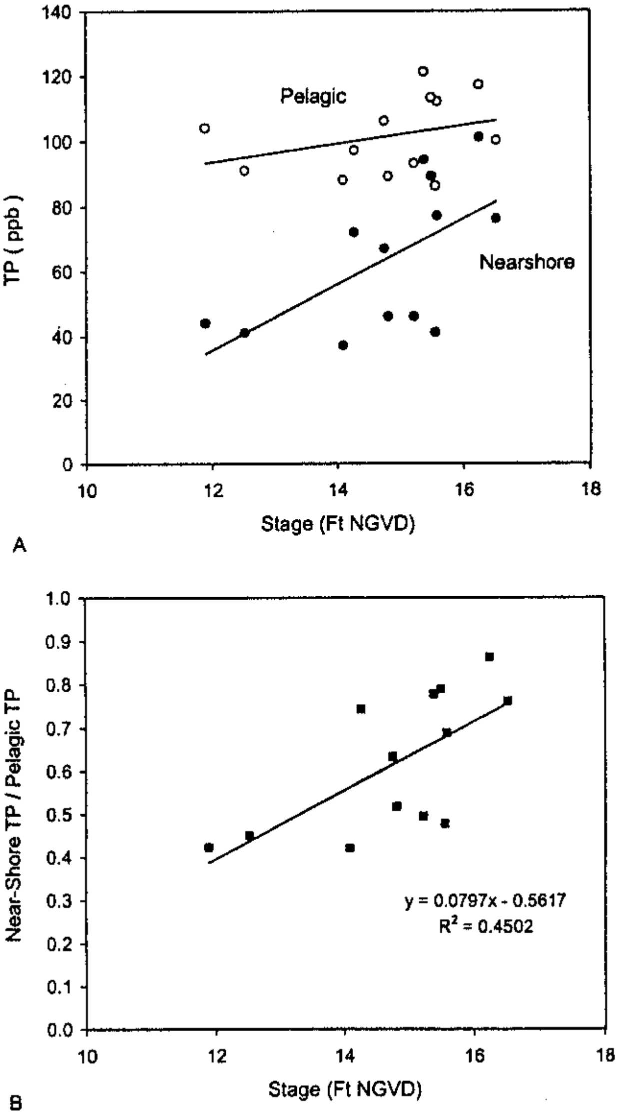

Figure 3.–Yearly mean total phosphorus concentrations versus lake stage for the pelagic (open symbols) and near-shore (filled symbols) regions of Lake Okeechobee (A), and the ratio of paired littoral and pelagic yearly means versus stage (B). Lines represent results of least-squares regression analysis.

are generally lower than pelagic values (particularly at low stage) and a margin of safety must be provided in the TMDL, the Technical Advisory Committee recommended that the 40 $\mu g \cdot L^{-1}$ near-shore total phosphorus goal should be extrapolated to the pelagic zone. The pelagic zone goal was expressed as a long-term-average phosphorus concentration of 40 $\mu g \cdot L^{-1}$ measured at eight pelagic monitoring stations (Fig. 1). The "long-term-average" is operationally defined using the 1973-1999 period of record containing the hydrologic and water quality data necessary for modeling lake water and phosphorus balances. Adoption of this goal by the FDEP enabled estimation of the TMDL using existing mass-balance models that predict phosphorus concentrations in the pelagic zone as a function of external phosphorus loads. Although the TMDL is computed to meet the pelagic-zone goal, it provides additional protection of the near-shore region, even in years when high lake stage results in mechanisms that favor increased concentrations of phosphorus.

Although not considered in the analyses presented here, it is noteworthy that the TMDL proposal also offers protection for the lake's western marsh. Under most lake stage conditions the marsh is hydrologically uncoupled from the open waters of the lake, since underwater currents tend to run parallel to the marsh-lake interface, rather than into the marsh itself (Jin et al. 2000). However, at high stage there may be considerable transport of water into the marsh (Havens 1997), such that with a reduced pelagic phosphorus concentration, marsh inputs and ecological impacts should be diminished. Additional research is needed to determine whether the combined effects of the TMDL, which addresses phosphorus, and the more regional Comprehensive Everglades Restoration Plan (USACE 1999), which also addresses lake stage, will protect the lake's marsh from ecological imbalance.

