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Setting Water Quality Goals for Restoration of Lake Apopka: Inferring Past Conditions

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ABSTRACT

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· Lake Apopka is a large (12,500 ha), hypertrophic lake in central Florida which is the subject of a state-sponsored restoration program. We used three quantitative methods in concert with an analysis of the history and general character of the lake and drainage basin to infer the past conditions. We specifically examined two past conditions: 1) pristine (before any major anthropogenic disturbance) and 2) antecedent (before a specific, major anthropogenic disturbance). For Lake Apopka the pristine condition ended in the 1890s when a canal was dug which lowered the elevation for surface water outflow. The antecedent condition ended in the late 1940s when most of the lake's 8,900 ha of floodplain marsh was drained for farming. History, general lake and basin characteristics, and the quantitative analysis indicate that Lake Apopka was mesotrophic; with clear-water and native, submersed macrophyte beds; in both the pristine and antecedent conditions. The three quantitative methods (reference lakes, empirical models, and a loading model) were used to infer the ranges of most probable values in the antecedent condition for total phosphorus, chlorophyll *a* and Secchi depth. These ranges were 32-51 mg·m^{-3} for total phosphorus, 8-38 mg·m^{-3} for chlorophyll *a*, and 1.39-0.76 m for Secchi depth. Lake Apopka has had a history strikingly similar to that described for Dutch lakes affected by cultural eutrophication with proliferation of macrophytes in the clearwater state preceding a rapid transition to the turbid, algal-dominated state induced by a large increase in the phosphorus loading rate.

Key Words: lake restoration goals, water quality, Lake Apopka, hypereutrophic.

Restoration has been defined as "the return of an ecosystem to a close approximation of its condition prior to disturbance" (National Research Council, 1992) and as "any active attempt to return an ecosystem to an earlier condition following degradation resulting from any kind of disturbance" (Welch and Cooke, 1987). If restoration is so defined then knowledge of past conditions becomes the first step in setting goals for ecosystem restoration programs.

Knowledge of past conditions may also be essential for interpretation of environmental standards set by law. In Florida, surface water standards for nutrients and transparency refer to "natural" and "natural background" conditions, respectively (Chapter 62-302, Florida Administrative Code). "Background" is defined as "...the conditions of the waters in the absence of the activity or discharge under consideration...". "Natural background" is defined as the "...condition of waters in the absence of man-induced alterations...". Interpretation of these standards, therefore, requires knowledge of past conditions. We use the term "antecedent" to denote the condition prior to a specific anthropogenic disturbance and the term "pristine" to denote the condition in the absence of major anthropogenic disturbances. "Past conditions," then, encompass the pristine condition and a series of antecedent conditions.

In cases where the goal is not restoration and where legal standards do not refer to past conditions, lake managers may still need to determine these conditions because they indicate the limits that can be achieved in management efforts (OECD, 1982; Moss et al., 1996). Ascertaining past conditions, therefore, serves to ensure that management goals are not set at unattainable levels.

Although knowledge of past conditions is often a prerequisite for setting restoration goals and can be essential for interpretation of legal standards, there is little guidance in the literature regarding procedures for determining the past conditions in lakes. In the common case where there are few observations or data which predate intensive human disturbance, past

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conditions can be difficult to establish. Indeed, a significant portion of the research designed to develop a restoration plan can be devoted to their estimation.

The first step in determining past conditions is gathering general information on the antecedent characteristics and history of the lake. Careful analysis of present and historical information can prevent misinterpretation of the causes of lake degradation and of the past ecological condition. Characteristics which can be especially useful are water clarity, the quality of the fishery, the depth distribution and abundance of vegetation, the species composition of vegetation, soil types and distribution, the nature of the drainage basin, and the history of modification of the basin. From such information, qualitative inferences can be drawn regarding probable past levels of water quality constituents and expected differences between recent and past water quality.

Once the past character of the lake has been established, there are several methods which might be used to draw quantitative inferences regarding the past water quality. Perhaps, the simplest method of inference is to use recent data for similar lakes which are less affected by human activities. This approach has been recommended and used by other lake managers (Heiskary et al., 1986; Payne et al., 1991; Griffith et al., 1994). Use of reference lakes is explicitly allowed by Florida law where, "The establishment of natural background for an altered water body may be based upon a similar unaltered water body..." (Chapter 62-302, F.A.C.).

Another method of inference is the use of empirical models, developed from broad-scale lake surveys, which describe the relationships among various measures of trophic state, especially water clarity, total phosphorus (P), and chlorophyll *a* (Chl *a*) (e.g., Sakamoto, 1966; Dillon and Rigler, 1974; Huber et al., 1982; OECD, 1982). Therefore, if past water clarity can be deduced from early observations or if early data on Secchi depth can be obtained, it is possible to estimate values for P and Chl *a*. Florida law (Chapter 62-302, F.A.C.) specifically permits the use of "historical pre-alteration data" to establish the "natural background" conditions. Recently, Moss et al. (1996), have advocated the use of regression models to hindcast the baseline (prior to subsidized, intensive agriculture) condition of British lakes.

Inferences can also be made from estimates of the past P loading rate. These inferences are derived by using mass-balance models (e.g., Vollenweider, 1969 cited in Reckhow and Chapra, 1983) or empirical models which relate the P concentration to areal P loading rate, hydraulic detention time, and mean depth (e.g., Vighi and Chiaudani, 1985; Salas and Martino, 1991). This method of inference has been recommended by the Organization for Economic Cooperation and Development (OECD, 1982).

We used each of these three quantitative approaches, in concert with a general analysis of past conditions and lake history, to estimate the antecedent levels of the major indicators of trophic state (P, Chl *a*, and Secchi depth) for Lake Apopka, a large, hypertrophic lake in central Florida which is the subject of a state-sponsored restoration program (Conrow et al., 1993). The goal of this program is to restore the lake approximately to its antecedent condition, that is, the state of the lake before large-scale agricultural development of its floodplain and concomitant eutrophication. The congruence of results we found using the three quantitative methods to estimate antecedent conditions suggests that any one of them could be an effective method of inference. The weight of evidence provided by using the quantitative methods in conjunction with analysis of general characteristics and lake history, however, lends greater credence to the results. These methods of inference may be practicable for other lake restoration programs.

General Characteristics and History of Lake Apopka

Lake Apopka is a large (125 km^2), shallow (mean depth = 1.65 m), hypertrophic (mean P = 200 $mg \cdot m^{-3}$; mean Chl *a* = 96 $mg \cdot m^{-3}$; mean Secchi depth = 0.22 m) lake located centrally on the Florida peninsula approximately 11 km northwest of Orlando, Florida (Table 1; Figs. 1-2). It is the headwater lake of the Harris Chain of Lakes and the Ocklawaha River.

Soils, Water and Nutrient Budgets

The distribution of hydric soils around Lake Apopka indicates that the lake and floodplain marsh once covered an area roughly circumscribed by the 21.3 m msl isopleth: about 21,400 ha (Fig. 2). Then, it was the second largest lake in Florida. For such a large lake, its drainage basin is small – about 48,000 ha – so that the historic lake basin accounted for about 45% of the drainage basin. Because most of the surrounding land has deep, sandy soils, surface runoff to the lake would have been low. Indeed, there are only a few streams and little lateral seepage (Brezonik et al., 1978; Stites et al., 1997). Thus, direct rainfall would have dominated the past water budget, accounting for about 93% of water inflow, assuming an average annual rainfall of 1.27 $m \cdot y^{1}$ (Fernald and Patton, 1984).

Table 1.–Characteristics of Lake Apopka, Florida, U.S.A., prior to implementation of restoration activities. Values are 5-year averages, 1988-1992 (n = 51 to 60).

Characteristic	Mean (± 95% C.I.)
area (m^2)	1.25×10^8
mean depth (m)	1.65
maximum depth (m)	5.03
volume (m^3)	2.04×10^8
hydraulic retention time (long-term est. in years)	2.5
alkalinity ($g \cdot m^{-3}$)	116 ± 4
Spec. Cond. (µS)	390 ± 6
pH	9.1 ± 0.1
chloride ($g \cdot m^{-3}$)	43.3 ± 0.87
total nitrogen ($g \cdot m^{-3}$)	5.2 ± 0.3
total phosphorus ($g \cdot m^{-3}$)	0.20 ± 0.01
inorg. nitrogen (NH_4-N + NO_X-N) ($mg \cdot m^{-3}$)	54 ± 0.013
soluble reactive phosphorus (PO_4-P) ($mg \cdot m^{-3}$)	28 ± 0.01
Chlorophyll *a* – uncorrected ($mg \cdot m^{-3}$)	95.5 ± 9.8
Turbidity (NTU)	33.78 ± 3.3
Secchi disk depth (m)	0.22 ± 0.02
Color (platinum-cobalt units)	36.8 ± 4.3

Another major source of water in the past condition would have been the large spring from the Floridan aquifer which flows from a cavern in the lake's floor. An early estimate of flow from the spring is 0.28 $m^3 \cdot sec^{-1}$ for each meter of effective head (Anderson, 1971). At average lake level (20.3 m msl) and average potentiometric head (21.9 m msl), this model yields an estimated flow of 14.2×10^6 $m^3 \cdot yr^{-1}$. Brezonik et al. (1978) found an average P concentration in the spring of 45 $mg \cdot m^{-3}$. The P concentration in rainfall from rural, non-agricultural-cultural areas has been estimated to be 34 $mg \cdot m^{-3}$ (Baker et al., 1981). These concentrations indicate a past, areal P loading rate from rainfall (0.043 $g \cdot m^{-2} \cdot yr^{-1}$) and springflow (0.003 $g \cdot m^{-2} \cdot yr^{-1}$) of 0.046 $g \cdot m^{-2} \cdot yr^{-1}$. Brezonik et al. (1978) reported an additional load from seepage of 0.0143 $g \cdot m^{-2} \cdot yr^{-1}$. They considered tributary inputs to be negligible. This gives a total estimated pristine P loading rate of 0.060 $g \cdot m^{-2} \cdot yr^{-1}$.

