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ECOLOGICAL CONSIDERATIONS OF RECLAIMED LAKES IN CENTRAL FLORIDA'S PHOSPHATE REGION

VOLUME I OF II

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FLORIDA INSTITUTE OF PHOSPHATE RESEARCH

ECOLOGICAL CONSIDERATIONS OF RECLAIMED LAKES IN CENTRAL FLORIDA'S PHOSPHATE REGION

FINAL REPORT

VOLUME I

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NOTE

Many of the tables and figures presenting water quality, lake morphology and biological community data in this document were generated by computer. The programs used by Environmental Science and Engineering, Inc. were not written to truncate output data with the appropriate number of significant figures. Consequently, some of the values are reported with greater precision than the sampling technique will allow. Investigators who use these results are urged to check the level of accuracy of the sampling method and to use only the appropriate number of significant figures in future calculations. The "raw" data that formed the basis of the calculated values are tabulated in Appendices 1-3, which are available at the Institute's library.

David J. Robertson, Ph.D.

DISCLAIMER

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EXECUTIVE SUMMARY

Excavated areas created by surface strip mining for phosphatic rock and subsequently reclaimed as lakes have been the subject of controversy since the promulgation of Chapter 16C-16 Mine Reclamation Rules (FAC) by the Florida Department of Natural Resources. Primary concerns of this issue have been: (1) whether or not these lakes function in the same manner as natural or unmined lakes; (2) whether or not the radiation environment associated with the phosphatic rock was injurious to wildlife or humans; and (3) whether or not there was a lake design which could ensure high water quality and high fish and wildlife value. Without sufficient baseline data on the physical, chemical, and biological environment, conclusions concerning these reclaimed phosphate pit lakes were subject to conjecture.

In October 1981, the Florida Institute of Phosphate Research sponsored a research program, “Ecological Considerations of Reclaimed Lakes in Central Florida’s Phosphate Region” which is documented in this report. This program included 12 reclaimed and 4 natural lakes. Data on each lake’s physical, chemical, and biological conditions were collected during a one-year sampling program. This report represents the most substantial source of baseline information on reclaimed lakes collected to date. This database was used to develop both descriptive information as well as for statistical analyses to determine potential lake design features which would enhance water quality and/or fish and wildlife habitat.

Morphologically, reclaimed lakes differ from natural lakes due to their non-uniform bottom contours and, in some cases, highly irregular perimeter shapes. Most natural lakes in central Florida have shallow, saucer-shaped bottom contours which are fairly uniform. Maximum depths for reclaimed lakes in this study were greater than the maximum depths for the natural lakes. However, the mean depths were similar because the reclaimed lakes generally had an irregular bottom area with both

deep and shallow depths. A statistical analysis indicated the potential benefits of the intermittent deep areas as nutrient sinks, removing nutrients and organic material from the water column due to natural chemical and sedimentation processes.

The chemical component of this investigation can be divided into three areas of interest:

1. Physico-chemical properties (i.e., pH, dissolved oxygen, etc.);
2. Water quality parameters; and
3. Radiation chemistry.

The primary physico-chemical differences between reclaimed and natural lakes were found to occur with water temperature and dissolved oxygen (DO). In natural lakes, thermal stratification and oxygen depression were usually temporary. The generally smoother bottoms and shallower conditions of natural lakes prevented persistent stratification, since localized wind events were capable of breaking down thermal stratification. Conversely, reclaimed lakes had irregular bottom contours with deep holes and shallow areas intermixed. This condition required greater wind energy to break down thermal stratification. Therefore, stratification appeared to be persistent at least from spring to fall. Within the upper 2-1/2 to 3 meters of depth, DO concentrations in these stratified lakes indicated a gradation from supersaturation (at the surface) to zero. All shallow areas (<3m) had measurable DO concentrations from surface to bottom. Only areas with a maximum water depth >2-1/2 to 3 meters exhibited stratification. Although these deep areas had DO concentrations which were below Class III water quality criteria (Chapter 17-3 FAC), the majority of each lake contained oxygenated water, and no problems due to low DO were encountered. In addition, mean DO for each lake station and for each lake overall was greater than the Class III standard. Stratification was found to provide a region in reclaimed lakes where nutrients and organic matter can be removed from the nutrient cycle for an extended period of time.

Water quality parameters, specifically those parameters which are state-regulated, were found to be similar for reclaimed and natural lakes. Only mercury exceeded Class III water quality standards in all lakes. Lead exceeded standards in one natural lake. As expected, nutrient levels *were* high in reclaimed lakes. Phosphorus concentrations were at the level where fluctuation in concentration had no impact on algal productivity. Nitrogen (or some undetermined micronutrient) was implicated as a nutrient which may limit primary productivity in reclaimed phosphate pit lakes. All reclaimed lakes and three of the natural lakes in this study would fit a "eutrophic" classification. The remaining natural lake would be within the "upper mesotrophic" level.

Radiation levels, principally radium-226 (Ra-226), were found to be higher in the sediments of reclaimed lakes than in the natural lakes. However, water column Ra-226 levels were equal to or lower than Ra-226 activity found in natural lakes. This finding appears to indicate that Ra-226 is bound to sediments and, therefore, not distributed throughout the water column unless there is a major wind activity which distributes bottom sediments into the water column. Lake stratification due to intermittent deep areas reduces the total bottom surface area available for resuspension of Ra-226 due to wind events. None of the lakes in this study exceeded state or federal water quality criteria for Ra-226.

Plant and animal tissues were also analyzed for Ra-226 activity. Grouping all plants collected from both reclaimed and natural lakes did not yield statistically significant ($P<0.05$) results for either above or below ground plant tissue from either reclaimed or natural lakes. One species, cattail, was statistically analyzed, independent of other species , showing statistically different (higher) Ra-226 in below ground tissue for reclaimed lakes. However, the above-ground tissues were not significantly different for either reclaimed or natural lakes. These results indicated that Ra-226 was not translocated throughout plant tissues at a higher rate in reclaimed lakes, regardless of the higher, below-ground Ra-226 activity levels.

Ra-226 analyses of fish samples yielded several statistically significant differences between reclaimed and natural lakes. Various fish tissues from natural lake specimens had higher Ra-226 geometric means than fish tissue taken from reclaimed lakes. These results generally were driven by the Ra-226 activity levels for fish from one natural lake. Overall, lower Ra-226 activity was observed within the higher trophic level fish species.

In terms of biological productivity, reclaimed lakes were found to be within the extremes represented by the natural lakes (Lakes Hunter and Hollingsworth representing the upper extreme and Lakes Arietta and Manatee representing the lower extreme). Population characteristics for phytoplankton, zooplankton, and benthic macroinvertebrates generally were indicative of mesotrophic to eutrophic conditions.

Fish populations in many reclaimed lakes were as diverse as those found in natural lakes. Reclaimed lakes that had physical connection to natural stream habitats had larger fish populations than lakes which were isolated. Largemouth bass spawning appeared to be higher in reclaimed lakes, with several spawning periods evident.

All physical, chemical, and biological data were statistically analyzed by simple correlations, multiple correlations, analysis of variance routines, and by principal components analyses. The objective was to determine which of the potentially controllable lake design features available during reclamation could affect water quality or fish populations. These controllable design features included:

1. Lake depth,
2. Lake size,
3. Lake hydrology, and
4. Lake configuration.

Fish population characteristics within the lakes studied were not highly correlated with any of these controllable design features. Lake design was more critical to water quality than to fish habitat requirements. Nutrient levels had a negative relationship with maximum depth and a positive relationship with mean depth. This indicated that the greater the maximum depth, the lower the nutrient concentration. Also, a greater mean depth would result in higher nutrient concentrations. Therefore, in order to control nutrient levels, overall lake depth should not be increased. Instead, a number of deep pockets could be incorporated in the lake design to act as nutrient sinks. This design takes advantage of an irregular lake bottom. Maximum lake depth in this investigation ranged from 5 to 13 meters, and mean depth ranged from 2.6 to 5.6 meters. Maximum depths towards the upper end of this range would indicate deep pockets; however, mean depths in the midrange also would be important in reducing potential lake eutrophication or controlling nutrient conditions. Lake size was not found to significantly impact water quality in this investigation.

Radioactivity levels were not significantly different in reclaimed lakes compared to natural lakes, nor were the radioactivity levels greater than state or federal water quality standards. However, one controllable design feature, hydraulic loading rate, did show a positive correlation with lake radioactivity (primarily in the form of Ra-226). As overall loading rates increased, overall mean Ra-226 levels also increased. This loading rate parameter measures the annual increase in lake level as a function of inflow normalized for average lake area. Hydraulic loading rates ranged from 1.7 to 12.7 meters per year for reclaimed lakes in this investigation. There is no evidence that increasing loading rates beyond those found in this investigation would necessarily increase Ra-226 levels above water quality standards. In fact, natural mechanisms within reclaimed lakes are apparently effective in removing soluble Ra-226 from the water column.

One objective of this investigation was to provide a matrix of lake design criteria which could be used to improve the concept of phosphate pit reclamation. This goal did not include the theoretical design of an "ideal" lake. The results of this investigation provided evidence that reclaimed lakes are dynamic systems, resembling newly-formed reservoirs. The conclusions of this investigation indicate that properly designed reclaimed lakes can be ecologically viable systems. Also, since these lakes are inherently eutrophic from their inception, any features which may retard the eutrophication process should be considered in lake design.

