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The restoration of Lake Apopka in relation to alternative stable states *

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Abstract

Lake Apopka (Florida, USA) changed in 1947 from being a clear, macrophyte-dominated lake, used primarily for fishing, into a turbid algal lake with a poor fishery. The lake has resisted various efforts to reverse the change and restore the previous state. The restoration approach emphasizes the reduction in phosphorus inputs to reduce algal blooms and clear the water. We examined the question of whether a deep-lake approach with nutrient reductions is going to work on this large (area 124 km^2) and shallow (mean depth 1.7 m) lake, or if techniques such as drawdowns or wind barriers developed for shallow lakes using the theory of alternative stable states are more applicable.

The assumptions upon which the current restoration is based are not supported. The poor transparency is due more to resuspended sediments than plankton algae, so the current Secchi disk depth of 0.23 m is predicted to increase to 0.34 m with any reasonable reduction in algal levels. The failure of the macrophytes to become re-established probably is due more to unstable sediments than lack of light reaching the lake bed, and the marsh flow-way developed by the St Johns River Water Management District will be ineffective in removing particles from the lake. It would take more than 300 years to remove the fluid mud and more than 800 years to remove the rest of the low density sediments. We conclude that the loss of macrophytes in Lake Apopka is an example of a forward switch in the theory of alternative stable states, and that it will take more than a nutrient reduction program to bring about the reverse switch to a macrophyte state. We suggest an alternative approach using wave barriers to create refuges for plants, macroinvertebrates, and fish to restore Lake Apopka's largemouth bass fishery.

Introduction

In late 1947, Lake Apopka, Florida, USA changed from being a clear, macrophyte-dominated lake used primarily for fishing into a turbid algal lake (Clugston, 1963). Since that time the lake has resisted various efforts to reverse the change and restore the previous state. The general approach used to date has been to follow the theories of nutrient inputs and trophic states laid down by Vollenweider (1968) and others that emphasizes the reduction in phosphorus inputs to reduce algal blooms and clear the water. To this end the State of Florida has recently purchased farms with drainage into the lake to take them out of production and is constructing a marsh flow-way to remove phosphorus-rich particles from the lake water (Lowe et al., 1992). These activities will make this one of the most expensive (> $US 100 million) lake restoration projects in the United States.

The theories of lake restoration based on reductions in nutrient inputs were based primarily on deep lakes where the littoral zone occupies only a small fraction of the lake surface area and sedimenting particles can carry attached phosphorus into deep areas where this nutrient cannot easily return to the euphotic zone (Sas, 1989). More recently it has been recognized that shallow eutrophic lakes differ from deep ones in many respects (Scheffer, 1998). They can switch between a clear macrophyte state and a turbid algal state without any change in nutrient inputs

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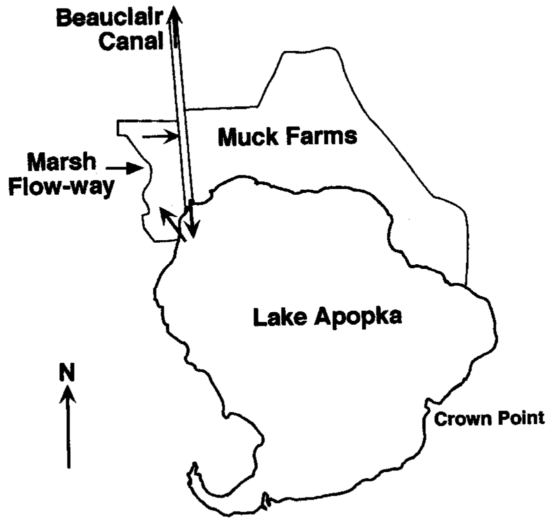

Figure 1. Lake Apopka showing the outlet (Beauclair Canal), marsh flow-way, and the remaining muck farms.

(Blindow et al., 1993; Scheffer et al., 1993; Moss et al., 1996). This is known as alternative stable states, and it has been proposed that when a lake is in one state there are a number of feedback mechanisms that tend to keep it in that state until some major event switches it to the other. There are forward switches that move lakes from macrophyte to algal states and reverse switches that can move them in the opposite direction (Moss et al., 1996).

In light of these new concepts and the fact that Lake Apopka is large and shallow (area 124 km^2, mean depth 1.7 m) we examined the question of whether nutrient reduction will restore Lake Apopka to a clear-water, macrophyte-dominated lake renowned for its fisheries. The goal of this study is to examine the limnological history of Lake Apopka to determine the causes of the current water quality problems in the lake and what needs to be done to restore the usefulness of the lake.

Limnological character and history of Lake Apopka

Lake Apopka in central Florida, USA is subject to a subtropical climate, is polymictic and never develops an ice cover. There are no inflowing surface streams, but water enters by a well-defined spring, groundwater seepage, precipitation, and water pumped from the adjacent muck farms (U.S. Environmental Protection Agency, 1978). Originally, water left the lake by sheet flow through marshlands on the northwest side of the lake. In 1893 a canal was completed to connect the lake with Lake Beauclair downstream (Figure 1), and the lake level was lowered by about 1 m (Delta Canal Company, 1895; Shofner, 1982). One purpose of the canal was to drain lake marshes on the north side of the lake in order to farm the rich muck soils, but high water tables during wet years made the farming venture less profitable than planned (Shofner, 1982).

Various activities around the lake increased the nutrient supply. In the 1920s the City of Winter Garden, on the south side of the lake, began discharging inadequately treated sewage effluent into the lake, and in 1948 a citrus processing plant started adding organic wastes (U.S. Environmental Protection Agency, 1978). At that time citrus groves occupied 43% of the watershed and fertilizers added to the groves were thought to have contributed an unknown amount of nutrients to the groundwaters seeping into the lake (Brezonik et al., 1978). A dike was constructed to separate 7,300 ha of farmland called muck farms from the lake in the early 1940s, and drainage canals were excavated within the agricultural areas to collect groundwater which was then pumped into the lake to lower the water table during wet periods (U.S. Environmental Protection Agency, 1978). This is thought to be a significant source of nutrients to the lake.