Lake Apopka is shallow. At its present-day mean elevation, about 20.3 m msl, its mean depth is approximately 1.65 m. Topography indicates, however, that prior to completion of the Apopka-Beauclair Canal, Lake Apopka would not have drained until reaching an elevation of about 21.3 m msl. Assuming that its average elevation was somewhat lower than this we can estimate its historical mean elevation at about 21 m msl. This indicates a pristine mean depth for the lake basin, excluding the floodplain marsh, of about 2.4 m (by adding to the present-day elevation the difference between the estimated pristine elevation and the present-day elevation). Early aerial photographs and present-day topography and soils indicate that about 8,900 ha of the pristine lake basin would have been shallow marsh less than a meter deep on average. Using 0.6 m as the mean depth of the marsh, we estimate the mean depth for the 21,400 ha lake-marsh system to be about 1.7 m. Using this estimate of mean depth gives a volume of 3.64×10^8 m^3. Long-term discharge records from the Apopka-Beauclair Lock and Dam indicate an average discharge of 7.051×10^7 $m^3 \cdot yr^{-1}$ (USGS, 1988). This yields a pristine water residence time of 5.2 yr. With a mean depth of 1.7 m, and an areal P loading rate of 0.060 $g \cdot m^{-2} \cdot yr^{-1}$, the nomogram of Vollenweider (1975, cited in Reckhow and Chapra, 1983) indicates a pristine condition on the border between oligotrophy and mesotrophy. A similar nomogram developed for warm-water subtropical lakes (Salas and Martino, 1991) indicates mesotrophy.

Completion of the canal lowered the mean elevation of the lake, but the marsh was still too wet for farming in most years (Bacon, 1974; Shofner, 1982). Assuming that the marsh had a mean depth in this antecedent condition of 0.1 m, the mean depth for the lake/marsh system would have been approximately 1.15 m. This gives an antecedent water residence time of 3.5 years. An antecedent, areal P loading rate of 0.076 $g\ P \cdot m^{-2} \cdot yr^{-1}$ (derivation given below) indicates mesotrophy in Vollenweider's nomogram and the upper boundary of mesotrophy in the nomogram of Salas and Martino.

Vegetation

Early aerial photographs (Fig. 3) and historical accounts (e.g., Clugston, 1963) indicate that submersed beds of vegetation covered much of the lake bottom before 1947. Additionally, organic sediments indicative of macrophyte dominance underlie the recent, algal-based sediments (Schelske, 1997). Thus, submersed, plant beds were characteristic of the past condition indicating higher water clarity and lower algal productivity than the present condition.

The character of soils surrounding Lake Apopka (Fig. 2), topography, early aerial photographs (Fig. 3), and historical accounts (Shofner, 1982; Bacon, 1974) indicate that Lake Apopka was once bordered, largely on the north, by an extensive, floodplain marsh

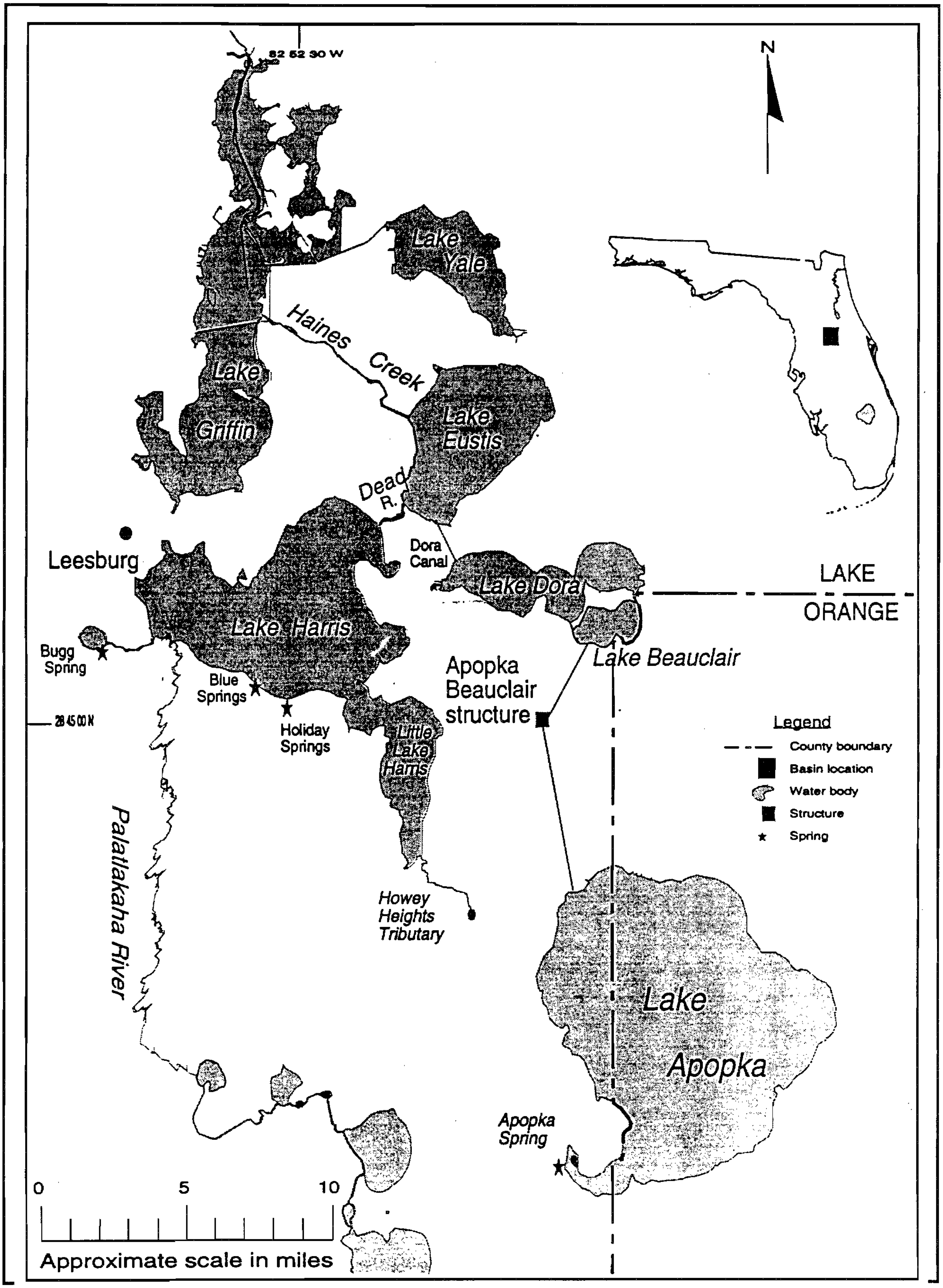

Figure 1.–Lake Apopka and the Harris Chain of Lakes.

