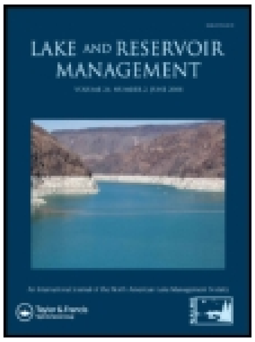

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A Management Alternative for Lake Apopka

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ABSTRACT

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We examine the idea that whenever high levels of planktonic algae impair a lake, nutrient control is the first step to be taken regardless of what other management actions might be contemplated. Our example is Lake Apopka, a 12,500 ha, shallow (1.7 m), polymictic lake in central Florida. Prior to 1947, the lake was dominated by macrophytes, was reputed to have clear waters, and had a national reputation for its largemouth bass fishery. Following a hurricane in 1947, the lake switched to a turbid, algal state and the bass fishery is all but gone. For over 30 years, it was either implied or stated directly that nutrient enrichment from anthropogenic activities, especially farms along the north shore, was to blame for this change and the lack of macrophyte recovery. The current management plan is to remove the farm nutrient supply by purchasing the farms under the theory that this will lower the total phosphorus concentration in the water and thus restore the lake. We have developed the most probable phosphorus budgets for the lake based on the studies of others and have determined that a fluid mud layer that is frequently resuspended by the wind will lead to high internal loading and slow the drop in phosphorus concentration. The equilibrium phosphorus concentration will lie between 52 and 88 $mg \cdot m^{-3}$, so the lake will remain in its eutrophic state. We propose an alternative management plan using artificial reefs that will focus on restoring the largemouth bass fishery in the immediate future. This idea is attractive because bass fishing was the dominant use of this lake in the past, it can be accomplished without waiting for a change in trophic state, and it can produce results in a relatively short period of time.

Key Words: restoration, alternative stable states, eutrophication, aquatic macrophytes, phosphorus, largemouth bass, fish management, and lake management.

In recent years it has become common practice with lake managers that whenever a lake is impaired by high levels of planktonic algae, phosphorus control is the first step to be taken regardless of what other management actions might be contemplated (Moss et al. 1996). The evolution of this idea starts with the findings of Vollenweider (1968) who examined several lakes and found that their trophic states were proportional to nutrient loading rates and inversely proportional to mean depth. In the 1960s, 1970s, and 1980s surveys of lakes demonstrated an empirical relationship between nutrients and chlorophyll concentrations in lakes (Sakamoto 1966, Dillon and Rigler 1974, Jones and Bachmann 1976, Canfield 1983, Smith 1982). Whole-lake experiments (Schindler 1975) and nutrient diversion projects, particularly at Lake Washington (Edmondson and Lehman 1981), also demonstrated that the addition or removal of nutrients could influence algal levels in lakes. Based on the weight of evidence and the success in reversing the eutrophication of Lake Washington by nutrient diversion, lake managers accepted the idea of nutrient control for lake restoration. This management action also became the keystone of the U.S. Environmental Protection Agency's Clean Lakes program.

We have examined the case of Lake Apopka, Florida, and have concluded that even though this lake currently is in a hypereutrophic state, a nutrient control program is not going to produce noticeable results (clear water and improved recreational fisheries) for decades, if ever. There are two main reasons for this finding: 1) there is reason to question the assumption that the current water quality problems are due to increases in phosphorus loading and 2) the available information indicates that the proposed nutrient reductions will not clear the waters due to internal phosphorus loading in this large shallow lake. We propose that management actions (creation of aquatic plant refuges and fish stocking) be taken concurrently with the current nutrient reduction program to restore the largemouth bass fishery. This idea is attractive because bass fishing was the dominant use of this lake in the past, it can be accomplished without waiting for a change in trophic state, and it can produce results in a relatively short period of time.

The eutrophication and restoration of Lake Apopka, a 12,500 ha lake located in central Florida, has been the subject of numerous studies (e.g., Huffstutler et al. 1965, Schneider and Little 1969, Brezonik et al. 1978, U.S. Environmental Protection Agency 1978, Lake Apopka Restoration Council 1986, Conrow et al. 1993). This lake has attracted national and statewide attention, because the lake has undergone major limnological and fisheries changes during the last 50 years. The elimination of anthropogenic nutrient inputs, especially those originating from the muck farms located along the lake's north shore, has been frequently accepted as the keystone for Lake Apopka's restoration. Important scientific issues regarding the trophic state response of Lake Apopka to decreased anthropogenic nutrient inputs, however, remain unresolved, and there is evidence that factors other than eutrophication played a major role in determining Lake Apopka's present condition (Huffstutler et al. 1965).

Successful lake management requires the identification of those lakes where nutrient control will be most beneficial and those lakes where other management techniques are more appropriate (Canfield and Hoyer 1989). In this paper we review the events that have contributed to Lake Apopka's present condition, and we use a vast amount of scientific information that has been collected by previous studies of Lake Apopka to determine if Lake Apopka's current condition is indeed a result of nutrient enrichment or if other factors such as the loss of submersed vegetation (Huffstutler et al. 1965) are more important. We specifically examine the question: Will reductions in the current nutrient loading expected from the removal of the muck farms lead to significant improvements in the condition of Lake Apopka in a reasonable amount of time? We also present a plan for the long-term management of Lake Apopka. We undertake this effort because a number of new and expensive programs for reducing nutrient inputs and in-lake nutrient availability have been proposed for Lake Apopka (Conrow et al. 1989). For example, the Florida Legislature in 1997 appropriated State funds to be used along with Federal funds (expenditures of close to $100,000,000) to buy out the muck farms and eliminate pumpage of drainage water to the lake. However, we believe there are alternative approaches that are more cost-effective and will make the lake more useful to the public in a shorter period of time.

A Historical View of the Lake Apopka Problem

Lake Apopka is the fourth largest natural lake in Florida (Shafer et al. 1986), and is also one of the older lakes in the state (MacNeil 1950). It is thought that the lake arose from a broad shallow sound when sea level fell below 30 m and that it became a freshwater marsh when sea level fell below 21 m (MacNeil 1950, Schneider and Little 1969). It was shallow and productive with a large (> 6,000 ha) adjoining sawgrass marsh located along its northern shore by the time European settlers reached the lake in the mid-1800s (Delta Canal Company 1895, Blackman 1973, Shofner 1982). In 1844 early settlers cleared the land along the south shore to make way for vegetable farms and orange groves (Blackman 1973). Transportation was the great problem of early farmers, so in 1877, citizens petitioned the Board of Trustees of the Florida Internal Improvement Fund to build a canal from the north end of Lake Apopka to Lake Dora (Blackman 1973). A canal was completed in 1886, but it was not sufficient for the permanent lowering of the lake (Blackman 1973).

In a subsequent effort the Delta Canal Company completed clearing the canal to Lake Dora around 1893 and extended the canal system to the Oklawaha River. They also constructed over 51 km of lateral ditches to drain the sawgrass lands on Lake Apopka's northern shore. These efforts reportedly lowered the lake by about 1.2 m and the Delta Canal Company reported water depths in Lake Apopka ranged from 0.9 to 2.7 m. The Delta Canal Company extensively promoted the agricultural potential of the drained marshes (Delta Canal Company 1895). They noted that the organic soils varied in depth from a few centimeters at the original lakeshore to a depth of more than 4.3 m near the edge of Lake Apopka and also remarked that the soil was fertile and that there were major deposits of "phosphatic marl" along the northern shore of Lake Apopka that could be used as a good fertilizer. Efforts to establish agriculture on the drained marshlands, however, generally failed because the outlet canal became clogged with vegetation and other debris; and the marsh became little changed from its original condition. A hurricane in 1926 returned the Zellwood Farm Area to its original state again (Connell and Associates 1954, Shofner 1982). Efforts to develop the Lake Apopka marsh remained limited until the early 1940s. The Florida Legislature then created the Zellwood Drainage District by special legislative act in June of 1941 and authorized the District to drain the marsh. About 16 km of dikes were constructed in the 1940s and pumps were installed to remove excess water from the District's lands. The drainage system was virtually completed by 1946 and successful muck farming of the newly drained lands began in the late 1940s.