In the early 1940s the lake was filled with macrophytes and its primary use was for fishing. Clugston (1963) stated “A heavy growth of the pondweed, *Potomogeton illinoensis*, began approximately 182 m from the shoreline and extended across the entire lake except in areas where the depth exceeded 2.4 m. Water hyacinth, *Eichhornia crassipes*, grew very profusely around the edge of the entire lake, and large floating mats of hyacinth occasionally shifted around on the lake surface.” He cited reports that the waters were extremely clear. Fishermen maintained paths through the plants, and the lake was noted for its largemouth bass (*Micropterus salmoides floridans*). At this time the lake could be described as a deepwater marsh. The large water mass also moderated the local climate and reduced the frequency of frosts in the surrounding citrus groves.

On September 17, 1947, a Category 4 hurricane moved across the state of Florida with the highest recorded winds for the state with the exception of Hurricane Andrew in 1992 (Williams & Duedall, 1997). While the eye of the storm tracked east to west across south Florida, hurricane force winds were recorded along the coast as far north as Cape Canaveral, just

Table 1. Average physical and chemical properties of the unconsolidated flocculent sediment layer (UCF) and the consolidated flocculent sediment layer (CF) in Lake Apopka based on 90 cores taken by Reddy & Graetz (1991) in 1987

Variable	UCF layer	CF layer
Dry bulk density (g dry cm^{-3})	0.035	0.086
Wet bulk density (g wet cm^{-3})	1.024	1.048
Water content (%)	96.1	91.9
% Volatile solids (%)	54.7	59.0
Total phosphorus in dry sediment (mg g^{-1})	0.97	0.60
Total nitrogen in dry sediment (mg g^{-1})	23.7	22.4

east of Lake Apopka. The state fisheries biologist assigned to Lake Apopka at that time (Mr. John Dequine, pers. comm.), stated that winds associated with the storm stirred up the bottom sediments and uprooted the macrophytes along the southeast shore near Crown Point. Large numbers of dead fish were seen floating in the lake. The macrophytes across the rest of the lake declined rapidly in the next few years, and all of the pondweeds disappeared by 1950 (Clugston, 1963).

The fishing public became alarmed when large fishkills were reported in local newspapers in 1950 and 1951 during periods of high winds which stirred up the highly organic, bottom sediments. Presumably, a high oxygen demand from the sediments caused an oxygen depletion. 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. The largemouth bass (*Micropterus salmoides floridans*) populations declined in the years following 1947, and there were large increases in the populations of the planktivorous gizzard shad, *Dorosoma cepedianum* (Clugston, 1963).

Twenty years after the loss of the macrophytes, it was noted by Schneider & Little (1969) that about 90% of the lake bed was covered with low density, highly organic sediments (Table 1) and the remainder with peat, sand, clay, or shells. They noted an upper layer of highly flocculent sediments which Reddy & Graetz (1991) termed the unconsolidated flocculent sediments (UCF). These sediments are watery in nature and lack structure while those immediately below are similar in their physical and chemical characteristics (Table 1) but are more cohesive. These are termed the consolidated flocculent sediments (CF). Schneider & Little (1969) found the UCF sediments averaged 10 cm in thickness in 1968, which increased to 32 cm in 1987 (Reddy & Graetz, 1991) and in 1996 to 45 cm (Schelske, 1997). The conventional interpretation is that the flocculent sediments represent the remains of dead algal cells that have been deposited in the lake since 1947 (Reddy & Graetz, 1991; Schelske, 1997).

The lake waters became turbid and algae blooms occurred shortly after the September storm (Schneider & Little, 1969; Schelske & Brezonik, 1992). This turbid state has persisted up to the present time. Currently, the phytoplankton community in the water column is dominated by Cyanobacteria, primarily *Synechococcus* sp., *Synechocystis* sp., *Microcystis incerta* Lemmermann, and *Lyngbya contorta* Lemmermann (Carrick et al., 1993). In addition, there is a meroplanktonic community of algae on the sediment surface that is dominated by diatoms with *Aulacoseira italica*, *Staurosia construens*, and *Staurosirella pinnata* being most common (Carrick et al., 1993). The zooplankton during the summer is dominated by a cyclopoid copepod, *Diaptomous floridanus*, and unnamed rotifers, but during the rest of the year cladocerans (*Bosmina longirostris*, *Chydorus sphaericus*, *Daphnia ambigua*) and cyclopoid copepods (*Cyclops vernalis*, *Mesocyclops edax*, *Tropocyclops prasinus*) are most prevalent (Brezonik et al., 1981). The benthic community is dominated by *Chaoborus punctipennis* and *Limnodrilus hoffmeisteri* (Brezonik et al., 1981). Currently, the gizzard shad is the dominant fish accounting for over 55% of the total fish biomass with the black crappie (*Pomoxis nigromaculatus*), bluegill (*Lepomis macrochirus*), striped bass (*Morone saxatilis*), redear sunfish (*Lepomis microlophus*), and blue tilapia (*Tilapia aurea*) making up an additional 35% of the total biomass (Canfield & Hoyer, 1992). Largemouth bass are presently found in the lake in small numbers; however, they show rapid growth rates (Canfield & Hoyer, 1992).

Current diagnosis and restoration plan

Because there were known anthropogenic sources of phosphorus at the time the lake switched from a macrophyte to a turbid algal state, it was assumed that Lake Apopka represented a case of cultural eutrophication. While there were no measurements in the 1940s, in the period 1976–1977 the estimated annual phosphorus inputs from the Winter Garden sewage effluents were 7,000 kg, the Winter Garden Citrus Co-op

1,300 kg and the muck farms 36,900 kg (Brezonik et al., 1978). The Gourd Neck Spring, lateral inflows, and precipitation contributed another 10,400 kg. The anthropogenic loadings were thought to have increased the phosphorus concentration in the lake which in turn caused the high algal concentration. The algae were thought to be responsible for the poor water transparency, which in turn prevented the macrophytes from becoming re-established. The lack of macrophytes was thought to be responsible for the loss of the largemouth bass fishery, which was the primary use for Lake Apopka.