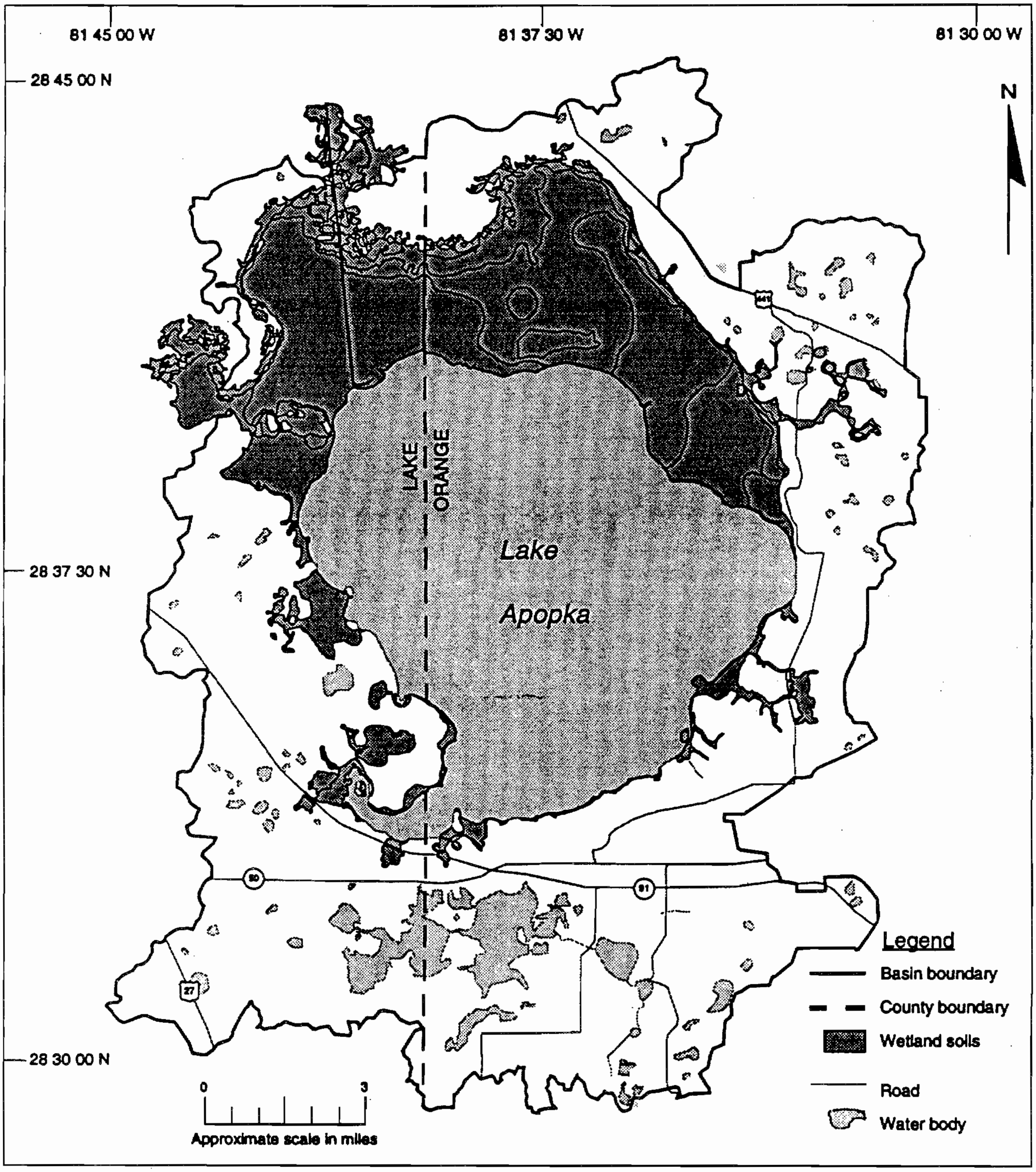

Figure 2.–Watershed of Lake Apopka. The darker shaded area indicates wetland soils. Most of this area was converted to agriculture.

dominated by sawgrass (*Cladium jamaicense*). The distribution of muck soils and topography indicate that the extent of the marsh was about 8,900 ha. Large expanses of sawgrass typically occur in ombrotrophic marshes with low concentrations of P in the water column, such as the Everglades (Davis, 1994). Autecological studies indicate that sawgrass has low nutrient requirements; this likely accounts for its dominance in Florida's large, oligotrophic marshes (Steward and Ornes, 1975; Davis, 1994). Moreover, sawgrass has a lesser ability to use high levels of P than one of its major competitors, cattail (*Typha* spp.); this makes sawgrass a poor competitor in marshes enriched in P (Davis, 1989, 1994; DeBusk et al., 1994). In the Everglades (WCA-2A), cattail invades sawgrass stands where the ambient concentration of TP is above approximately 25 $\mathrm{mg \cdot m^3}$ (McCormick et al., 1996). Presently, at Lake Apopka, cattails tend to dominate shallowly-flooded areas, and sawgrass is virtually absent. Thus, the large sawgrass marsh which once grew on Lake Apopka's floodplain indicates an antecedent trophic state much lower than that of the present.

Figure 3.–Aerial photograph of a portion of the northwestern shoreline of Lake Apopka taken January 30, 1941. Bottom vegetation is visible through water.

Fisheries

As would be expected from its abundance of submersed plants, Lake Apopka once had a very productive sport fishery. It had a national reputation as a fine recreational lake where record bass could be caught (American Automobile Association, 1935; Kimball, 1935; Sheffield and Kuhrt, 1970; Bacon, 1974). It was once described as "the world's most dependable fishing lake" (American Automobile Association, 1935) and as "the finest [fish] breeding lake in America" (Kimball, 1935). The Oakland Hotel became a mecca for fishermen throughout the United States and fishermen were quoted as saying "the fishing is so good and the water so clear you can pick the particular bass you want to catch. It's the best freshwater fishing in the United States." (Bacon, 1974). Residents around the lake indicated that there was good fishing and clear water until 1940 (Sheffield and Kuhrt, 1970).

Modification of the Lake Basin

Significant modification of Lake Apopka began in the late 19th century with construction of the Apopka-Beauclair Canal, which connected Lake Apopka with Lake Beauclair (Fig. 1). The canal was constructed to provide for navigation and to drain, for cultivation, the sawgrass marsh (Bacon, 1974; Shofner, 1982). It was completed in 1893 (Shofner, 1982) and, based on topography and historical accounts (Bacon, 1974; Shofner, 1982), apparently lowered the lake's water level approximately 1 m. Topography indicates that prior to construction of the canal, the lake drained through Double Run Swamp and into Little Lake Harris to the northwest. With the lowering of the lake's level, outflow through Double-run Swamp ceased and the canal became the only surface outflow. By 1893, after many years of work by the Apopka Canal Company and later by the Delta Canal Company, about 8,000 ha of the sawgrass marsh was deemed to be dry enough for cultivation (Shofner, 1982). The drainage works at that time consisted of 19 km (12 mi) of canal, 6 m (20 ft) wide and from 1-3 m (3 to 9 ft) deep, and 51 km (32 mi) of lateral drainage canals to draw water off the sawgrass marsh (Shofner, 1982).

Some cultivation of the marsh for vegetables apparently began as early as 1887 (Bacon, 1974). The early drainage and cultivation efforts were never sufficient for large-scale farming of the floodplain. Apparently, the early drainage canals were not adequate to permanently lower the level of the lake or perennially drain the marshes. Following a severe hurricane in 1926, which deeply flooded the marsh, all attempts at farming ceased until the early 1940s (Shofner, 1982).

Chronology of Eutrophication

Based on aerial photographs, more than 3,000 ha of the floodplain marsh were diked, ditched, and drained for agriculture during the 1940s. In subsequent decades additional farmland was developed until more than 7,300 ha of the floodplain marsh had been diked and drained. Since the 1940s, the farms have pumped large volumes (1989-1994 mean = $51 \times 10^6\ \mathrm{m^3 \cdot yr^{-1}}$) of excess water, enriched in P (1989-1994 mean TP = $0.87\ \mathrm{g \cdot m^{-3}}$), to the lake (Stites et al., 1997). Based on estimates of potential P release rates from the local soils when subjected to the drying and flooding cycles typical for the farms (Reddy, 1983), the majority of P released to the lake likely stemmed from mineralization and release of organic P in the peat soils. At times during the past 50 years, Lake Apopka has received as much as ten times its antecedent annual P load from the farms (e.g., Sheffield and Kuhrt, 1970). Beginning in the 1920s and continuing until the 1970s, Lake Apopka also received waste water from citrus processing plants and effluent from the Winter Garden sewage treatment plant. These sources were small relative to the farm load, and they were reduced in the 1970s (Brezonik, 1978; USEPA, 1979), but we estimate that by 1940 they represented a 36% increase in P loading above the pristine rate (see below).

Beginning in about 1940, there was an increase in plant density and cover. Sheffield and Kuhrt (1970) state that "about 1940, a dense growth of aquatic weeds appeared." Through 1946, Lake Apopka was described as being extremely clear, with a dense growth of *Potamogeton illinoensis* which began approximately 182 m (200 yd) from the shoreline and extended across the entire lake except in areas where the depth exceeded 2.44 m (8 ft) (Clugston, 1963). Water hyacinth (*Eichhornia crassipes*) grew profusely around the edge of the lake and formed large, floating mats that would shift over the surface of the lake. This description of the lake is supported by aerial photographs taken in 1941 which show clear water and scattered, submersed plant beds (Fig. 3). It has been reported that the first algal bloom occurred in 1947, after a hurricane in the late forties uprooted aquatic plants (Scheffield and Kuhrt, 1970). Between 1947 and 1950 rooted aquatic vegetation declined, apparently due to the turbidity associated with the algal bloom (Sheffield and Kuhrt, 1970; Clugston, 1963). It was reported that by 1950, no *P. illinoensis* could be found in the lake (Clugston, 1963); however, there is some evidence that submersed plant beds persisted until at least 1951 (Moody, 1972).

Game fishing in Lake Apopka apparently peaked during 1950-1955 (USEPA, 1978). In 1947, when the algal bloom was first noted, game fish (*Micropterus salmoides, Lepomis* spp., *Pomoxis nigromaculatus*) accounted for about 35% of the fish population and gizzard shad (*Dorosoma cepedianum*) accounted for about 20% by weight (Clugston, 1963). By 1950, game fish made up 69% of the total fish population by weight, and the weight of the entire fish population was estimated to have increased tenfold (Clugston, 1963). By 1957, 82% of the population was rough fish (primarily gizzard shad) and only 18% was game fish (Clugston, 1963). Despite massive rotenone treatments which killed as much as 18 million kg of shad, the rough fish population remained at 82% in 1970 (USEPA, 1978).