During the latter part of the 19th century and the first part of the 20th century, recreational fishing also became an important industry. Lake Apopka by the 1920s had attracted national attention for its recreational fishing (Shofner 1982). Communities in the region, such as Leesburg and Apopka, sponsored bass tournaments and fish rodeos to market Lake Apopka as a major attraction (Shofner 1982). As fishing, especially bass fishing, became more popular numerous fish camps began to develop around the lake to serve the recreational anglers. By the early 1950s there were over 12 fish camps with a value over $1,000,000 (Shofner 1982).

Lake Apopka was a shallow lake dominated by lush growth of aquatic macrophytes during the first part of the 20th century. The average depth of Lake Apopka in 1932 was approximately 2 m at 19.8 m mean sea level (U.S. Engineer Office, Jacksonville, Florida; File No. 1-14-9339). The lake contained mostly a marl-like sediment that has been termed calcareous gyttja with gyttja being defined as a fine detritus, amorphous material that is usually more soup-like than colloidal (Davis 1946). Heavy growths of submersed vegetation especially pondweed (*Potomogeton illinoensis*) and eelgrass (*Valisneria americana*), however, extended across the lake except where lake depths exceeded 2.4 m (Dequine 1950, Clugston 1963, Chestnut and Barman 1974). There were also major infestations of water hyacinth (*Eichhornia crassipes*). Water hyacinth grew profusely around the entire edge of the lake and formed large floating mats that shifted around the lake (Clugston 1963). Boating around the lake was restricted to areas where hyacinths did not form extensive mats or to trails through the submersed vegetation.

The city of Winter Garden began to discharge sewage to Lake Apopka during the 1920s (U.S. Environmental Protection Agency 1978). Pumpage from the farms along the northern edge began in the early 1940s, and Lake Apopka also received nutrients from citrus processing plants. A hurricane in September 1947 uprooted many of the macrophytes and coincided with a switch to a turbid algal state that has persisted to this day (Bachmann et al. 1999). In 1977 rooted aquatics covered only 0.03% of the lake area (U. S. Environmental Protection Agency 1978). In 1950 and 1951 local newspapers reported that fishermen were alarmed over large fishkills during periods of high winds which stirred up the highly organic, bottom sediments and presumably caused oxygen depletions. In 1952, a water control structure was added to the outlet canal in order to prevent low water levels (U. S. Environmental Protection Agency, 1978) and in part to reduce the chances for wind-driven waves to stir the bottom sediments.

Modern sewage treatment facilities were constructed both for the City of Winter Garden and the citrus processing plant (U. S. Environmental Protection Agency, 1978) thus significantly reducing that phosphorus source. Major efforts were undertaken to reduce nutrient discharges from the muck farms located on the north shore of Lake Apopka by constructing treatment ponds and reducing the amount of water pumped to the lake. The St. Johns River Water Management District (SJRWMD) has also constructed a Marsh Flow-Way for the purpose of enhancing the recovery of Lake Apopka (Lowe et al. 1992). Although millions of dollars have been expended, these nutrient abatement methods have left Lake Apopka virtually unchanged.

Basic Limnological Data for Lake Apopka

Lake Apopka (Fig. 1) is a subtropical, polymictic lake with a surface area of 125 km^2. Water levels are maintained by a structure on the outlet canal, and during the period 1976-1997 water levels averaged 20.3 m above mean sea level (U.S. Geological Survey 1997). At this elevation the lake has a mean depth of 1.7 m (Danek and Tomlinson 1989). The average volume of flow at the outlet for the period 1958-1994 was 2.11 m$^3\cdot$sec-1 or 6.64 x 10^7 m$^3\cdot$yr^{-1} (USGS 1997). Therefore, the average water turnover time would be 3.2 yr. A water budget was estimated for the period 1989-1990 (Stites et al. 1997) that showed that rainfall was the major source of water to the lake (Table 1). The next major source is pumpage from the farms followed by Gourd Neck Spring that supplies groundwater from the Floridian Aquifer at a rate that varies depending on lake level. There are no major streams entering the lake.

An area of uncertainty with regard to the hydrology of the lake concerns pumpage from the muck

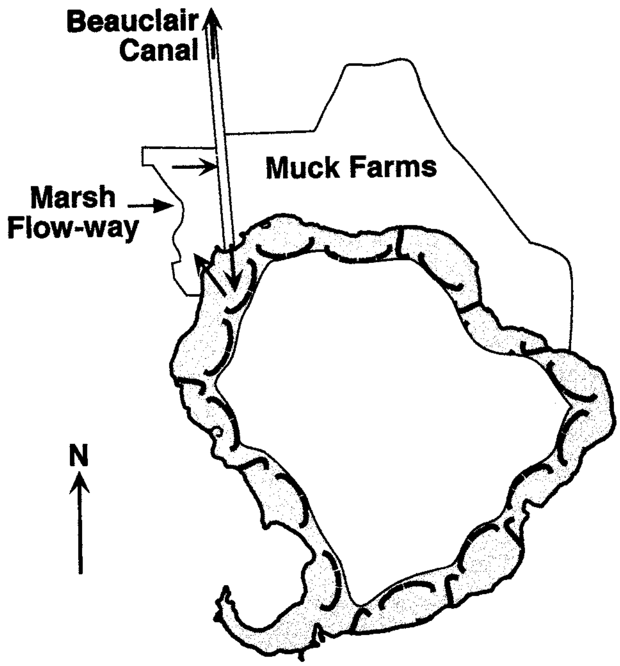

Figure 1.–Map of Lake Apopka showing location of outlet canal, marsh flow-way and muck farms. Also indicated are the proposed artificial reefs that would be used to establish plant refuges.

farms on the north side of the lake. An area of former sawgrass marsh was separated from the lake by an earthen dike in the 1940s. Drainage ditches were constructed within the diked area, and pumps were and are still used to remove excess water from the fields. Some of these pumps discharge into the lake and others flow into the outlet canal (Schiffer 1994). Various studies have attempted to estimate the amount of water pumped from the fields to the lake, but a number of technical problems have made it difficult to obtain reliable numbers. In the years 1989-1990 the annual pumpage ranged from 18.1 x 10^6 to 131 x 10^6 $m^3 \cdot yr^{-1}$ and averaged 62.1 x 10^6 $m^3 \cdot yr^{-1}$.

In terms of the water budget for the lake, the amount of water pumped from the farms has to be considered as gross because some of the water pumped originates from the lake itself. Controlled amounts of water are moved from the lake to the farm areas for irrigation when needed or to flood fields for pest control and to prevent soil oxidation. Seepage under the dike also brings lake water into the farms because the farm areas are over 1 m lower than the surface of the lake, and the water table is generally lowered under the fields by pumpage to prevent waterlogging of the soils. The dike also leaks water into the farms, thus the amount of water pumped from the farms into the lake represents not only surplus rainwater and groundwater, but also water that originated from the lake (irrigation, pest control, and leakage water). Consequently, measured pumpage overestimates the net amount of water added to the lake from the farms. In our opinion the seepage estimates of Stites et al. (1997) probably underestimate the amount of lake water that moves from the lake back into the farms.

Anderson (1971) noted that the potentiometric surface, which reflects the hydrostatic pressure in the artesian aquifer, is higher than the lake level on the south side of the lake but is lower than the lake level on the north side where the farms are located, thus water tends to flow out of the lake towards the farms under normal circumstances. He used a water budget approach to estimate by difference that 102 x 10^6 $m^3 \cdot yr^{-1}$ of water moved from the lake to the farms by the combined effects of seepage, irrigation, and flooding for pest control, but thought this estimate was probably high. Another estimate of seepage can be obtained from seepage coefficients developed for flood control dikes surrounding Lake Okeechobee. Meyer (1971) studied seepage through the dikes at six locations relative to length of the dike and height of head and found a range of seepage coefficients from 6 to 53 $L \cdot s^{-1} \cdot km^{-1} \cdot m^{-1}$. Using these values with a value of 17 km for the dike separating the farms from Lake Apopka, and a head difference of 1.8 m between the lake surface and the land surface of the farms (Mr. Paul Wolf, Zellwood Drainage District, personal communication), seepage at Lake Apopka would range from 5.8 x 10^6 to 51 x 10^6 $m^3 \cdot yr^{-1}$. Applying a weighted average of the coefficients developed at Lake Okeechobee (21 $L\ s^{-1} \cdot km^{-1} \cdot m^{-1}$) provides an annual seepage of approximately 20 x 10^6 $m^3 \cdot yr^{-1}$.