At various times macrophyte plantings have been tried; however, the main focus of restoration over the years has been on reducing nutrient inputs. Modern sewage treatment facilities were constructed both for the City of Winter Garden and the citrus processing plant (U.S. Environmental Protection Agency, 1979), and by chance severe winter freezes caused the citrus groves to be abandoned, thus removing these sources of phosphorus. The muck farms remain the only major anthropogenic source of phosphorus. Recently, scientists for the St Johns River Water Management District (SJRWMD), Palatka, Florida, (pers. comm.) have estimated phosphorus budgets for the years 1989–1995 that show that the phosphorus contribution from the muck farms amounts to about 80% of the total annual P input. Over the years various plans have been implemented to reduce phosphorus inputs from these farms, including recycling of water and nutrients (U.S. Environmental Protection Agency, 1979). Most recently, most of the remaining muck farms are being purchased to remove the land from agricultural production and thus eliminate the pumping of drainage water to the lake. In addition, gizzard shad removal by netting was instituted in 1993 as a means of removing phosphorus from the lake. According to Crumpton & Godwin (1997), 2,200,000 kg of gizzard shad containing about 16,000 kg of phosphorus were removed in 5 years. The annual removal rate of 3,200 kg of P by fish netting can be compared to the total phosphorus content of the open waters of the lake (phosphorus concentration x lake volume) exclusive of fish of about 43,000 kg.

As a supplement to the reduction in nutrient inputs a marsh flow-way is being developed by SJRWMD to remove particulate phosphorus from the lake water and thus speed up the time that it would take phosphorus concentrations to reach equilibrium levels following reductions in nutrient inputs (Lowe et al., 1992). The marsh flow-way is located on 13 km^2 of former muck farms just northeast of the lake. When the flow-way is completed, water will flow into a system of marshes where particles are removed by mechanical filtration in the emergent vegetation with an estimated particle removal efficiency of 85%. After passing through the marsh, the water is moved by pumps into the Beauclair canal where about 15% flows out of the lake system and the remainder returns to the lake (Figure 1).

Materials and methods

We have used data collected by others over the past 30 years. Particularly useful has been a series of studies monitoring water quality in Lake Apopka (Brezonik et al., 1978; Tuschall et al., 1979; Pollman et al., 1980). We have also obtained unpublished data collected since 1987 by SJRWMD. Each month they have made measurements of total suspended solids, Secchi depth, chlorophyll, total nitrogen, and total phosphorus on samples taken at 0.5-m depth in the center of the lake. Previous studies have shown that the water column is well-mixed in Lake Apopka (Brezonik et al., 1978). A nonparametric trend test for seasonal data with serial dependence (Hirsch and Slack, 1984) was used to determine if these variables were changing over time.

To estimate the effect of living algal cells on water transparency, we calculated a logarithmic regression of Secchi disk depth vs. chlorophyll concentration and compared it with similar regression lines developed by Jones & Bachmann (1976) for northern lakes and by Canfield & Hodgson (1983) for Florida lakes. The Canfield & Hodgson equation takes into account both chlorophyll and water color. The Jones and Bachmann equation is

$$\text{Log (SD)} = 0.807 - 0.549 \text{ Log(CHL} + 0.03), \quad (1)$$

where SD is the Secchi depth in m and CHL is the chlorophyll concentration in mg m^{-3}. The Canfield & Hodgson equation is:

$$\begin{aligned} \ln \text{(SD)} &= 2.0 - 0.37 \ln\text{(CHL)} \\ &\quad - 0.278 \ln \text{(COLOR)} \qquad (2) \end{aligned}$$

where COLOR is the water color in mg l^{-1} Pt units. The Lake Apopka average color is 34 mg l^{-1} Pt based on measurements by SJRWMD.

To model the effects of a phosphorus reduction program that reduced phosphorus concentrations in the lake by 80%, we calculated the new chlorophyll concentration with an equation developed from the a database of Florida lakes (Florida LAKEWATCH, 1997) with ratios of TN/TP >17:

$$\text{Log (CHL)} = -0.558 + 1.27\ \text{Log (TP)}, \qquad (3)$$

where CHL is the chlorophyll concentration in mg m^{-3}, and TP is the total phosphorus concentration in mg m^{-3}. The regression of Secchi disk depth vs. chlorophyll concentration for the Lake Apopka data was then used to find the new Secchi depth. To determine the impact of increased Secchi disk depth on aquatic macrophyte colonization, we used the relationship between the maximum depth of macrophyte colonization in Florida lakes and Secchi disk depth as developed by Canfield et al. (1985):

$$\text{Log (MDC)} = 0.41 + 0.42\ \text{Log (SD)}, \qquad (4)$$

where MDC is the maximum depth of macrophyte colonization in meters. The per cent of the lake area potentially available for colonization was determined from the hypsographic curve for Lake Apopka (Danek & Tomlinson, 1989).

We used two methods to estimate the portion of the total suspended solids due to living algal cells. First, Carrick et al. (1993) made detailed counts of the various algal taxa in Lake Apopka and determined the cell volumes for each taxon by measurements of cell dimensions. From these measurements they calculated cell volumes and converted them to algal carbon. At the same time they measured chlorophyll concentrations. The average ratio of algal carbon (mg) to chlorophyll (mg) for all of their samples was 42. Because the organic content of phytoplankton algae is about 2 times the carbon content (Reynolds, 1984), then 1 mg of chlorophyll would be equivalent to 84 mg of algal dry weight. A second estimate of the average weight of living algal cells was made with constants summarized by Reynolds (1984). He showed literature values of the chlorophyll content of Cyanobacteria to average 1.15% of the dry weight of the living cells and those of diatoms to average 1.57%. Carrick et al. (1993) found that their phytoplankton samples from Lake Apopka were about 90% Cyanobacteria and 10% diatoms, so the weighted average estimate of the chlorophyll content of the algal biomass would be 1.19% of the dry wt. This also amounts to 1 mg of chlorophyll for each 84 mg of algal dry wt.

