Battoe L.E., Coveney M.F., Lowe E.F. & Stites D.L. (1999) The role of phosphorus reduction and export in the restoration of Lake Apopka, Florida. In: Phosphorus Biogeochemistry of Subtropical Ecosystems (Eds K.R. Reddy, G.A. O'Connor & C.L. Schelske), pp. 511 -526. Lewis Publishers, Boca Raton

22 The Role of Phosphorus Reduction and Export in the Restoration of Lake Apopka, Florida

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22.1 ABSTRACT

Lake Apopka is a large (125 km^2), shallow ($\bar{Z}$ = 1.6 m) lake in central Florida made hypereutrophic by 50 years of agricultural stormwater discharges from farms on 80 km^2 of drained littoral marshes. The lake is characterized by high nutrient levels, high turbidity caused by algae and resuspended sediments, and almost no remaining submersed or emergent macrophytic vegetation. Phosphorus loading to Lake Apopka is being reduced through the purchase of the riparian farms and restoration to aquatic habitat. Additional management activities to accelerate recovery of the lake are creation of a treatment wetland to remove nutrients and suspended solids from lake water, removal of gizzard shad (*Dorosoma cepedianum*), and replanting of littoral vegetation. Because of concerns that reduction in phosphorus (P) loading will be ineffective in restoration of Lake Apopka, we have reexamined the empirical and theoretical basis for P load reduction as a lake restoration technique.

Case studies of control of P loading show that a proportional improvement in lake trophic condition often is obtained when a significant reduction in P loading is effected. Restoration of hypereutrophic, shallow, turbid lakes requires reduction in P loading to lower the stability of phytoplankton dominance and increase the stability

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of macrophyte dominance. Several characteristics of Lake Apopka increase the probability that the lake will respond to reduction in P loading from adjacent farms. First, P loading (approx. 0.55 g P m^{-2} yr^{-1}) to the lake during the last 30 years has been elevated about seven-fold compared to prefarming levels, and P loading is dominated by farm discharges. Second, biogeochemical processes will dampen internal loading from P-rich sediments after external loading is reduced. The majority of P enters the lake as soluble reactive P. However, as a result of chemical and biological processes, almost 80% of the P in surficial sediments is in Ca-Mg-bound (33%) or organic (46%) forms resistant to rapid biological uptake.

Since summer 1995, trophic indicators (TP, TSS, Chl, Secchi depth) in Lake Apopka have improved significantly based on an 11-year data set. These changes are consistent with modest reductions in P loading achieved since 1993 through regulatory actions. Recently, patches of submersed vegetation (e.g., *Vallisneria*, *Chara*) have established naturally at more than 20 sites around the lake.

22.2 INTRODUCTION

Lake Apopka is the fourth largest lake in Florida. Once a nationally famous fishing lake, Lake Apopka suffers from hypereutrophication as a result of receiving agricultural drainage water rich in phosphorus (P) for the past 50 years. Based on diagnostic research and critical evaluations of restoration techniques (Conrow et al., 1993), we recommended phosphorus load reduction as the primary restoration strategy.

Phosphorus loading to Lake Apopka will be drastically reduced through the purchase of almost all of the 80 km^2 of riparian farms and restoration of these areas to aquatic habitat. Phosphorus stores in the lake will be reduced by filtration of algae and resuspended sediments in a recirculating treatment wetland and by the mass removal of gizzard shad. Gizzard shad removal may further contribute to improved water quality through biological control mechanisms (biomanipulation) (Moss et al., 1996). Finally, habitat restoration is starting through planting of native vegetation in the littoral zone.

Recently, some limnologists have argued that, for many hypereutrophic lakes, release of internal stores of P can be so substantial that a reduction in P loading may not cause a decline in limnetic P concentration, or that the decline may require many decades (Chapra and Canale, 1991; Welch and Cooke, 1995; Carvalho et al., 1995). Moreover, some workers have taken recent theories of alternative stable states in shallow lakes (Scheffer et al., 1993) to mean that P load reduction is unnecessary or ineffective for shallow lakes (Canfield et al., 1996). In the case of Lake Apopka, several arguments have been made against P load reduction as a means for restoration.

1. The present state of the lake did not result from increased P loading but did result from a hurricane in the late 1940s that destroyed submersed plant beds, and P load reduction will not reverse these effects.
2. Frequent sediment resuspension releases enough P from the sediments that the effectiveness of P load reduction will not reduce the P concentration.

3. A decrease in the P concentration will be ineffective, because resuspended sediments will maintain turbid conditions and prevent reestablishment of macrophytes (Bachmann and Canfield, 1996; Canfield et al., 1996; Bachmann et al., 1997, 1998).

These arguments indicated to us a need to reexamine the empirical and theoretical basis for P load reduction as a lake restoration technique for lakes in general, and for Lake Apopka specifically.

22.3 LOCATION AND DESCRIPTION

Lake Apopka is a large (125 km^2), shallow (mean depth = 1.6 m) lake located centrally on the Florida peninsula in Lake and Orange Counties and approximately 11 km northwest of Orlando (Fig. 22.1). It is the headwater lake of the Harris chain of lakes and the Ocklawaha River that flows into the St. Johns River. A spring is located at the southern end of Lake Apopka, and a few small streams flow into the lake, but the major source of water is rainfall on the lake surface. A single, artificial outflow, the Apopka-Beauclair Canal, was dug for navigation and completed in the late 1890s. The canal apparently lowered the lake's high water level approximately 1 m. Topography indicates that prior to construction of the canal, the lake drained through a swamp to the northwest (Double Run Swamp) and into Little Lake Harris.

