AN APPROACH FOR THE EVALUATION OF EFFICACY OF WETLANDS-BASED PHOSPHORUS CONTROL PROGRAMS FOR EUTROPHICATION–RELATED WATER QUALITY IMPROVEMENT IN DOWNSTREAM WATERBODIES

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Abstract. It has been suggested that re-creation of the marshes that used to exist in the Lake Okeechobee watershed is the key to the prevention of further eutrophication of this Florida lake. This paper presents a review of the information available on water quality characteristics of this lake and characteristics of its watershed and presents an evaluation of the potential impact of this management alternative on Lake Okeechobee's eutrophication-related water quality. While data were limited and recommendations were made specifying study needs, it was concluded that the construction of the proposed wetlands may have limited impact on eutrophication-related water quality of the lake.

1. Introduction

The Special Project to Prevent the Eutrophication of Lake Okeechobee (Special Project) was created and funded by the Florida State Legislature in 1973 out of concerns expressed by the public, at the Governor's Conference on Water Management in South Florida, and by some of the scientific community (FDA-DSP, 1976; Federico and Brezonik, 1975). The focus of much of the expressed concerns was the channelization of the Kissimmee River and its relation to the eutrophication problems experienced in Lake Okeechobee. According to the Florida Department of Administration (FDA-DSP, 1976), the conclusion of a report by a group of Florida scientists (Marshall *et al.*, 1972), as well as the Governor's Conference, was that in order to maintain and improve the quality of Lake Okeechobee waters, primary consideration should be given to reflooding of the Kissimmee Valley floodplain. According to FDA-DSP (1976) one of the key findings of the Special Project study was that recreation of the marshes throughout the study area is the key to prevention of further eutrophication of Lake Okeechobee.

There are several aspects of this approach that need to be considered in order to determine whether or not the creation of upstream wetlands will have an effect on Lake Okeechobee or the upper lakes of the Kissimmee Basin area (Figure 1). First and foremost is the need for information on the factors controlling algal and other aquatic plant growth in Lake Okeechobee. Obviously, the control efforts must be directed toward the input of a chemical species which either is or can be made to be

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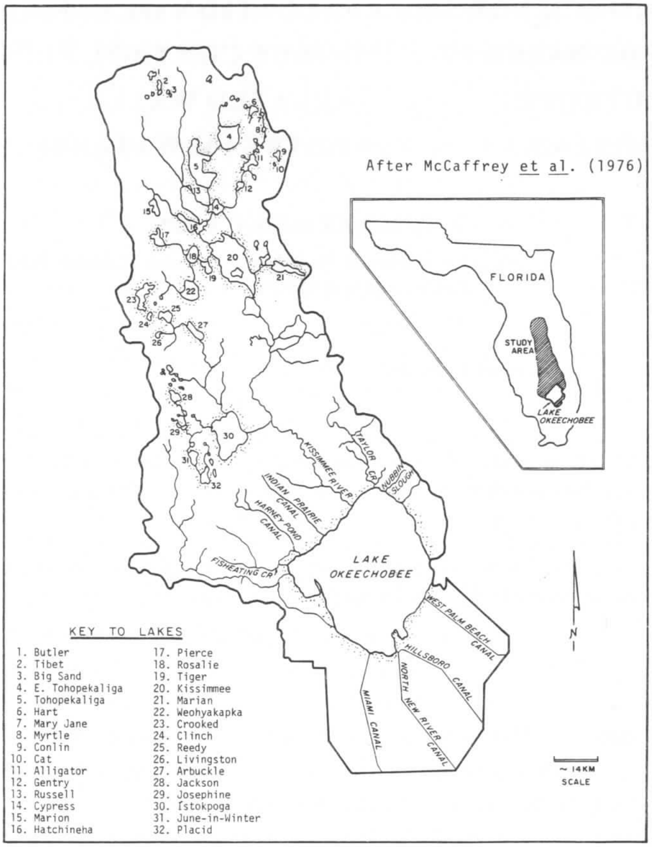

Fig. 1. Map of Special Project study area.

controlling algal biomass in this, or other lakes of concern. The second factor that must be considered is the cycling of the controlling element(s) through restored wetlands. The basic issue in this regard that must be resolved is whether or not a Florida wetland in the area of interest is a significant nutrient trap.

The third aspect is the assessment of the possibility of developing a sufficient acreage of wetlands to maintain and, where possible, improve water quality in Lake Okeechobee. This paper discusses information that is pertinent to each of these three aspects.

2. Limiting Nutrients in Lake Okeechobee

2.1. Previous studies

Currently, Lake Okeechobee experiences algal blooms, growths of nuisance aquatic macrophytes, and floating mats of hyacinths (Brezonik and Federico, 1975). As stated in FDA-DSP (1976), the intent of the 1973 Special Project legislation was to

'... prevent the loss of those characteristics of Lake Okeechobee deemed to be of value to man'. These characteristics were not clearly delineated. In order to develop effective management procedures to control the occurrence of nuisance aquatic plant growth in Lake Okeechobee, it is necessary to define those types of growths that need to be controlled and the factors affecting and limiting their growth. Of the studies conducted as part of the Special Project, however, few were devoted to a description or assessment of the existing water quality problems in Lake Okeechobee.

Dye *et al.* (1975) did a limited amount of algal assay work on the factors limiting algal growth in various areas of the lake. They concluded that in some areas of Lake Okeechobee, P appeared to limit algal growth but that in the majority of water samples used for assays, algal growth exhibited an unusual pattern of having an extended lag phase. Some assays showed limited growth stimulation by either N or P spiking. This led Dye *et al.* (1975) to conclude that some type of algal inhibitor was present in the water. After testing for limitation by trace metals and effects of adding chelators, they concluded that some unidentifiable algal inhibitor was limiting algal growth in Lake Okeechobee.