We determined the potential for sediment resuspension in Lake Apopka using techniques reported by Carper and Bachmann (1984). A grid with 329 points was established on a morphometric map of the lake, and for each grid point we calculated the minimum wind velocity required for wave movements to reach the sediment surface for each of 36 wind directions. These data were combined with a 5-year record of the frequencies of winds of various velocities and directions collected at a tower in the center of the lake maintained by SJRWMD to derive a curve showing the frequency with which different percentages of the lake bed were being disturbed by wind-driven waves.

We also calculated the removal of sediments by the marsh flow-way by multiplying the amount of water flowing into the flow-way each year times the concentration of suspended particles times the fraction of the particles that will be removed by the marsh (85%). We also accounted for the particles that are removed from the lake by the portion of the water that flows out of the lake system through the Beauclair Canal. To balance the budget for the fine particles in the lake, it is necessary to take into account the amount of sediments that might be expected to be added to the sediment pool each year in the absence of any cultural eutrophication. Our estimate was based on the historic sedimentation rates in the lake for the century prior to the hurricane and the diking of the muck farms. We used the results of a study that dated sediment cores taken in 1996 using ^{210}Pb (Schelske, 1997). Schelske used a modified constant rate of supply model (Appleby & Oldfield, 1978) to date the sediments in which the boundary between the upper layer of flocculent sediments and the more cohesive sediments below was assumed to be 1945. The purpose of Schelske's modification was to account for any change in sedimentation patterns that might have occurred as a result of diking off the farms and the loss of the macrophytes in the lake. We used his data to date the portions of those cores that were in the cohesive sediments following the method of Appleby & Oldfield (1978). We found the amount of sediment that was accumulated between dated horizons and divided by the time interval to find the average sedimentation rate per square meter. This was multiplied times the lake area to find the annual rate of sediment accumulation. The net change in the weight of fine sediments in Lake Apopka was the difference between the rate of removal by the marsh flow-way and the rate of accumulation of new sediments expected for the lake.

To compare the calculated rates of removal of suspended particles from the lake with the normal fluctuations in suspended particle concentration from day to day, we looked at measurements by Reddy & Graetz (1991) of the total suspended solids in Lake Apopka made approximately every 2 days between September

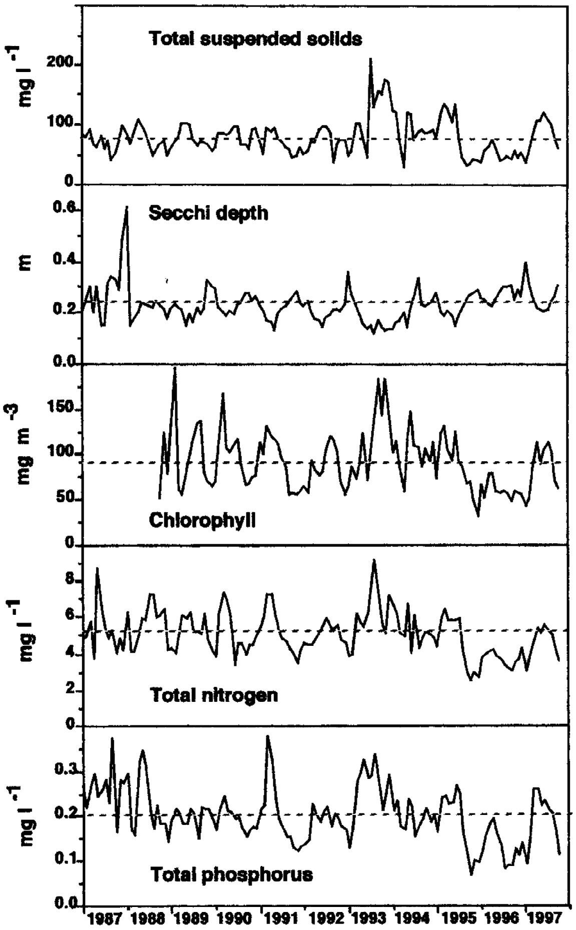

Figure 2. Monthly averages for total suspended solids, Secchi depth, chlorophyll, total nitrogen, and total phosphorus in Lake Apopka in 1987 through 1997. The dashed lines represent the means for the period of record.

1988 and June 1990. We calculated the average change (plus or minus) in total suspended solids in 2 days, based on 277 pairs of observations.

Results

The monthly values for total suspended solids, Secchi depth, chlorophyll, total nitrogen, and total phosphorus from January 1987 through October 1997 at the center station are presented in Figure 2. The lake is characterized by having a low Secchi disk transparency, and high concentrations of total suspended solids, chlorophyll, total nitrogen, and total phosphorus (Table 2). These values place Lake Apopka in the hypereutrophic category according to the trophic classification system of Ryding & Rast (1989). The

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 l^{-1})	79	79	112
Chlorophyll (mg $m^{-3)}$	92	32	89
Total phosphorus (mg l^{-1})	0.204	0.059	113
Total nitrogen (mg l^{-1})	5.14	1.20	113
Secchi depth (m)	0.23	0.07	109

plots (Figure 2) show considerable seasonable variability that obscures long term trends; however, the nonparametric test (Hirsch & Slack, 1984) did suggest declines in total nitrogen and chlorophyll that were statistically significant at the 5% level of probability.

The fact that the concentration of total suspended matter did not follow the decline in algal chlorophyll indicates that living algae may not be an important component of the suspended particles. This is also supported by the calculation that in Lake Apopka with an average chlorophyll of 92 mg m^{-3} (Table 2) the dry algal weight would average 7.73 mg l^{-1} or 9.8% of the average total suspended solids concentration of 79 mg l^{-1} (Table 2). This finding shows that living algal cells make up only a very small portion ($\sim$10%) of the dry weight of the suspended materials in Lake Apopka.