It is important to note that this investigation did not answer (and was not capable of answering) all scientific questions pertaining to reclaimed phosphate pit lakes. The conclusions of this investigation, which were based on average trends, appear to indicate that currently mandated reclamation practices may be inconsistent with the achievement of water quality goals. Increased percentages of shallow areas within these lakes tend to enhance their eutrophic nature, thereby potentially diminishing long-term benefits to these lake systems.

1.0 INTRODUCTION

1.1 BACKGROUND

Florida is a state with over 7,700 freshwater lakes (Edmiston and Myers, 1983). Although lakes are formed by a variety of processes, they can generally be divided into two categories: natural and man-made. Among the man-made lakes which are prevalent in the state are those which are created as a result of phosphate mine reclamation in central Florida (i.e., phosphate lakes).

Central Florida contains one of the richest deposits of phosphate ever discovered. Each year approximately 2,630 hectares (6,500 acres) of the major phosphate deposits (Hawthorn and Bone Valley Formations) are surface strip mined. Mining has been concentrated within Polk and Hillsborough counties since 1879. In addition, phosphate reserves exist in Manatee, Hardee, Sarasota and DeSoto counties.

The regulatory framework for phosphate lake reclamation is found in Chapter 16C-16 of the Florida Administrative Code (FAC). This Chapter contains specific guidelines relating to health and safety, water quality, and fish and wildlife resources which reflect features of natural lake systems found in Florida. Reclamation guidelines provide for a variety of subsequent potential land use scenarios. The U.S. Environmental Protection Agency (1978) estimates that between 1977 and 1985, approximately 7,280 hectares (18,000 acres) of phosphate-mined land will become lakes as a result of reclamation.

Very little data have been collected on phosphate pit lakes. Relationships between physical and biological characteristics and the effectiveness of Chapter 16C-16 in developing use-specific, viable lake systems has not been a research topic. The present study, "Ecological Considerations of Reclaimed Lakes in Central Florida's Phosphate Region," was designed to provide an assessment of baseline physical, chemical and biological conditions for 12 reclaimed and 4 natural or un-mined lakes. Based upon analyses of this assessment, a management matrix of expected lake conditions , given a variety of lake design criteria, has been developed.

1.2 OBJECTIVES

The purpose of this study was to provide background ecological and water quality information on existing reclaimed lakes and natural lakes. Following the data gathering phase, an evaluation of characteristics within the data was undertaken. A matrix of lake design criteria was constructed using statistical models. Pertinent research questions which were considered included, but were not limited to, the following:

1. How do reclaimed lakes compare to natural or nonphosphate mining-related lakes based on water quality criteria, radium-226 concentrations, and ecological productivity?
2. What is the relationship between fish productivity and water quality, and how does the productivity relate to the manner in which the lakes were reclaimed?
3. Which combinations of lake depth, bathymetry, percentage of littoral zone, and flow dynamics can be correlated to develop lake design criteria based on future use of the system and gradations in water quality characteristics?

The objective in deriving a matrix of observations for consideration in lake design criteria was not to design the “ideal” lake, but rather to provide analytically derived evaluations to be used as guidance during the lake design procedure within each individual reclamation program.

Major tasks for this program can be divided into the following areas:

1. Survey of fish populations in 16 lakes relative to lake age, morphometry, and water quality;
2. Seasonal abundances and distributions of plankton, benthos, and fish in reclaimed lakes;
3. Hydrology and water quality of existing lakes, with implications towards lake construction and contouring for future reclamation;

4. Ra-226 distribution in relation to water quality and biological communities associated with reclaimed lakes;
5. Modeling the environmental controls of Ra-226 in the reclaimed lake environment; and
6. Overall ecological considerations for reclaimed lake design.

Enumeration of Specific Objectives

Elements of this project involving qualitative and/or quantitative evaluation of data included the following:

1. Determination of the ecological "health" and water quality of the 16 selected lakes;
2. Determination of monthly water budgets and bathymetry for 16 lakes;
3. Determination of Ra-226 distribution within 16 selected lakes;
4. Provision of recommendations on design criteria for future reclaimed lakes with the understanding that the recommendations do not include economic considerations or land-to-lake ratios; and
5. Comparison of design criteria determined from analysis of 16 lakes and design criteria published by FDER, FDNR, and FGFWFC.

The total program consisted of two phases. Phase I included all field and laboratory analyses. Phase II tasks included data analysis and interpretation as well as computer model generation.

1.3 LAKE SELECTION

An initial step in the development of this study was the establishment of guidelines for selecting the study lakes. Agencies such as the Florida Game and Freshwater Fish Commission (FGFFC) and the Florida Institute of Phosphate Research (FIPR) assisted in this development process during 1981. The following list indicates criteria which were considered prior to lake selection:

1. Identification of as many potential lakes for study as possible, with diversity in age, size, depth, etc.;

2. All surface and subsurface geological data in proximity to identified lakes collected prior to and during the existence of the lakes;
3. Engineering maps or other data showing lake dimensions and characteristics at discrete times during the lake's existence, if available;
4. All available ecological, water quality, or hydrological data concerning the lakes;
5. Identification of reclamation procedures used to create the lake system;
6. Historical data on attempted fish stocking or lake management; and
7. Permission from property owners to conduct a one-year study program.

Given that the lake selection process would be qualitative, it was mutually agreed by ESE and FIPR that the descriptors for each lake would be generic. Final lake selection would only approximate this set of criteria.

The search for suitable study lakes began in July 1981. Candidate lakes were to include flow-through as well as isolated systems. After inquiries about the availability of reclaimed lakes for inclusion in the study were made, three phosphate mining companies [Agrico Mining Company (AGRICO), International Minerals and Chemical Corporation (IMC), and W.R. Grace, Incorporated (WRG)] offered access to their lakes for evaluation.

Preliminary site visits to areas within Polk, Hillsborough and Manatee counties resulted in a list of 39 candidate reclaimed and natural lakes. The lakes proposed for final selection were required to have the following general characteristics:

1. Reclamation should have been completed at least 2 years prior to this study;

2. Deep lakes should have depths greater than 2 meters;
3. Deep lakes should exhibit the potential for stratification during part of the year;
4. Deep lakes should have a shallow zone (nearness to outflow areas not a criterion);
5. Shallow lakes should be near the same age as deep lakes;
6. Shallow lakes should be less than 2 meters in depth;
7. Representative natural lakes should exhibit hydrological and physiochemical characteristics similar to the reclaimed water bodies; and
8. None of the reclaimed lakes should be associated. with any on-going mining processes.

Using the available information, 16 lakes were ultimately selected for inclusion in the study (Figure 1-2.1). Of these, 12 were reclaimed phosphate lakes and 4 were natural or unmined reference lakes. An equal proportion of shallow and deep lakes was represented in each group. In the context of this program, the terms "deep" and "shallow" are relative terms applicable to Florida lakes only.

The majority of the study lakes are located in the Polk Upland physiographic region. Only two lakes (Arietta and Manatee) are outside of this region and lie in the Winter Haven Ridge and Gulf Coastal Lowlands, respectively. All lakes selected for the program have an underlying deposit of either Hawthorn or Bone Valley Formation (see references in Canfield, 1981). Table 1.2-1 provides descriptive information concerning each lake. Additional detailed information for each lake is included in Section 5.2.

1.4 PROGRAM DESCRIPTION

To provide baseline input into the development of a lake management matrix, four specific interest areas were identified in the project plan:

1. Lake Morphology;
2. Water Quality;

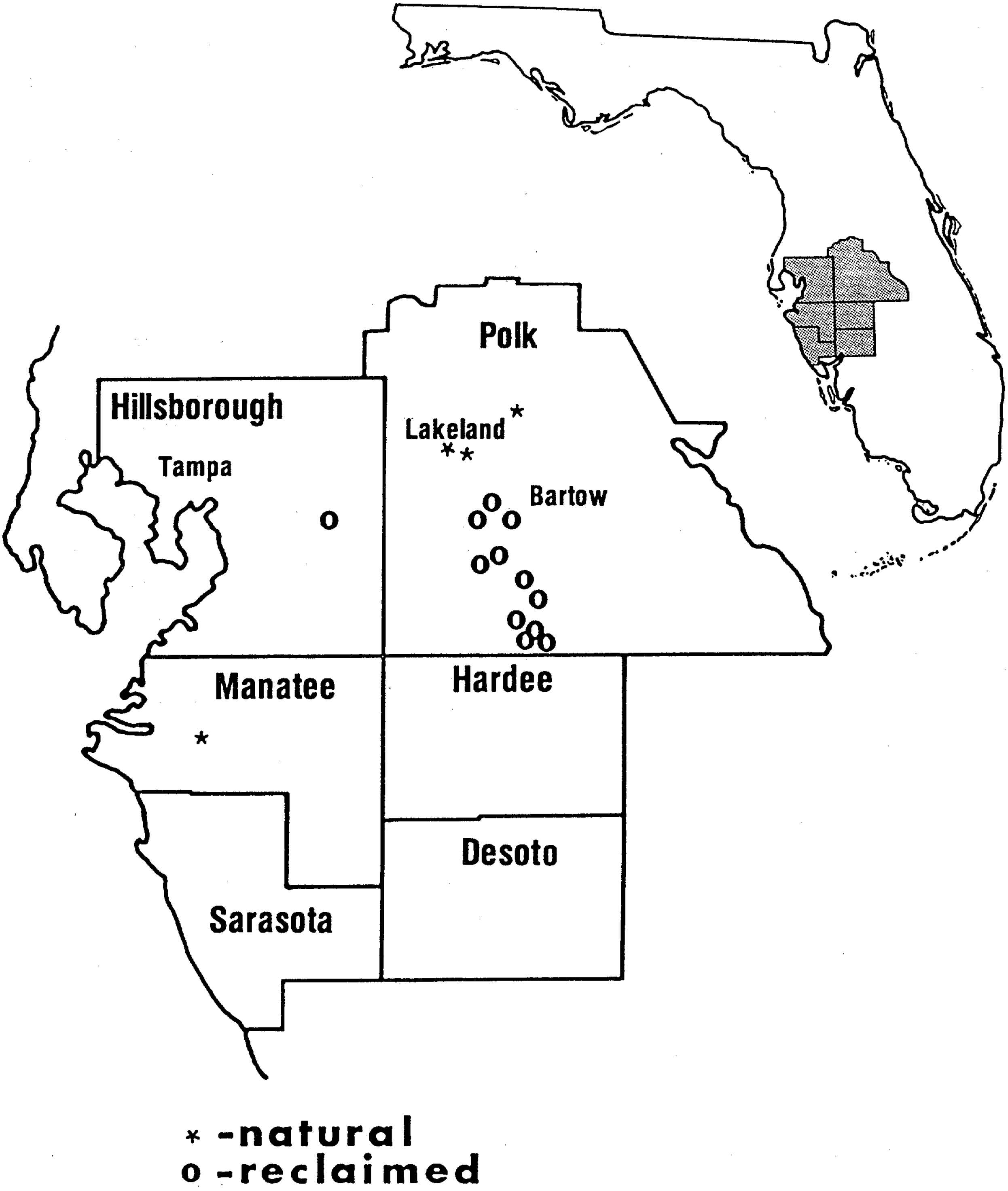

FIGURE 1.2-1
LOCATION OF RECLAIMED AND NATURAL LAKES SELECTED FOR CHEMICAL, PHYSICAL AND BIOLOGICAL EVALUATION

Source: ESE, 1983.

Table 1.2-1. Location and Description of Reclaimed and Natural Lakes Selected for the FIPR Lakes Program

Lake	Ownership	Type	County	Age**	Location
Bradley	W.R. Grace	Flow-through, Reclaimed	Polk	4	T29S R24E S19,30
McLaughlin	W.R. Grace	Flow-through, Reclaimed	Polk	4	T29S R24E S30
Brown	W.R. Grace	Flow-through, Reclaimed	Polk	9	T30S R24E S16
Law	W.R. Grace	Flow-through, Reclaimed	Polk	9	T30S R24E S9,16
1215	W.R. Grace	Isolated, Reclaimed	Polk	3	T29S R24E S35
Clark James	IMC*	Isolated, Reclaimed	Polk	25	T30S R24E S23
North Triangle	IMC	Isolated, Reclaimed	Polk	3	T30S R24E S35
AG-1	AGRICO	Flow-through, Reclaimed	Polk	11	T32S R24E S3,4,9,10
AG-2	AGRICO	Isolated, Reclaimed	Polk	6	T32S R24E S10
AG-4	AGRICO	Isolated, Reclaimed	Polk	6	T32S R24E S15
AG-6	AGRICO	Isolated, Reclaimed	Polk	6	T32S R24E S15
Medard Reservoir	SWFWMD†	Flow-through, Reclaimed	Hillsborough	12	T29S R21,22E, S25,30,31,32,36
Manatee	Manatee County	Flow-through, Impoundment	Manatee	15	T34S R20E, S1-3,19,25,28-34
Arietta	Polk County	Isolated, Natural	Polk		T27S R25E, S27,28,33,34
Hollingsworth	City of Lakeland	Isolated, Natural	Polk		T28S R23E, S19,20,30
Hunter	City of Lakeland	Flow-through, Natural	Polk		T28S R23E, S23

* International Minerals and Chemical Company.

† Southwest Florida Water Management District-Operated as county park by Hillsborough County Parks and Recreation Department, originally mined and reclaimed by American Cyanimid, Inc.

** Age at time of lake section in 1981.

Source: ESE, 1983.

3. Aquatic Ecology; and
4. Radiation.

After the final list of 16 reclaimed and unmined, natural reference lakes was completed, water level recording equipment was installed (Section 5.1) and monitored on a monthly basis. Bathymetric surveys of each lake were completed prior to the selection of lake sampling stations (Section 5.2).

All 16 lakes had representative deep (greater than 2 m) and shallow (less than 2 m) stations. Seven lakes, designated as flow-through systems, had additional sampling stations located at inflow and outflow areas.

Four seasonal sampling trips were scheduled to correspond with: (1) cold, dry season (January-February); (2) warm, dry season (April); (3) hot, wet season (July); and (4) cold; wet season (October- November). Each field sampling effort required approximately three weeks, making it impossible to sample each lake under exactly the same climatic conditions.

Twenty-three water quality parameters, including seven trace elements, were measured in each lake during at least one of the four sampling events (see Section 6.0). An ecological survey (Section 7.0) included examination of the composition and structure of phytoplankton, zooplankton, macroinvertebrate and fish communities within each lake. Littoral zone and near-shore transitional zone vegetation was described and mapped for each lake system.

To achieve the project objective of providing a management matrix based on interactions between these data, statistical and multivariate analyses were accomplished. Section 3.0 discusses the interrelationships between abiotic (physical, chemical) and biotic (aquatic communities) conditions in reclaimed phosphate pit lakes. Results of these multivariate analyses were used to formulate the spectrum of lake design criteria found in Section 4.0.

This report is composed of four volumes. Volume I contains an overview of reclaimed and natural lakes, results of the statistical analyses and the lake design matrix. Volume II presents the physical, chemical and biological characteristics of the study lakes. Volumes III and IV are appendices which contain a compilation of data tables.

2.0 RECLAIMED VERSUS NATURAL LAKES--AN OVERVIEW

Florida has an extensive marine environment, yet approximately 8 percent (1.2 million ha) of its total surface area is occupied by freshwater (Reddy et al. 1983). In the past, marine investigations have been predominant in the scientific literature. Only recently (coincident with the enhanced environmental awareness of the early 1970's) has there been an emphasis placed on the quantity and quality of Florida's freshwater resources. As the population of Florida continues to grow, the demand for freshwater also increases. The integrity of Florida's surface water supply is important to its existing and future populations. Natural and reclaimed lake systems examined during this investigation will be compared to general trends for lake condition and lake trophic status in other Florida lakes. In addition, the following discussion will outline key components for consideration of surface water quality.

Lake trophic status provides a description of the relative degree of productivity found within a system. Oligotrophy generally describes a system that has low productivity, and the majority of the nutrients within the system are regenerated. Very little organic deposition occurs in an oligotrophic lake. At the opposite end of the scale, eutrophic lakes are highly productive. Nutrient regeneration is still an important system function; however, eutrophic lakes create more organic material than the system can effectively degrade. Rates of organic matter deposition and accumulation are higher in eutrophic lakes.

In much the same fashion that humans are the product of their genetic makeup, lakes are the product of their physical and chemical environment. Geochemical inputs to lake basins, coupled with morphometric characteristics and changes in both the morphology and drainage patterns influence lake productivity (Wetzel, 1975). From the viewpoint of lake ontogeny, all freshwater aquatic systems are in a transition state, moving towards becoming terrestrial systems. Based on paleolimnological records for numerous lake systems it appears that if a lake remains undisturbed it will remain in a steady-state condition for a very long time. Alterations in drainage basin constituents by either natural or anthropogenic events can accelerate lake transition states. Hutchinson (1973) concluded that the kind of eutrophication which seems most natural is the increase in organic production up to a steady state that may persist for a very long time. Accumulation of organic matter in excess of production is fundamental to the terminal stages of the biotic transition from lake systems to a terrestrial landscape (Wetzel, 1975). Transition from a lake system to wetlands is relatively slow when primary production is based on planktonic algae. Organic sedimentation in these systems is balanced more closely by degradation. Lakes with sufficiently shallow depths which are found in a tolerable humid climate develop into systems in which primary production is dominated by littoral vegetation. These higher plants produce more biomass or organic matter than planktonic based systems, exceeding the decompositional capacity for oxidation and/or removal, which leads to greater organic matter accumulation (Wetzel, 1975).

Early investigations of Florida lake systems were primarily academic in origin (see Robertson and Boody, 1982). More recent investigations (Huber et al. 1982; Baker et al. 1981; Canfield 1981) have attempted to characterize not only lake types but also lake water quality or trophic status. A review of the above studies, as well as Dye et al. (1980), Fontaine and Ewel (1981), McDiffett (1980), Putnam et al. (1972), Ford (1978) and others, results in the following Florida lake profile:

- Florida lakes are generally shallow, subject to wind induced mixing.
- Few Florida lakes exhibit stable seasonal thermal stratification or have anoxic hypolimnia. Lakes may exhibit short-term stratification periods.
- Seasonal variation in chlorophyll a, algal standing crops, or nutrient concentrations are minimal. Values of ecosystem production are roughly similar throughout the year.