Lake Apopka is hypereutrophic (mean TP = 0.204 mg L^{-1}, mean chlorophyll-*a* = 0.092 mg L^{-1}, mean Secchi depth = 0.23 m) (Table 22.1). Almost the entire lake bottom is covered by organic sediments, with high water and P content deposited since the 1940s. These sediments of algal origin are underlain by a more-consolidated organic sediment of macrophytic origin and by peat, sand, or marl (Schneider and Little, 1969; Reddy and Graetz, 1991; Schelske, 1997). Dense phytoplankton and suspended surficial sediments cause high turbidity. Diffuse extinction coefficients for photosynthetically active radiation range from 3.1 to 12.8 m^{-1} (Schelske et al., 1992). In enrichment bioassays, nitrogen (N) was most frequently the limiting nutrient for production of phytoplankton (Aldridge et al., 1993). This situation is expected given the high P loading.

22.4 BRIEF HISTORY OF LAKE APOPKA

Through 1946, the lake had clear water and submersed vegetation dominated by *Potamogeton illinoensis* growing to a depth of 2.4 m (Clugston, 1963). The lake was nationally recognized as a trophy bass fishery, and more than 24 fish camps ringed the lake. The original lake/marsh system had an area of approximately 214 km^2 (Lowe, et al., 1998). During the 1940s, portions of the lake bottom and most of the approx. 80 km^2 saw grass (*Cladium jamaicense*) marsh across the north end of Lake Apopka were diked, ditched, and drained for agriculture.

The first recorded lake-wide algal bloom occurred in 1947. Some reports attribute a sudden shift from macrophyte to phytoplankton dominance to uprooting of vegetation by a hurricane in the fall of 1947 (USEPA, 1978; Schelske and Brezonik,