Our regression line for the relationship between Secchi disk depths and chlorophyll concentrations in Lake Apopka (Figure 3) was

$$\text{Log (SD)} = 0.152 - 0.417\ \text{Log (CHL)}. \qquad (5)$$

The Lake Apopka points (Figure 3) all fall below both the Jones-Bachmann line for northern lakes and the Canfield-Hodgson line for Florida lakes, again suggesting that living algal cells are not the only materials determining light penetration in this lake. A part of this difference might be the water color (34 mg l^{-1} Pt) in Lake Apopka; however this effect is small as indicated by the difference between the Jones-Bachmann and the Canfield-Hodgson lines at comparable chlorophyll levels.

A similar conclusion with regard to the effects of suspended sediments can be reached from the findings of Schelske et al. (1995) who measured light extinctions in Lake Apopka. They found a linear relationship between the extinction coefficient for light and suspended algal chlorophyll. They point out that their intercept of 1.23 m^{-1} is much larger than the expected

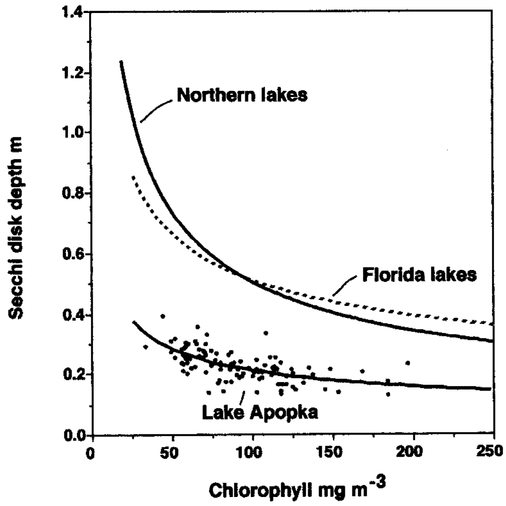

Figure 3. Secchi disk depths in Lake Apopka at different chlorophyll concentrations in 1988 through 1997. The upper line (Jones & Bachmann, 1978) represents the best fit line for a broad group of lakes from the literature, and the broken line represents the best fit line for Florida lakes with a color value of 34 mg l^{-1} Pt (Canfield & Hodgson, 1983). The bottom line represents the best fit regression for the Lake Apopka data and has the equation Log (SD) = 0.152 −0.417 Log (CHL).

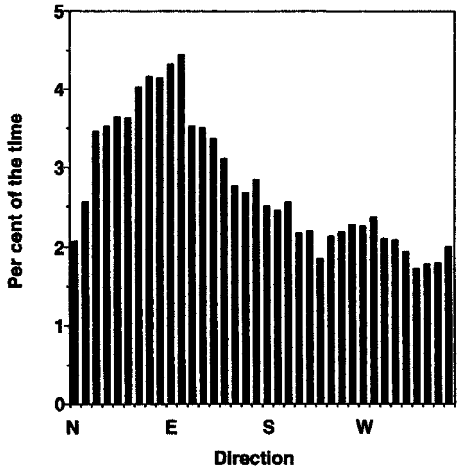

Figure 4. Frequency distribution of wind directions at the center of Lake Apopka based on a 5-year record.

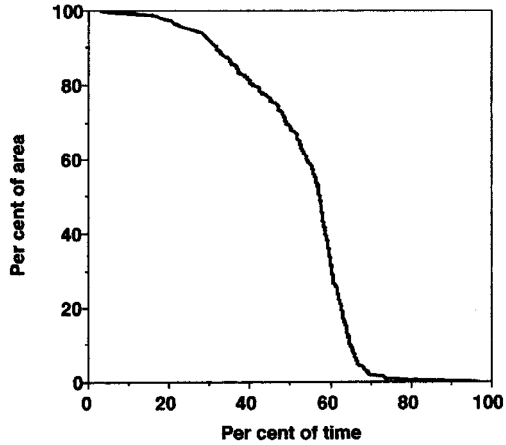

Figure 5. Per cent of the lake bed of Lake Apopka subject to wave action for different percentages of time as calculated in this study.

value of 0.033 m^{-1} for water without algae (Parsons et al., 1984) indicating a large effect of non-living materials suspended in the water. From their regression equation (Schelske et al., 1995) the extinction coefficient in Lake Apopka for a chlorophyll concentration of 92 mg m^{-3} would be 5.4 m^{-1}. The expected coefficient based on the chlorophylls alone (Bannister, 1974) would be only 1.5 m^{-1}, indicating that living algae accounted for only about 28% of the light extinction coefficient. This is similar to the situation in the non-vegetated portion of the shallow and turbid Lake Veluwemeer, The Netherlands, where the data of Van den Berg et al. (1998) for July and August of 1995 show that living algae were responsible for only 25% of the extinction coefficient. Schelske et al. (1995) also note that their slope is about 3 times larger than expected for algal chlorophylls (Bannister, 1974). We think that the results of Schelske et al. (1995) show the effects of wind resuspension of sediments. Carrick et al. (1993) show that variations in chlorophyll levels in Lake Apopka are related to wind resuspension of the upper layer of the sediments. While this layer has a high concentration of living algal cells, it also contains non-living resuspendable materials. Thus, the increase in extinction found with increases in algal chlorophyll is not going to be due to algal cells alone.

The wind at Lake Apopka (Figure 4) blows from the east 35% of the time and less frequently from the north (23%), south (23%), and the west (19%). Because the lake is roughly circular in shape and rather uniformly shallow, almost all of the lake bed is subject to wind disturbance at one time or another, and a large fraction of the sediments is disturbed on a daily basis (Figure 5). The frequency distribution shows that 15% of the time 99% of the lake bed is influenced by wave action, 46% of the time 75% of the area is influenced, and 60% of the time 30% is disturbed.