It is important to note that there were problems inherent in the approach used by Dye *et al.* (1975) in making their assessment. One important problem was the fact that assays were conducted only on samples collected during late fall and winter. As shown by Marshall (1977), these are periods of low productivity and low algal biomass in Lake Okeechobee. Further, the late fall-winter period is not likely to be a time of intensive recreational use of the water body when algal growth would restrict its use. Chemical and biological studies to determine the element(s) limiting algal growth should be conducted during the periods of water quality concern, i.e., generally at peak algal biomass. Inferences cannot be made of the limiting nutrient during periods of concern based on limiting factors at other times of the year unless the ratios of available N to available P remain constant over the year and the concentration of the element present in the least amount relative to algal demand is reduced to concentrations which would be limiting to algal populations during the summer growing season. This is a very unlikely occurrence since it means that the relative rates of supply of available nutrients from both internal and external sources, the relative rates of their utilization by algae, and conversion of nutrients to unavailable forms must remain constant over the annual cycle. In order to determine the factor limiting the growth of algae during bloom periods, it is necessary to conduct limiting nutrient studies during periods of peak algal growth. The determination of growth limiting factors during late fall and winter generally provides little information that would be useful in assessing factors crucial to maintaining water quality for its intended use.

Marshall (1977) found in his study of the phytoplankton and primary productivity in Lake Okeechobee, that the periods of maximum productivity occurred in the spring and late summer. For some stations monitored, these periods corresponded to peaks in algal biomass and/or biovolume. Algal density and biovolume data indicated that generally the summer bloom was dominated by a blue-green alga whereas the spring bloom was caused largely by diatoms. Largest blooms were found to occur in late summer near inflows. Blue-greens tended to be the predominant algal type present throughout much of the year.

Brezonik and Federico (1975) conducted a survey of Lake Okeechobee which consisted of taking one sample from a number of stations in two areas of the Lake. The southern part, in the area of the Miami and Hillsboro Canals (Figure 1), was sampled in early August 1974. The northern portion of the lake near the point of discharge of the Kissimmee River, Taylor Creek and Nubbin Slough, was sampled at five locations in early September 1974. From their data, it was possible to compute ratios of available N (nitrate plus ammonia) to available P (soluble orthophosphate) to try to determine the nutrient likely limiting algal growth in the summer in Lake Okeechobee. These ratios, for samples collected within an approximately 40 km^2 area of the southern part of the Lake, ranged from about 1.8 to 15 (on a mg l^{-1} basis). It was not possible, therefore, to make a conclusion concerning the limiting nutrient because of the large range of values for the ratios within one area of the Lake. Examining the data further, it was evident that there were generally excess amounts, compared to what algae typically need, of both available N and available P present in the water at the stations monitored. This indicated that at the time of sampling, some factor other than these nutrients was controlling the growth of planktonic algae at those stations.

It appears from examination of Brezonik and Federico's data that color may play an important role in limiting the rate of algal growth in Lake Okeechobee. Values for color were typically 100 to 200 mg l^{-1} Pt in the areas sampled, indicating that light likely limits the rate of algal growth in this Lake to a much greater extent than in many water bodies.

As presented in McCaffrey *et al.* (1976), results of studies have shown that the circulation of the open Lake is distinct from the shore zone and that the South Bay region is largely segregated hydraulically from the main body of the Lake. Since this area receives the backpumped water from nearby drained agricultural areas during the summer, and this water is likely to be largely contained there, the area of the Lake studied by Brezonik and Federico (1975) may not be typical of Lake Okeechobee as a whole in terms of algal growth. In addition, this area of the Lake has considerable aquatic macrophyte growth. Brezonik and Federico's (1975) data show that in the northern part of the Lake sampled, the ratios of available N to available P and data on their concentrations indicate that N may limit growth in that area. Color levels, however, were as high as 200 mg l^{-1} Pt, which would affect the rate of algal growth.

2.2. Guide to future studies

Review of the data made available by the Coordinating Council on the Restoration of the Kissimmee River Valley and Taylor Creek-Nubbin Slough Basin staff on the factors controlling the growth of algae and aquatic macrophytes in Lake Okeechobee results in a somewhat confused picture of the significance of phosphorus as a factor controlling fertility in this Lake. The previous studies have not provided adequate data to serve as a basis for development of an assessment of the potential benefits to lake water quality that may be derived as a result of controlling P loads to the water body. Studies need to be conducted in which water samples are collected at two to three-week intervals during the late spring, summer, and early fall from representative locations throughout the Lake in order to determine the amounts of available forms of nitrogen and P present. Also, algal bioassays should be conducted to determine whether, in fact, there is some yet undefined factor limiting algal growth during the summer. The importance of conducting the limiting nutrient studies during the summer growing season cannot be overemphasized.

Another area of concern is the role that the high color present in the Lake Okeechobee water plays in influencing algal growth. It appears that light could be one of the major factors controlling the rate of algal growth. This would be consistent with the data that have been made available which seem to indicate that P is not being used to the extent that it should for a chemical species that is supposed to be limiting algal growth in the water body. If the data that have been made available on the color in Lake Okeechobee are representative of that present during the summer growing season, then studies should be conducted to investigate the role of the high color in preventing maximum algal biomass based on the nutrient content of the water. If it is found that color causes light to be a major factor limiting algal growth rate, then control of P through wetlands restoration could result in the expenditure of large amounts of funds with little or no impact on the eutrophication-water quality characteristics of Lake Okeechobee.

For the purposes of this paper, because of lack of adequate information in this area, it is *assumed* that P is the key element limiting phytoplankton and aquatic macrophyte growth in Lake Okeechobee and that the lake will respond to a change in P load in a manner similar to that of other P limited lakes.

3. Phosphorus Cycling Through Wetlands

3.1. Mass balance

It is generally believed that wetlands serve as significant sinks (storage depots) for aquatic plant nutrients. A review of the literature on nutrient cycling through wetlands shows, however, that there have been few credible studies in which a mass balance has been made on the nutrients entering and leaving a wetland over an annual cycle. This is, in part, a result of the fact that the hydrology of such systems is often complex. Wetlands usually receive nutrients from surrounding lands via many small tributaries; it is often difficult to gage water flow and collect samples from such areas. It is equally difficult to measure the discharge from these areas. Another factor that greatly complicates acquisition of a good mass balance on nutrients into and out of wetlands is the fact that these areas are often groundwater discharge areas. While ordinarily groundwaters do not transport large amounts of P (Jones and Lee, 1977), there are some situations, such as the volcanic soils near Lake Biwa in Japan, where the fertilizers used for growing rice are transported in large amounts through the groundwater system to the lake or marshy areas along the lake's shore.