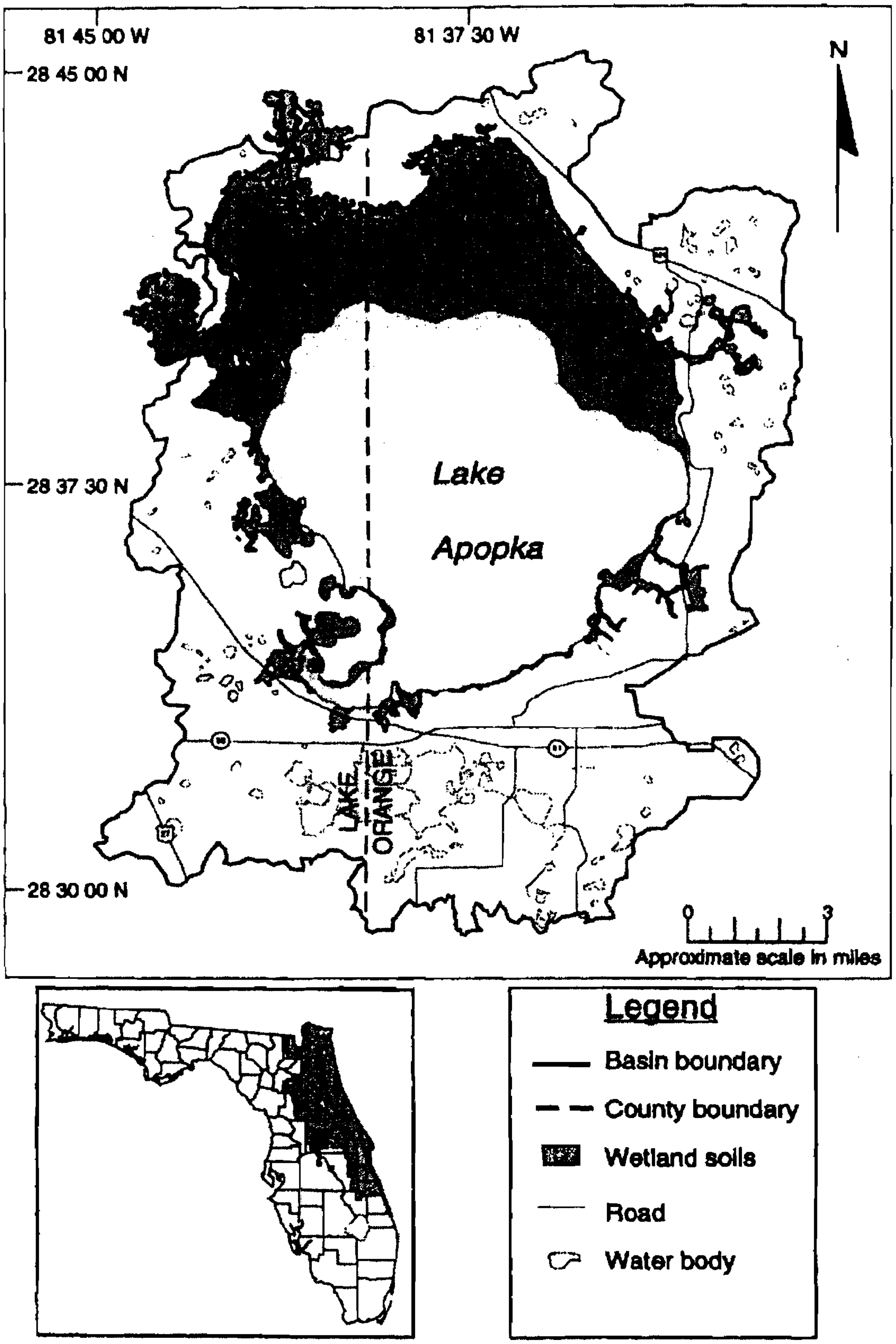

FIGURE 22.1 Location of Lake Apopka, Florida. The agricultural area is indicated approximately by the shading showing wetland soils (contours within the shaded area show different wetland soil types).

TABLE 22.1
Characteristics of Lake Apopka, Florida

Variable	Mean	SD	Method
Mean depth, m	1.63	NA	NA
Secchi depth, m	0.23	0.07	25-cm diameter disk
Chlorophyll-*a*, mg L^{-1}	0.092	0.033	EPA 10200 H (not corrected for pheopigments)
Total phosphorus, mg L^{-1}	0.204	0.063	EPA 365.4
Total nitrogen, mg L^{-1}	5.14	1.27	Sum of Kjeldahl N (EPA 351.2) and NO_3/NO_2 N (EPA 353.2)
Total suspended solids, mg L^{-1}	79.0	31.2	EPA 160.2

Notes: Mean values and standard deviations (SD) were calculated for January 1987–February 1997. Mean depth was calculated at lake surface elevation 66.5 ft NGVD. Sampling frequency was variable but was at least monthly. EPA: Kopp and McKee (1983). NA = not applicable.

1992; Bachmann and Canfield,1996). However, no hurricane passed within 160 km of Lake Apopka in 1947. Photographic evidence and historic accounts suggest that the increase in phytoplankton and decline in macrophytes actually occurred over a several-year period from 1947 to 1951 (Lowe et al.,1998). Since the 1950s, the lake has had high levels of P and N, high turbidity caused by algae and resuspended sediments, almost no remaining submersed macrophytes, and only a thin fringe of emergent macrophytic vegetation.

In 1985, with the passage of the Lake Apopka Restoration Act (LARA), the Florida State Legislature directed that an "environmentally sound and economically feasible" means be found to restore Lake Apopka to Class III water quality standards and identified the St. Johns River Water Management District (SJRWMD) as the lead agency. In Florida law, Class III refers to a lake suitable for recreational use and for the propagation of fish and wildlife. In 1987, the Surface Water Improvement and Management (SWIM) Act augmented the LARA and provided further emphasis and funding for Lake Apopka as one of several priority waterbodies requiring restoration work.

In the ensuing years, eight diagnostic projects were conducted to better understand the problems and the character of Lake Apopka, and ten alternate restoration methods were reviewed and evaluated (Conrow et al., 1993). Several restoration techniques originally proposed for Lake Apopka were found on examination to be either ineffective or too costly. These included large-scale dredging, phosphorus inactivation in the lake sediments, enhanced microbial decomposition, and the introduction of exotic fish species. A pilot-scale wetland filtration system was operated for six years, and several littoral zone revegetation demonstration projects were completed.

22.5 SOURCES AND EXTENT OF POLLUTION

For the last 50 years, Lake Apopka has been a source for irrigation water for the approx. 80 km² area of farms established on the former littoral marsh. In addition, fallow fields periodically have been flooded with lake water to prevent subsidence of the organic soils and to help control nematode plant pests. Because surface elevations of the farms are below lake level, excess storm water and flood water, enriched with P and N, have been pumped into the lake. Farm pumping contributed an average P loading of more than 50×10^6 g P yr^{-1} in a recent six-year P budget (Stites et al., 1997).

Lake Apopka also received waste water from citrus processing plants and effluent from the Winter Garden sewage treatment plant. Phosphorus loading from these sources combined was about 4×10^6 g P yr^{-1} in the 1940s and had increased to about 7×10^6 g P yr^{-1} when these sources were controlled in 1977 (Lowe, et al., 1998). These point-source loads were appreciable when compared with pristine loading from precipitation, spring flow, seepage, and runoff (about 14.7×10^6 g P yr^{-1} for the original 214 km^2 lake/marsh system) (Lowe et al., 1998), but were much less than loading from the farms.

Areal P loading (approx. 0.55 g P m^{-2} yr^{-1}) during at least the last 30 years (Coveney, 1997) has been elevated about seven-fold compared to prefarming levels (approx. 0.077 g P m^{-2} yr^{-1}). Farm nutrient loading has decreased in recent years because of a consent agreement between the farmers and the SJRWMD, but further decreases are necessary for the lake to meet Class III standards.