An 80% reduction in the phosphorus concentration in the lake would yield an equilibrium concentration of total phosphorus of 41 mg m^{-3}. We find from Equation (3) the chlorophyll concentration would be predicted to drop to 31 mg m^{-3} and from Equation (5)

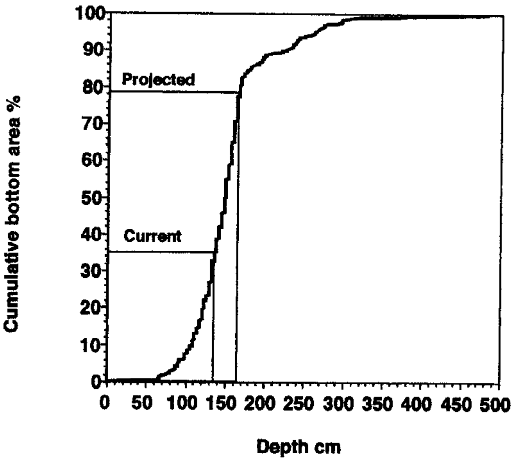

Figure 6. Per cent of the lake bed of Lake Apopka covered by water of the indicated depths or less. The current calculated depth of maximum macrophyte colonization is indicated along with the depth projected with phosphorus control (see text).

Table 3. Sediment removal by the marsh flow-way and its impact on the amounts of suspended materials in Lake Apopka

The marsh flow-way	
Inflow of lake water (m^3 yr^{-1})	457×10^6
Inflow of suspended solids to marsh (kg yr^{-1})	36.1×10^6
Marsh particle removal rate (%)	85
Weight particles deposited in marsh (kg yr^{-1})	30.7×10^6
Weight particles leaving marsh (kg yr^{-1})	5.42×10^6
Portion of outflow leaving lake by canal (%)	15
Weight particles leaving lake by canal (kg yr^{-1})	0.813×10^6
Total weight of particles removed from lake (kg yr^{-1})	31.5×10^6
Sediments and suspended solids	
Dry weight of total suspended solids in lake (kg)	16.7×10^6
Dry weight fluid mud (kg)	2.21×10^9
Dry weight other low density sediments (kg)	5.50×10^9
Pre-1947 rate of sediment accumulation (kg yr^{-1})	24.8×10^6
Net rate of particle loss (kg yr^{-1})	6.7×10^6
Portion of fluid mud removed per year (% yr^{-1})	0.09
Time required to remove sediments	
Fluid mud (yr)	329
Other low density sediments (yr)	821

the Secchi disk depth would increase to approximately 0.34 m. This increase from the current average of 0.23 m (Table 2), a difference of 0.11 m, would be visually difficult to notice. For the current average Secchi depth of 0.23 m (Table 2), Equation (4) yields a calculated maximum depth of colonization of 1.39 m. This means that currently approximately 39% of the lake bed has sufficient light for plant colonization (Figure 6). With an increased Secchi depth of 0.34 m, the depth of colonization would be calculated to be 1.63 m or about 78% of the lake area.

Our particle budget for the lake and marsh flow-way showed the estimated combined sediment removal by the marsh flow-way and the canal to be 3.15×10^7 kg yr^{-1}(Table 3), while the historic rate of new sediment accumulation averaged 2.48×10^7 kg yr^{-1}. Thus we calculate the net change in the weight of fine sediments in Lake Apopka as $6.7 \times$x 10^6 kg yr^{-1}. This represents a removal from the water column of 0.8 mg l^{-1} every 2 days. For comparison, the measurements by Reddy & Graetz (1991) in Lake Apopka showed an average change (plus or minus) of 17 mg l^{-1} in total suspended solids in 2 days. This indicates that sediment resuspension and settling take place at much greater rates than removal by the flow-way.

As suspended particles are removed from the lake they will be replaced by resuspended particles from the flocculent sediment layer. When the weight of the UCF sediments is divided by the annual net rate of loss of particles from the lake system, we find that it would take over 300 years to remove those sediments with the marsh flow-way (Table 3). A similar calculation showed that it would take over 800 years to remove the fine sediments in the CF layer, because these would most likely be converted to fluid mud by the waves as the upper layers were removed. During this period, the lake waters would still be turbid with resuspended sediments, so that the lake would show little if any improvement in water clarity.

Discussion

A basic assumption of the Lake Apopka restoration has been that the high concentration of suspended materials in the water and the low Secchi disk transparencies have been due to blooms of plankton algae (Lowe et al., 1992). Our findings do not support this hypothesis. Only about 10% of the suspended particles represent living algal cells, the Secchi disk depths are less than would be expected from algal chlorophylls alone, and decreases in chlorophyll concentrations over time have not been followed by similar decreases in suspended particle concentrations (Figure 2). We also showed that even if the phosphorus concentration could be reduced by 80%, the Secchi depth would only increase from the current 0.23 m to 0.34 m. This change in light conditions alone would not bring about significant increases in macrophytes, since the macrophytes currently are not found in the areas of the lake with sufficient light for plant colonization, and thus there would be no increase in the habitat necessary to restore the largemouth bass fishery.

The source of the non-algal portion of the total suspended matter is most likely the resuspension of particles from the sediments. Lake Apopka has few sources of surface runoff, so water borne inputs are not important. Tuschall et al. (1979) noted the brownish cast of the seston in the lake as evidence for the role of sediment resuspension in the poor water clarity of the lake. Other authors have noted increases in suspended materials in Lake Apopka related to wind events (Brezonik et al., 1978; Pollman et al., 1980). Pollman (1983) described a wind event of July 11, 1979 when an intense convective disturbance crossed the lake and caused visible sediment resuspension and resulted in the lake color changing from a greenish cast to a muddy brown appearance. Total suspended solids increased from 87 mg l^{-1} to 252 mg l^{-1}. Pollman (1983) used this information along with the bulk density of the sediments to calculate that this wind event resuspended about 3.2 cm of sediments. Carrick et al. (1993) estimated that 5 cm of the surface layer of sediments were resuspended in one wind event, while Reddy et al. (1996) used vertical profiles of soluble reactive phosphorus in sediment cores and overlying water to infer that 8 cm had recently been resuspended. Undoubtedly, greater quantities of sediments have been resuspended during the largest wind events when large waves would make it unsafe to obtain water samples from the lake.

Sediment resuspension is to be expected given the long fetches and shallow depths in Lake Apopka. We calculated that 46% of the time wind-driven waves would disturb 75% of the sediment area in Lake Apopka. Unlike deep lakes, almost all of the lake bed is subject to wind disturbance at one time or another, and a large fraction of the sediments are disturbed on a daily basis.