- Lakes in the central physiographic region exhibit the greatest variability in water quality. However, the majority of lakes in Florida are mesotrophic to eutrophic.
- Unlike northern temperate zone lakes, many Florida lakes are nitrogen limited, indicating sufficient phosphorus resources.
- For a given concentration of phosphorus, Florida lakes have less chlorophyll a than do temperate lakes because of nitrogen limitation. Where nitrogen is not limiting, chlorophyll levels are similar.

The fact that many natural Florida lakes are eutrophic conforms with the basic limnological trends. The concept that "shallow lakes are more productive than deep ones" is one of the oldest biological laws, dating back to 1898 (Fee, 1979). On a global scale, all Florida lakes are considered shallow. Uhlmann (1982) states that "not only is primary production inversely proportional to the mean depth, but likewise the occurrence of eutrophication." The topography of Florida's landscape offers little obstruction to wind. Resuspension of sediment in shallow systems by wind action not only increases the mobilization of phosphorus but may also decrease the nitrogen/phosphorus (N/P) ratio by denitrification (Uhlmann, 1982).

Natural lakes in Florida may be the same geological age as many northern temperate lakes, but the favorable climate, their shallow nature and background nutrient levels combine to create lakes that may be higher on the trophic scale than their northern counterparts. Add to these conditions the impacts-due to man, and it is easy to explain existing conditions in Florida's natural lakes.

Lake restoration, and the methodology used in an attempt to reverse eutrophic conditions, can provide insight for problems and solutions associated with shallow lakes. Many cities and counties realize that lakes within their jurisdiction are eutrophic. The citizenry complains about odors, overabundant aquatic plant growth, or fish kills. In response, the city/county initiates a lake restoration program which is an effort to reverse the eutrophication process. Restoring damaged lakes through lake restoration programs is an attempt to undo harmful perturbations that have either natural or anthropogenic sources (Maugh, 1979). Mechanisms for lake restoration include physical methods (dredging, biomanipulation, aeration/mixing) as well as pollution control measures (diversion of effluents, non-point source control). It has been found that in very shallow, eutrophic lakes much of the phosphorus necessary for the growth of phytoplankton, including nuisance blooms of bluegreen algae in the summer, can be recycled from the bottom sediment (Stefan and Hanson, 1981). Peterson (1982) states that sediment removal via dredging usually includes one or more of four basic objectives:

1. To design a lake for improved recreational use,
2. To remove toxic sediment,
3. To reduce nuisance aquatic macrophyte growth, and
4. To prevent or reduce the internal cycling which may represent a significant fraction of the total nutrient loading.

Greater lake depth provides a larger volume of hypolimnetic water which in turn contains a larger quantity of oxygen. The hypolimnion of a deeper lake would take longer to become anaerobic than the hypolimnion of a shallower lake (Wetzel, 1975; Stefan and Hanson, 1981).

Lake restoration is a problem of national and international magnitude (USEPA, 1981a). However, Florida lakes, being predominantly shallow, are particularly subject to restoration programs as well as pollution abatement. Lake Hunter, one of the urban natural lakes included in this investigation, is the target of an ongoing sediment removal lake restoration program sponsored by the City of Lakeland, Polk County, Florida. Both lake drawdown and dredging were being employed to address items 1, 3, and 4, from above.

Where then do reclaimed phosphate pit lakes fit into the realm of "natural" Florida lakes? Based on appearance, these lakes are generally smaller than natural lakes, and their shoreline is usually more irregular than natural lakes. Reclaimed lakes examined in this program had a slightly greater mean depth than natural lakes (3.28m versus 3.07m) and are also basically shallow systems. One morphometric characteristic that separates reclaimed from natural lakes is the highly irregular lake bottom, a relict feature of their origin as strip mines. Smooth bottoms in shallow lakes reduce the potential for stable thermal stratification in natural lakes. Based on all other similarities between these systems, it is hypothesized that deep holes interspersed within reclaimed lakes prevent complete water column mixing, allowing stable thermal stratification. By reducing the amount of water column available for wind-induced mixing, these lakes may provide a natural mechanism (i.e., sedimentation, adhesion, etc.) for removal of excess nutrients. With this lake design there is also the potential for anoxia in bottom waters, at least in the deepest areas. Data from this investigation did not provide evidence of harmful effects due to anoxic deep waters. Circumstances of surface to bottom anoxia or fish kills due to oxygen stress were not observed in any lake during this investigation.

There are differences between phosphate pit lakes and natural lake systems which relate to the origin of the reclaimed systems. Several factors, beyond those exerted equally on natural lakes in the central Florida region, are responsible for their productive capacity. Phosphate pit lakes are by-products of surface strip mining reclamation. Unlike other surface mining operations (e.g., coal, metals), reclamation of phosphate-mined lands is a relatively minor problem from, either a technical or mechanical or environmental hazard viewpoint (Farmer and Blue, 1978). Mining activities generally result in one or more of the following categories of impacts that can damage biota:

- Excessively acid or alkaline waters;
- Silted streambeds, ponds, lakes, and reservoirs;
- Turbid, unproductive waters;
- Heavy metals contamination of waters and sediment;
- Secondary impacts; and
- Synergistic effects of mining wastes acting in combination with all other types of pollutants (from Mason, 1978).

Very few of these issues impact the aquatic communities of reclaimed phosphate pit lakes (Boyd and Davies, 1982). Data from this investigation also provided no indication of the above adverse effects on aquatic biota. Irregular contours and a diversity of lake sizes and shapes provided a net-positive impact from phosphate mined land and its restoration/reclamation for fish and wildlife habitat. Numerous reports of fishing potential in reclaimed lakes can be found in national sports magazines and also in internal reports produced by Florida's Game and Freshwater Fish Commission.

Radiation exposure for fish, wildlife, and humans as a result of disruption of the phosphate-bearing matrix is one post-mining concern (Starnes, 1983). Results from this investigation, however, indicate that mean Ra-226 activity in the water column of reclaimed lakes was not statistically different from Ra-226 activity in the water column of natural lakes indicating the importance of natural chemical mechanisms in reducing aqueous Ra-226 activity. There is some evidence that the dynamics of barite ($BaSO_4$) dissolution and precipitation control the activity of radium in reclaimed lakes. Sulfate levels on the average are significantly higher in reclaimed lakes (presumably because of FeS_2 oxidation) while Ba levels in turn are significantly lower. The net result is nearly identical ion activity products (IAPs) in both classes of lakes; comparison of IAPs with the solubility product of barite indicates slight supersaturation in the water column and suggests that the mineral phase controls the distribution of Ba in the water column. Ra is scavenged or removed from the water column by precipitating $BaSO_4$. An alternative mechanism considers adsorption of Ba and Ra on the surface of hydroxyapatite granules; for example, Murray et al. (1983) demonstrated efficient Ra removal from uranium mine effluent solutions containing 0.01 to 1 molar calcite and potassium phosphate. Both mechanisms are supported by considerably higher Ra-226 activities in the sediments relative to the overlying waters. In addition, fish from reclaimed lakes did not show trends that they were more likely to incorporate Ra-226 at levels higher than fish found in unmined systems. As a result of over 1,400 analyses of fish bone, flesh, and whole fish, the data indicate, that for species collected and analyzed from both mined and unmined systems, there is as much variability for Ra-226 activity in fish tissue within a lake as there is between lake types.

In much the same fashion that phosphate fertilizer is created for use on America's croplands, a natural chemical reaction occurs in the mined lands which releases phosphate, thereby fertilizing the lakes. Recent evidence has determined that pyrite, common within the phosphatic ore-body, is oxidized to produce sulfuric acid. This sulfuric acid reacts with calcium fluorapitite forming gypsum ($CaSO_4$) and reactive phosphate (H. Barwood, FIPR, pers. comm., 1984). Material eroded or generated in a lake's basin and washed into the lake produces a fairly constant nutrient supply (Hutchinson, 1973). In the case of phosphate pit lakes, there is more phosphate (P) available than the biota can utilize. In this sense, phosphate pit lakes are similar to many other natural lakes in Florida, appearing to be at least nitrogen (N) limited. Unlike temperate lakes where P-control is the key to controlling eutrophication (Fee, 1979; Schindler, 1978; Vollenweider, 1968, 1975; Vollenweider et_al. 1974; and others), P does not control growth in reclaimed lakes, it only supports it. However, N may not be the only limiting nutrient for aquatic productivity in reclaimed lakes. Although limiting-nutrient analyses were not included in this program, there appeared to have been sufficient N and P to fuel even greater primary productivity, indicating other element(s) may have been limiting factors.

Reclaimed lake productivity may also be related to the concept of trophic upsurge/trophic depression. All man-made impoundments, whether they are fish ponds, reservoirs or borrow pies, regardless of size, undergo a degree of nutrient enrichment when inundation first occurs. The cycle begins with direct leaching of minerals (particularly P) from previously upland soils, combined with decomposition of terrestrial vegetation, providing both N and P to the system (Ackermann et_al. 1973; Grimard and Jones 1982; Boyd 1971b; Bayne et_al. 1983; and others). This trophic upsurge phase also has as a net result an expanding fish community as the surface area available for foraging and reproduction expands. Fish populations grow rapidly since there is an abundance of food resources in response to the short plankton-to-fish food chain (Bayne et_al. 1983). Algal communities may be more productive under conditions of high flushing rates in impoundments. Flushing rates affect nutrient retention and nutrient transformation rates (Turner et al., 1983). The degree of biotic response to recent impoundment is proportional to the availability of nutrients.