The potential significance of aquatic macrophytes and attached algae in the removal of nutrients has been well demonstrated by numerous studies on the relationships between these forms of aquatic plants and that of planktonic algae in lakes. It is generally recognized that given an adequate period of time for growth, aquatic macrophytes and attached algae can represent important storage reservoirs for phosphorus and other nutrients. Death of the aquatic macrophytes without removal from the water column will often stimulate planktonic algal growths due to the release of P during mineralization of the dead plants.

Many of the studies that have been conducted on wetlands, which apparently serve as a basis for the conclusion that wetlands are efficient nutrient traps, were conducted for short periods of time during the active growing season. Under conditions of low water velocity within the wetlands and active aquatic plant growth, removal of N and P compounds from the water would be expected. However, many wetlands show a typical annual cycle of rapid growth during the months of prolonged sunshine and elevated temperatures and little or no growth during the winter. During this latter time, it would be expected that little or no nutrients would be removed from the water.

One of the more comprehensive studies that has been conducted on freshwater wetlands was conducted by Bentley (1969) and Lee *et al.* (1975). Lee *et al.* concluded that freshwater marshes studied in Wisconsin act like a sponge with respect to retention of P. During the period of time when there is active aquatic plant growth, P is taken up by the plants. However, associated with the spring thaw, most of the P which had been removed from the inflowing water during the previous year is released. While it was very difficult to get an accurate P mass balance of the wetlands, it was concluded that over an annual cycle, several Wisconsin freshwater marshes are probably essentially in a steady state with respect to total P in and out (Lee *et al.*, 1975). It appears that this type of release pattern may also be experienced in some of the Kissimmee River wetland basins (McCaffrey, 1978).

It is possible that certain wetlands may act as a nutrient sink over extended periods of time, in which P is added to the wetland and retained within it. In this case, the wetland would be acting like a buffer where the addition of P does not result in increased release of P over the annual cycle. It appears that wetlands containing large amounts of peat may have high sorptive capacities for P. It is concluded that one cannot generalize about the ability of wetlands to trap P. Each wetland must be studied on an individual basis in order to determine its potential efficacy in permanantly retaining what enters it from its inflows.

3.2. Factors affecting P cycle in wetland

The ability of a particular wetland system to remove P is highly dependent on its hydrologic characteristics and the climate of the region. Particular import is given to rainfall patterns since the tendency for precipitation to occur in a few large storms versus numerous small storms greatly influences patterns of runoff. It is unlikely that any wetland nutrient removal system can handle the flows associated with a typical large-storm situation unless the system is very large. Obviously, the key factor in removing adequate time of contact for the aquatic and terrestrial plants present in the system to utilize the nutrients and grow to the maximum possible extent based on the nutrient content of the water. If the rate at which the water moves through the system is much more rapid than the ability of the aquatic plants to remove P and grow to maximum population densities based on the limiting nutrient or other factors, then there will be appreciable leakage of P through the wetlands removal system.

One of the extremely important aspects of the way in which wetlands cycle and transport P is that many of them tend to release available P at relatively high concentrations compared to those which are necessary to stimulate algal growth in natural waters. These necessary concentrations are generally on the order of 10 μg P l^{-1}. Lee *et al.* (1975) found that often, even during peak growing seasons, the waters discharged from natural wetlands in Wisconsin still had concentrations of soluble orthophosphate in the order of 50 to 100 $\mu g\ l^{-1}$ P. While there was no question that these concentrations were less than in the inflowing waters, they still were considerably in excess of the levels which are generally needed to grow excessive amounts of algae in a water body.

3.3. Availability of P Released from Wetlands

Lee *et al.* (1975) found that the discharges from wetlands in Wisconsin tended to have much higher concentrations of what were measured as soluble organic P compounds than typical natural waters. The measurements were made on 0.45 μm pore size membrane filtered sample after strong acid digestion. These compounds were not measured in the molybdate procedure without the acid digestion. No bioassay work was done to determine whether this 'organic P' was available or could be readily converted into an available form for stimulation of planktonic algal and other aquatic plant growth. Studies of this type need to be done, however, in order to assess the potential significance of this source of P in causing excessive fertilization of natural waters downstream from wetlands, in this case, Lake Okeechobee.

Thus far, the studies that have been conducted related to restoration of the Kissimmee River-Taylor Creek-Nubbin Slough wetlands seemed to have focused on the total P and soluble orthophosphate content of the lake and tributary waters. Attention should be given to determining the other potentially available forms of P. In addition to determining whether the soluble 'organic P' is or can be made available to support algal growth, studies should be conducted using an approach similar to that used by Cowen and Lee (1976) to determine how much of the particulate organic and inorganic P forms are made available to support algal growth. Cowen and Lee (1976), in their studies of tributaries of Lake Ontario, and of urban drainage in Madison, Wisconsin, found that about 20% of the difference between the soluble orthophosphate and total phosphate concentrations would likely become available in Lake Ontario to support algal growth. This figure should not be extrapolated to wetland systems since the particulate forms of P leaving wetlands are likely to be markedly different in character than those studied by Cowen and Lee (1976). There should be much greater proportions of organic P compounds in the discharge from wetlands than typically found in most surface waters.

The origin of the relatively large amounts of soluble organic P in wetland systems is unknown. It could be derived from partial mineralization of particulate P by bacterial action, or it may be the product of the aquatic macrophyte 'pumping' the P from the sediments through the leaves to the water column. Because a portion of this organic P is likely to have been derived from breakdown of vegetation, some portion is likely to have become refractory and will not be converted to available forms. Golterman (1973) concluded that with each growth cycle, only 1 to 5% of the phosphate is not returned from algae into the biochemical cycle. He pointed out that over a growing season, this could represent a significant loss (i.e., becoming refractory) of available P of 20 to 100% of the phosphate taken up by algae. The AWWA Water Quality Division Committee on Nutrients in Water (1970) reported that the literature suggests that under both aerobic and anaerobic conditions, between 30 and 70% of algae and associated organisms are not readily degraded. This refractory material contains a significant amount of P originally in algal cells. Some portions of the organic P fraction, however, would likely be converted through bacterial mineralization processes to soluble orthophosphate.