Forecasting Bloom Frequencies Under TMDL Conditions

Mass-balance modeling results indicate that an average external phosphorus load of 140 metric tons per year (relative to 1973-1999 mean of 498 metric tons yr^{-1}) would provide a long-term-average phosphorus concentration of 40 $\mu g \cdot L^{-1}$ in the pelagic zone. (FDEP 2000). Considerable year-to-year variance around the long-term mean is expected. Within the 1973-1999 period, the year-to-year standard deviation of the pelagic-mean total phosphorus concentration was 24% of the long-term mean and the maximum concentration was 140% of the mean. The following section evaluates potential effects of year-to-year variations in pelagic phosphorus concentrations and stage on bloom frequencies in the near-shore region under historical and potential future (TMDL) conditions. A caveat to the approach is that it assumes that correlations derived from recent data reflect causal linkages between blooms and total phosphorus, and that these linkages held in the past.

Consistent with results derived from cross-tabulating paired chlorophyll *a* and phosphorus samples, significant correlations between near-shore total phosphorus concentrations and bloom frequencies also are evident when the data are averaged by year (Figure 4 A-B). Regression models predict the first two moments of the chlorophyll *a* distribution (geometric mean, coefficient of variation (standard deviation of ln-transformed chlorophyll-*a* samples)) as a function of total phosphorus concentration. It is important to note that these data reflect averaged conditions, whereas the focus of previous analyses (and subsequent analyses below) were concerned with extreme observations (events described as blooms) and their frequency of occurrence.

Bloom frequencies can be predicted on a yearly basis assuming that spatial/temporal variations in near-shore chlorophyll *a* concentrations within each year follow a log-normal distribution (Walker 1985). Comparisons of observed and predicted frequencies of moderate and severe blooms as a function of phosphorus (Figure 4C) and year (Figure 4D) support the validity of this assumption. Results indicate that a near-shore total phosphorus concentration of 40 $\mu g \cdot L^{-1}$ corresponds to bloom frequencies of approximately 10 and 5% for the bloom criteria of 40 and 60 $\mu g \cdot L^{-1}$ chlorophyll *a*, respectively. The resulting equations for predicting bloom frequencies as a function of near-shore total phosphorus concentrations are summarized below:

$$\text{Freq (Chl a} > C^*) = 1 - \text{Normal}(Z^*) \qquad (1)$$

$$Z^* = \ln(C^* / GM) / S \qquad (2)$$

$$GM = 0.364\, P_N \qquad (r^2 = 0.63) \qquad (3)$$

$$S = 1.042 - 0.0056\, P_N \qquad (r^2 = 0.53) \qquad (4)$$

where,

C^* = bloom criterion (Chl *a* = 40 or 60 $\mu g \cdot L^{-1}$)

Normal = cumulative standard normal frequency distribution

Z^* = standard normal deviate

P_N = yearly mean near-shore total phosphorus concentration ($\mu g\ L^{-1}$)

GM = yearly geometric mean chlorophyll-a concentration ($\mu g \cdot L^{-1}$)

S = within-year standard deviation of natural log-transformed chlorophyll a

The above equations can be linked with the regression model in Fig. 3B (near-shore / pelagic total phosphorus vs. stage) to predict near-shore bloom frequencies as a function of pelagic mean total phosphorus and stage in any year:

$$P_N = (0.0797\text{Stage} - 0.562) * P_P \quad (r^2 = 0.71) \qquad (5)$$

where,

P_P = yearly mean pelagic total phosphorus ($\mu g \cdot L^{-1}$)

Stage = yearly mean stage (feet, NGVD)

We apply this methodology using yearly mean phosphorus concentrations in the pelagic and near-shore regions along with yearly mean stage for the 1973-1999 period of record used to derive the TMDL (FDEP 2000, and Fig. 5A). A corresponding series under TMDL conditions was developed by removing the long-term trend from the historical time series of pelagic phosphorus concentrations and then re-scaling the de-trended series so that it has a long-term (27-year) mean of 40 $\mu g \cdot L^{-1}$ (Fig. 5B). The near-shore predicted total phosphorus concentrations are calculated from the pelagic phosphorus means and stage using equation (5). Results indicate a range of 15 to 35 $\mu g \cdot L^{-1}$ in the