The trophic depression aspect of this concept is the result of exhaustion of available. nutrients from the flooded land and the gradual flushing of the impoundment towards a steady-state lake system. Declining fish populations are one obvious sign that trophic depression has already begun. During the past few years, researchers have tried to estimate the time frame between lake inundation and trophic depression (Ostrofsky, 1978; Grimard and Jones, 1982), with time frames between 8 and 20 years indicated. Long-term, continuous monitoring programs have been suggested as being a necessity in determining, from a position of nutrient enrichment, when a man-made system reaches a state of stability. In the case of reclaimed phosphate pit lakes, the nutrient cycle is well established; P is available from the soils, and N is regenerated through decomposition of organic-N (available from plants, animals and excretory products) and/or accumulated through direct rainfall. As stated previously, other elements may be the key to limited production in reclaimed lakes and also may be responsible for extending the time between trophic upsurge and trophic depression. Further research in this area would be invaluable in structuring viable long-term lake systems.

Fish community composition can also change after the initial upsurge phase and during the trophic depression phase (Ackermann et_al. 1973). Both gizzard and threadfin shad are members of the fish community in eutrophic Florida lakes. Their populations in both reclaimed and natural lakes from this investigation (with the exception of Lake Arietta) are generally very large, dominating the open water areas of each lake. Crisman and Kennedy (1982) suggested that gizzard shad promote lake eutrophication both through elevation of orthophosphate concentrations and differential digestion of diatoms and green algae thus increasing the competitive advantage of blue-green or nuisance algae. The results of this investigation suggest that both gizzard and threadfin shad are a critical link in the nitrogen cycle. Regeneration of fish fecal pellets by bacteria could supply sufficient N to maintain algal populations. This aspect of reclaimed lake ecology also warrants further investigation.

The question then may be raised whether or not reclaimed phosphate pits are abnormal. From a trophic status viewpoint, reclaimed lakes in this investigation were generally eutrophic, although closer to mesotrophic than hypereutrophic. Once created, reclaimed lakes fit the mold of the majority of "natural" lakes in Florida. However, the critical component of reclaimed lakes is whether or not their current design or future designs (as per Chapter 16c-16 F.A.C.) will provide for systems that will be viable and productive for both short and long-term considerations. Chapters 3 and 4 will address lake design more thoroughly. However, the basic concepts of limnology (e.g., shallow lakes are more biologically productive) were supported by this investigation. In the sense of lake design, more productivity does not necessarily equate to beneficial results.

3.0 STATISTICAL ANALYSIS OF PHYSICAL, CHEMICAL AND BIOLOGICAL CHARACTERISTICS OF RECLAIMED LAKES

The primary objective of this phase of data analysis was to determine which controllable lake features affect water quality. This necessitated analyses of a substantial quantity of information collected during the project, and determination of the relationships between water quality parameters and physical characteristics of reclaimed lakes.

A data base was constructed using biological, chemical (water and sediment), and physical input data. The experimental unit of analysis is a lake/sampling-trip/sampling station combination. Of course, physical characteristics (e.g., lake area) are constant over all sampling trip/sampling station combinations for each lake.

The following subsections detail various aspects of the statistical analysis and outline reasons for selecting methodologies employed in the analysis.

3.1 RECLAIMED VERSUS NATURAL LAKES

The primary objective within this research program was to characterize reclaimed lakes through the potential mechanisms which control chemical and/or biological conditions. A secondary project component was an evaluation of differences between reclaimed and natural lakes. The first part of the statistical analysis was designed to determine whether statistically significant differences exist between reclaimed and natural lakes with respect to key water quality parameters. Parameters compared included dissolved oxygen, ammonia, nitrate, ortho-phosphate, chlorophyll, radium-226 and mercury. Statistically significant differences ($P<0.05$) were found on four parameters, with dissolved oxygen and mercury concentrations significantly lower and ammonia and ortho-phosphate significantly higher in reclaimed lakes. In addition, morphometric differences between the two lake types were also apparent. For example, the natural lakes generally comprised substantially greater surface areas than the reclaimed lakes. Three of the four natural lakes were among the four largest of the 16 lakes in the survey.

Subsequent analyses were designed to determine the relationships between water quality and lake design features. Because significant differences were found between natural and reclaimed lakes, the analyses presented here were confined to those lakes whose design could be controlled, i.e., reclaimed lakes.

3.2 PRINCIPAL COMPONENTS ANALYSIS

Perhaps the major problem in the analysis of these data was one of dimensionality. Up to 80 water quality parameters were measured, so that the task of determining how lake characteristics affect water quality was extremely tedious. However, many of the parameters measure similar aspects of water quality. A principal components analysis (PCA) enables one to combine many parameters into a few important "factors" or "components" by taking advantage of the intra-correlations of the parameters to construct the factors.

In other words, each factor is a vector or linear combination of all the various water quality parameters. The character of the factor is determined primarily by the parameters which correlate most highly with it; thus, the factors tend to be dominated by variables which are correlated with one another (i.e., intra-correlated). The factors or components are uncorrelated with one another, and a few components often account for most of the variation of the entire set of parameters. The net result is that water quality can be represented by fewer parameters, making the analyses more manageable.

Loadings of parameters on a particular factor may be interpreted in a similar fashion as correlation coefficients. They range from -1 to 1, with -1 indicating perfect negative correlation, 1 a perfect positive correlation, and 0 no correlation. The loadings are correlations between each variable and the corresponding factor, so that a high correlation indicates that the variable is an important contributor to that factor.

Principal components analysis was conducted on the water quality data (from reclaimed phosphate pit lakes only) both before and after seasonal and spatial variability was removed. (See Section 3.3 for a discussion of removing seasonal-spatial variation.) Results were very resistant to changes in the parameters and the removal of extraneous variability. The principal components shown as row variables in Table 3.2-1 correspond to those obtained by removing seasonal and spatial variability, while those shown as column variables correspond to principal components without the variability removed. The coefficients shown in the table indicate that the first six factors are very similar, with coefficients ranging from 0.93, to 0.98. The last four factors have little correspondence, with coefficients ranging from -0.32 to 0.007. Inspection reveals that these are season-station groupings, containing variables like temperature and dissolved oxygen. Thus, the factors that were used in the analyses have seasonal and spatial variability removed, so that the contribution of the design features of the reclaimed lakes can be the focus.

3.3 MODEL CONSTRUCTION

In order to determine how water quality parameters and lake design features were related, both seasonal (trip) and spatial (station) variability must be controlled. Therefore, each of the water quality parameters was modeled as a function of season and station, and the least squares residuals were calculated. Least squares residuals are the differences between each actual observation and the mean for the corresponding trip-station combination.

Figure 3.3-1 illustrates sequentially the process that was initially used toward model development and construction. Biological and chemical data were first merged to form a unified data set. At this point, the natural lake set was deleted from the analysis because of the inherent differences between the two types of lakes. After inspection, the reduced data set indicated that the distribution was highly skewed, therefore all data were transformed logarithmically to achieve a normal distribution. PCA was then performed by two iterative processes conducted in parallel, In the first procedure (left side of Figure 3.3-1), station/season variability was removed before performing the PCA. The extracted principal components were then evaluated and all variables which did not contribute strongly to a particular factor were

Table 3.2-1. Correlation coefficients of residual factors with station-season variability removed (RF1, RF2, ...) versus intact (no variability removed) factors (F1, F2, ...).

	RF1	RF2	RF3	RF4	RF5	RF6	RF7	RF8	RF9	RF10
F1	0.96576 0.0001 168	0.01261 0.8712 168	0.09281 0.2315 168	-0.04403 0.5709 168	0.07843 0.3122 168	-0.05853 0.4511 168	-0.42444 0.0001 168	-0.09689 0.2115 168	0.14448 0.0617 168	0.15465 0.0453 268
F2	0.05899 0.4475 168	0.98040 0.0001 168	-0.08512 0.2726 168	-0.00985 0.8992 168	0.08929 0.2498 168	0.07658 0.3238 168	0.00839 0.9140 168	0.02073 0.7897 168	0.33775 0.0001 168	-0.07198 0.3538 168
F3	0.05204 0.5029 168	-0.01305 0.8666 168	0.95001 0.0001 168	-0.01180 0.8793 168	0.02622 0.7359 168	0.02536 0.7442 168	-0.03184 0.6821 168	0.04601 0.5537 168	-0.04629 0.5513 168	0.03321 0.6691 168
F4	-0.01798 0.8170 168	0.00081 0.9917 168	0.07495 0.3342 168	0.93445 0.0001 168	-0.07866 0.3108 168	-0.01636 0.8333 168	-0.39127 0.0001 168	-0.14897 0.0540 168	-0.32983 0.0001 168	0.07427 0.3387 168
F5	0.08697 0.2623 168	0.05380 0.4885 168	-0.00359 0.9632 168	-0.08159 0.2931 168	0.94308 0.0001 168	-0.16249 0.0353 168	-0.07082 0.3617 168	-0.04319 0.5783 168	0.08559 0.2700 168	-0.05044 0.5161 168
F6	0.02722 0.7262 168	0.02727 0.7256 168	-0.00082 0.9915 168	0.03301 0.6710 168	-0.01142 0.8832 168	0.93446 0.0001 168	0.00262 0.9731 168	0.02855 0.7134 168	0.00399 0.9591 168	-0.00249 0.9744 168
F7	-0.03414 0.6604 168	0.02451 0.7525 168	0.09070 0.2423 168	-0.10025 0.1960 168	-0.02039 0.7930 168	-0.02875 0.7115 168	-0.32135 0.0001 168	0.91333 0.0001 168	-0.23962 0.0018 168	0.09503 0.2205 168
F8	0.00683 0.9300 168	0.05696 0.4633 168	0.12623 0.1030 168	-0.18763 0.0149 168	-0.06088 0.4331 168	-0.07433 0.3383 168	0.37329 0.0001 168	-0.14393 0.0627 168	-0.28378 0.0002 168	0.05513 0.4778 168
F9	0.00140 0.9856 168	0.00224 0.9770 168	-0.03284 0.6726 168	-0.06928 0.3722 168	0.07586 0.3284 168	-0.06981 0.3685 168	0.17671 0.0219 168	-0.03508 0.6516 168	0.00667 0.9316 168	0.86581 0.0001 168
F10	-0.00608 0.9377 168	0.02288 0.7684 168	-0.05772 0.4574 168	-0.06304 0.4169 168	0.04314 0.5787 168	0.16045 0.0377 168	0.27079 0.0004 168	0.03102 0.6898 168	-0.06050 0.4359 168	-0.00772 0.9209 168

Where: values equal - correlation coefficients (r)
probability > |R | under H0:RHO = 0
number of observations

Note: All data were initially transformed logarithmically.