On the Causes of Eutrophication

Some workers have concluded that the destruction of aquatic plants by a hurricane in the fall of 1947 caused the first algal bloom and a permanent change in the lake from macrophytic to algal dominance (USEPA, 1978; Schelske and Brezonik, 1992; Bachmann and Canfield, 1996). Although it was reported that algal blooms began to be persistent in late 1947 (Dequine, 1950), aerial photographs of the lake taken in March of 1947, indicate an extensive algal bloom (Fig. 4). In addition, no hurricane passed through the Apopka region (i.e., within 160 km [100 mi] of Lake Apopka) in 1947 (Neumann et al., 1981; Fig. 5). From 1886 through 1946, however, seven hurricanes and 21 tropical storms passed over or within 80 km (50 mi) of Lake Apopka. Fourteen hurricanes and 41 tropical storms passed within 160 km (100 mi) of Lake Apopka. The strongest hurricane to pass within 80 km (50 mi) of the lake occurred in 1928; it was a category 3 storm on the Saffir/Simpson scale at its closest approach to the lake, a very strong hurricane with winds of 179-209 km · hr^{-1} (111-130 mi · hr^{-1}) (Neumann et al., 1981). Category 2 storms (winds of 154-177 km · hr^{-1}) (96-110 mi · hr^{-1}) passed over Lake Apopka in 1944 and in 1945.

If storms could, on their own, cause an ecological shift in Lake Apopka from macrophytic to algal dominance, then one would expect these earlier storms would have elicited this shift, but they did not. Aerial photographs of Lake Apopka in 1941 indicate a clear water column and rooted submersed plants (Fig. 3). As noted earlier, the historical record indicates that Lake Apopka was dominated by rooted, submersed plants and had clear water through 1946, only one year following two hurricanes which passed over the lake. Although the storms of the 1940s may have accelerated Lake Apopka's shift to algal dominance, it is highly unlikely that any fundamental ecological change would have occurred in the absence of the large increase in P loading which was concomitant with development of the floodplain for farming.

Most early writers attribute the loss of macrophytes to shading by algae (Clugston, 1963; Sheffield and Kuhrt, 1970). Observations of large areas of submersed vegetation as late as 1951 (Moody, 1972) support a gradual decline in submersed plants caused by algal blooms. This is not to say that disturbance from storms, through their effects on internal loading, would not have accelerated the transition to phytoplankton dominance. In this regard, the observations of one early writer are particularly perceptive. Burgess (1964) wrote "...in 1947, [Lake Apopka] had reached a climax condition insofar as the submersed aquatic vegetation was concerned. Upon having reached this condition, almost any disturbance of any consequence would have caused the change from rooted aquatics to that of unicellular algae."

Figure 4.–Aerial photograph of a portion of the northwestern shoreline of Lake Apopka taken March 17, 1947. An extensive algal bloom is visible.

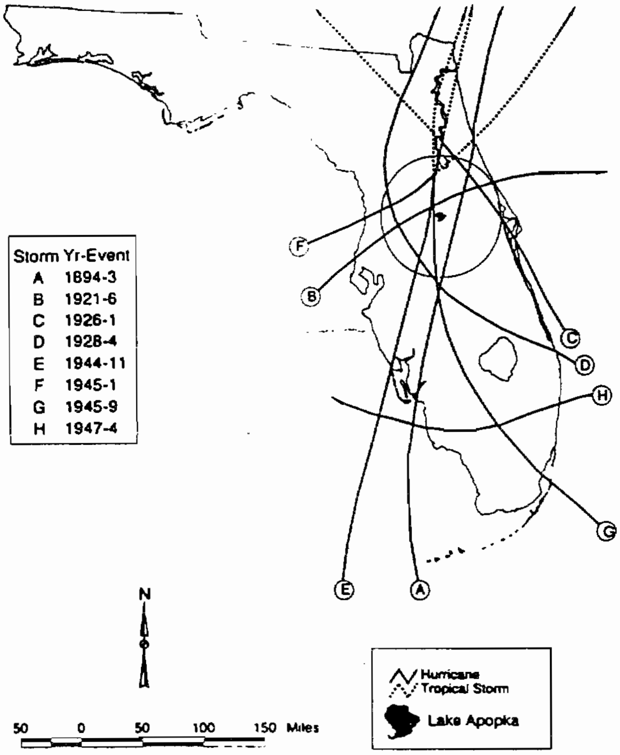

Figure 5.–Hurricane tracks within a radius of 80 km (50 mi) of Lake Apopka (circle) and the track of the 1947 hurricane (H).

Inferences Regarding Water Quality

Inferences from Reference Lakes

Few lakes in Florida can be considered pristine. This means that reference lakes cannot be used to infer pristine water quality in most instances. To infer antecedent (prior to farm development) water quality we used data for lakes similar to Lake Apopka, yet not severely affected by cultural eutrophication. Since trophic state variables were the parameters we wished to infer, they were not used as criteria to select lakes. We selected lakes by two methods: 1) consideration of geology and physiography and 2) consideration of morphology and hydrology.

For the first method, we referred to maps of the physiographic and geologic regions of Florida (Brooks, 1981a, 1981b) and a USGS map of the water bodies and wetlands of Florida (USGS, 1967). Using these maps, lakes were selected for their similarity to antecedent Lake Apopka in five characteristics: 1) lake area, 2) character of inflows and outflows (i.e., riverine lakes were excluded), 3) size and character of the floodplain, 4) local physiography, and 5) local geology. Lakes known to be strongly affected by cultural eutrophication were excluded.

We found no lakes strikingly similar to Lake Apopka, but did find seven lakes we judged to be sufficiently similar and unimpacted to roughly approximate its antecedent condition (Table 2). The levels of trophic state indicators for these lakes were 20-76 mg·m^{-3} for P, 5-25 mg·m^{-3} for Chl *a*, and 0.8-2.1 m for Secchi depth (data from Huber et al., 1982). The mean P for these lakes was 43 mg·m^{-3}; the median was 40 mg·m^{-3}.

For the second method, we used data on lake morphometry and hydrology for 176 Florida lakes (Huber et al., 1982). This information was used to select lakes most similar to Lake Apopka through the use of a set of coarse filters (Fig. 6). The selection process was as follows: 1) select lakes that have a ratio of drainage area to lake surface area (da/sa) no greater than 26 (10 times that of Lake Apopka which is 2.6), 2) from the subset obtained in step 1, select lakes with average depths ($\bar{z}$) no greater than 3 m (i.e., no more than about twice that of Lake Apopka), 3) from the subset obtained in step 2, select lakes which have a surface area (Å) no less than 1,215 ha (about 1/10 that of Lake Apopka), 4) from the subset obtained in step 3, select lakes with a hydraulic retention time (τ_W) greater than 6 months (long-term τ_W for Lake Apopka in its present condition is approximately 2.5 years; Coveney, 1997).

Twelve lakes were selected by this process,

Table 2.–Lake surface areas and trophic state characteristics for reference lakes selected on the basis of geology and physiography. Data from Huber et al., 1982.

Lake	Surface Area (km^2)	Total Phosphorus (mg·m^{-3})	Chlorophyll *a* (mg·m^{-3})	Secchi (m)
Weir	23	20	6.2	2.1
Louisa	15	26	5.0	0.9
Yale	16	36	17.8	1.5
Panasoffkee	20	40	10.8	1.3
Orange	53	48	20.0	1.0
Lochloosa	36	54	24.5	0.8
Istokpoga	112	76	15.2	1.4
Median		**40**	**15**	**1.3**

including Lake Apopka (Table 3). Doctor's Lake was removed from the list because it is estuarine. Lake Okeechobee and Newnan's Lake were listed as problem lakes, with regard to trophic state, by Huber et al. (1982). Lake Okeechobee has been impacted by increased P loading and is the subject of a restoration program. Total P in Lake Okeechobee increased from 49 mg·m^{-3} to 122 mg·m^{-3} from 1974 to 1988 (Janus et al., 1990). For Lake Okeechobee, we substituted data from 1974 (Federico et al., 1981) in order to represent a less degraded condition. Newnan's Lake has likely been degraded by stormwater runoff (Adamus and Bergman, 1993) and by construction of a weir in its outlet (Gottgens and Crisman, 1993). We excluded Newnan's Lake because we had no pre-impact data. Lake Apopka was also removed from the list.

For the resulting set of nine lakes, P ranged from 11-76 mg·m^{-3} (Table 3). The mean P was 42 mg·m^{-3} and the median P was 46 mg·m^{-3}. Secchi depth ranged from 0.60-2.87 m with a mean of 1.49 m and a median of 1.39 m. Chl *a* ranged from 3.4-24.5 mg·m^{-3} with a mean of 12.9 mg·m^{-3} and a median of 8.3 mg·m^{-3}.

Although the two methods of selecting reference lakes produced quite similar ranges of trophic state variables, we favor the second method because the selection criteria were more objective and explicit and because the first set included lakes with short retention times. We tested the sensitivity of this method to the selection criteria by using less-restrictive and more-restrictive sets of criteria (less restrictive = da/sa ≤ 52; $\bar{z} \le 6$ m; Å ≥ 607 ha; $\tau_w > .25$ yr) (more restrictive = da/sa ≤ 13; $\bar{z} \le 2$ m; Å ≥ 4000 ha; $\tau_w > 1$ yr). The less restrictive screening criteria selected 36 lakes rather than 12. For these lakes, P ranged from 11 mg·m^{-3} to 911 mg·m^{-3} with a mean of 117 mg·m^{-3} and a median of 48 mg·m^{-3}. Secchi depth ranged from 0.4 m to 12.7 m, with a mean of 1.6 m and a median of 1.2 m. Chl *a* ranged from 1.5 mg·m^{-3} to 153 mg·m^{-3} with a mean of 27 mg·m^{-3} and a median of 9.8 mg·m^{-3}. The more restrictive screening criteria selected only one lake, Lake Apopka.