22.6 WHY PHOSPHORUS CONTROL? THE EMPIRICAL AND THEORETICAL BASIS

As discussed above, it has been argued that P load reduction will be ineffective for restoration of Lake Apopka (Canfield et al., 1996; Bachmann et al., 1997, 1998). These arguments stemmed from two basic conclusions: (1) the P concentration will not fall following P load reduction because of internal P loading, and (2) the lake is in an algal-dominated state that will not change as a result of declining P concentration. It was suggested that the theory of alternative stable states (Scheffer et al.,1993) supports the conclusion that P load reduction will be ineffective. We find no support for these views either in new or classical theories of lake eutrophication, in data from lake surveys, in case studies of P-load reduction, or in studies of Lake Apopka.

It has long been recognized that the P concentration of lakes stems from the balance between P loading and P losses through flushing and sedimentation. Many simple mass balance models have been developed on this premise and employed to predict lake responses to P-load reductions (Reckhow and Chapra, 1983). Since these early models were developed, it has been recognized that internal recycling of P between the sediments and water column render the simple models inadequate for predicting the time-course of decline in the P concentration following P-load reduction because, for a time, the sediments can be a net source of P to the water column (e.g., Chapra and Canale, 1991).

Most concede, however, that P-load reduction eventually will lower the P concentration even in lakes with large sedimentary P stores (Marsden, 1989; Chapra and Canale, 1991; Cooke et al., 1993; Welch and Cooke, 1995). Case studies support this view. For example, Sas (1989) reviews the responses of 18 lakes to P-load reduction and concludes that the period of net P release from the sediments is a transient state and that a new steady state is "gradually approached as the old stock of phosphorus in the water-phase is flushed out and net annual release from the phosphorus pool in the sediment decreases and stops." Lake Sammamish, Washington, has been used as an example of the reduced response from a shallow lake because of internal P loading, compared to Lake Washington's rapid recovery (Henderson-Sellers and Markland, 1987). However, 14 years after the diversion of P loading from Lake Sammamish, a 36% decrease in P load had resulted in a 45% decrease in lake P concentration (Cooke et al., 1993). Shagawa Lake, Minnesota, responded more rapidly to reduced P loading (Cooke at al., 1993) than predicted by an internal P loading model (Chapra and Canale, 1991). Reductions in P concentration following P-load reduction also occurred in Lake Tohopekaliga, Florida (James et al., 1994) and Lake Thonotosassa, Florida (SWFWMD, 1992; Brenner et al., 1996). For most lakes in this diverse set, the percent reduction in P concentration is roughly equivalent to or greater than the percent reduction in the P load (Fig. 22.2).

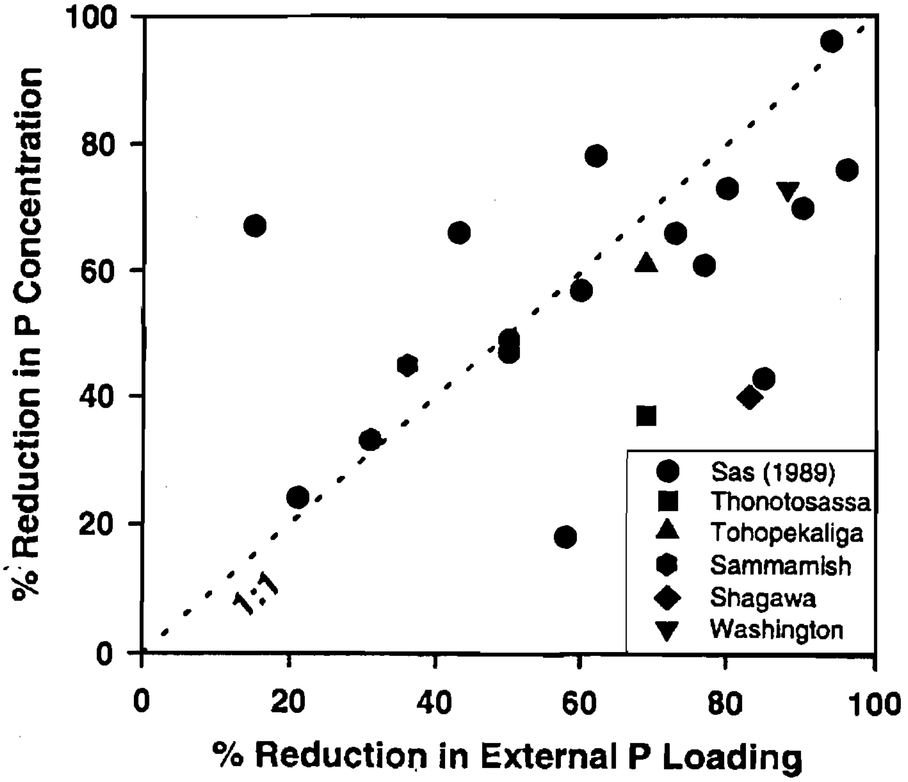

FIGURE 22.2 Percent change in lakewater TP concentration related to percent reduction in external P loading for a number of lake restoration projects. Dotted line indicates 1:1 relationship. Changes in loading and concentration were calculated from the extreme high and low annual values in each case study by Sas (1989) and for Lake Thonotosassa. For the other lakes, multiyear mean values were used to calculate changes in loading and concentration. All case studies analyzed in Sas (1989) are shown here except for Lough Neagh, where no systematic decrease in loading was demonstrated.