Table 1.–Water budget for Lake Apopka for 1989-1994 (from Stites et al. 1997). Flows are in millions of cubic meters per year.

Water inflows	
Rainfall	135.1
Farm pumpage	62.1
Gourd Neck Spring	36.5
Other sources	13.2
Total inflows	246.8
Water outflows	
Apopka-Beauclair Canal	44.9
Seepage	5.27
Inlet to farms	4.25
Total outflows	55.2
Evaporation (1989-90 average)	163

Records kept by Mr. Wolf in the period June 1987 to May 1988 indicated that irrigation and flooding of the farms used about $37.8 \times 10^6\ m^3 \cdot yr^{-1}$. He also kept track of the amounts of water pumped out of the ditches collecting seepage and leakage water during a period of drought and estimated water inputs from Lake Apopka ranging from 6.4×10^6 to $60.5 \times 10^6\ m^3 \cdot yr^{-1}$ with an average of $28.4 \times 10^6\ m^3 \cdot yr^{-1}$. These records would indicate that about $66.2 \times 10^6\ m^3 \cdot yr^{-1}$ of water moved from the lake to the farms in 1987-88. The conclusion is that a significant amount of water flows from the lake to the muck farms and carries with it phosphorus from the lake that is then moved back into the lake when the pumps are used to move water back from the farms to the lake. This recirculation of water and phosphorus needs to be taken into account in any phosphorus budget developed for the lake.

A significant factor in the limnology of Lake Apopka is a layer of flocculent sediments that covers most of the lakebed and is frequently resuspended by wind-driven waves (Bachmann et al. 1999). This sediment layer is about 98% water and contains 65% organic matter (Schelske 1997) and meets the definition of fluid mud in that the individual particles are in suspension rather than being supported by the particles below (Maa and Mehta 1988). The layer has increased in thickness from about 10 cm in 1968 (Schneider and Little 1969) to 45 cm in 1997 (Schelske 1997). It is commonly believed that the flocculent sediments represent dead algal cells that have accumulated since the loss of aquatic macrophytes in 1947. The amounts of phosphorus in this layer have been used to estimate phosphorus storage rates in the lake since 1947 (Lowe et al. 1992, Schelske 1997). The sediments immediately below are very similar in major composition, but are consolidated rather than flocculent, and do not contain the diatoms characteristic of the algal stage in the lake (Schelske 1997). An alternative hypothesis for sediment origin is that the unconsolidated sediments represent, in part, underlying consolidated sediments that have been fluidized by water pressure fluctuations due to surface waves in this shallow lake. Such a process has been described for muddy coastal shores, and has been used to explain a similar layer of flocculent sediments in Lake Okeechobee, Florida (Hwang 1989).

Average values for some water quality variables for the period 1989-94 are presented in Table 2. While there are seasonal fluctuations, the averages have remained rather constant since the 1970s, however there has been a drop in the levels of total phosphorus, total suspended solids, and algal chlorophylls since mid-1995 (Battoe et al. 1999). Much of the total suspended solids can be traced to resuspended sediments but Carrick et al. (1993) have shown that a layer of meroplankton algae on the sediment surface contributes to water column chlorophyll levels when they are resuspended by wave action. Battoe et al. (1999) attributed the decline in total phosphorus to regulatory actions, however Bachmann et al. (2000) have shown that the declines correspond with a drop in average wind velocities at the nearby Orlando Airport and may be related to reductions in the amounts of sediments resuspended by wind-driven waves.

Table 2.–Averages and standard deviations (SD) of monthly measurements of water quality in Lake Apopka made by the St Johns River Water Management District from January 1987 through December 1996.

Variable	Mean	SD	N
Total suspended solids ($mg \cdot L^{-1}$)	79	79	112
Chlorophyll ($mg \cdot m^{-3}$)	92	32	89
Total phosphorus ($mg \cdot L^{-1}$)	0.204	0.059	113
Total nitrogen ($mg \cdot L^{-1}$)	5.14	1.20	113
Secchi depth (m)	0.23	0.07	109

The Nutrient Enrichment Hypothesis

Previous nutrient budgets

In the early 1960s, Huffstutler et al. (1965) conducted the first limnological survey of Lake Apopka and suggested that nutrient enrichment from anthropogenic activities could be responsible for the algal growth in the lake. Between 1970 and 1984, various studies (Brezonik et al. 1978, Preston 1983) attempted to estimate the lake's nutrient budget, with Brezonik et al. (1978) providing the most comprehensive phosphorus budget for Lake Apopka (Table 3). These studies provided estimates of phosphorus discharges from the farms ranging from 36,880 $kg \cdot yr^{-1}$ to 51,000 $kg \cdot yr^{-1}$. In addition Lowe et al. (1992) used a farm loading estimate of 132,000 $kg \cdot yr^{-1}$ of P in a Vollenweider model to estimate an in-lake phosphorus concentration of 24 $mg \cdot m^{-3}$ if the farm inputs were eliminated, and this became the target concentration

Table 3.–Phosphorus budget for Lake Apopka for the 1977 water year as estimated by Brezonik et al. (1978).

Source	Annual phosphorus input ($kg \cdot yr^{-1}$)
Winter Garden Sewage Effluent	7,090
Winter Garden Citrus Co-op	1,300
Muck farms	36,880
Precipitation	6,322
Gourd Neck Spring	2,470
Lateral inflow	1,690
TOTAL	55,750

of phosphorus for the Lake Apopka restoration. More recently the target was raised to 55 $mg \cdot m^{-3}$ (Battoe et al. 1999).

In a recent phosphorus study (Stites et al. 1997) for the period 1989-1994 (Table 4) it was estimated that the muck farms added on average 53,080 $kg \cdot yr^{-1}$ with inputs ranging from a low of 17,260 $kg \cdot yr^{-1}$ to a high of 113,670 $kg \cdot yr^{-1}$ of P. Although total inputs of phosphorus fell during the study from a high of about 128,000 $kg \cdot yr^{-1}$ to a low of approximately 25,000 $kg \cdot yr^{-1}$ (an 80% decrease), in-lake total phosphorus concentrations remained near or above 200 $mg \cdot m^{-3}$ (Fig. 2). This is probably related to internal loading, for Reddy and Graetz (1991) estimated internal phosphorus loading rates were between 1.7 and 2.7 $mg \cdot m^{-2} \cdot day^{-1}$ based on laboratory studies of Lake Apopka's sediments. The annual rates for the lake of from 77,000 to 122,000 $kg \cdot yr^{-1}$ of total phosphorus is probably an overestimate, but indicates that internal loading will be an important factor in slowing the recovery of Lake Apopka.

Between 1977 and the present, there have been major changes in the handling of wastes from the sewage treatment plant and the citrus plant, so that the reduction in point source inputs in recent years is probably real. We, however, note that the atmospheric loading estimates of Brezonik et al. (1978) and the SJRWMD amounted to about 51 and 40 $mg \cdot m^{-2} \cdot yr^{-1}$ respectively, but they may be underestimates. A recent study (Dixon et al. 1996) of atmospheric deposition for the Tampa Bay region just to the southwest of Lake Apopka for the years 1985-1991 showed an average phosphorus deposition of 91 $mg \cdot m^{-2} \cdot yr^{-1}$. Applying this rate to Lake Apopka gives about 11,000 $kg \cdot yr^{-1}$, a deposition that would increase background loading.

In our opinion, the values for the muck farm inputs (Table 4) are probably still too large to represent

Table 4.–Phosphorus budget for Lake Apopka for the years 1989-1994 as estimated by the SJRWMD (Stites et al. 1997). The annual inputs and losses are listed as averages for 6 years.