Because the less-restrictive screening selected lakes with morphometry and hydrology fairly dissimilar to

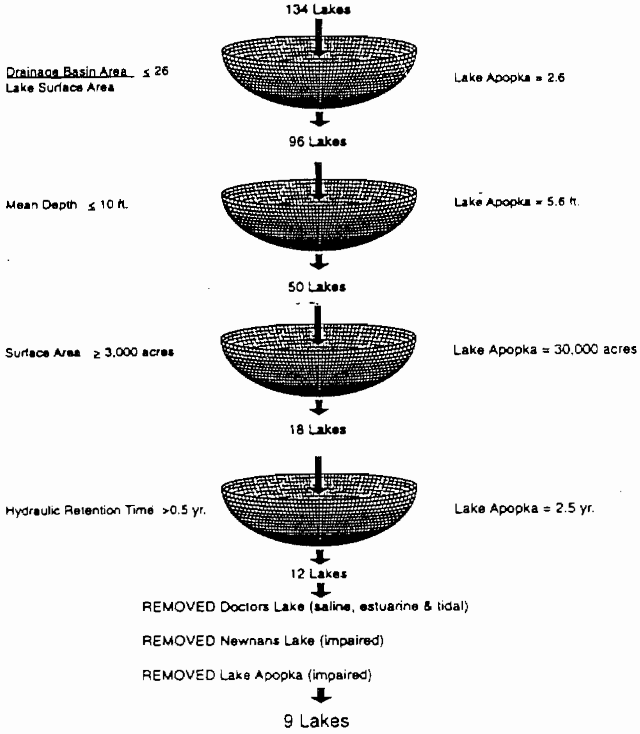

Figure 6.–The "sieve" method of selecting reference lakes similar to Lake Apopka.

Table 3.–Characteristics of reference lake selected on the basis of morphometry and retention time.

Name	Surface Area (km²)	Depth (m)	Volume (m³)	Drainage Area (km²)	Retention Time (yr)	Ratio of Basin Area Lake Area	TP (mg·m⁻³)	Color (Pt units)	Secchi (m)	Chlor *a* (mg·m⁻³)
Iamonia	23	2.13	4,904,500	262	0.59	11.4	11	29	2.23	8.3
Jackson	13	2.87	3,761,000	37	5.4	2.8	27	35	2.87	5.3
Alligator	14	2.35	3,230,600	69	1.8	5.0	30	47	1.78	3.4
Pierce	15	2.19	3,318,200	153	0.86	10.1	35	28	1.18	21.4
Weohyakapka	31	1.6	4,880,000	242	0.79	7.9	46	42	1.11	8.1
East Tohopekaliga	48	2.75	13,311,000	798	0.66	16.5	49	32	1.39	6.2
Lochloosa	36	2.65	9,444,000	228	1.9	6.4	54	61	0.82	24.5
Istokpoga	111	1.76	19,610,000	572	1.3	14.1	76	92	1.43	15.2
Okeechobee	1764	3.0	529,310,000	14,634	0.66	8.3	49	52	0.6	24.0
Median							46	42	1.39	8.3
Mean							42	46	1.49	13.0
Geometric Mean							37		1.37	10.0
95% Conf. Interv.							26-54		1.0-1.8	6.4-15.5

Lake Apopka, we favor the moderately-restrictive screening which selected 12 lakes, of which 9 could be used. The antecedent condition of Lake Apopka reasonably could be expected to lie within the range of conditions found in these 9 lakes. The most-probable, antecedent condition for an unsampled lake in this Apopka-like set of lakes would be described by the mode of the distribution for each trophic-state variable, but this sample of lakes is too small to discern modes. Because the frequency distribution of each trophic-state variable is skewed for Florida lakes (Figs. 7 a, b, and c) the median lies closer to the mode and is a better estimator of central tendency than the mean. By this reasoning, 46 mg·m⁻³ (the median P for the 9 lakes) is the best estimate of the most probable value for mean P in Lake Apopka prior to its degradation. By the same reasoning, most-probable values for Chl *a* and Secchi depth would be 8.3 mg·m⁻³ and 1.39 m, respectively. To obtain an estimate of the variance associated with our most-probable values, we log-transformed the data to reduce the skewness. We then determined the 95% confidence interval for the geometric mean of each variable. These intervals ranged from 26-54 mg·m⁻³ for P, from 1.0-1.8 m for Secchi depth, and from 6.4-15.5 mg·m⁻³ for Chl *a* (Table 3).

Inferences from Lake Survey Models

Starting with an inferred, antecedent Secchi depth, we used regression models developed for Florida lakes which describe the relationships among Secchi depth, Chl *a*, color, and P. Because there are no water quality observations which predate major human influences, pristine water quality could not be estimated using these models. From antecedent Secchi depth we estimated the antecedent level of Chl *a* using the linear regression of Canfield and Hodgson (1983), which relates Secchi depth to Chl *a* and color as follows:

$$\ln(SD) = 2.01 - 0.370 \ln(Chl\ a) - 0.278 \ln(C) \quad (1)$$

where SD is the Secchi depth (m), Chl *a* is in units of $mg \cdot m^{-3}$, and C is color in platinum-cobalt units (Pt units or pcu). The Chl *a* value derived from the Canfield and Hodgson model was then used as input in the least absolute value regression of Huber et al. (1982), which relates P to Chl *a*:

$$\ln(Chl\ a) = 1.64 \ln(P) - 2.81 \quad (2)$$

where P is the concentration of P ($mg \cdot m^{-3}$).

Because there are no antecedent data for Secchi depth, it also had to be inferred from an early observation by Dequine (cited in Clugston, 1963). He reported that through 1946, Lake Apopka was extremely clear and densely vegetated with *Potamogeton illinoensis* to a depth of 2.4 m. This indicates that the compensation depth for submersed, aquatic macrophytes was approximately 2.4 m. We used this estimate of compensation depth in the Lambert-Beer equation:

$$I_z = I_0 e^{-kz} \qquad (3)$$

where I_z is light intensity at depth z, I_0 is light intensity at the surface, and k is the light extinction coefficient (Hutchinson, 1975; pg. 391). The extinction coefficient was calculated based on literature values for the percentage of surface light remaining at the inferred compensation point (2.4 m). Using the calculated extinction coefficient, Secchi depth was calculated based upon literature values for the percentage of surface light remaining at the Secchi depth. The inferred, antecedent Secchi depth was then used as input to the regression model of Canfield and Hodgson (1983). The entire chain of equations is shown in Fig. 8.

The statistical errors of the regression relationships developed from lake surveys are large. For example, the relationship of Canfield and Hodgson (1983) has a 95% confidence interval of 47-224% of the calculated value for Secchi depth. Confidence intervals were not reported by Huber et al., (1982), but the scatter of observations about the regression lines indicates a wide variation about the calculated values. In recognition of the lack of precision of these empirical models, we examined their sensitivity to changes in input variables. Because the Lambert-Beer equation was part of the chain of calculations we also varied its inputs (the percentage of surface light at the compensation depth and at the Secchi depth).

We varied our assumptions in use of the Lambert-Beer equation from 0.5 to 3 percent for the percentage of surface light remaining at the maximum depth of macrophyte colonization, and from 5 to 24 percent for

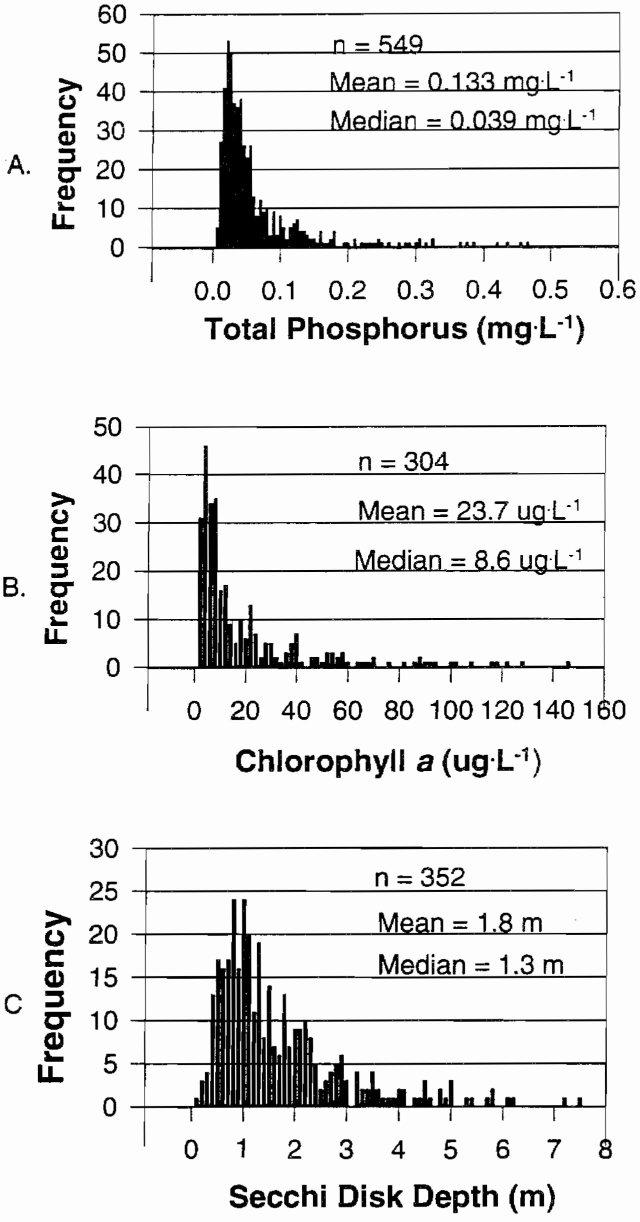

Figure 7.–(A) Distribution of Total Phosphorus values in Florida lakes, (B) Distribution of values for Chlorophyll *a* in Florida lakes, and (C) Distribution of values for Secchi Disk Depth in Florida lakes.