In parallel to the work that related the P concentration to the P load, a large body of evidence was developed that related the P concentration to other indicators of trophic state. In the 1970s, Schindler (1974) demonstrated that P, rather than C or N, elicited the changes associated with cultural eutrophication. Many cross-system studies showed a strong, positive correlation between P concentration and algal abundance as indicated by chlorophyll-*a* (Reckhow and Chapra, 1983). This log-linear relationship also holds for Florida lakes (Canfield, 1983; Huber et al., 1982). Thus, both experimental and correlational evidence indicates that P concentration controls algal abundance. Algal abundance, as measured by chlorophyll-*a*, in turn, is negatively correlated with water clarity, as measured by Secchi disc depth across a broad range of lakes (Reckhow and Chapra, 1983) including Florida lakes (Huber et al., 1982; Canfield and Hodgson, 1983).

Improvements in the trophic condition of lakes following reductions in P loading may not always meet a specific restoration goal, such as a shift from a eutrophic to a mesotrophic classification. These situations can be caused by insufficient reduction in overall P loading or insufficient elapsed time to achieve a new equilibrium. However, these situations do not indicate that lakes fail to improve in response to lower external P loading (Cooke et al., 1993).

Recent theories that envision two alternative states in shallow lakes are particularly applicable to Lake Apopka and do not support the view that reducing the P concentration will be ineffective. As discussed by Scheffer et al. (1993), shallow lakes may exist in three conditions determined by P levels.

1. A stable, macrophyte-dominated, clear-water condition when P levels are low
2. A stable phytoplankton-dominated, turbid condition when P levels are high
3. A condition with two alternate, quasistable states when P levels are intermediate

In the third condition, the lake may be either macrophyte dominated and clear or algae dominated and turbid, and the state may shift in response to climatic or anthropogenic perturbations (Scheffer et al., 1993).

A change in state from a stable, turbid condition to a clear condition requires a decline in P loading and P concentrations at least to a level where two quasistable states are possible. For large, temperate lakes, this threshold concentration for P appears to be around 100 mg TP m^{-3} (Jeppesen et al., 1990; Klinge et al., 1995). At or below this level, the lake may oscillate between turbid and clear phases initiated by perturbations such as a major water level fluctuation (Blindow et al., 1993), ice-scouring of the bottom, or reduction in planktivorous fish (Scheffer et al., 1993). At a lower range in P concentration, about 25 to 50 mg TP m^{-3}, the transition to a stable, macrophyte-dominated, clear-water state can occur (Moss et al., 1996).

In this theory, the restoration of shallow, hypereutrophic lakes requires reduction of P loading to lower the stability of phytoplankton dominance and increase the stability of macrophyte dominance. Once the P concentration falls below the threshold for stable algal dominance, other strategies may hasten the shift from phytoplankton to macrophyte dominance. These include biomanipulation of the fish community (removal of planktivores or increase in piscivores) and planting littoral vegetation (Moss et al., 1996).

Lake Apopka was apparently in a stable, macrophyte-dominated state prior to the 1940s. Evidence for this conclusion is found in historical accounts of macrophyte growth and water quality, and in the fact that extreme perturbations, for example numerous hurricanes, did not elicit a change to a turbid state. After P loading was greatly increased through the development of agriculture, the lake entered a turbid, phytoplankton-dominated state. This condition has been stable since the early 1950s and was unaffected by periods of extremely low water in 1956 and 1971.

22.7 RESPONSE OF LAKE APOPKA TO P LOAD REDUCTION

Several characteristics of Lake Apopka indicate that a large reduction in farm P loading will result in a large reduction in the P budget and that lake P concentrations will respond. First, because other important anthropogenic sources of P were mitigated in the 1970s, P loading to the lake is dominated by farm discharges. In a recent six-year P budget study (Stites et al., 1997), farm discharges (0.42 g P m^{-2} yr^{-1}) averaged 85% of total P loading. Once this massive farm loading is curtailed, the overall P budget will fall precipitously. By comparison, areal P loading from uncontrollable sources (seepage, direct basin runoff, spring flow, atmospheric deposition) from 1989 to 94 averaged about 0.06 g P m^{-2} yr^{-1} (Stites et al., 1997) which was equal to estimated areal loading to Lake Apopka in its original, pristine condition (Lowe et al., 1998).

Second, biogeochemical P cycling in Lake Apopka will dampen internal loading from P-rich sediments. Redox potential had minimal effects on soluble reactive P (SRP) levels in sediment porewater from Lake Apopka (Olila and Reddy, 1997). The lake water is calcium rich (mean Ca = 46 mg L^{-1}). Based on chemical extraction, high levels of Ca-Mg-bound P were present in the sediments (Olila et al., 1995). These compounds are poorly soluble in lake water and should be relatively unavailable for algal growth. In addition, high year-round algal productivity, algal sedimentation, and bacterial decomposition create refractory forms of organic P. The majority of P enters the lake as soluble reactive P. However, as a result of chemical and biological processes, almost 80% of the P in surficial sediments was in mineral (33%) or organic (46%) forms resistant to rapid biological uptake (Reddy and Graetz, 1991; Olila et al., 1995). These processes should continue to convert available P in the water column and sediments to refractory P after external loading is reduced.