Source	Annual inputs and losses of phosphorus ($kg \cdot yr^{-1}$)	Range
Inputs		
Point sources	640	390-1,040
Overland flow	470	370-700
Muck farms	53,080	17,260-113,670
Precipitation	5,030	2,670-8,930
Gourd Neck Spring	1,410	940-1,820
Lateral inflow	470	490-540
Tributaries	1,450	1,250-1,650
Total Inputs	62,550	24,580-127,720
Losses		
Seepage	90	40-190
Farm inlets	950	340-2,250
Canal	9,950	4,450-24,350
Total losses	10,990	4,830-25,700
Sediment storage by difference	51,560	8,430-121,920

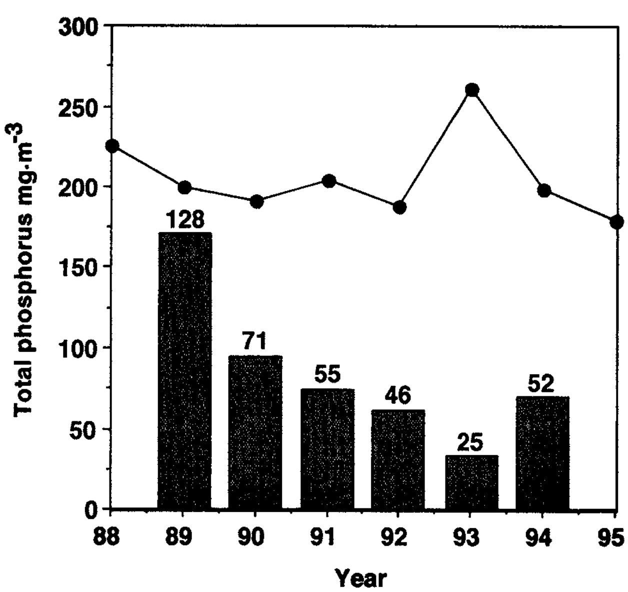

Figure 2.–Average annual total phosphorus concentration in Lake Apopka based on monthly measurements by SJRWMD. The bars represent the annual total phosphorus loading in metric tons

net additions of phosphorus to the lake from the farms. For comparison, a study of about 3900 ha of vegetable farms located on muck soils in the Everglades Agricultural Area of Florida (CH2M Hill 1978) showed an annual phosphorus loss through back pumpage of 2.4 kg $\cdot ha^{-1} \cdot yr^{-1}$. Applying this rate to the 5540 ha of muck farms at Lake Apopka would give an estimated farm loading of only 11,700 kg $\cdot yr^{-1}$. Further, some of the Apopka drainage water is pumped directly into the outlet canal rather than the lake itself, and would not contribute to the phosphorus budget of the lake. We think that the discrepancy comes from the phosphorus which moves from the lake to the farms through seepage, dike leakage, and irrigation and flooding activities. It then is counted a second time when pumped back into the lake. Previously we estimated that in 1987-88 about 66.2 x 10^{6} $m^3 \cdot yr^{-1}$ of water flowed from the lake to the farms. With an average concentration of 220 mg $\cdot m^{-3}$ at that time, this would account for about 14,575 kg of phosphorus that should be subtracted from the measured farm inputs to the lake.

Phosphorus inputs estimated from sediment storage

Because there is such variation in the nutrient budgets from year to year in addition to the problems mentioned in obtaining good numbers, we used an independent means to place limits on the average annual phosphorus input over the past 50 years. Schelske (1997) made a detailed study of 46 sediment cores that were spaced in an equal area grid. He found that the flocculent sediments contained 2.21 x 10^9 kg of dry weight and 2.25 x 10^6 kg of total phosphorus. If the flocculent layer represents new sediments laid down since 1947, then the average rate of phosphorus storage since the switch to an algal state would be 45,000 kg $\cdot yr^{-1}$.

On the other hand, it is possible that this is an overestimate if the flocculent sediments consist partially of pre-1947 consolidated sediments that have been fluidized by waves. At the extreme, we might suppose that they consist entirely of fluidized consolidated sediments to which has been added phosphorus that has sedimented out over the past 50 years. To estimate storage, we would subtract the phosphorus that would have been contained in the older sediments. The average total phosphorus content of the consolidated sediments for 210 samples below the interface with the flocculent sediments was calculated from the data of Schelske (1997) as 0.55 (SE=0.02) g $\cdot kg^{-1}$ dry weight which would yield a total of 1.22x 10^6 kg of old phosphorus in the flocculent layer. If we subtract this from the total amount of phosphorus in the layer and divide by 50 years, we get a value of 21,000 kg $\cdot yr^{-1}$ as the estimated annual phosphorus storage under this set of assumptions.

We also needed an estimate of phosphorus lost through the outlet to add to storage in order to calculate total loading. This was estimated as 13,300 kg $\cdot yr^{-1}$ by multiplying the average total phosphorus concentration of the lake water times the average annual outflow volume. The end result of looking at the sediment record is that we can put limits on the estimates of annual loading with a maximum annual phosphorus loading of 58,300 kg $\cdot yr^{-1}$ and minimum phosphorus loading of 34,300 kg $\cdot yr^{-1}$. These values are considerably lower than the value of 132,000,000 kg $\cdot yr^{-1}$ used by Lowe et al. (1992) to model the recovery of Lake Apopka.

Phosphorus loading by calculation

Another independent estimate of annual loading can be obtained by applying the regression equation of Bachmann (1984) based on studies on 626 lakes. His calculated regression was:

$$\ln(L) = 1.87 + 0.847\ln(TP) + 0.88\ln(z) + 0.679\ln(\rho)$$

where L is the phosphorus loading per unit of surface area (mg $\cdot m^{-2} \cdot yr^{-1}$), TP is the concentration of total phosphorus in the lake water (mg $\cdot m^{-3}$), z is the mean depth of the lake (m), and ρ is the hydraulic flushing rate (yr^{-1}). Applying this equation to Lake Apopka yields an annual loading estimate of 422 mg $\cdot m^{-2} \cdot yr^{-1}$ or about 52,700 kg $\cdot yr^{-1}$ for the lake. This lies within the limits calculated previously though it is not possible to state an exact value due to the wide 95% confidence limits (26 to 421%) for this type of calculation.

Phosphorus loading prior to 1947

The current management plan is to buy the muck farms and take them out of production, so that there will be no more loading from these areas. We, therefore, estimated what proportion of the current loading would remain after the loss of this source. Our approach was to compare the maximum and minimum current loadings with the background or historic loading.

We estimated the historic loading prior to the 1947 hurricane using the results of a study that dated sediment cores taken in 1996 using ^{210}Pb (Schelske 1997). We used Schelske's data to date the portions of the cores that were below the boundary between the flocculent and consolidated sediments following the method of Appleby & Oldfield (1978). We found the amount of total phosphorus that had accumulated between dated horizons and divided by the time interval to find the average phosphorus storage rate per square meter. This was multiplied by the lake area to find an average annual rate of sediment phosphorus storage of 14,000 kg $\cdot$ yr^{-1} with a standard error of 3,000 kg $\cdot$ yr^{-1}. As before we need to add the annual loss through the outlet to find the estimated loading, but we have no measurements of total phosphorus in the water column prior to the 1960s. We can, however, make an estimate by looking at the phosphorus concentration in other Florida lakes within the same lake region (Griffith et al. 1997). Most of the lakes in the central lake region that includes Lake Apopka have total phosphorus concentrations that range from 20 to 80 mg $\cdot$ m^{-3}. If we use the lowest value of 20 mg $\cdot$ m^{-3} for Lake Apopka then the outlet loss would be about 1,300 kg $\cdot$ yr^{-1} for a total historic loading of about 15,000 kg $\cdot$ yr^{-1}. If the phosphorus concentration in the water were higher, the estimated historic loading would be higher as well. Our value is in good agreement with an independent estimate of 14,700 kg $\cdot$ yr^{-1} made by Battoe et al. (1999) using a land use model.

Phosphorus concentration following elimination of muck farms

The question others and we are trying to answer is what the total phosphorus concentration would be when the farm loading is eliminated. As a starting point we can estimate what per cent of the total phosphorus input is not due to farm input. Previously we used sediment storage to show that the total average annual input since 1947 had to lie between 34,300 kg $\cdot$ yr^{-1} and 58,300 kg $\cdot$ yr^{-1} while the nonfarm input (historic) was about 15,000 kg $\cdot$ yr^{-1}; thus the nonfarm input would lie between 26% and 44% of the total phosphorus inputs. If we apply these percentages to the current concentration of total phosphorus (200 mg $\cdot$ m^{-3}), we estimate final theoretical equilibrium phosphorus concentrations of 52 to 88 mg $\cdot$ m^{-3}.