Source: ESE, 1983.

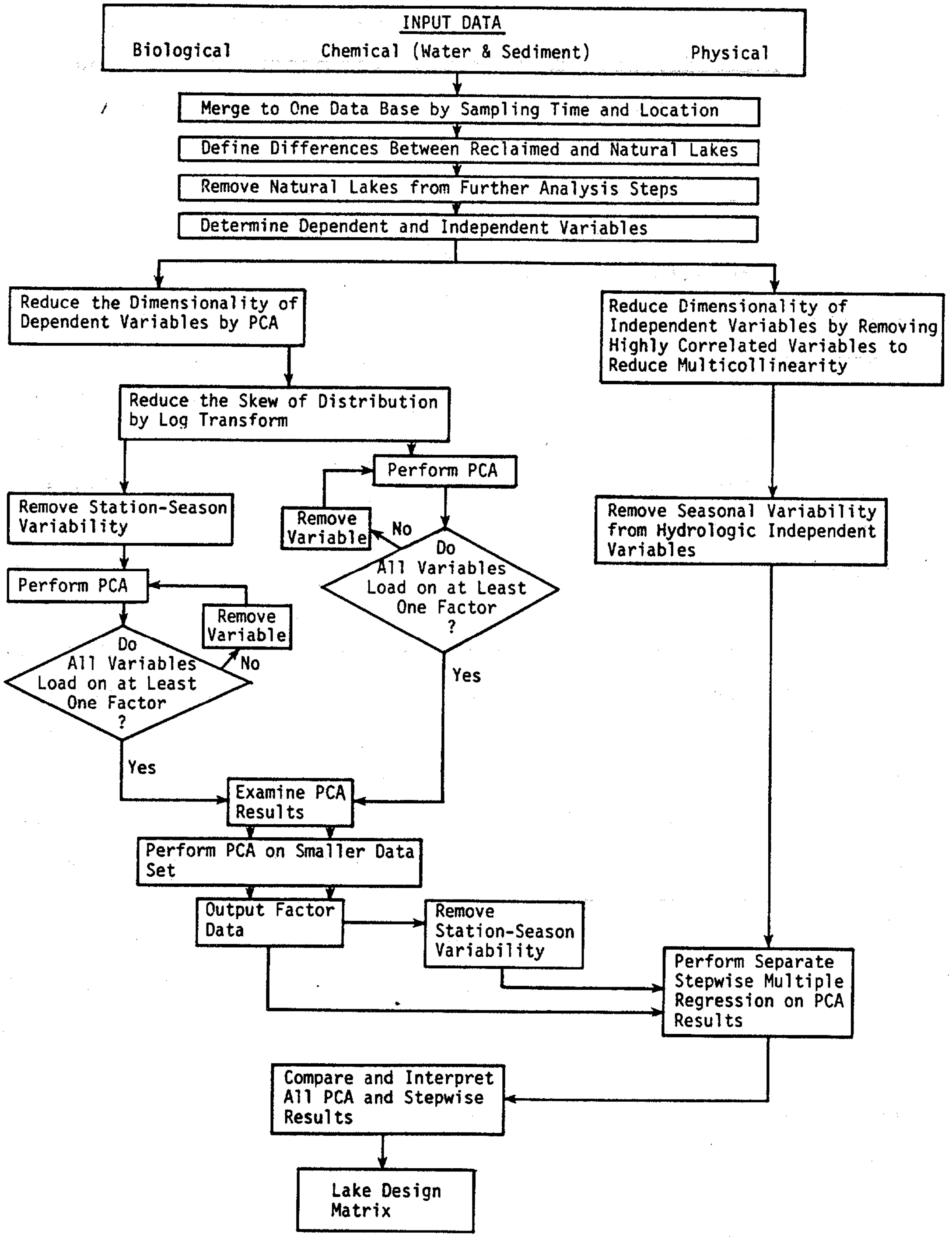

Figure 3.3-1

SCHEMATIC FOR DATA EVALUATION PROCEDURES FOLLOWED FOR INTERPRETATION OF PHOSPHATE PIT LAKE DATA

assumed to be a relatively minor components of water quality and removed from further iterations. This process was continued until only contributory variables were retained.

The second or parallel method of PCA was virtually identical with one important difference: station-season variability was removed after PCA. Although the two different approaches yielded relatively comparable results in terms of factor composition, the initial approach (i.e., removing station-season variability and then performing PCA) was selected for further analysis because the framework was theoretically more sound. Both methods generated factors composed of residuals; however, the second method altered or transformed the factors after extraction and introduced an element of uncertainty into the interpretation of the results.

Factors from the PCA were subsequently subjected to stepwise multiple linear regression with a set of morphometric/hydrologic parameters. This approach was used as a model building process to determine which combinations of independent variables were highly correlated with water quality factors. The procedure used each of the water quality factors (determined by PCA) as a dependent variable and then added independent variables to the model in their order of importance as explanatory variables. Variables were added as long as their contribution to the model was statistically significant at the alpha = 0.15 level. The stepwise model building procedure acts as a type of filter that screens the most important independent variables. It is not intended to provide a predictive model, but instead to indicate those associations that are strongest.

In the final analysis, a reduced set of controllable morphometric variables was used to facilitate interpretation of the regression results. The selected parameters were features that can be reasonably controlled during the course of reclamation design and encompassed all aspects of lake morphometry and hydrology. The parameter list consisted of:

- AREA = total lake surface area (ha)
- FLTOT = hydraulic loading rate (m/yr)
- TIME = hydraulic residence time (yr)
- SDI = shoreline development index
- VDI = volume development index
- VOL = total lake volume (m^3)
- WSIA = annual wind stress index (orientation parameter)
- Z = mean lake depth (m)
- ZMAX = maximum lake depth (m)

A more complete description of these parameters is presented in Section 5.

After performing stepwise regression on the PCA factors, it became apparent that the relationships developed by including biological and chemical attributes in the same analysis were very complex. In order to eliminate ambiguity and simplify the factors, the final analysis entailed separating the chemical or abiotic variables from the biological variables. Principal components were then developed for both data types (abiotic and biotic) and stepwise regression models developed. The results of this analysis are discussed in the following subsections.

3.4 CHEMICAL CHARACTERISTICS

3.4.1 Development of Abiotic Factors

Principal components analysis (PCA) was performed on the reclaimed lake data base after segregating the data into two groups: (1) abiotic or lake chemistry parameters, and (2) biotic variables, including chlorophyll *a*. This section discusses results of PCA of the abiotic parameters and the influence of lake design features (i.e., morphometric variables), on the different chemical factors derived from PCA.

The results of PCA on total analytical concentrations of the various chemical parameters are presented in Table 3.4-1, which is restricted to those loadings exceeding or equal to 0.50. Individual eigenvalues and the percent of the total variance explained by each factor are also included in the table. Over 50 percent of the total variance in the data set was explained by the first four factors, with Factors 1 and 2 accounting for 33.3 percent. Factor 1 is related primarily to the inorganic constituency of sediments in the reclaimed lakes with sediment-associated chromium (Cr) and total phosphorus (TP) loading most highly on the factor (r = 0.93 and 0.87). Sediment moisture content, which is indicative of the energy state or depositional environment prevailing at the sediment-water interface (see Hakanson, 1982a and b; Pollman, 1983), also loaded relatively highly on Factor 1, although the correlation was weaker (r = 0.56).

The second factor reflects primarily major dissolved components in the water column. Total dissolved solids (TDS) and conductivity are indicative of the ionic strength of the water column and are strongly correlated with Factor 2 (r = 0.88 and 0.74, respectively). Calcium and magnesium dominate the factor with alkalinity (i.e., bicarbonate) and to a lesser extent fluoride associated with Factor 2 as the counter ions. Sulfate, which is the predominant anion on an average basis for the 12 reclaimed lakes, loaded rather weakly on Factor 2 despite its close correlation with Ca (r = 0.54).