Recent changes in water chemistry in Lake Apopka provide strong support that our understanding of the functioning of Lake Apopka is accurate, and that reduction in P loading is the correct restoration strategy. Starting in summer 1995, trophic state indicators (TP, TN, TSS, Secchi depth, Chl-*a*) in Lake Apopka significantly improved compared to previous years in an 11-year data set. For example, total P, chlorophyll-*a*, and suspended solids averaged about 30% lower after mid-1995, and Secchi depth averaged about 23% greater (Figs. 22.3 and 22.4). Evaluated with a

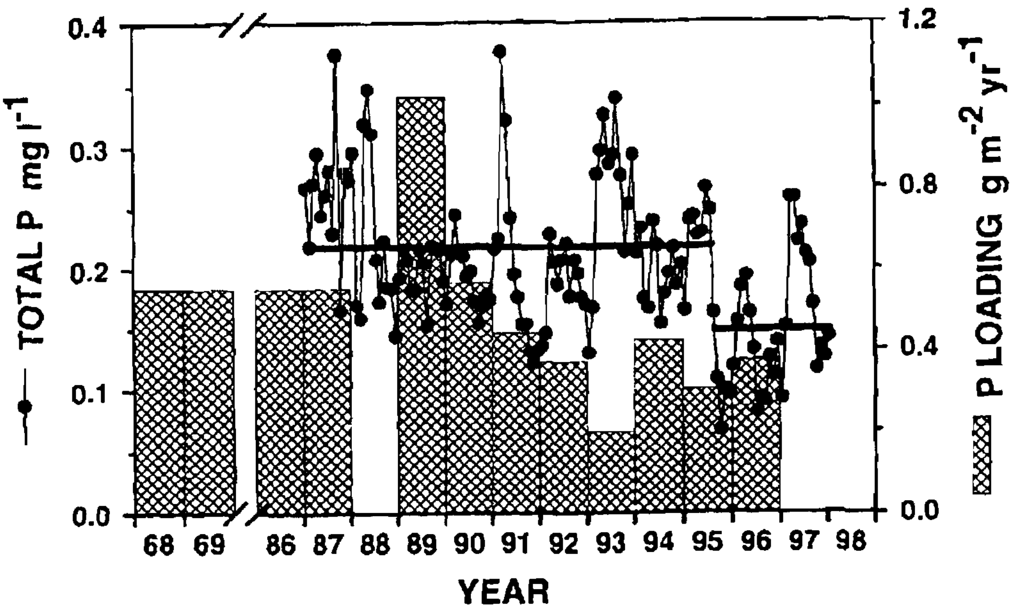

FIGURE 22.3 Annual P loading and mean monthly TP concentrations for Lake Apopka. A mean value for annual loading for the period 1968–87 was derived from sediment stratigraphy (Coveney, 1997), and annual loading for each year 1989–94 was measured (Stites et al., 1997). Annual loading was not measured in 1988 and has not yet been evaluated after 1996. TP concentrations are shown for the SJRWMD period of record January 1987 to the present. Horizontal lines indicate mean TP concentrations for the periods January 1987 to July 1995 and August 1995 to January 1998. Mean values for these two periods differ significantly ($p < 0.005$).

distribution-free resampling technique, mean values for each variable were significantly different before and after mid 1995 ($p < 0.005$).

The most likely explanation for these changes was a decrease in P loading that began around 1992 as a result of improved water management required by regulatory agreements between the SJRWMD and the farmers (Fig. 22.3). In 1993, improved management practices and low summer rainfall resulted in the lowest annual P load to the lake on record (0.20 g P m^{-2} yr^{-1}). Phosphorus loading in subsequent years was higher, but mean annual loading in 1993 to 1996 (0.32 g P m^{-2} yr^{-1}) was still about 40% less than long-term annual loading for 1968 to 1987 (0.55 g P m^{-2} yr^{-1}) derived from sediment studies (Coveney, 1997). A two-year delay between the lowest P loading (1993) and reduced levels of TP in lake water (1995) is reasonable, given internal loading and the mean 2.2-yr hydraulic residence time for 1993 to 1995.

The period after mid 1995 also has seen the spontaneous development of macrophyte (*Vallisneria americana, Chara sp.*) beds at more than 20 sites around the lake. Regrowth of submersed macrophytes in response to increased transparency is the response that we predict to occur when the P concentration in Lake Apopka is reduced below the threshold where the macrophyte-dominated state is favored. The modest improvement in water quality apparent in 1995 likely will not be permanent, since farm loading typically will vary until final discharge limits are met. However, the improved conditions demonstrated that the concentration of P in Lake Apopka will decline following load reduction. With lower P levels, beneficial ecological