The effects of internal loading

These estimates are probably too low for experience in other shallow lakes where phosphorus reduction programs have been carried out has shown that phosphorus concentrations do not drop in proportion to loading in lakes that have been subject to a high loading over a long period of time. Four recent books dealing with eutrophication (Cooke et al. 1993, Moss 1997, Scheffer 1998, Sas 1989) and many papers (e.g. Ekholm et al. 1997, Kleeberg and Kozerski 1997, Van Liere and Gulati 1992, Van der Does et al. 1992) have emphasized that, in shallow lakes, recovery is inhibited by internal loading from the sediments that keeps the phosphorus from dropping as far as might be predicted from a simple proportion to the decrease in loading. For example, in Lake Norrvican, Sweden, (Sas 1989) sewage diversion was used to reduce phosphorus loading by about 90 per cent, yet after 10 years the total phosphorus concentration had decreased to only 31% of the original concentration, but was still 3.1 times larger than the projected concentration based on a direct proportion. The flushing rate in this lake is 0.8 years, so this represents 12.5 flushing of the lake. In the United States Shagawa Lake in Minnesota had its phosphorus loading reduced by 80% (Larsen et al. 1979), yet after 20 years the phosphorus concentration (Bruce Wilson, Minnesota Pollution Control Agency, St. Paul, personal communication) was still equal to 47% of the original concentration and 2.3 times larger than the concentration predicted by proportion (Fig. 3). This time period represents 27 flushing of the lake. In Lake Apopka 27 flushing would represent about 76 years.

Detailed measurements of the nutrient budget in Shagawa lake showed that the sediments became net sources of phosphorus for 5 years following the reduction in inputs and supported the elevated phosphorus concentrations in that lake. Moss (1997) suggests that one should add 50% to the expected equilibrium total phosphorus concentration to account for internal loading in a shallow lake. In light of the Lake Norvviken and Shagawa Lake experiences, this seems a conservative estimate of the effects of internal loading. The phosphorus budgets developed for Lake Apopka by Stites et al. (1997) for 1989-94 show the effects of

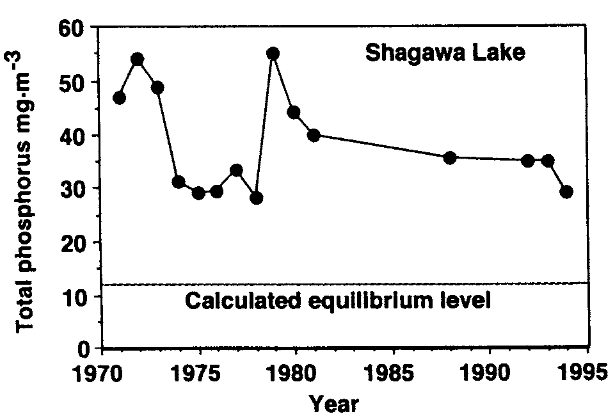

Figure 3.–Average annual total phosphorus concentration in Shagawa Lake, Minnesota. There was an 80% reduction in phosphorus loading in 1973 as a part of an experiment to determine the effects of nutrient reductions in lakes. Early data are from Larsen et al. (1979) and later data are from Bruce Wilson (personal communication).

interactions between sediments and phosphorus. Loading was very high in 1989 at 128,000 kg of P and then dropped progressively for the next 4 years to 25,000 kg (Fig. 2), but the average total phosphorus concentration in the lake showed no corresponding change. Seemingly phosphorus concentrations are uncoupled from annual phosphorus inputs in Lake Apopka.

When we calculate annual phosphorus sedimentation coefficients (annual P input minus annual P loss to outflows plus change in p storage in the water column divided by the average water column p mass), we find that phosphorus sedimentation rises in years of high phosphorus input and decreases in years of low input (Fig. 4). When phosphorus inputs were at their lowest in 1993, the phosphorus sedimentation coefficient was negative indicating a net movement of phosphorus from the sediments to the water in that year. The effect of this process is to keep the phosphorus concentration in the water more or less constant in spite of changes in annual phosphorus loading. This indicates that like lakes Norvviken and Shagawa, Lake Apopka will be slow to respond to reductions in external phosphorus loading.

There is every expectation that internal loading will have the same effect in inhibiting the recovery of Lake Apopka as in other shallow lakes that have been studied following nutrient reduction. After examining the recovery of several lakes, Sas (1989) concluded that when the total phosphorus concentration of the upper 15 cm of the sediments is 1 mg $\cdot g^{-1}$ of dry sediment or greater, then several years of net annual

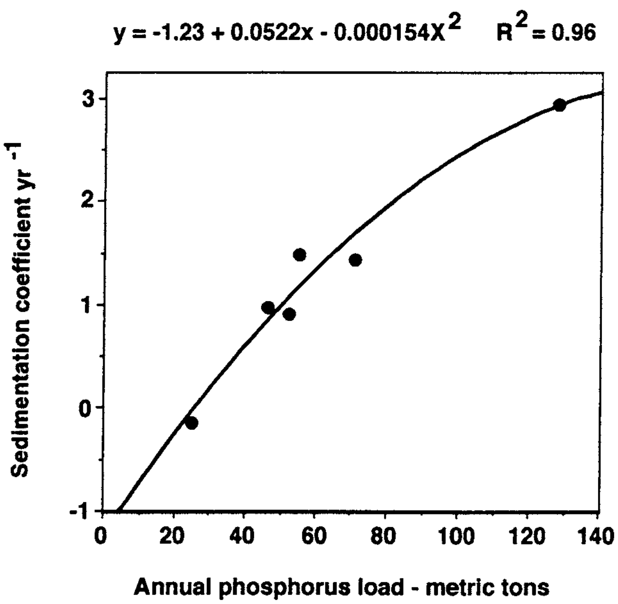

Figure 4.–Annual phosphorus loading and phosphorus sedimentation coefficients for the years 1989-94 in Lake Apopka.

release from the sediments are likely to be observed. From the 46 cores of Schelske (1997) the average total phosphorus content of the upper 15 cm of Lake Apopka sediments is 1.48 mg$\cdot g^{-1}$ (SE = 0.17) indicating net release of phosphorus is likely from this source. Reddy et al. (1996) studied internal loading from Lake Apopka sediments and concluded that it would delay the recovery of the lake. He found that the SRP concentrations in the pore waters of the top 8-cm of the flocculent sediments were low and comparable to those in the water column while the concentrations increased deeper in the core. He interpreted this to mean that the upper 8 cm was regularly resuspended, and the porewater SRP was released directly to the water column. Various authors have indicated that sediment resuspension is a mechanism that facilitates internal loading of phosphorus in shallow lakes (James et al. 1995).

In theory, internal loading is decreased with time as phosphorus-rich sediments become buried by a layer of new sediments with smaller phosphorus concentrations. In Lake Apopka, there are no inflowing streams, so there is not a good source of low-phosphorus particles to carry out the burial. Further frequent sediment resuspensions means that it will not be possible to create of layer of low phosphorous sediments at the surface, since they will tend to be mixed in with the older sediments.

It has also been suggested (Battoe et al. 1999) that chemical processes within the sediments will cause phosphorus to be bound up in an irreversible manner over time and will reduce internal loading. A recent study indicates that this is not happening in the Lake Apopka sediments. Kenney (1997) used algal bioassays to determine the amounts of bioavailable phosphorus in sediments taken at different depths within the flocculent sediments of Lake Apopka. He found that bioavailable phosphorus averaged 7% of the total phosphorus at the surface of the sediments and increased to 25% of the total phosphorus at the bottom of the flocculent layer indicating that phosphorus was becoming more rather than less available with depth in Lake Apopka.