Sediment resuspension is also likely due to the character of the sediments over most of the lake bed. The UCF layer described for Lake Apopka fits the definition of the fluid mud layer previously described for marine coastlines with muddy sediments (Maa & Mehta, 1988) and have also been found in inland lakes, such as Lake Okeechobee, Florida (Hwang, 1989; Mehta, 1996). The reported lack of structure of the UCF layer in Lake Apopka and an average density (1.024 g cm^{-3}) (Table 1) that lies within the range of densities for fluid mud layers (1.01 to 1.10 g cm^{-3}) as outlined by Ross (1988), supports the idea that the UCF layer is a fluid mud layer. While we have insufficient information to determine if the fluid mud layer in Lake Apopka was formed by liquefaction of the sediments laid down during the macrophyte phase or represents new sediments, the wind acting on long fetches and shallow water depths most likely allows wave energy to maintain the surface sediment layer in a watery state.

The hypothesis that the high concentrations of suspended materials in the water and the low Secchi disk transparencies are due primarily to blooms of plankton algae is not supported. The turbidity problems in the lake are due less to eutrophication than to wind resuspension of the fluid muds on the lake bed. Many other studies have shown the importance of wind-driven waves in resuspending sediments and increasing the concentrations of suspended particles in the water column. (Jackson & Starrett, 1959; Andersen & Lastein, 1981; Luettich & Harlman, 1990; Bengtsson & Hellstrøm, 1992; Kristensen et al., 1992; Evans, 1994; James & Barko, 1994; Lijklema et al., 1994; Ekholm et al., 1997). Significant increases in sediment resuspension were reported in Lake Tämnaren, Sweden (Wallsten and Forsgren, 1989) and Rice Lake, Wisconsin, USA (Engel & Nichols, 1994) following major reductions in the coverage of aquatic macrophytes just as we have proposed for Lake Apopka. Hamilton and Mitchell (1996) developed regression equations relating suspended solids to shear stress in seven New Zealand lakes. They found that the slopes of the regressions were negatively related to macrophyte biomass which ranged from 0 to 80 g m^{-2}in their lakes. While we have no plant data for Lake Apopka when it was in the macrophyte stage, average standing crops of submersed macrophytes in similar Florida lakes range from 1000 to 5000 g m^{-2} (Florida LAKEWATCH, 1997). Applying those values to the Hamilton and Mitchell equations implies virtually no resuspension in Lake Apopka when it was in the macrophyte state.

The macrophyte beds that were lost following the 1947 hurricane have not returned in spite of limited attempts to replant them in the lake. By 1977, rooted macrophytes covered only 0.03% of the lake area (U.S. Environmental Protection Agency, 1978), and only isolated patches of submersed plants can be found at the present time. The assumption underlying the restoration plan is that the plants are not re-establishing themselves because the water is too turbid; but if the water can be cleared, the macrophytes will return to the lake. When we examined this hypothesis by looking at the relationship between the maximum depth of macrophyte colonization in Florida lakes and Secchi disk depth as developed by Canfield et al. (1985) we found that currently 39% of the lake bed has sufficient light for plant colonization (Figure 6).

These data would indicate that some other factor limits plant re-establishment in Lake Apopka. Schneider & Little (1969) suggested that the shifting of the flocculent sediments by wave action in Lake Apopka prevents the re-establishment of macrophytes, and Chesnut & Barman (1974) also credited the loose sediments as a contributing factor in the loss of the submersed macrophytes from the lake. It has been reported (U.S. Environmental Protection Agency, 1978) that in some areas sand is exposed and plants germinate but then are covered and smothered by a 'fluid-like muck'. These hypotheses seem plausible, since the fluid mud covers most of the lake bed. Since the fluid mud represents a dense suspension rather than a cohesive sediment, plant roots would not be able to anchor themselves against the forces of wave-driven water movements and plant re-establishment would be precluded. Schiemer and Prosser (1976) proposed a similar process was limiting the establishment of young plants in Neusiedlersee.

Some investigators have suggested that the lake would have lost its macrophytes with or without the hurricane winds, citing the theory that eutrophication of lakes results in a decline in macrophyte abundance (Wetzel & Hough, 1973). We cannot demonstrate that this is the case in Lake Apopka. While Scheffer (1998) cites two lakes where macrophyte loss was associated with inceases in plant nutrients, Moss et al. (1996) has cited a number of experiments that failed to demonstrate a loss of macrophytes with nutrient additions. Balls et al. (1989) could not displace the plants in well established macrophyte communities by adding high concentrations of phosphorus and nitrogen unless the plants were first artificially removed by raking. The lack of an annual ice cover and winter macrophyte dieback in Florida lakes would also tend to contribute to the stability of the macrophyte communities in the lakes in the face of increases in nutrient loading.

The conclusion is that light most likely is not the only limiting factor preventing the re-establishment of the macrophytes in Lake Apopka. A large fraction of the lake has sufficient light for plant colonization, but the plants are not there. Wave action and fluid sediments most likely also are responsible for the current lack of macrophytes.

Our model of the marsh flow-way showed that it would be ineffective in removing suspended particles from Lake Apopka. As suspended particles are removed from the lake water, they will be replaced by particles resuspended from the fluid mud on the lake bed, and that the lake waters will remain turbid until all of the fluid mud is removed. We showed that it would take several hundred years to remove the fine sediments with the flow-way, and in the short term the effects of the flow-way will be overshadowed by the normal fluctuations in total suspended solids from day to day.

Application of the theory of alternative stable states

Lake Apopka seems to fit the pattern for alternative stable states that has been described for other shallow lakes that have lost most of their macrophytes such as lakes Tåkern and Krankesjön, Sweden (Blindow et al., 1993), Lake Zwemlust, The Netherlands (van Donk & Gulati, 1995), and Lake Tämnaren, Sweden (Wallsten and Forsgren, 1989). Prior to the 1947 hurricane, Lake Apopka was in the macrophyte state with most of the lake covered with macrophytes. The water was clearer then because the plants prevented the development of large wind-driven waves, so the waters within the plant beds were relatively calm. This situation is unfavorable to the development of plankton algae for several reasons (Moss et al., 1996). The relatively calm waters within the plant beds are not favorable to phytoplankton that require turbulence to keep themselves in the water column. Furthermore, the macrophytes provide a refuge from predation for grazing microinvertebrates, and the macrophytes and associated epiphytes can outcompete the suspended algae for the available nutrients. The stability of this situation is enhanced by the mild climate in Florida where macrophytes do not experience a dramatic annual dieback with the coming of winter such as is found in lakes in more temperate regions.