The third factor extracted from the principal component analysis is indicative of trophic state and is similar to trophic state factors derived by Shannon (1970) and Preston (1983) for other Florida lakes. The nutrient forms, total nitrogen and total phosphorus, as well as parameters indicative of light transparency (i.e., turbidity and secchi disk transparency) are associated with this factor. The significance of this factor is further verified by earlier analyses which included biotic components in the PCA. Under these conditions, the extracted

Table 3.4-1. Eigenvalues, Percent Variance Explained, and Loadings for PCA for Reclaimed Lake Chemistry Parameter

	Factors									
Variable	1	2	3	4	5	6	7	8	9	10
Moisture	0.59			0.56						
SCa	0.61									
SMg	0.56									
SK	0.82									
SBa	0.84									
STP	0.87									
SCr	0.93									
SPb	0.82									
SCd	0.77									
SeRa226	0.82									
SSr90	0.75									
pH		0.59								
Conductivity		0.74								
TDS		0.88								
Ca		0.94								
Mg		0.97								
Alkalinity		0.76								
F		0.64								
TOC		0.58								
Turbidity			0.67							
Secchi			-0.84							
Total P			0.65							
Total N			0.61							
SO$_4$			-0.63							
STOC				0.86						
STOTN Total N				0.77						
SNH$_3$				0.57						
SCl				0.62						
Cd					0.78					
SHg					-0.73					
SOP					0.78					
K						0.68				
Ra 226						-0.71				-0.54
SSO$_4$						0.76				
SNO$_x$						0.69				
SAs							0.88			
SPb							0.76			
NH$_3$								0.72		
NO$_x$								0.85		
SSe									0.88	
DO$_2$										0.76
Eigen-value	7.44	6.55	4.19	3.50	3.24	2.88	2.50	1.82	1.50	1.33
Percent Variance	17.7	15.6	10.0	8.3	7.7	6.9	6.0	4.3	3.6	3.2
Cumulative Variance	17.7	33.3	43.3	51.6	59.3	66.2	72.1	76.5	80.0	83.2

Note: Variables preceded by a S are for sediment data (i.e., SCa = sediment calcium).

Source: ESE, 1983.

factor included chlorophyll *a* as an important component along with other estimators of standing crop.

The strongest loading on Factor 3 is Secchi disk transparency, which loads negatively on the factor and implies reduced light transparencies in enriched or eutrophied reclaimed lakes. More difficult to explain is the association of sulfate with this factor. *A priori* considerations suggest that variability in sulfate levels would be most closely associated with a factor related to ionic distribution and weathering (i.e., Factor 2). The correlation of sulfate with Factor 3 may reflect sulfate reduction and depletion in hypolimnetic waters, a process (Kelly et_al., 1982) recently demonstrated to be rather significant in the hypolimnion of a productive, softwater lake.

The fourth factor, which accounts for 8.3 percent of the total variance in the data, is essentially an organic matter deposition factor and relates those variables that tend to be most influenced by the accumulation of sedimentary organic matter. The highest loading is for sedimentary total organic carbon (TOC), followed by sedimentary total organic nitrogen (TON). Also associated with Factor 4 is interstitial ammonia (NH_3) which builds up in the pore water as a direct consequence of catabolic processes within the sediments.

It is interesting to observe that sediment moisture content loads in a positive sense for Factor 4 as well as Factor 1, which relates inorganic sediment variables. Previous studies have demonstrated a close relationship between sedimentary water content and organic content (e.g., Nisson, 1975; Pollman, 1977, 1983; Hakanson, 1982); however, sediment moisture content also reflects selective size sorting processes and increases with decreasing particle size due to interparticle repulsion (Berner, 1971). This implies that the sedimentary accumulation of trace elements identified in Factor 1 is the result of adsorption to clay particles, which generally carry a net negative charge and have larger surface area:mass ratios than coarser particles.

Projection of reclaimed lake scores from PCA into two dimensional factor space described by Factors 1 and 4 is shown in Figure 3.4-1. It is obvious from the figure that no clear sedimentary typology exists but that reclaimed lakes are characterized by a continuum of sediment types. This is evidenced by the lack of clustering of lakes in the plot and may reflect the artificial nature of reclaimed basin development and the extremely young age of the lakes relative to natural systems. Dean and Gorham (1976), for example, observed that Minnesota lakes tend to be segregated into two groups, one showing carbonate enrichment and the other organic enrichment, with few lakes showing enrichment in both carbonate and organic matter.

Of the remaining factors that exceed the minimum eigenvalue threshold level of 1.0, Factors 8 and 10 are of the most interest. Factor 8 is essentially an inorganic nitrogen factor and comprises ammonia plus nitrate- and nitrite-nitrogen forms. Factor 10 is mainly the result of the positive correlation of dissolved oxygen and the negative correlation of dissolved radium-226 (Ra-226). Factors 7 and 9 result from the correlation of sedimentary arsenic (As) and lead (Pb) (Factor 7) and sedimentary selenium (Se) (Factor 9). The remaining factors (Factors 5 and 6) are complex and difficult to interpret with respect to underlying causes.

3.4.2 Relationship Between Abiotic Factors and Lake Morphometry

Through regression analysis, several models have been developed that relate various aspects of lake trophic state to lake morphometry. Examples include Rawson (1952), Brylinsky and Mann (1973), Fee (1979), and Zimmerman et_al. (1983). In a similar fashion, this section represents a multiple linear regression (MLR) approach to determine the relationship between specific morphometric features and reclaimed lake chemistry.

The abiotic factors were dependent variables and lake morphometric and hydrologic variables were the independent variables for the MLR. The

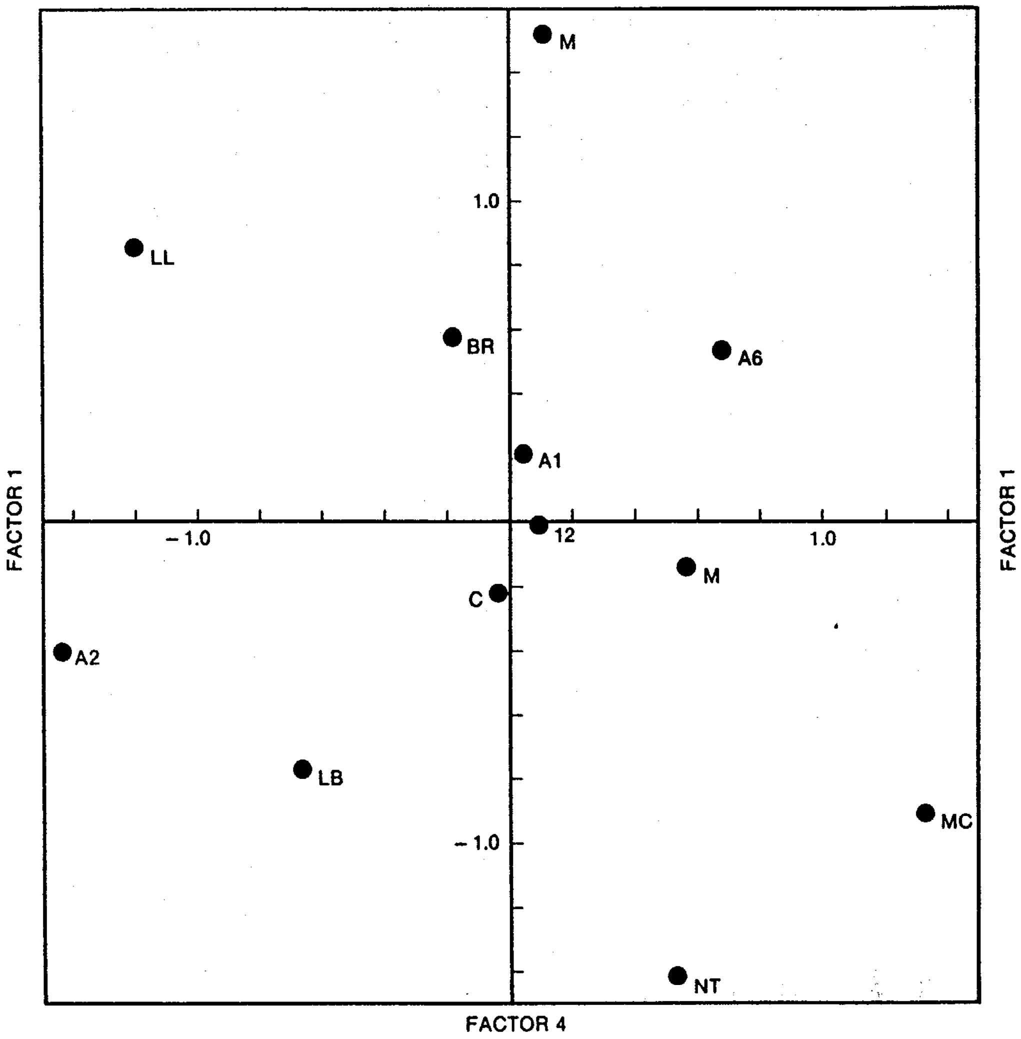

Figure 3.4-1
PROJECTION OF RECLAIMED LAKE SCORES FROM PRINCIPAL COMPONENTS ANALYSIS INTO TWO-DIMENSIONAL FACTOR SPACE DELINEATED BY THE SEDIMENTOLOGICAL FACTORS ONE AND FOUR

SOURCE: ESE, 1983.

approach is summarized schematically in Figure 3.4-2. Table 3.4-2 summarizes the results of the MLR analysis for the major factors of interest.

From a trophic state perspective, the most interesting model is represented by the relationship between Factor 3 and the lake morphometry/-hydrology (see Table 3.4-2).