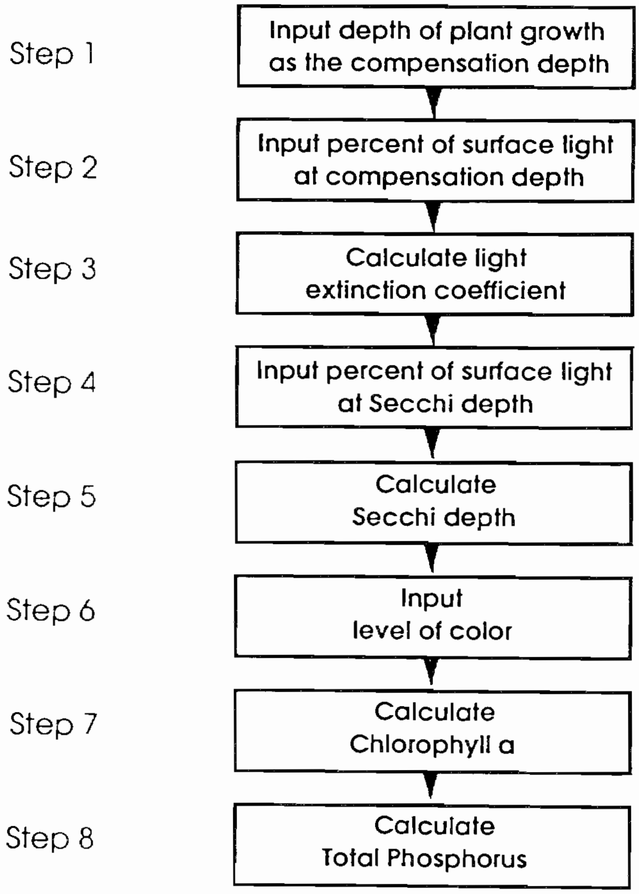

Figure 8.–Procedure for use of empirical models.

the percentage of surface light remaining at the Secchi depth (Reynolds, 1984). We varied color, as input to the Canfield and Hodgson model, from 20-40 Pt units. The present (1987-1997) mean color for Lake Apopka is 33.2 Pt units. Varying these inputs produced a wide range of values for Secchi depth (2.08-0.66 m), Chl *a* (2-75 mg·m^{-3}), and P (8-77 mg·m^{-3}) (Table 4).

The most probable antecedent levels of these variables will not lie at either extreme of the range of values produced by the sensitivity analysis. Instead, the most probable levels will be associated with the most probable values of the input variables. Compensation depth, which should correspond to the maximum depth of macrophyte colonization, is widely held to be that depth where approximately 1% surface light remains (Lind, 1974; Odum, 1971). Reynolds (1984) indicated that the compensation depth is at 0.5% to 3% of surface light. In practice, it will vary with the optical properties of the water column and with the species under consideration. Chambers and Prepas (1988) found that the mean percentage of surface photosynthetically active radiation (PAR) received at the maximum depth of angiosperm colonization for north temperate lakes varied from a minimum of 1.7% (for low-color, eutrophic lakes) to a maximum of 14.8% (for high-color, oligotrophic lakes). For mesotrophic lakes, they found a mean of 6.2% for low color lakes and a mean of 8.4% for high color lakes. They suggested that the variation in this relationship results from variation in spectral attenuation associated with color. Variation is also introduced by the physiological differences among species. For example, for marine vascular plants, the compensation depth appears to range from 4% to 37%, depending upon the species (Dennison et al., 1993; Kenworthy, 1993). In Lake Erie, the compensation point for a variety of submersed vascular plants was about 2% of surface light (Meyer et al., 1943, cited in Welch, 1952, p. 175). In a variety of Florida lakes, the maximum depth of occurrence for aquatic macrophytes ranged from 0.5% transmittance of full sunlight for *Hydrilla verticillata* to 9% transmittance for *Mayaca aubletii* (Canfield et al., 1985). Only *H. verticillata* occurred at less than 1% of surface light. Considering these data, the likely minimum illuminance required by native submersed plants is 1% of surface illumination.

In order to relate the compensation depth to other constituents of water quality, such as P, and Chl *a*, it must be used to infer the Secchi depth. According to Hutchinson (1975), Secchi depth typically is at the point of 5% of surface light. Wetzel and Likens (1991) state that Secchi depth ranges from 1-15% of surface light. Reynolds (1984) gave a range of 5-24% with a mean of 15%. He further stated that the compensation depth is 1.2 to 2.7 times the Secchi depth with a mean of 1.7. These studies indicate that the most likely value for Secchi depth is about 15% of surface illumination.

From these considerations, the most probable, antecedent values for these trophic state indicators are given by assuming that the compensation point is at 1% of surface illumination, that the Secchi depth is at 15% of surface illumination, and color is equal to 30 Pt units (close to the present mean). These input values yield 1.0 m for Secchi depth, 18 mg·m^{-3} for Chl *a*, and 32 mg·m^{-3} for P (Table 4).

Secchi depth also can be inferred from its empirical relationship to the maximum depth of macrophyte colonization. For Florida lakes, the relationship is described by the equation

$$\log(\mathrm{MDC}) = 0.42 \log(\mathrm{SD}) + 0.41$$

where MDC is the maximum depth of colonization (m) and SD is Secchi depth (m) (Canfield et al., 1985). If 2.4 m is taken as the maximum depth of macrophyte colonization (Clugston, 1963), this method gives an estimate of antecedent Secchi depth (0.9 m) that is similar to that derived above. We defer to the estimate based on compensation depth (1.0 m) because the Canfield et al. (1985) data set included many lakes which had the exotic species *H. verticillata.* Their study indicates that *H. verticillata* can grow at lower light levels than can other species; only *H. verticillata* was observed below 1% transmittance of surface light. Therefore, their model is likely to underestimate the clarity required for colonization by *P. illinoensis,* the species for which the antecedent depth distribution was reported. (In this regard, it is noteworthy that if the compensation depth is assumed to be at 0.5% of surface light rather than 1.0%, and if the assumptions for Secchi depth and color are held at 15% and 30 Pt units, respectively, the chain of equations using compensation depth also predicts an antecedent Secchi depth of 0.9 m.)

Recently, Prairie, Peters, and Bird (1995) argued that predictive regressions are inappropriate models to use in empirically-defined statistical relationships for lakes. They propose that structural relationships should be used. For the purpose of prediction, however, others have argued that the appropriate model is the predictive regression of y on x, even in the case of a bivariate, normal relationship (Neter and Wasserman, 1974, pp. 400-401). The predicted relationship between x and y can differ for ordinary least squares regressions depending upon the direction of the regression (i.e., x on y, or y on x; Prairie, Peters and Bird, 1995). Although we used y on x regression in the reverse direction, that is as x on y, the use of the regressions, ultimately, is the control of P loading rates. Therefore, the predictions will apply in the direction in which the regressions were developed, i.e., as y on x.

Table 4.–Relationship between input and output values used in empirical models. Top and bottom shaded bars denote limits of values for color equal to the present value (30 Pt units). Inner narrow shaded bars denote values when Secchi depth is assumed to be at 15% of surface light. The darker shaded bar denotes values selected as most probable for the antecedent condition of Lake Apopka (i.e., where color is 30 Pt units, the Secchi depth occurs at 15% of surface light, and compensation depth occurs at 1% of surface light). Units for Chl *a* and TP are mg·m^{-3}. Cdepth % is the assumed percentage of surface light at the compensation depth, Secchi % is the assumed percentage of surface light at the Secchi depth. Equations 1, 2 and 3 are defined in the text.