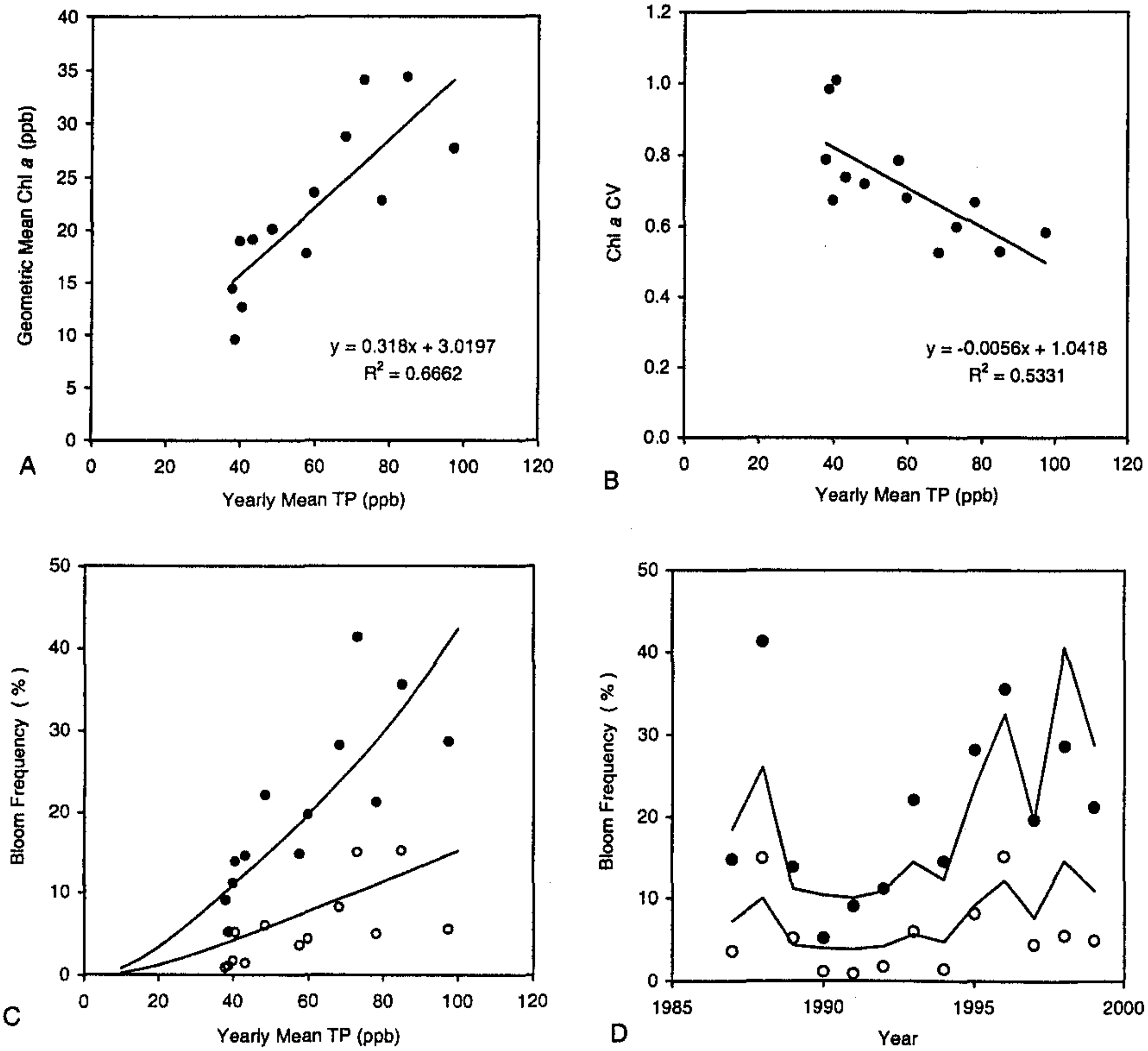

Figure 4.–Yearly geometric-mean chlorophyll (A) and coefficient of variation (B) correlated with yearly mean total phosphorus concentrations in the near-shore region. Near-shore bloom frequencies (C, D) predicted from total phosphorus concentrations using regression models (A, B) and assuming that the spatial/temporal distribution of chlorophyll a within follows a lognormal frequency distribution. Closed symbols correspond with frequencies of moderate (40 $\mu g \cdot L^{-1}$) blooms; open symbols indicate severe (60 $\mu g \cdot L^{-1}$) blooms. Lines are model predictions.