It is important to emphasize that work on the available forms of P must be done with bioassay procedures in which there is adequate time for bacterial mineralization of organic phosphate forms in the water. Chemical analyses will not, in general, provide a reliable indication as to how much of the P present in particulate matter will become available to affect algal growth. Use of procedures developed by Plumb and Lee (1975) and used by Cowen and Lee (1976) will provide the types of information needed by those responsible for the wetlands restoration project to assess what the potentially available P load is to Lake Okeechobee from various sources. They can then devote their attention to controlling these sources, which may not be the same as the major sources of total P load. This may be especially true for water bodies which receive substantial amounts of P from wetland sources. It is becoming increasingly clear that when working on diffuse sources of P for the purpose of eutrophication control, much greater attention has to be given to available and potentially available P load rather than total P load since substantial parts of the total P are not available for support of algal growth.

3.4. Effects of P removal in wetlands on downstream water quality

The hydraulic residence time of the downstream water body is an important factor in determining the water body's response to wetlands retention of nutrients. In lakes with short residence times, on the order of a few weeks to a few months, the passage of the tributary waters through a wetland, where there is adequate time for interaction with the wetlands aquatic plant nutrient system, prior to entering a water body, could be of significance in reducing the P load to a water body during the critical growing season. Release of the nutrients stored during the summer typically occurs during the winter period when algal growth in the downstream waters is minimal. If the spring flows are sufficiently high, the previous year's stored nutrients could be released to tributary waters, but would be flushed through the downstream lake and thereby not have any significant adverse effect on the water quality during the following summer. This is applicable to only short residence time lakes and to wetlands systems which act like a sponge, storing nutrients during the growing season and releasing them in a large mass over a short period of time in the winter and early spring. For a lake such as Okeechobee, with a longer hydraulic residence time (about a year), the storage of nutrients in upstream 'sponge-like' wetlands would likely not cause a significant reduction in the fertility of the Lake. This is because the nutrients released from the wetlands in the winter-spring would likely not have been flushed through the lake before onset of the algal growing period in the lake.

It is the opinion of the authors that the proposed P control programs for Lake Okeechobee, involving restoration of wetlands, will remove some P from influent waters during the growing season. Appreciable parts of the P, however, could be released to tributary waters during periods of reduced aquatic and terrestrial plant growth within the storage system. Unless there is harvesting of aquatic plants within the wetland P removal system, there would probably be a net P balance over the annual cycle, with essentially all of the nutrients entering the wetland system from upstream sources being released to the outlet of the wetlands.

4. Wetlands Destruction

It is of interest to consider the impact of the destruction of the Kissimmee and Taylor-Nubbin Slough River Basin wetlands on water quality in Okeechobee. Lee *et al.* (1975) found that the drainage of a wetland in Wisconsin could result, over a several-year period, in excess of 25 kg ha^{-1} of P being released from wetlands drained. This was compared to a typical value of 0.5 kg ha^{-1} yr^{-1} for Wisconsin agricultural lands. While the ultimate magnitude of the impact of such a drainage process would be dependent upon the nature of each of the types of marshes that exist, as well as the characteristics of the receiving waters, it is likely that the drainage of the wetlands in the Kissimmee River area and other parts of Central Florida would have caused a very significant increase in the amounts of P entering the surface waters and ultimately Lake Okeechobee. It should be noted that a drained wetland should not continue to yield large amounts of P for long periods of time to the downstream waters. While the time over which the P release would occur is dependent on the manner in which the drained land is used, it is likely that under intensive farming conditions, the rate of mineralization of the organic P present in the former marsh soils should be greatly accelerated, resulting in very significant releases of P over a short period of time. Within a few years, the mineralization processes should have been essentially completed in the readily leachable part of the soils, thereby creating a situation where limited amounts of P would be released from the drained marsh. Under these conditions, the P flux from the soil would be controlled primarily by the amounts of P introduced into the system from external sources.

5. Assessing Water Quality Responses to Altered Phosphorus Loads

5.1. OECD EUTROPHICATION MODELING APPROACH

About 5 yr ago, the Organization for Economic Cooperation and Development (OECD) initiated a eutrophication study program which had as its primary purpose the formulation of algal nutrient load-lake and impoundment response relationships. This study is being conducted in western Europe, Japan, Australia, Canada, and the United States where a total of approximately 200 water bodies are being investigated. Within the U.S., the U.S. EPA was the lead agency for the OECD eutrophication studies. Under contract with the U.S. EPA, selected researchers compiled, using a standardized format, the results of their previous studies on approximately 40 U.S. water bodies or parts thereof. These investigators prepared a series of reports which were submitted to the U.S. EPA covering nutrient load-response relationships for their respective water bodies. These reports have been summarized by Seyb and Randolph (1977).

Under contract with the U.S. EPA, Rast and Lee (1978) prepared a summary report in which they critically examined each of the individual investigator's reports for their data reliability and comparability. Rast and Lee (1978) found that the U.S. OECD eutrophication study water bodies' nutrient load-response relationships can be formulated into relationships similar to those developed by Vollenweider (1975, 1976). Vollenweider found, for a group of lakes, that the average summer chlorophyll *a* concentration was related to the P load normalized by mean depth and hydraulic residence time. Rast and Lee (1978) have shown that this relationship is applicable to a wide variety of U.S. water bodies as well. They have also been able to extend Vollenweider's relationship to include formulation of a P load-average summer Secchi depth, and P load-average hypolimnetic oxygen depletion rate relationships. Recently, Jones *et al.* (1979) have extended this work to include the maximum summer chlorophyll *a* concentration based on the average summer chlorophyll *a* concentration. Based on these efforts, it is now possible to predict for many water bodies the impact of altering a P load on the water quality of a lake or impoundment.