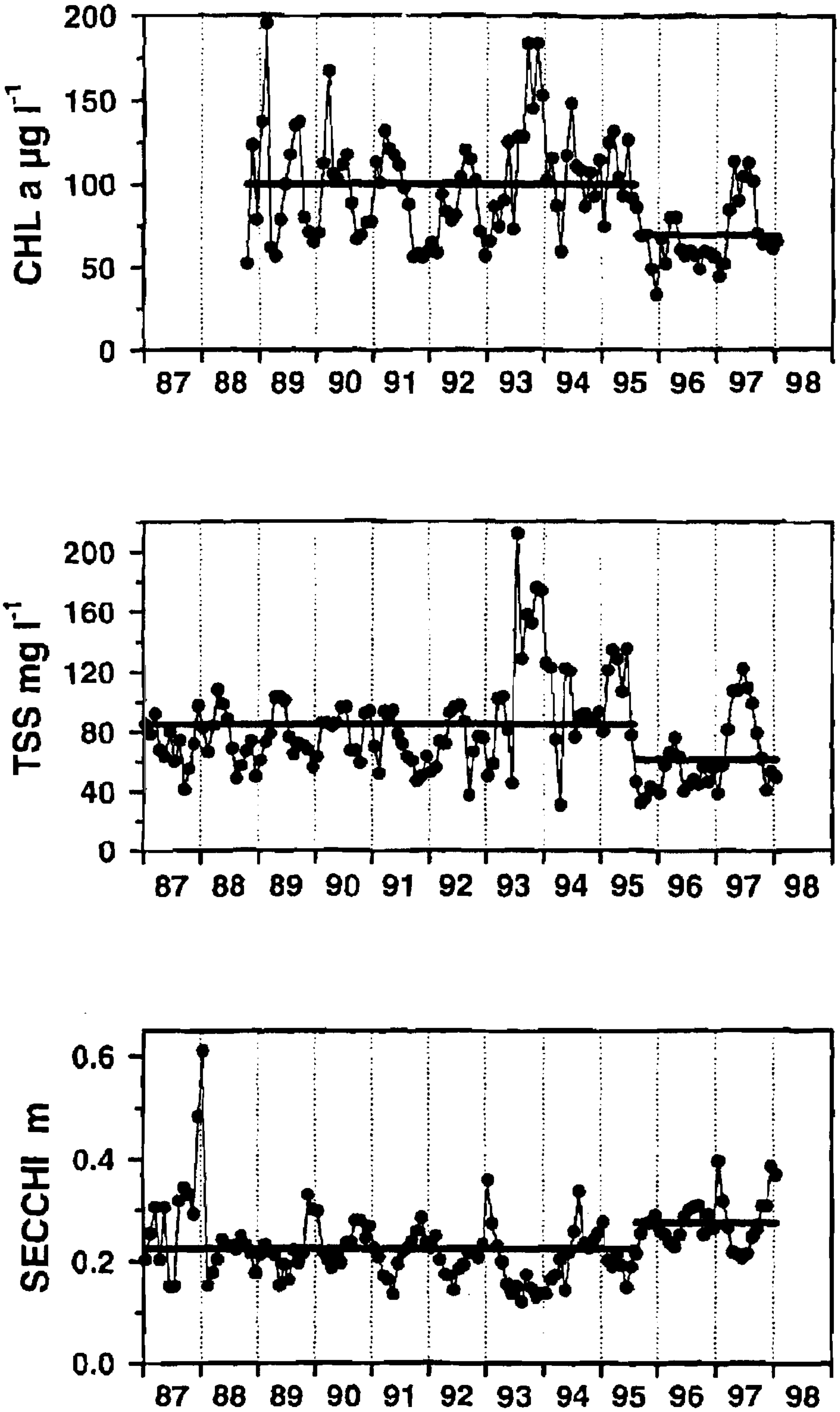

FIGURE 22.4 Mean monthly concentrations of chlorophyll-*a*, total suspended solids, and Secchi depth for Lake Apopka. Data are shown for the SJRWMD period of record January 1987 to the present (chlorophyll data start October 1988). Horizontal lines indicate mean values for the periods January 1987 through July 1995 and August 1995 through January 1998. Mean values for the two periods differ significantly ($p < 0.005$). Secchi depth values in December 1987 and January 1988 likely are erroneous but were not excluded from the analyses.

changes such as lowered algal biomass, increased transparency, and increased growth of macrophytes will occur.

22.8 THE RESTORATION PLAN

Using a variety of methods, we inferred probable ranges for trophic variables for Lake Apopka prior to the after 1940s period of increased nutrient loading from agriculture. Probable ranges were 32 to 51 mg m^{-3} for TP, 8 to 38 mg m^{-3} for chlorophyll-*a*, and 1.39 to 0.76 m for Secchi depth (Lowe et al., 1998). These ranges and the historical descriptions of Lake Apopka are consistent with an earlier mesotrophic condition.

The restoration goal for Lake Apopka is Florida Class III water quality (suitable for recreation and fish and wildlife). Class III standards allow some degradation in water quality from natural background conditions. Therefore, the restoration target range for TP was established by extension of the upper limit for TP under antecedent conditions to 55 mg P m^{-3}. Subsequently, the SJRWMD adopted by rule this upper limit as a P criterion or target P concentration for Lake Apopka. This total P concentration (55 mg P m^{-3}) would provide a high probability for restoration of mesotrophic conditions according to a trophic state classification developed for warm-water tropical lakes (Salas and Martino, 1991).