We have some indication of the ability of the sediments in Lake Apopka to maintain high total phosphorus concentrations in the face of reduced external loading during the years 1989 through 1994 (Fig. 3). During major changes in the phosphorus loading, there were no corresponding changes in average total phosphorus concentrations in the lake. This uncoupling of phosphorus concentration from loading has been observed in other shallow lakes such as Lake Pyhäjärvi in Finland (Ekholm et al. 1997) and Lake Okeechobee in Florida (James et al. 1995). This is another indication that internal loading is going to be a major factor in resisting changes in the total phosphorus concentrations in the waters of Lake Apopka.

Clearly, there remains a great deal of uncertainty in estimating the total phosphorus concentration in Lake Apopka when the muck farm loads are eliminated. The calculated concentrations of from 52 to 88 mg $\cdot m^{-3}$ as well as the current target of 55 $\cdot$mg $\cdot m^{-3}$ are all within the eutrophic range, and experience elsewhere indicates that it will be a very long time before those levels can be reached.

The Macrophyte Loss Hypothesis

For over 20 years, the focus of lake managers at Lake Apopka has been on nutrient control. In the first major study of the lake, Huffstutler et al. (1965) hypothesized that nutrient enrichment was a potential problem, but they also noted that the lake's problem might not be chemical, but biological. They observed that the water of Lake Apopka was clear not because of the infertility of Lake Apopka, but because of the presence of a lush growth of submersed aquatic vegetation that covered more than 70% of the lake bottom. Huffstutler et al. (1965) further noted that although enrichment has been cited by many as the singular cause for many of the changes in the lake, this thesis fails to consider the enormous quantity of nutrients bound in the submersed plants prior to any great amount of discharges of nutrient-rich water from anthropogenic sources.

We attempted to assess Huffstutler et al. (1965) concern by using available data and our experience with Florida lakes. Based on U.S. Army Corps records, Lake Apopka had an average depth of approximately 2 m in 1932. Macrophytes covered from 70% to 80% of the lake bottom (Clugston 1963). From descriptions by commercial fishermen who used nets, the maximum depth of macrophyte colonization was about 2.4 m. Because the maximum depth of macrophyte colonization is related to water clarity, we used a Florida model and a worldwide model to predict water clarity in Lake Apopka prior to the establishment of the farms.

Reports of clear water in Lake Apopka prior to 1947 were based on observations that the water was clear within the plant beds, but according to John Dequine (personal communication), the state fisheries biologist at the lake in 1947, the open waters in the center of the lake were turbid during the macrophyte phase. This is similar to the situation in Lake Veluwemeer (Van den Berg et al. 1998) where clear waters were found in dense macrophyte beds in an otherwise turbid lake. Because 70% of the lake was occupied by macrophytes, the principle of alternative stable states still holds for this lake. We estimated Secchi disc depths in Lake Apopka prior to the farms probably ranged from 0.9 m to about 1.6 m. These estimates clearly support Huffstutler et al. (1965) view that Lake Apopka was not an infertile water body. If lake trophic status were assessed using the Secchi disc readings alone, Lake Apopka would not be classified as an oligotrophic or mesotrophic lake, but as a eutrophic or hypereutrophic lake. The Secchi disc estimates, however, also provide an understanding why Lake Apopka was described as a clear-water lake. With these type of Secchi depth values, users of Lake Apopka, as reported by John Dequine, could see the lake's bottom in most of the lake, thus a clear-water lake.

Many Florida lakes change dramatically when they lose their aquatic macrophyte population. For example, Lake Baldwin in Orange County had Secchi disc readings greater than 5 m, total phosphorus concentrations less than 11 mg $\cdot m^{-3}$, and chlorophyll concentrations less than 3 mg $\cdot m^{-3}$ when hydrilla (a nonnative submersed aquatic plant introduced into Florida) covered 80% of the lake's bottom in 1981 (Shireman et al. 1984). After the loss of macrophytes in Lake Baldwin through the use of grass carp, Secchi disc transparencies decreased to less than 2 m, total phosphorus concentrations averaged 30 mg $\cdot m^{-3}$, and chlorophyll values averaged 21 mg $\cdot m^{-3}$. Unfortunately, there are no aquatic plant biomass or water quality measurements prior to the establishment of the farms, so any assessments of the effects of macrophyte loss on the water quality of Lake Apopka remains somewhat speculative.

To evaluate the potential effect of losing the macrophyte population on in-lake total phosphorus concentration, we used the method of Canfield (1983), a range of plant biomass that we typically find in Florida lakes, and three in-lake total phosphorus concentrations that would be found in lakes of different trophic status (Table 5). This analysis indicated in-lake total phosphorus concentration would be < 50 mg $\cdot m^{-3}$ only if the lake had very low phosphorus concentration and low aquatic plant biomass. Phosphorus levels would only be < 100 mg $\cdot m^{-3}$ if plant biomass in fresh weight remained about 2 kg $\cdot m^{-2}$ and in-lake phosphorus levels did not exceed 10 mg $\cdot m^{-3}$; else potential phosphorus concentrations exceed 100 mg $\cdot m^{-3}$ for all other combinations of plant biomass and in-lake phosphorus concentration (Table 5). Based on this analysis and descriptions of extensive and heavy growths of submersed plants, we conclude that Huffstutler et al.

Table 5.–Estimated contribution of aquatic macrophytes to the phosphorus content of Lake Apopka in 1947 for various values of macrophyte biomass (wet weight) and three different potential in-lake phosphorus concentrations. End phosphorus concentrations were calculated using the method of Canfield et al. (1983) and assuming a lake-wide macrophyte coverage of 80%.

Plant biomass (fresh weight kg · m^{-2})	Potential starting phosphorus concentration (mg · m^{-3})		
	10	30	60
1	48	68	98
2	85	105	135
3	122	142	172
4	160	180	210
5	198	218	248
6	235	255	285

(1965) view that submersed plants significantly influenced the limnology of Lake Apopka prior to discharges of nutrient-rich water from anthropogenic sources should not be ignored. Further, we believe based on the weight of evidence that the loss of macrophytes is largely responsible for the current conditions found at Lake Apopka.

The information presented here and elsewhere (Bachmann et al. 1999) suggests that Lake Apopka is an example of a shallow lake that has switched from a clear-water macrophyte state to a turbid algal state according to the theory of alternative stable states (Scheffer et al. 1993). These switches can occur with no change in nutrient input. In the macrophyte stage, waters are clear within the plant beds, but the whole lake becomes turbid and algal dominated when the macrophytes are lost. Experience elsewhere has shown that nutrient reductions alone are usually not sufficient to switch a lake back to a clear-water, macrophyte stage. Because of the flocculent sediments, large surface area, and shallow depths, sediment resuspension in Lake Apopka will prevent the establishment of clear-water conditions. Only the establishment of abundant macrophyte communities within the lake will achieve the clear-water state. Consequently, any lake management plan must directly address the issue of submersed aquatic plants.

The Marsh Flow-Way Management Proposal

A marsh flow-way has been proposed by the St. Johns River Water Management District as a means of removing particulate phosphorus from Lake Apopka (Lowe et al. 1992). In brief, lake water will be pumped through 13 km^2 of emergent vegetation on one of the former muck farms where it is estimated that 85% of the suspended particles will be removed by mechanical filtration. The water will then flow into the outlet canal where about 15% will leave the lake, and the rest will flow back into Lake Apopka.

The volume of water to be pumped per year (4.57×10^8 m^3 · yr^{-1}) amounts to 2.15 times the lake volume. The lake has an average total suspended solids concentration of 79 mg · L^{-1} and 70 % of the total phosphorus is associated with particles. We have previously modeled the expected effects of the flow-way on particles in the lake (Bachmann et al. 1999). The flow-way will remove 31,500,000 kg · yr^{-1} of particles, but the lake ordinarily accumulates about 24,800,00 kg · yr^{-1} of new particles in the sediments showing that the flow-way will remove more particles in a year than would be expected to be deposited through sedimentation. Because the fluid muds are continually resuspended in this shallow lake, we reasoned that as particles are removed through filtration they would be replaced by resuspension. Consequently, there will be a net movement of particles from the lakebed into the water column (6,700,000 kg · yr^{-1}), and eventually to the marsh flow-way and the outlet. At this rate, it will take about 300 years to remove all the fluid mud.