The authors used data made available to them by the Coordinating Council on the Restoration of the Kissimmee River Valley and Taylor Creek-Nubbin Slough Basin staff to determine whether or not these general relationships can be applied to Lake Okeechobee. As discussed previously, few of the studies done in conjunction with the Special Project were devoted to characteristics of Lake Okeechobee.

5.2. TOTAL P LOAD TO LAKE OKEECHOBEE

Phosphorus loads to Lake Okeechobee have been computed for 1973 by Davis and Marshall (1975) as cited and revised in Federico and Brezonik (1975) and also for

1969 by Joyner (1971) as cited by and revised in Brezonik and Federico (1975). These loads and associated parameters have also been cited by McCaffrey *et al.* (1976), and also by FDA-DSP (1976) as cited from Gayle (1975). In order to determine whether or not the calculated values for the P loads are reasonable with reference to how lake systems have been found to typically behave, both the 1973 (Federico and Brezonik, 1975) and the 1969 (Brezonik and Federico, 1975) load characteristics were plotted on the Vollenweider P load evaluation diagram (Figure 2). Table I presents the values of characteristics of Lake Okeechobee which form the basis of this relationship. As seen in Table I, the total P load reported for Lake Okeechobee in 1973 was about half of what it was in 1969. Further, since the reported discharges for 1969 and 1973 were markedly different, it would be important to investigate the effect that these differences and associated differences in load characteristics and residence time could have on the Lake. However, detailed data were not available for such examination.

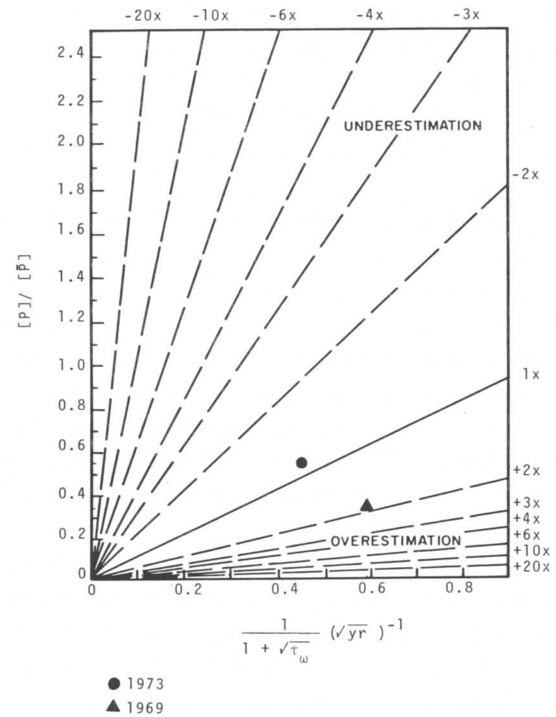

Fig. 2. Evaluation of estimates of Lake Okeechobee P loadings.

The mean input P concentration, $[\bar{P}]$, was determined by dividing the annual total P load by the estimated annual flow into the Lake. Using the method suggested by Vollenweider (1975, 1976), $[\bar{P}] = L(P)\ q_s^{-1}$ (where $L(P)$ is the areal P load in $g\ P\ m^{-2}\ yr^{-1}$ and q_s is the mean depth/hydraulic residence time in $m\ yr^{-1}$), essentially the same values were found for average inflow P concentrations. The average in-lake total P concentrations for 1969 and 1973, [P], were reported in FDA-DSP (1976) as cited from Joyner (1974) and Davis and Marshall (1975), respectively, from Gayle

TABLE I

Evaluation of total P loads to Lake Okeechobee, Florida

Characteristic	1973	1969
Total P load (kg P yr^{-1})	4.44×10^5 [a]	7.47×10^5 [b]
Average total discharge to lake (m^3 yr^{-1})	3.37×10^9 [a]	10.5×10^9 [d]
Volume (m^3) [c]	5.24×10^9	5.24×10^9
Average input concentration – Total P, $[\bar{P}]$ (mg P l^{+1}) [e]	0.13	0.07
Average in-lake concentration – Total P, [P] (mg P l^{+1})	0.071 [g]	0.024 [h]
Hydraulic residence time, τ_ω (yr^{-1}) [f]	1.55	0.5
$\frac{1}{1+\sqrt{\tau_\omega}}$	0.45	0.59
$[P]/[\bar{P}]$	0.55	0.34

[a] Federico and Brezonik (1975) based largely on the work of Davis and Marshall (1975).

[b] Joyner (1971) as modified in Brezonik and Federico (1975).

[c] Brezonik and Federico (1975).

[d] Joyner (1974) in FDA-DSP (1976).

[e] Total P load divided by total average discharge.

[f] Based on lake volume given in Brezonik and Federico (1975), and average discharge.

[g] Davis and Marshall (1975) in Gayle (1975) as reported by FDA-DSP (1976).

[h] Joyner (1974) in Gayle (1975) as reported by FDA-DSP (1976).

(1975). The average of the total P concentrations in single samples collected from about 35 stations in the south and northernmost parts of Lake Okeechobee by Brezonik and Federico (1975) in mid-August and September 1974 was 0.056 mg P l^{-1}, about midway between the cited 1969 and 1973 values. The hydraulic residence times were calculated for both years based on the lake volume and average inflow to the lake.

The 'lx' line on the Vollenweider P load evaluation diagram (Figure 2) indicates where a lake with a given hydraulic residence time should theoretically plot in relation to P concentration in the lake and in lake inputs. It was put forth by Rast and Lee (1978) that for a lake which plotted within ± 2 times the $[P]/[\bar{P}]$, the P load has been estimated with an acceptable degree of accuracy. It can be seen by examination of Figure 2 that both years' loading estimates fall within the acceptable ± 2 range. The 1973 load used, as demonstrated in this figure and confirmed by McCaffrey (1978), was probably the more accurate of the two presented in this paper.