Input Values				Output Values		
				EQN. 3	EQN.1	EQN.2
Cdepth (%)	Secchi (%)	Color (pcu)	ext. coef.	calc. Secchi (m)	calc. Chl *a*	calc. TP
0.5	24	20	2.17	0.66	75	77
1.0	24	20	1.89	0.76	51	61
2.0	24	20	1.60	0.89	33	47
3.0	24	20	1.44	0.99	25	39
0.5	15	20	2.17	0.87	35	48
1.0	15	20	1.89	1.00	24	38
2.0	15	20	1.60	1.18	15	29
3.0	15	20	1.44	1.32	11	24
0.5	5	20	2.17	1.38	10	23
1.0	5	20	1.89	1.59	7	18
2.0	5	20	1.60	1.87	4	14
3.0	5	20	1.44	2.08	3	12
0.5	24	30	2.17	0.66	55	64
1.0	24	30	1.89	0.76	38	51
2.0	24	30	1.60	0.89	24	39
3.0	24	30	1.44	0.99	18	33
0.5	15	30	2.17	0.87	26	40
1.0	15	30	1.89	1.00	18	32
2.0	15	30	1.60	1.18	11	24
3.0	15	30	1.44	1.32	8	20
0.5	5	30	2.17	1.38	7	19
1.0	5	30	1.89	1.59	5	15
2.0	5	30	1.60	1.87	3	11
3.0	5	30	1.44	2.08	2	10
0.5	24	40	2.17	0.66	45	56
1.0	24	40	1.89	0.76	31	45
2.0	24	40	1.60	0.89	20	34
3.0	24	40	1.44	0.99	15	29
0.5	15	40	2.17	0.87	21	35
1.0	15	40	1.89	1.00	14	28
2.0	15	40	1.60	1.18	9	21
3.0	15	40	1.44	1.32	7	18
0.5	5	40	2.17	1.38	6	17
1.0	5	40	1.89	1.59	4	13
2.0	5	40	1.60	1.87	3	10
3.0	5	40	1.44	2.08	2	8

Inferences from Loading Models

We used loading estimates to infer both antecedent and pristine conditions. The antecedent loading rate was derived from recent annual P budgets for Lake Apopka (Stites et al., 1997) by subtracting farm loads and adding estimates of anthropogenic P loads which predated the farms. Pristine loading was estimated using a land-use/runoff model (Adamus and Bergman, 1993). In this model, the loading rate was estimated using four variables: subbasin area, rainfall, soil-type, and land-use. The nutrient load was determined for each subbasin by applying a runoff coefficient for each land-use and a nutrient concentration for runoff from each land-use. Estimates of past loading rates were used as input to the steady-state formulation of Vollenweider's 1969 mass-balance model (Reckhow and Chapra, 1983) to predict equilibrium P concentrations. We used Lake Apopka's recent (1968-1987 and 1989-1996) mean P sedimentation coefficient of 1.024 yr^{-1} (Coveney, 1997).

Nutrient budgets for Lake Apopka were developed for the period 1989-1992 (Stites et al, 1997). These budgets indicate that current, non-farming sources of P (rainfall, springflow, seepage and runoff) total about 9.04 t (metric tons) $P \cdot yr^{-1}$. Scaling up atmospheric deposition to the area of the lake/marsh ecosystem which existed prior to development of the farms gives an estimate of the antecedent load of 12.61 $t P \cdot yr^{-1}$. To this load we added P loads from citrus processing wastes (1.3 t; 1977) and sewage effluent (7.1 t; 1976-1977) which entered the lake from the 1920s until the late 1970s (Brezonik et al., 1978). Since estimates from citrus wastes and sewage were from the late 1970s, we scaled the sewage load according to the population of the local municipality (Winter Garden) in 1980 (6,780) and in 1940 (3,060), a scaling factor of 0.45. Similarly, we scaled the loading from citrus wastes according to the number of boxes of citrus produced in Lake and Orange Counties in 1948 (20,808,000) and 1978 (47,829,000), a scaling factor of 0.44. This resulted in a total, antecedent load of 16.4 $t P \cdot yr^{-1}$. Using the antecedent area of the lake/marsh system gives an areal loading of 0.077 $g P \cdot m^{-2} \cdot yr^{-1}$. With this antecedent loading, and using our estimate of antecedent lake volume (2.46 x 10^8 m^3), the Vollenweider model predicts a steady-state P concentration of 51 $mg \cdot m^{-3}$.

We modified the runoff model of Adamus and Bergman (1993) by adding land-use categories for open water and wetlands. The runoff coefficients for these categories were set at 100% because all rainfall hitting these areas enters the lake. To assess the accuracy of the runoff model, we calculated recent loadings in addition to pristine loadings. For recent conditions, we used recent, site-specific, mean values for the P concentration of farm runoff (860 $mg \cdot m^{-3}$) and bulk precipitation (35 $mg \cdot m^{-3}$) (Stites et al., 1997). Prior to the 1940s, the farming area and the area used by a peat mine were sawgrass marsh. To mimic this condition, agricultural lands and the peat mine were modeled as 'wetlands or open water'. In addition, all upland land uses were changed to values reflecting undeveloped land. The pristine P concentration for 'open water and wetland' was set at the level found in bulk precipitation on rural non-agricultural land (34 $mg \cdot m^{-3}$; Baker et al., 1981). For both recent and pristine conditions, we added P loads not derived from runoff: spring flow (1.41 $t P \cdot yr^{-1}$) and seepage (0.56 $t P \cdot yr^{-1}$) (Stites et al., 1997).

When the model was run for recent land-uses, the predicted annual P loading was 54 t. This loading yielded a predicted equilibrium P concentration of 188 $mg \cdot m^{-3}$. These values are similar to recent annual loadings as determined by measurement of all P loads (63 $t P \cdot yr^{-1}$; Stites et al., 1997) and to the recent mean P concentration (200 $mg \cdot m^{-3}$, Table 1).

Substituting pre-development land-uses into the model results in an estimated pristine loading of 14.7 $t P \cdot yr^{-1}$. With this load, and using the estimated pristine volume of 3.64 x 10^8 m^3 (see above), the Vollenweider model predicts a steady-state P concentration of 33 $mg \cdot m^{-3}$.

Discussion

Lake Characteristics and History

Our analysis indicates that the past conditions of Lake Apopka were quite different from the recent condition with regard to trophic state. In both the antecedent and pristine conditions we predict much lower P and Chl *a*, and substantially greater Secchi depth. Major changes in the lake began with construction of an outflow channel near the turn of the century which reduced the lake's depth, decreased its volume, and began drainage of its wetlands. Sewage and citrus waste discharges, which began in the 1920s, likely increased the lake's productivity. All of these early changes, however, did not change the basic character of the lake: it remained a clear-water lake with abundant submersed macrophytes and good game-fishing until the late 1940s. Large-scale drainage of wetlands for farming began in the early 1940s. Historical accounts suggest that aquatic macrophytes proliferated contemporaneously with farm development. Moreover, the difference between aerial photographs from 1941, which show scattered submersed plant beds, and literature descriptions of vegetation in the lake during the late 1940s (Clugston, 1963), which indicate nearly continuous coverage by submersed plants, suggests a proliferation of submersed plant beds. The growth of aquatic macrophytes was likely the first response to the large increase in P loading which accompanied floodplain development.

Aerial photographs and historical descriptions indicate that algal dominance began in 1947. Paleolimnological study of Lake Apopka sediments also indicates a transition to higher trophic state and phytoplankton dominance (Schelske, 1997). The TC/TN ratio and abundance of periphytic and benthic diatoms decrease rapidly moving upward through the transition between the antecedent and recent sediment layers. These changes indicate that Lake Apopka had macrophyte beds in the antecedent condition and that these beds were eliminated as phytoplankton abundance increased. Coincident with these changes, the P deposition rate increased.

The sequence of changes at Lake Apopka is strikingly similar to that described for Dutch Lakes affected by cultural eutrophication (Klinge et al., 1994). In the Netherlands, lakes which were clear with submersed macrophytes became turbid and dominated by blue-green algae in the second half of the 20th century. Dutch lakes passed through three stages: 1) clear water and virtually no submersed macrophytes; 2) clear water and abundant submersed macrophytes; and 3) turbid water and no submersed plants. In this scheme, Lake Apopka, in its pristine and antecedent conditions, was a stage 2 lake. The proliferation of vegetation which began in 1940 was probably the beginning of a transition to stage 3. Once submersed plant beds had reached maximum biomass and lake sediments had been enriched in P, internal loading would have increased, and an increase in water column P concentrations would have followed. Light limitation imposed by algal turbidity subsequently eliminated submersed vegetation. Elimination of submersed plants and increased lake productivity changed the composition of the fish fauna.

Inferences Regarding Water Quality

Only one of the quantitative methods could be used to estimate pristine water quality so comparisons among methods cannot be made for this condition. Our single estimate, however, suggests that the pristine condition was not radically different from the antecedent condition.

Estimates of antecedent water quality were similar among the three methods and were compatible with historical descriptions of the lake (Table 5). Most probable values for P from the reference lakes approach and the empirical models approach were 46 and 32 mg · m^{-3}, while Chl *a* values were 8 and 18 mg · m^{-3}, respectively, and Secchi depth values were 1.39 and 1.00 m, respectively. The loading model predicted a P concentration of 51 mg · m^{-3}. Using the regressions relating P, Chl *a*, color, and Secchi depth, and holding color at 30 Pt units, 51 mg · m^{-3} P would yield a concentration of Chl *a* of 38 mg · m^{-3} and a Secchi depth of 0.76 m. Thus, the most probable values for the antecedent condition range from 32-51 mg · m^{-3} for P, from 8-38 mg · m^{-3} for Chl *a*, and from 0.76-1.39 m for Secchi depth (Table 5). For P and Secchi depth, these ranges are similar to the 95% confidence intervals for the geometric means of the nine reference lakes (Table 3). For Chl *a*, the range of most probable values overlaps, but runs considerably higher than, the confidence interval for the reference lakes. For all variables, the range of most probable values lies within the range of values generated by the empirical models, even assuming that color is held constant at 30 Pt units (Table 4).