The restoration plan for Lake Apopka consists of four components. The first step is to significantly reduce the P loading to the lake. This component is the most important because it is required to destabilize algal dominance. If the reduction is sufficiently large, the lake will improve in time even if no further steps are taken. To achieve a large reduction in farm loading (the largest external source of P) the SJRWMD has purchased most of the riparian farms using state and federal funds. Restoration of the approximately 80 km^2 of agricultural lands to wetlands and other aquatic habitat and regulation of any remaining farm P load will decrease overall P loading to about 0.13 g P m^{-2} yr^{-1}. Input-output modeling with a sedimentation coefficient for P developed for Lake Apopka predicts that the resultant equilibrium TP will meet the 55 mg P m^{-3} target (Coveney, 1997).

The remaining three components of the restoration plan will hasten the recovery of the lake and improve the quality of water discharged to downstream lakes. If Lake Apopka follows the alternative stable-state paradigm (Scheffer et al., 1993), then the additional restoration strategies will help to accelerate the shift toward macrophyte dominance as lowered nutrient levels make the phytoplankton state less stable.

The first of these additional components is a treatment wetland to filter suspended solids from the lake water (Lowe et al., 1992). Algae and resuspended lake sediments will be removed by sedimentation in the 14 km^2 wetland. The projected storage of P in the wetland of about 30×10^6 g P yr^{-1} is significant compared with measured long-term mean sedimentation of P in Lake Apopka (about 46×10^6 g P yr^{-1}; Coveney, 1997; Schelske, 1997). The wetland will have a flow capacity sufficient to treat two lake volumes per year. The performance for six years of a 2 km^2 demonstration wetland has substantiated the nutrient removal ability of the larger wetland (Coveney et al., 1998).

Another component of the restoration plan is the continued removal of gizzard shad (*Dorosoma cepedianum*) from the lake by commercial fisherman. In addition to being a relatively inexpensive method for P removal (less than \$0.05 g^{-1} P, depending on market conditions), the trophic effects of shad removal can include a decrease in the rate at which P is recycled from particulate to soluble forms, a reduction in sediment resuspension, and an increase in zooplankton populations (Schaus et al., 1997). These effects combine to cause a decrease in algal abundance. Gizzard shad dominate the fish community in Lake Apopka and account for 96% to 99% of all fish caught in commercial gill nets. From 1993 through 1997, annual removal of gizzard shad averaged 4.4×10^5 kg (fresh weight), equivalent to 3.1×10^6 g P (Crumpton and Godwin, 1997). A pilot gizzard shad removal project conducted by the SJRWMD in hypereutrophic Lake Denham was followed by reduced P and chlorophyll levels and greater water transparency (SJRWMD, unpublished). There was also increased growth of submersed macrophytes, and increased gamefish recruitment (W. F. Godwin, personal communication). Reduction of planktivorous fish populations, either through their removal or through stocking of predatory fish, is a biomanipulation technique that has been used successfully to promote shifts from phytoplankton to macrophytes in the restoration of shallow European lakes (Moss et al., 1996). For more than a decade, however, it has been recognized that biomanipulation will not be effective in hypereutrophic lakes without reduction of P loading (Benndorf, 1987).

The final component of the restoration plan calls for replanting littoral macrophyte beds around the lake, and 25 sites have been planted with varying success in a pilot-scale effort. Along with submersed macrophyte beds that spontaneously develop, these plantings will help to stabilize the sediments and provide habitat for spawning of gamefish. Theoretical and empirical evidence shows that once a threshold water clarity is achieved in shallow lakes, then growth of submersed macrophytes results in direct and indirect feedback mechanisms to further reduce nutrient levels, algal biomass, and turbidity (Scheffer, 1993). Macrophytes reduce wind-driven resuspension of sediments by stabilizing sediments and damping wind-generated water movements. Less resuspension decreases the flux of nutrients from sediments to water and increases water clarity. The large fetch and shallow depth of Lake Apopka make this step very important. Macrophyte beds provide habitat for piscivorous fish and for macro- and microinvertebrates that prey on phytoplankton, and macrophytes compete with phytoplankton for nutrients. We expect that initial establishment of macrophyte beds will, through these feedback mechanisms, further improve local water clarity so that expansion of macrophytes occurs. Improvement in water quality and littoral habitat in Lake Apopka will be a progressive process.

22.9 CONCLUSIONS

The preponderance of lake management theory and experience indicates that the long-term trophic condition of lakes is determined primarily by P loading, sedimentation, and flushing. Decreased P loading to lakes results in an approximately proportionate decrease in P concentration (Marsden, 1989). Moreover, availability of P in lake water typically controls algal abundance (Schindler, 1974; Dillon and Rigler, 1974; and others). Shallow lakes can occupy different stable states at the extremes of the range of P concentrations. At intermediate P concentrations shallow lakes may be either macrophyte-dominated and clear or phytoplankton-dominated and turbid and can switch between these alternate quasistable states (Scheffer et al., 1993; Klinge et al.,1995).

The large body of experience and theory leads to the conclusion that P load reduction should be the primary tool for restoration of Lake Apopka and other large hypereutrophic lakes. The response to reduced P loading may be small if the reduction in loading is insufficient to limit phytoplankton growth. The response may be slow until internal loading declines. The response may be strongly nonlinear in shallow lakes where multiple feedback loops stabilize the turbid state. These factors should be considered in prediction of the temporal response to P load reduction or of the equilibrium condition. However, these factors do not mean that initial control of P loading is ineffective or unnecessary.

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