The general physical and chemical characteristics of Lake Okeechobee needed to plot this lake on the Vollenweider P loading curve are presented in Table II. The areal P loads from this table (A points) are plotted as a function of the mean depth/hydraulic residence in Figure 3, the Vollenweider P loading diagram. For both 1969 and 1973 loads, Lake Okeechobee plots close to the 'Excessive' loading line in the area where many water bodies classified as mesotrophic to eutrophic, based on an

TABLE II

Characteristics of Lake Okeechobee for Vollenweider P loading diagram

Characteristic	1973	1969
Total P load (kg P yr^{-1})	4.44×10^{5} [a]	7.47×10^{5} [b]
Surface area of lake (km^2)[c]	1891	1891
Areal P load (g P m^{-2} yr^{-1})	0.235	0.395
Mean depth, $\bar{z}$ (m)[c]	2.8	2.8
Hydraulic residence time, τ_ω (yr^{-1})[d]	1.55	0.5
$\bar{z}/\tau_\omega$ (m yr^{-1})	1.8	5.6

[a] Federico and Brezonik (1975) based largely on Davis and Marshall (1975).
[b] Joyner (1971) as modified in Brezonik and Federico (1975).
[c] Brezonik and Federico (1975).
[d] See Table I.

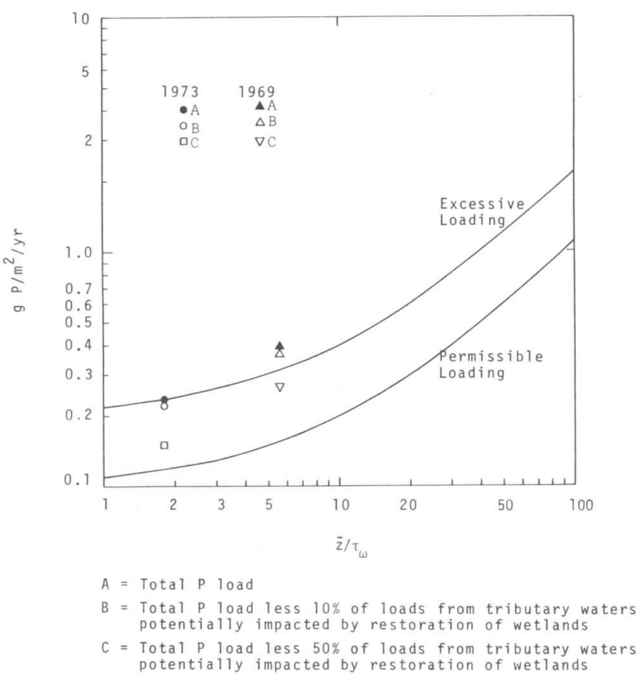

Fig. 3. Positions of Lake Okeechobee on Vollenweider P loading – relative eutrophication-related water quality diagram with perturbations of P load – 1969 and 1973.

investigator's description, plot. This description appears to be appropriate based on how a number of investigators have characterized Lake Okeechobee (Joyner, 1974 in FDA-DSP, 1976; Davis and Marshall, 1975 in FDA-DSP, 1976; Brezonik and Federico, 1975).

The Vollenweider loading diagram may also be used to illustrate the change with respect to the 'Excessive' and 'Permissible' lines and, in general, in relation to oligotrophic and eutrophic groups of lakes, that should result if the P load is perturbed. A number of the tributaries and their associated P inputs to Làke Okeechobee would likely be affected if the wetlands of the Kissimmee area were to be restored. These include the Kissimmee River, Taylor Creek-Nubbin Slough, Harney Pond Canal and Fisheating Creek. It is of interest, therefore, to determine how changes in total P load from these waters to Lake Okeechobee, which would result from wetlands restoration or other P control measures, would affect the lake's positions (1969 and 1973) on the loading diagram. Table III presents the literature values for the 1973

TABLE III

Perturbations of total P loads to Lake Okeechobee

Nutrient Source	Total P load 1973[a] ($\times 10^5$ kg yr^{-1})			Total P load 1969[b] ($\times 10^5$ kg yr^{-1})		
	A	B	C	A	B	C
Kissimmee River	0.81	0.73	0.405	2.42	2.18	1.21
Taylor Creek/Nubbin Slough	1.55	1.4	0.78	1.94	1.75	0.97
Harney Pond Canal	0.58	0.52	0.29	0.184	0.166	0.092
Indian Prairie Canal	0.15	0.14	0.075	0.06	0.054	0.03
Fisheating Creek	0.22	0.2	0.11	0.326	0.293	0.163
Rainfall	0.48	0.48	0.48	1.02	1.02	1.02
EAA backpumping[c]	0.65	0.65	0.65	1.45	1.45	1.45
Catfish Bait	—	—	—	0.066	0.066	0.066
Total P load	4.44	4.12	2.79	7.47	6.98	5.0
Areal P load (g P m^{-2} yr^{-1})	0.235	0.218	0.148	0.395	0.369	0.264

Dash (—) indicates no data found.
[a] Based on Federico and Brezonik (1975) which is based largely on Davis and Marshall (1975).
[b] Based on Joyner (1971) as modified by Brezonik and Federico (1975).
[c] Includes Miami, Hillsboro, and North River Canals.
A – Total P load.
B – Total P load less 10% of loads from tributary waters potentially impacted by restoration of wetlands.
C – Total P load less 50% of loads from tributary waters potentially impacted by restoration of wetlands.

and 1969 loads from each major source (A), the P loads that would result from a 10% reduction (B), and a 50% reduction (C) in the total P load from the tributaries that may be affected by wetlands restoration. These loads, as normalized by lake surface area, are also plotted in Figure 3. Examination of the changes in position that could result from these changes in P load shows that if the creation of wetlands could cause as much as a 50% reduction in all potentially affected tributary loads, a readily discernible change in the P load could be achieved. It should be noted that indirect ramifications of altered P loads such as may be related to the irrigation backpumped water P loads from the southern part of the drainage basin, are not being considered.