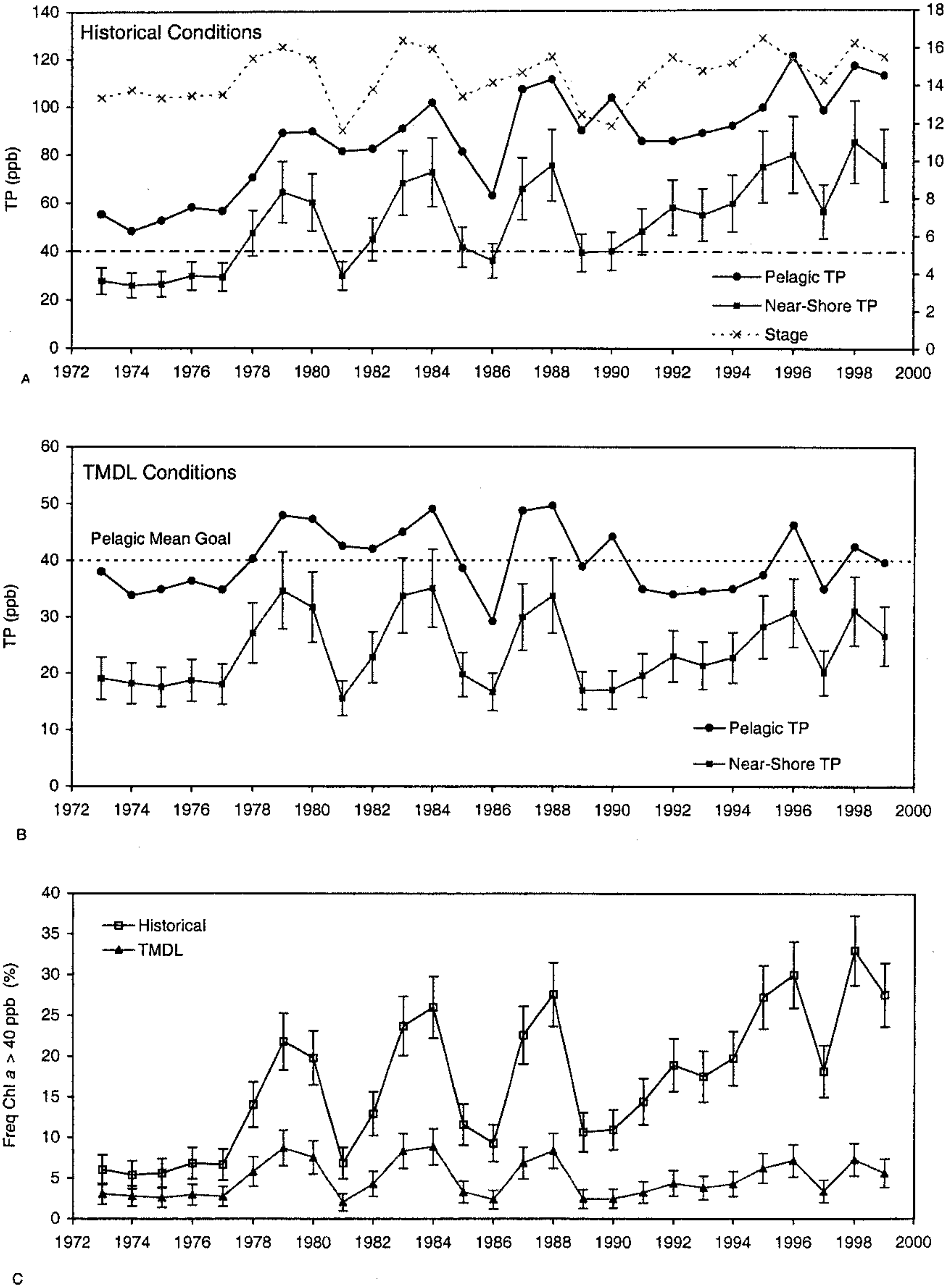

Figure 5.–Yearly-mean total phosphorus concentrations in the pelagic and near-shore regions under historical conditions (A) and hypothetical TMDL conditions (B). In both cases the near-shore TP concentrations are predicted from pelagic values and stage (Figure 3). Bloom frequencies in near-shore region (C) under historical and TMDL conditions predicted from near-shore TP concentrations (Fig. 4).

yearly-mean near-shore total phosphorus concentrations under TMDL conditions, as compared with 25 to 90 μg · L^{-1} under historical conditions.