Once Lake Apopka had lost its macrophytes, it switched to the turbid state. Without the damping action of the macrophytes, large wind-driven waves can develop that resuspend the low density, organic sediments. These in turn keep the water perpetually turbid and the sediments unstable. The creation of fluid mud and the wave action in shallow areas of the lake inhibit the re-establishment of the macrophytes and make the plankton algae the dominant plants in the lake. The intimate contact between the water and sediments will tend to uncouple phosphorus concentrations in the lake water from external phosphorus loading and make predicted reductions in total phosphorus concentrations in the water very difficult to achieve. This, along with the fact that the poor transparency is primarily related to resuspended sediments and not plankton algae, means that nutrient reduction alone is most likely not going to be an effective method of restoration for Lake Apopka.

From the above analyses it seems clear that the shallowness of Lake Apopka and not external nutrient loading must be considered the dominant limnological factor in determining its current state. It behaves like other shallow lakes in the turbid state where wind resuspension of sediments is the most important factor determining the levels of total suspended solids. Examples of some lakes with this problem would include lakes Arreskov (Anderson & Lastein, 1981) and Arresø in Denmark (Kristensen et al., 1992), Lake Balton, Hungary (Luettich & Harlman, 1990), Lake Marken, The Netherlands (Lijklema et al., 1994), Lake Okeechobee, USA (James et al., 1997), Lake Pyhäjärvi, Finland (Ekholm et al., 1997), Lake Tämnaren, Sweden (Bengtsson & Hellström, 1992), and seven New Zealand lakes reported by Hamilton & Mitchell (1996). Even if it were possible to make significant reductions in the levels of plankton algae by nutrient controls, the lake would remain turbid. Wave action on the bottom sediments most likely keeps the surface sediments in a fluid mud state that prevents the re-establishment of rooted macrophytes.

Attempts to 'restore' Lake Apopka by definition should mean re-establishing the largemouth bass population, because fishing for that species was the major beneficial use of Lake Apopka prior to the loss of the macrophytes. This fishery is largely gone because the largemouth bass population in large Florida lakes ($>$ 300 ha) requires about 15% coverage with aquatic macrophytes to allow young of the year to recruit into adults (Hoyer & Canfield, 1996). Thus, with the loss of rooted aquatic plants largemouth bass recruitment is greatly reduced in Lake Apopka.

This goal could be met if we could shift Lake Apopka to the original macrophyte state, thereby providing the necessary habitat and refuge to generate a largemouth bass population. Scheffer (1998) has documented several case studies from the literature where lakes such as Lake Veluwemeer, Lake Zwemlust, Lagoon of the Islands, and Lake Christina shifted from turbid states to clear water macrophyte states but points out that it requires dramatic environmental change (e.g. total removal of fish populations, large scale dewatering and re-establishment of plants). We have shown that current phosphorus control attempts in Lake Apopka will not make the dramatic change needed to shift Lake Apopka from a turbid open water state to a clear water macrophyte state, but the lake drawdown and dewatering of the sediments previously recommended for the restoration of Lake Apopka (U.S. Environmental Protection Agency, 1978), might provide the switch. These can be effective methods for restoring fish populations in Florida eutrophic lakes (Wegener & Williams, 1974; Johnson et al., 1981; Nordhaus, 1989). Detailed plans were formulated for a significant drawdown of Lake Apopka over a 9-month period to consolidate the flocculent sediments and promote the growth of aquatic macrophytes (Greening & Doyon, 1990). This project, however, was never conducted due to concerns raised both by government agencies and the public about the side effects of the drawdown such as kills of fish, birds, and alligators and unanswered technical questions (U.S. Environmental Protection Agency, 1979).

The drawdown approach, however, is not without problems. Pumps would be needed to drain the deeper parts of the lake, and increased outflows of nutrient-rich water from the lake might cause water quality problems in downstream lakes. There is also the chance that upon reflooding the lake bed might be colonized by emergent plants such as *Typha* sp. rather than the desired submersed plants. Lastly, there is insufficient information to know if the switch to a macrophyte state for Lake Apopka would be permanent, because this approach to shallow lake management is relatively young. Lake Christina, Minnesota, USA was switched to a macrophyte state in 1988 following fish removal and stocking of predatory fish (Hanson & Butler, 1994). In 1998 it still retained the macrophytes (M. G. Butler, pers. comm.), however in Lake Zwemlust, The Netherlands, the turbid state returned 6 years after a biomanipulation without nutrient reduction that had switched it to a clear water state (van Donk & Gulati, 1995). There is no guarantee that a drawdown would provide a permanent switch to a macrophyte state in Lake Apopka.

In view of this uncertainty we suggest an alternative approach aimed at restoring Lake Apopka's largemouth bass fishery that does not depend on establishing clear water conditions in the entire lake. We propose that in selected areas of the lake wave barriers be constructed parallel to the shore to provide protected areas of calm water between the barriers and the shore for the establishment of macrophytes. Initially, these might be placed about 100 m from shore on the west side of the lake where the frequencies of longshore winds would be least. A limited drawdown to consolidate the sediments in these areas and plantings of macrophytes might be needed to provide the initial plant colonization. These areas would increase habitat for recruitment of largemouth bass. Once the largemouth bass recruit in Lake Apopka, the planktivorous fish (primarily gizzard shad) will provide an ample supply of food. Additionally, advanced fingerling largemouth bass could be stocked to enhance the recruitment of largemouth bass into adults. This management option could be carried out in a relatively short period of time and would not preclude the search for other techniques to provide clear water in Lake Apopka.

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