5.3. Quantification of Water Quality Response to Altered P Load to Lake Okeechobee

Based on their work on about 40 U.S. water bodies, Rast and Lee (1978) have defined a relationship between the mean summer chlorophyll *a* concentration in a lake in which planktonic algal growth is P limited, and the P load to the lake normalized by the lake's mean depth and hydraulic residence time, $(L(\mathrm{P})\, q_s^{-1})/(1 + \sqrt{\bar{z}/q_s})$. This relationship and approach allow the mean summer chlorophyll *a* concentration of a lake, or changes in the mean summer chlorophyll concentration, to be predicted based on the lake's P load, mean depth and hydraulic residence time. It has been repeatedly demonstrated that this approach can be applied to many lakes throughout the world. Where sufficient information has been available, it has been shown that this approach provides accurate predictions of changes in lake water quality (as measured by mean summer chlorophyll *a* concentrations) resulting from altered P load or hydraulic residence time.

In order to determine whether or not this relationship holds true for Lake Okeechobee, the mean chlorophyll concentration must be plotted against the value of the loading term, $(L(P)\, q_s^{-1})/(1 + \sqrt{\bar{z}/q_s})$, and compared to the U.S. OECD line of best fit determined by Rast and Lee (1978). The one value for chlorophyll concentration for Lake Okeechobee found (17 μg l^{-1}) was reported in FDA-DSP (1976) from Joyner's (1974) study cited in Gayle (1975). The basis for this value was not reported by FDA-DSP (1976). It was assumed, therefore, for the purposes of this discussion, that it represented a summer mean value. The chlorophyll value as well as the other characteristics of Lake Okeechobee needed to use this approach are presented in Table IV. As seen in Figure 4, the chlorophyll level in Lake Okeechobee appears to respond to P load in a manner similar to that of many other U.S. water bodies, i.e., especially for the 1973 load-chlorophyll relationship, the lake plots within a short distance from the line of best fit for some 40 U.S. water bodies.

This relationship can also be used to predict the change in average chlorophyll concentration which would be expected to result from an altered P load such as may occur as a result of wetlands restoration. The areal total P loads were calculated for

TABLE IV

Characteristics of Lake Okeechobee for mean summer chlorophyll *a*-normalized P load relationship and mean summer Secchi depth-normalized P load relationship

Characteristic	1973	1969
Areal total P load, $L(\mathrm{P})$ (mg P m^{-2} yr^{-1})	235[a]	395[b]
$\bar{z}$ (m)[c]	2.8	2.8
τ_ω (yr)	1.55[c]	0.5[c,d]
$q_s = \bar{z}/\tau_\omega$ (m yr^{-1})	1.8	5.6
$\dfrac{L(\mathrm{P})/q_s}{1 + \sqrt{\bar{z}/q_s}}$	58	41.3
Chlorphyll *a* (μg l^{-1})[d]	17	17
Secchi depth (m)	0.3[e] 0.73[c]	0.5[d]

[a] Federico and Brezonik (1975) based largely on Davis and Marshall (1975). See Table III.
[b] Joyner (1971) as modified in Brezonik and Federico (1975). See Table III.
[c] Brezonik and Federico (1975).
[d] Joyner (1974) in Gayle (1976) as reported by FDA-DSP (1976).

TABLE V

Effects of perturbations of total P load to Lake Okeechobee on chlorophyll concentrations

Characteristic	1973			1969		
	A	B	C	A	B	C
Areal P load (mg P m^{-2} yr^{-1})[a]	235	218	148	395	369	264
$\frac{L(P)/q_s}{1+\sqrt{\bar{z}/q_s}}$ (mg P m^{-3})	58	53.9	36.6	41.3	38.6	27.6
Chlorophyll a (μg l^{-1})	17[b]	16.5[c]	11.6[c]	17[b]	16[c]	11.6[c]

A – Total P load.
B – Total P load less 10% of loads from tributary waters potentially impacted by restoration of wetlands.
C – Total P load less 50% of loads from tributary waters potentially impacted by restoration of wetlands.
[a] See Table III for derivation of load.
[b] Based on Joyner (1974) in Gayle (1976) as reported by FDA-DSP (1976).
[c] Predicted by model (Figure 4).

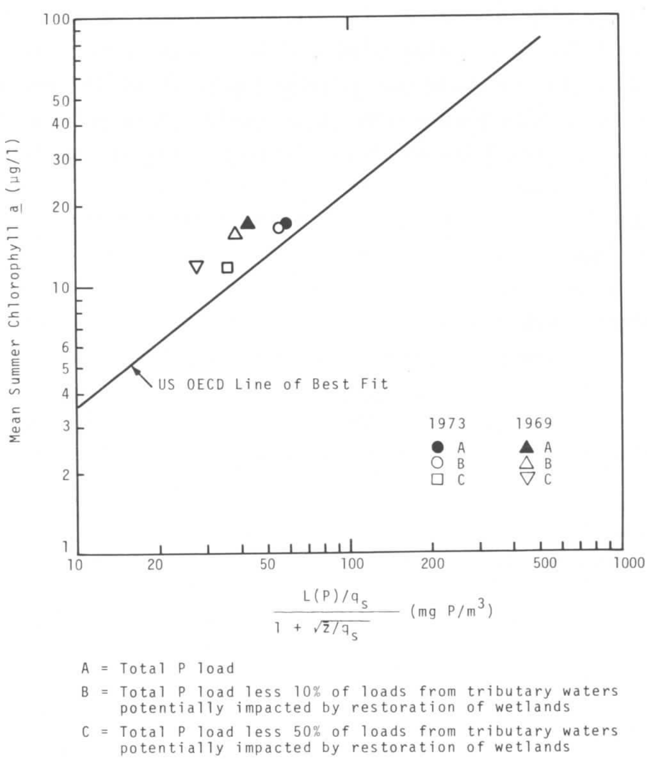

Fig. 4. Relationship between P load and mean summer chlorophyll a concentrations in Lake Okeechobee with perturbations of P loads – 1969 and 1973.

conditions where the total P load from the tributaries that may be affected by wetlands restoration were reduced by 10% (B) and 50% (C). These values, the areal P loads derived from literature P load data (A), and the values of the associated normalized

P loads are presented in Table V. In order to use Figure 4 to predict the level of chlorophyll expected under the perturbed conditions in 1973, a line parallel to the U.S. OECD line of best fit must be drawn through the 1973 load point (A) and the altered P load values plotted along that line. This was done for the perturbed 1969 and 1973 loads in Figure 4. Examination of this figure shows that by removing 10% of either the 1973 or 1969 P load from tributaries that may be affected by wetlands restoration, the average summer chlorophyll content of Lake Okeechobee should decrease by 0.5 and 1 μg l^{-1} to 16.5 μg l^{-1} and 16 μg l^{-1}, respectively. If 50% of the designated load was removed from either the 1969 or 1973 loading characteristics, an average chlorophyll value of 11.6 μg l^{-1} would be expected for the Lake. Whereas, it is doubtful that the 1 μg l^{-1} change could be detected either by people using the water or by analytical techniques commonly used, the average 4.5 μg l^{-1} change could probably be perceived as an improvement in water quality.