Near-shore bloom frequencies (chlorophyll *a* > 40 μg · L^{-1}) were determined under historical and TMDL conditions (Fig. 5C) computed from the corresponding near-shore phosphorus concentrations using equations (1) to (4). Yearly bloom frequency ranges from 2 to 9% under TMDL conditions, as compared with 5 to 33% under historical conditions. Successful implementation of the TMDL should significantly reduce near-shore bloom frequencies relative to recent historical conditions. Although the TMDL phosphorus goal is expressed as a long-term mean (40 μg · L^{-1} in the pelagic zone) the analysis shows that this goal corresponds to a range of 2–9% in near-shore bloom frequencies when expected year-to-year variations in phosphorus and stage are considered. The requirement to consider spatial and temporal variability ("critical conditions") in deriving the TMDL (USEPA 1999) is therefore met.

Long Term Implications

The appropriateness of the 40 μg · L^{-1} TMDL goal for total phosphorus in Lake Okeechobee is supported by results of the near-shore bloom frequency analysis. Under TMDL conditions, bloom frequencies will be less than the minimum values experienced in recent history (post-1973), when the lake has been impacted by phosphorus (FDA 1976).

Modeling results indicate that achieving the 40 μg · L^{-1} TMDL goal for phosphorus will require a reduction of ca. 72% in external phosphorus loads to the Lake (Walker 2000, Pollman 2000, FDEP 2000). There is considerable uncertainty associated with forecasting the effectiveness of large-scale watershed controls required to meet the external loading goal. Given the size and complexity of the watershed, the planning and implementation time scale is likely to be measured in decades. The FDEP has stated that the phosphorus TMDL for Lake Okeechobee will be revisited at approximately 5-year intervals. This time scale will provide opportunities for refining the goal and its corresponding TMDL as better information on the effectiveness of watershed controls and on the relationship between phosphorus concentrations and other indicators of ecological imbalance become available.

In addition to external load reduction, it may be necessary to reduce internal phosphorus loads to meet the goal of reduced lake water total phosphorus. This reflects the fact that under present conditions, internal loading is approximately equal to external loading on an annual basis (Olila and Reddy 1993). The buffering effect of internal loading may result in a very long response time of lake water total phosphorus to reductions in external loads, as has occurred in other shallow eutrophic lakes (Sas 1989). At this time the South Florida Water Management District is carrying out a detailed evaluation to consider the economic, engineering, and ecological feasibility of removing or chemically treating (e.g., alum) the phosphorus-rich organic mud (approximately 300 million m^{3}) at the lake bottom, as a way to decrease ecosystem response time.

Parallel implementation of hydrologic restoration efforts also might affect the lake's ability to assimilate phosphorus. The Comprehensive Everglades Restoration Plan (CERP) is a multi-billion dollar project funded by the US Army Corps of Engineers and the State of Florida (USACE, 1999). The project includes regional storage reservoirs, water treatment areas, and large-capacity aquifer storage and recovery wells. Hydrologic modeling runs indicate that when implemented, CERP will substantially reduce the frequency of high stages in Lake Okeechobee. This is expected to result in conditions more favorable for growth of submerged vegetation and reduce the occurrence of high-stage conditions favorable for horizontal transport of phosphorus-rich water to the lake's near-shore region (Havens 2000). Completion of these projects might affect the relationship between near-shore and pelagic total phosphorus. Difficulty in forecasting these changes requires an adaptive TMDL process driven by continued monitoring and research efforts. The 40 μg · L^{-1} TMDL goal for lake phosphorus concentrations is sufficient to initiate the long-term process of restoring water quality conditions and ultimately meeting water quality standards in the Lake.

ACKNOWLEDGMENTS: The authors developed the in-lake concentration goal for phosphorus as part of the activities associated with the TMDL Technical Advisory Committee of the Florida Department of Environmental Protection (FDEP). Funding for W.W. Walker was provided by FDEP and the U.S. Department of the Interior. Comments from N. Iricanin, J. Jones, R. T. James, G. Redfield, A. Steinman, and an anonymous reviewer were helpful in revising the draft manuscript.

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