We have looked at how the marsh flow-way will influence the phosphorus concentration in the lake following the loss of the farm loading. Initially, the lake will have a drop in phosphorus concentration as the lake adjusts to the reduced loading. Eventually a new equilibrium will be reached where the losses of phosphorus will be balanced by the annual inputs.

Phosphorus losses from the lake will all be from pumpage to the marsh flow-way and outlet because the sediments are a source rather than a sink for phosphorus.

$$L_t = Q_p\ TP/1000000$$

where L_t is the total annual loss of phosphorus in kg $\cdot$ yr^{-1}, Q_p is the annual pumpage in m^3 $\cdot$ yr^{-1}, and TP is the total phosphorus concentration in mg $\cdot$ m^{-3}. The constant 1000000 converts milligrams to kilograms. Substituting for Q_p yields:

$$Lt = 457TP$$

There will be three sources of phosphorus inputs to the lake water which include the background or historic loadings (15,000 kg $\cdot$ yr-1), the loading from the water that returns to the lake from the marsh flow-way, plus the phosphorus contained in the sediments being eroded from the lakebed.

The quantity of phosphorus in the return flow is equal to the amount of phosphorus pumped minus the amounts lost to the marsh and to the outlet. Because the marsh is projected to remove 85% of the particles and 70% of the total phosphorus is in the particulate phase, the marsh removal equals 272TP, and the amount of phosphorus left to flow to the canal would be 185TP. Because 85% of this flow will return to the lake, then the phosphorus loading back to the lake would be 157TP.

The phosphorus content of the sediments in the upper 15 cm of the fluid mud layer (about what will be eroded in the first 50 years) can be calculated from the data of Schelske (1997) as 1.4 mg P $\cdot$ g^{-1} dry weight of sediments. This yields an annual input from this source of 9400 kg $\cdot$ yr^{-1}. Therefore:

$$I_t = 15{,}000 + 9400 + 157TP$$

where I_t is the total annual phosphorus input from all sources at equilibrium.

If we make losses equal to inputs and solve the equation for the equilibrium TP, we get a equilibrium phosphorus concentration of 81 mg $\cdot$ m^{-3}. This is higher than the high phosphorus concentration expected without the marsh flow-way, and results from the fact that the sediments are not retaining phosphorus but are serving as a source because the upper layer is being physically transported into the water column.

These analyses again show that there is a great deal of uncertainty in predicting the future trophic state of Lake Apopka based on a nutrient budget approach. The weight of the evidence, however, seems to indicate that Lake Apopka will still be in the eutrophic category several decades following the nutrient reduction and may always be in that state. A eutrophic state would be consistent with the Florida lake region in which it is found (Griffith et al. 1997).

The Future Management of Lake Apopka

In 1997, the Florida Legislature authorized the purchase of the muck farms (estimated cost close to $100,000,000) along Lake Apopka's north shore. Since the late 1980s, the Florida Legislature and the St. Johns River Water Management District also have spent millions for land purchase, construction, and operation of the marsh flow-way. These projects were conceived and implemented based on the belief that external nutrient enrichment was and is the singular cause for many of the changes in the Lake Apopka. The nutrient enrichment hypothesis will now be directly tested.

We believe the uncertainties that we have discussed earlier in this paper will still limit the success of the nutrient control programs. Additional management will be needed and it will be needed sooner rather than later because the longer Lake Apopka remains in its current condition the faster public frustration and distrust will grow. Making Lake Apopka into a valuable public resource again will, however, require a fundamental shift in the thinking of those individuals responsible for solving the lake's problems. First, there is currently an emphasis on the restoration of Lake Apopka, not its management. Lake Apopka will not be restored to its original condition; and if we come close, there will still be problems that require lake management and moneys to support the activities. Some policy-makers and some of the public currently believe that once the lake is restored, additional expenditures will not be needed. Second, we believe that successful management of Lake Apopka requires an acceptance of Huffstutler et al. (1965) view that the problem at Lake Apopka is not chemical, but biological.

One aspect of the biological problem is the growth of submersed plants, but this part of the biological problem must be approached very carefully otherwise a massive, costly, aquatic weed problem will be created. Lake Apopka was described as a clear-water lake prior to the construction of the farms. From the early descriptions of the lake, aquatic macrophytes densely covered over 70% of the lake bottom (a weed problem for most of today's Floridians). Our studies of Florida lakes indicate that a lake would have to have a bottom coverage of more than 50% to have a chance of producing clear water (Canfield and Hoyer 1992). Although a management objective of establishing plant coverage > 50% to 70% to obtain clear water in the lake would seem reasonable, this type of objective would most likely cause more problems than it would be worth.

The primary method for restoring submersed macrophytes (and associated fish habitat) in Florida lakes is water level drawdown (Wegener and Williams 1975, Moyer et al. 1995). A major drawdown of Lake Apopka would dry and compact the bottom sediments and a firmer bottom would promote the regrowth of submersed aquatic plants. The use of an extreme drawdown on Lake Apopka, however, would certainly be needed to have a chance of establishing plant coverage > 50%. Although it would most certainly improve habitat for fish populations (Greening and Doyon 1990), there would be opposition as a drawdown in the late 1970s was thought responsible by the public for an outbreak of disease that killed a large number of fish and wildlife. The St. Johns River Water Management District also has not supported a drawdown for Lake Apopka in part because the drawdown would cost at least $20 million (Lowe et al. 1992). A further negative aspect of a drawdown would be the increased flow of nutrient-rich Lake Apopka water to the downstream lakes (U.S. Environmental Protection Agency 1978). Finally, there has to be a concern as to what types of aquatic plants would reappear. Before the switch to an algal state, water hyacinth (*Eichhornia crassipes*) was abundant in the lake and a drawdown could cause a resurgence of this weed species. Likewise, the State of Florida is currently conducting a herbicide program in Lake Apopka to try to eliminate hydrilla (*Hydrilla verticillata*). A massive drawdown would certainly expand the hydrilla pockets, and this plant has the ability to colonize the whole lake. Hydrilla, occupying over 6000 ha of Lake Apopka, would be an expensive aquatic weed problem.

Another major concern regarding the use of drawdown to reestablish submersed plant coverage in the lake is how stable the new plant communities would be. The original loss of the submersed plants was attributed to the September 1947 hurricane. Whether the loss of the plants was caused by the winds of the hurricane can be debated, but wind is a major environmental factor that needs to be considered in the management of Lake Apopka. For example, the current Secchi disc readings indicate that submersed macrophytes could colonize about 39% of the lake bottom if light were the only limiting factor (Bachmann et al. 1999). Submersed plants currently cover less than 1% of the lake. Inspection of Lake Apopka's shoreline clearly shows winds are strong enough to blow trees down and uproot emergent vegetation. Submersed plants now grow only in protected areas. Consequently, winds could again disrupt a reestablished submersed plant community and cause a switch from a clear-water macrophyte state to a turbid algal state according to the theory of alternative stable states (Scheffer et al. 1993).

When we view the whole Lake Apopka problem and consider Huffstutler et al. (1965) view that the problem at Lake Apopka is not chemical, but biological, we conclude Lake Apopka is primarily a fisheries management problem. Reestablishment of Lake Apopka's recreational fishery, which was the primary use of the lake prior to 1947, requires in part the creation of habitat that will support gamefish. Water quality, especially the establishment of clear water, should not be the primary concern for lake managers because gamefish such as black crappie (*Pomoxis nigromaculatus*) and sunshine bass (*Morone chrysops* X *Morone saxatilis*) live in the lake and provide some fishing. However, the largemouth bass (*Micropterus salmoides floridanus*) population of Lake Apopka, the most desired sportfish, is a remnant population. Estimates by the Florida Game and Fresh Water Fish Commission and the University of Florida indicate that there is < 1 harvestable largemouth bass per hectare, but the largemouth bass, that are present, grow rapidly to a large individual size (Canfield and Hoyer 1992). Further the high algal populations would not be a detriment to this species. A recent study (Bachmann et al. 1996) of fish and trophic state in Florida lakes showed that largemouth bass do just as well in hypereutrophic lakes as they do in lakes of lesser productivity. Another study (Reid et al. 1999) showed that turbidity was not an important factor in the ability of largemouth bass to prey on forage fish.