These changes in average chlorophyll can be expressed in terms of changes in expected maximum summer chlorophyll concentration by use of an empirical relationship developed by Jones *et al.* (1979). Although insufficient chlorophyll data were available for Lake Okeechobee to determine whether or not this relationship is applicable to this lake, the developed relationship has a correlation coefficient of 0.96 for the nearly 100 water bodies or parts of water bodies used in its formulation. If the restoration of wetlands cause a 50% total P load reduction to Lake Okeechobee,

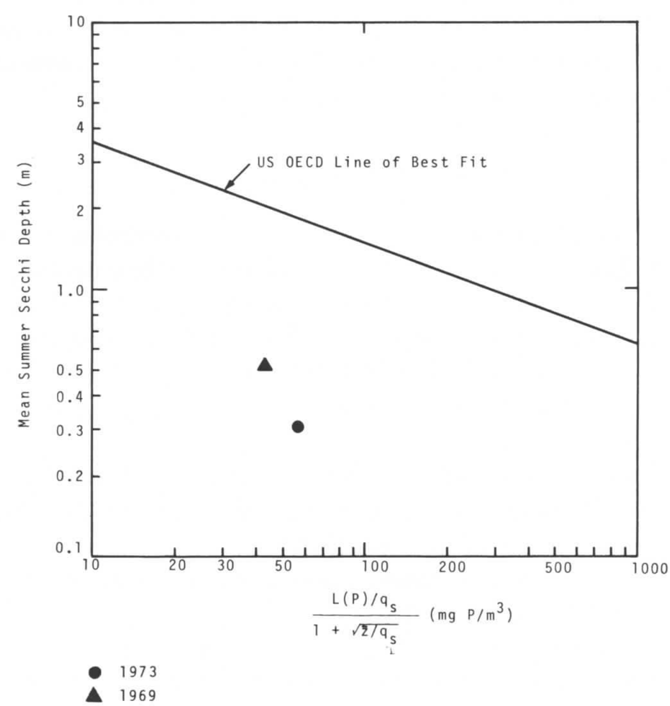

Fig. 5. Relationship between P load and mean summer Secchi depth in Lake Okeechobee with perturbations of P load – 1969 and 1973.

the maximum summer chlorophyll content would be expected to decrease from about 31 to 22 μg l^{-1}. It would be likely that this change would also be seen as a noticeable improvement in water quality. A 10% decrease in P loads would not likely cause a detectable change in maximum summer chlorophyll concentration.

Rast and Lee (1978) developed a relationship and approach for mean summer Secchi depth in lakes in which the planktonic algal growth is P limited, similar to that developed for chlorophyll *a*. Although Secchi depth is generally a less sensitive water quality parameter than chlorophyll for moderately eutrophic to eutrophic water bodies, this relationship and the predictive capabilities of this model have been demonstrated for a wide variety of lakes.

Characteristics of Lake Okeechobee which are needed to apply this approach are presented in Table IV. Values for 1973 Secchi depth were reported by FDA-DSP (1976) from the work of Davis and Marshall (1976) as cited in Gayle (1975). FDA-DSP (1976) also cited Gayle's (1975) reference to Joyner's (1974) Secchi depth values. These values are presented in Table IV. As with the chlorophyll data, these values were assumed to be representative of a mean summer value.

As shown in Figure 5, the Secchi depth-P load relationship did not appear to be applicable to Lake Okeechobee. The Secchi depth values are considerably lower than those typically found in lakes having the same normalized P loads as Lake Okeechobee. This would be expected because of the amount of color found in the Lake water. As discussed previously, values for color in parts of the Lake were typically on the order of 100 to 200 mg l^{-1} Pt (Brezonik and Federico, 1975). The presence of this amount of color would cause a reduction of transparency beyond that normally associated with the presence of algae.

6. Conclusions

Further study is needed before the benefits to Lake Okeechobee water quality that can be derived from wetlands control of phosphorus can be determined.

Factors influencing aquatic macrophyte and algal growth in Lake Okeechobee need further investigation, especially during the summer growing season. Particular attention must be given to the role of P in influencing algal growth. Also, the significance of the high color in creating light limitation of algal growth rate must be evaluated.

From the limited data available, it appears that the Vollenweider OECD eutrophication study approach is a viable model for predicting the planktonic algal chlorophyll response to P load in Lake Okeechobee.

Additional studies need to be conducted to define the cycling of nutrients through Florida wetlands in the areas of interest.

Particular attention must be given to:

Net annual balance of P for various types of wetlands. Amounts of algal available P released from the wetlands.

Based on the limited data available and the experience of the authors, it appears that the construction of wetlands as proposed by the Coordinating Council on the Restoration of the Kissimmee River Valley and Taylor Creek-Nubbin Slough Basin, may have limited impact on water quality within Lake Okeechobee. This should not be taken to mean that wetland areas should not be reconstructed. It does mean that the original goals intended to be achieved by their construction should be re-evaluated. Wetlands have a number of beneficial aspects including wildlife habitats and retention of erosional materials, etc.

Subsequent to completion of this study, a considerable amount of work has been done by the authors evaluating and refining the OECD eutrophication-modeling approach. Jones and Lee (1980) should be consulted for more current information.

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