There are other empirical models, not specific to Florida, which might also have been used to estimate

Table 5.–Summary of results from different methods to estimate trophic state variables for Lake Apopka in the antecedent condition (before muck forms). Values shown for Reference Lakes and Empirical Models are the most probable values (and ranges).

Method	Total Phosphorus mg · m^{-3})	Chlorophyll *a* (mg · m^{-3})	Secchi depth (m)
1. Reference Lakes	46(11-76)	8(3-25)	1.39(2.87-0.60)
2. Empirical Models	32(8-77)	18(2-75)	1.00(2.09-0.66)
3. Mass Balance and Empirical Models	51	38	0.76
4. Salas & Martino (1991)	60		
5. Vighi & Chiaudani (1985)	32-37		

the antecedent condition. Two appropriate, more general, models are those of Salas and Martino (1991) and Vighi and Chiaudani (1985). Salas and Martino (1991) developed a multiple regression equation for warm-water, tropical lakes which predicts lake P concentration (P) in $g \cdot m^{-3}$, from hydraulic detention time (T) in years, mean depth (Z) in meters, and the areal P loading rate (L) in $g \cdot m^{-2} \cdot yr^{-1}$:

$$P = 0.290 (L^{0.891}) (T^{0.676})/Z^{0.934}.$$

Using the best estimates of the antecedent loading rate ($16.4 t \cdot yr^{-1}$; $0.076 g \cdot m^{-2} \cdot yr^{-1}$), antecedent detention time (3.5 yr), and antecedent mean depth (1.15 m) yields a predicted P concentration of $60 mg \cdot m^{-3}$. This is slightly above the upper limit of the range of most probable values derived from our analysis (Table 5).

Vighi and Chiaudani (1985) developed two regression equations relating lake P concentration to alkalinity ($mequiv \cdot L^{-1}$), conductivity (uS), and mean depth (m) for nearly unimpacted North American lakes. The best fit regression was that relating P concentration (P) in $mg \cdot m^{-3}$ to mean depth (Z) and alkalinity (Alk):

$$\log P = 1.44 + (0.33 \pm 0.10)\log (Alk/Z).$$

Using values of 1.15 m for antecedent mean depth and 2.32 $mequiv \cdot L^{-1}$ for alkalinity, this equation calculates antecedent P concentrations of 32-37 $mg \cdot m^{-3}$. These concentrations lie within the range of most probable values for antecedent conditions and are within the 95% confidence interval for the geometric mean P for the reference lakes.

Other models for the relationship between maximum depth of macrophyte colonization and Secchi depth are also available (Chambers and Kalff, 1985; Chambers and Prepas, 1988). For a data set of 90 north temperate lakes, Chambers and Kalff (1985) found a linear relationship between the square root of the maximum depth of colonization in meters (z_c) and the logarithm of Secchi depth (SD) in meters:

$$(z_c)^{0.5} = 1.33 \log (SD) + 140.$$

This model predicts that macrophytes would colonize to depths of from 1.8-2.5 m for Secchi depths ranging from 0.9-1.4 m, respectively. Thus, this model supports the conclusion that our range of most probable values for antecedent Secchi depth corresponds well with the observation that macrophytes once grew to depths of 2.4 m in Lake Apopka.

To provide a broad-scale perspective for our inferences, we produced frequency distributions for P (549 lakes), Chl *a* (304 lakes), and Secchi depth (352 lakes) from the data of Huber et al. (1982) (Figs. 7 a, b, c). These frequency distributions show that the ranges we deduced to represent antecedent conditions in Lake Apopka are not atypical for Florida lakes.

Perspective on our inferences is also provided by the work of Salas and Martino (1991) and Klinge et al. (1994). For warm-water, tropical lakes, Salas and Martino (1991) calculated the conditional probability of five trophic states (ultraoligotrophy, oligotrophy, mesotrophy, eutrophy, and hypereutrophy) over a wide range of P concentration. These trophic states were defined by criteria other than P, including impairment of multipurpose uses. Their analysis indicates that the antecedent range of P concentration that we have inferred (32-51 $mg \cdot m^{-3}$) includes the region of highest probability of achieving mesotrophic conditions. Klinge et al. (1994), concluded that for large shallow Dutch Lakes, mesotrophy, characterized by clear water and extensive beds of submersed vegetation, will be a stable condition only when P lies within the range of 30 $mg \cdot m^{-3}$ - 100 $mg \cdot m^{-3}$. Given the historical descriptions of Lake Apopka (clear water, extensive submersed plant beds, and a productive fishery), mesotrophy, as defined by Klinge et al. (1994), would be its expected antecedent condition. These two broad-scale studies indicate that the range of most probable values for P for the antecedent condition which we have derived is associated with a high probability for stable, mesotrophic conditions.

Although the congruence of results from the various methods we used suggests that any one of them could have provided sound inferences, we believe that several independent methods should be used to infer past conditions. This weight-of-evidence approach should prevent acceptance of erroneous conclusions from any single technique. In addition to the methods of inference we have used here, paleolimnological techniques may provide another suite of inferential methods. Recently, regression models have been developed which relate sedimentary diatom assemblages and rates of nutrient accumulation in the sediments to water column concentrations of P and Chl *a* (Brenner et al., 1993). If paleolimnological data are available, or if resources are sufficient to obtain such data, these techniques could be used to increase the weight of evidence for the inferred past condition. In the case of Lake Apopka, such confirmation has been obtained (Schelske, 1997).

Past conditions should not be misconstrued as restoration goals. In many restoration efforts, neither pristine nor antecedent conditions will become the restoration goals. Instead, past conditions will be the foundation for consideration of other factors, such as economics and constraints of law. For example, Florida law allows a 10% decrease in the pristine compensation depth which allows transparency to decline from the pristine condition and the P concentration to rise. Such considerations will often lead to goals that approximate, but do not duplicate, past conditions.

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Figure 3

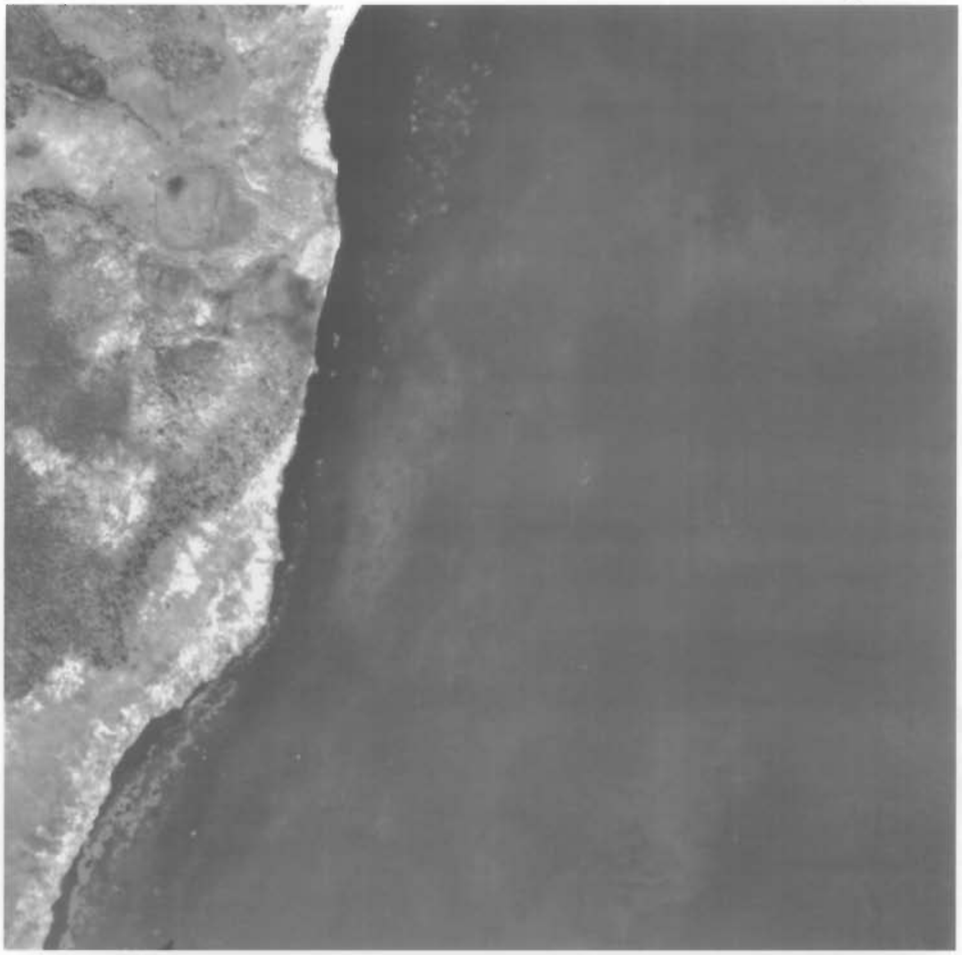

Figure 4