The available evidence suggests that the focus of a fisheries management plan should to a large extent be on the establishment of a reasonable submersed aquatic plant coverage. Large Florida lakes without aquatic vegetation can have a bottleneck related to the survival of young-of-year largemouth bass because shoreline habitat may be the only available refuge from predation (Hoyer and Canfield 1996). In Florida, most lakes are near circular and the abundance of shoreline habitat per surface area of these lakes decreases dramatically as the surface area of a lake increases (Gasith and Hoyer 1997). Large lakes, therefore, need aquatic macrophytes to support young-of-year largemouth bass more than do small lakes because of the reduced shoreline to surface area ratio. From our studies of Florida lakes, it seems that plant coverage of about 10% is sufficient to support a recreational fish population (Canfield and Hoyer 1992).

Submersed aquatic plants once occupied approximately 70% of Lake Apopka; thus 10% coverage is feasible. The problem is the large size of Lake Apopka that permits wind action to roil the bottom thus preventing the rooting of plants. This limitation, however, can be overcome through the use of artificial reefs, which will disrupt wind and water currents. To reestablish Lake Apopka's multimillion dollar recreational fishery, we propose a plan of action that focuses on the creation of critical fishery habitat in Lake Apopka through the establishment of artificial reefs and the direct planting of submersed aquatic plants. The plan also calls for the establishment of a fish hatchery at Lake Apopka that will produce and grow large (10 to 15 cm) largemouth bass for stocking into the lake. This effort is proposed now because we believe a substantial sportfishery can now be established at Lake Apopka within 5 years and that a sizable sportfishery worth tens of millions of dollars can be established within the decade.

We propose over the next decade to construct a series of artificial reefs along the shore of Lake Apopka. Reefs can be constructed from concrete rubble and tires. These two materials have proven to be very effective in both marine and freshwater applications (D'Itri 1985). Concrete rubble will be especially effective in Lake Apopka because it will provide a hard bottom that will produce not only fish-food organisms, but also provide a substrate for the spawning of gamefish like the largemouth bass. Concrete rubble and tires are also very abundant in the region and industry will readily donate these materials because in many situations they are considered waste products.

Concrete and tire reefs will be constructed primarily in the shape of semicircles, which will provide small sheltered areas along the shoreline of Lake Apopka for the planting of submersed aquatic plants and the stocking of gamefish. Gaps, however, will be left in the reefs to provide some water circulation and boat access. J-shaped fishing jetties will also be constructed of concrete rubble in select locations. These jetties will provide not only sheltered areas for the planting of submersed aquatic plants, but shoreline fishing areas for anglers that do not have boats. These jetties will be topped with soil that could be dredged from the lake's bottom. A major advantage of this approach is that deep dredge holes will be a repository for much of the nearby fluid-mud. It is anticipated that construction of the reefs will continue throughout a decade until approximately 10% of Lake Apopka's surface area is protected from wind action.

Behind the protective barriers, native submersed aquatic plants such as eelgrass (*Vallisneria americana*) and Illinois pond weed (*Potamogeton illinoensis*) will be experimentally planted to provide shelter and spawning habitat for gamefish. It is possible that native plants will initially fail to root in Lake Apopka's flocculent bottom and that the nonnative hydrilla will colonize the protected areas. Hydrilla has, however, been documented as a positive environmental factor when considering largemouth bass populations in eutrophic or hypereutrophic Florida lakes (Moxley and Langford 1982). While the establishment of hydrilla is not desirable, the small size of the wind-protected areas relative to the overall size of Lake Apopka will limit the expansion of this plant (as well as other plants) and there are aquatic plant management programs that can remove hydrilla while encouraging native plants. An excellent example of this approach is Lake Okahumpka, Sumpter County, FL, where we have observed that vallisneria and Illinois pondweed have replaced hydrilla.

The largemouth bass population of Lake Apopka is a remnant population and reestablishing critical habitat will not by itself bring back the largemouth bass population. We, therefore, propose a concurrent fish enhancement project. First, largemouth bass fishing should be immediately regulated in Lake Apopka to include only the catch and release of these fish. Once largemouth bass reach a sufficient size (> 10 cm), studies have shown the bass grow rapidly and to a large size. Stocking of millions of fry has not jump-started the bass population in Lake Apopka. We, therefore, propose to establish a temporary fish hatchery along the north shore of Lake Apopka in the former muck farms to grow largemouth bass to 10 or 15 cm, and stock these large fish into the lake.

The St. Johns River Water Management District has recently purchased the majority of muck farms bordering Lake Apopka. Aquaculture ponds have existed on these lands and additional temporary ponds can be established quickly and cheaply. These ponds can be easily supplied with water from the lake and our past work at earlier ponds has shown the lake's water can be effectively used to grow largemouth bass to stocking size. We, suggest that brood fish initially be collected from lakes located throughout Florida. Hatchery personnel will then spawn these adult largemouth bass and fry will be stocked directly into the Apopka ponds for grow-out to a size of approximately 10 cm. The 10-cm bass will ultimately be stocked directly into areas where artificial reefs and submersed aquatic vegetation have been established. It is anticipated that 100,000, 10-cm bass can be produced per year.

After stocking, the 10-cm fish will be of sufficient size to recruit to spawning size within 2 years and thus provide natural spawning within the newly established submersed vegetation. Because the survivability of stocked largemouth bass increases greatly with an increase in individual fish size, we also propose to use late spawning largemouth bass to restock the Apopka ponds following the stocking of the 10-cm fish. New experimental feeding techniques will then be used to raise the largemouth bass to a size of 15 to 20 cm. It is anticipated that this double cropping of largemouth bass will permit the stocking of approximately 20,000 additional subadult fish per year. If the feeding program is successful, additional ponds could be built and more fish could be produced per year.

Fishery personnel will be required to monitor fish populations in Lake Apopka to document the survivability of stocked largemouth bass. Additional personnel will be needed for the spawning activities and expenditures will have to be made for fish food and other supplies. It is currently anticipated that a sizable number of largemouth bass will be spawning naturally in Lake Apopka within 5 years. If all goes well, hatchery operations should cease within a decade and the largemouth bass sport fishery should be reestablished and self-sustainable. A rough estimate of the cost of this alternative management plan would be approximately $1,000,000 per year for 5 to 10 years or less that 10% of the moneys that have already been spent on Lake Apopka.

Conclusion

The control of nutrients is an important paradigm in lake management. Certainly, the control of nutrients from a wastewater treatment plant can have a significant effect on the limnology of many lakes. Not all lakes, however, are nutrient limited and it is time that lake managers no longer accept the proposition that nutrient control strategies must be implemented before anything else can be done.

Lakes are complex, but the lake management community would be well served by acknowledging the warning given by Chamberlain in the late 18th century (1889). Chamberlain in his paper, *Multiple Working Hypotheses*, which was first published in 1890 and republished in 1965, cautioned scientists to withhold judgment when the evidence is insufficient to justify conclusions. He further warned about the dangers of parental affection for a favorite theory, which he believed could be circumvented with the method of multiple working hypotheses. Lake managers must also acknowledge that lake management is a mixture of science and politics. If the selected programs will not work then this should be made abundantly clear to policy-makers and the public. If there is any doubt, failure will not be the responsibility of the policy-makers or the public. Failure will be attributed to the actions of the lake managers and at best funding to the programs might be temporarily cut or at worst programs may be eliminated.

When developing a lake management plan, economics should be considered closely. Sometimes, the most economically sound management plan is not a broad-based eutrophication plan, but is an aquatic plant management plan or a fisheries management plan. Most likely, it will be a combination of individual plans because of the multiple-uses that take place at a lake. As we noted earlier, the thesis that nutrient enrichment from anthropogenic sources is one of the primary reasons, if not the singular reason, why Lake Apopka is in its current condition is now being tested directly. Before an adequate scientific evaluation will be possible decades will have to pass. We believe that steps should be taken now to restore the largemouth bass fishery, so that the usefulness of the lake can be enhanced without waiting for the waters to clear if they ever do. In addition, the Lake Apopka example should inspire members of the lake management community to redouble their efforts in evaluating the effectiveness of past lake management efforts and to consider whether nutrient management always has to be the first step in lake management.

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