The parameters TIME, VDI, Z, and ZMAX were all found to be significantly correlated ($P < 0.0001$) with the trophic state factor (Factor 3). Inclusion of other variables in the regression equation did not sufficiently improve the coefficient of determination ($r^2 = 0.50$) to justify increasing the complexity of the model. Inspection of calculated F values for each variable indicates that lake maximum depth and volume development index exert the greatest influence on the factor (Table 3.4-3). Of these two, the most important variable in the relationship is ZMAX, which was negatively related to the factor. The relationship between the trophic state factor and ZMAX agrees with established limnological principles, *viz.*, all other factors being equal, overall lake nutrient levels should decrease with increasing depth because of the reduced rate of nutrient recycling across the sediment water interface. Furthermore, sediment focusing may occur in lakes with deep holes, effectively removing detrital material from interacting with the trophogenic zone of the water column.

The positive correlation of mean depth with the trophic state factor conflicts with the influence of maximum depth and further illustrates the relative importance of deep holes on reclaimed lake chemical dynamics. Within a particular class of lakes, internal loading of nutrients in response to disturbances at the sediment-water interface created by wind-driven circulation and other processes tends to diminish in importance as mean depth increases. This of course reflects the greater amount of energy that must be applied at the lake surface for wind-induced wave energy to extend to the bottom in deeper lakes

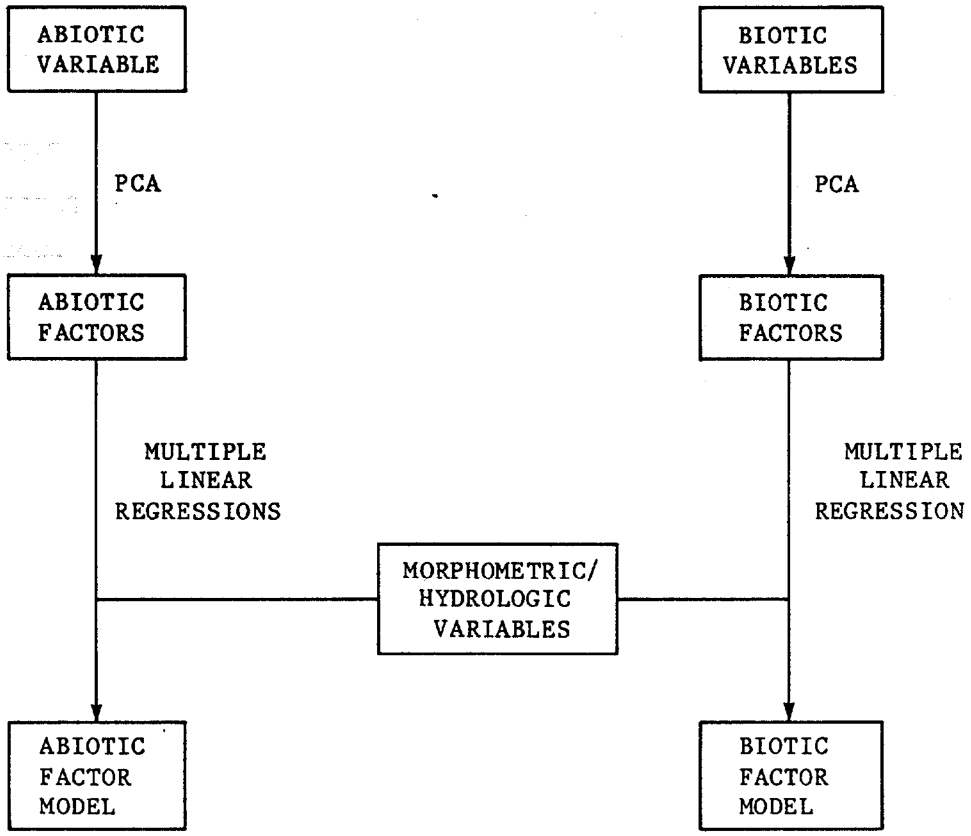

Figure 3.4-2
SIMPLIFIED SCHEMATIC OF MULTIPLE LINEAR REGRESSION APPROACH TO DEVELOPING MODEL RELATIONSHIPS BETWEEN LAKE MORPHOMETRY/ HYDROLOGY AND ABIOTIC AND BIOTIC FACTORS

SOURCE: ESE, 1984.

Table 3.4-2. Multiple Linear Regression Relationships Between Abiotic PCA Factors and Lake Morphometry/Hydrology

Factor Characteristic	Factor No.	Significant Morphologic Features	R^2
Sediment Inorganic Constituents	1	= 1.26 – 0.151 (Z MAX)	0.14
Water Column Ionic Content	2	= 8.65 – 9.41 (VDI) + 1.82 (WSIA) + 3.43 (Z) – 1.25 (Z MAX)	0.77
Trophic State Indicators	3	= 9.86 – 0.0930 (TIME) – 7.04 (VDI) + 2.08 (Z) – 0.924 (Z MAX)	0.50
Sediment Organic Matter Deposition	4	= –1.34 + 0.814 (VDI) + 0.00274 (VOL)	0.42
Water Column Inorganic Nitrogen	8	= –1.33 + 0.291 (FLTOT) + 1.11 (TIME) – 0.359 (Z)	0.37
Dissolved Oxygen/ Radium-226	10	= –0.272 + 0.0672 (FLTOT)	0.04

Where:
ZMAX = Maximum lake depth.
Z = Mean depth.
VDI = Volume development index (bottom configuration).
WSIA = Annual wind stress index (lake orientation to prevailing winds).
TIME = Hydraulic residence time.
VOL = Lake volume.
FLTOT = Annual loading rate.

Source: ESE, 1983.

Table 3.4-3. F Values for Stepwise Regression Relationships of Morphometric/Hydrologic Variables with Abiotic Factors

Variable	Factor 1	2	3	4	6	8	10
AREA							
VOL				113			
Z		329	94.7			8.43	
Z MAX	25.4	289	123				
VDI		247	114	20.6			
HYPCO					27.9		
FLTOT						51.6	6.55
TIME			22.6			41.4	
WSIA		296					
SDI							
R^2	0.14	0.77	0.50	0.42	0.15	0.37	0.04

Source: ESE, 1983.

(U.S. Army Coastal Engineering Research Center, 1977; Mortimer, 1974). The net effect of the sediments as an ultimate sink for nutrients, therefore, increases with mean depth (e.g., Vollenweider, 1975). Baker et_al. (1981), for example, derived the following empirical expression to describe the net loss of phosphorus to the sediments for a series of 26 Florida lakes:

$$R_p = 0.500 + 0.353 \log \bar{z} \cdot tw \qquad (1)$$

where:

R_p = the fractional phosphorus retention coefficient,

T_W = hydraulic flushing rate, and

$\bar{z}$ = mean depth.

The fact that reclaimed lakes with greater mean depths tend to have increasing values for the trophic state factor is indicative of the extremely shallow nature of these lakes and suggests that other factors beyond lake hydrodynamics and simple increases in assimilative capacity are associated with changes in mean depth. Mean depth for the 12 lakes ranged from 1.8 to only 5.4 m. Chapra (1982) indicates that the effects of sediment resuspension is probably significant in lakes with a mean depth of 10 m or less. It seems likely, therefore, that sediments throughout the basins for each reclaimed lake are periodically disturbed and resuspended, with deposition and removal occurring only in deep holes. The resultant effect of deep holes would be increased water clarity because of lower turbidity levels and decreased rates of algal productivity (see Section 6.5).

Within the depth range of the reclaimed lakes surveyed, it is apparent that increasing $\bar{z}$ has virtually no distinguishable effect on internal loading processes. The positive effect of mean depth on the trophic state factor instead suggests that penetration of the lake basin into the phosphatic bedrock underlying the surficial unconsolidated layer of sands contributes to the trophic state of reclaimed lakes. Reclaimed lakes with shallower mean depths included in this study generally were constructed by filling the initial mine pit with a relatively larger volume of overburden; consequently, these lakes are less influenced by residual tailings and clay.

Hydraulic residence time also affects the trophic state factor in a negative sense, although the relatively low F value indicates that the role of this parameter is not as important as the physical structure of reclaimed lakes. For a series of lakes receiving similar nutrient inputs, steady-state nutrient concentrations decrease in lakes with longer residence times because of the nonconservative or reactive nature of nutrients. Because of their brief age compared with natural lakes, it is erroneous to assume that reclaimed lakes have reached steady-state conditions but are more properly considered as systems in transition towards an undefined equilibrium state. In general, the ontogeny of natural lakes proceeds towards increasing eutrophy or nutrient enrichment (cf. Wetzel, 1975). Because of the nature of reclaimed phosphate lake formation, reclaimed lakes are initially enriched with excessive levels of nutrients and phosphorus in particular. Consequently, the early years in life of a reclaimed lake are characterized by extremely high rates of primary productivity in excess of levels capable of being supported by external inputs alone. The sediments function as a net nutrient sink as detrital material is buried in the sediments; consequently, nutrient levels in the water column should decrease with lake age until nutrient losses are balanced by external inputs and internal rates of recycling.

This is illustrated by a modified phosphorus budget model developed by Ostrofsky (1978) to depict the maturation process in reservoirs (Figure 3.4-3). Ostrofsky's model accommodates the time-dependent release or pulse of nutrients within the reservoir basin following its

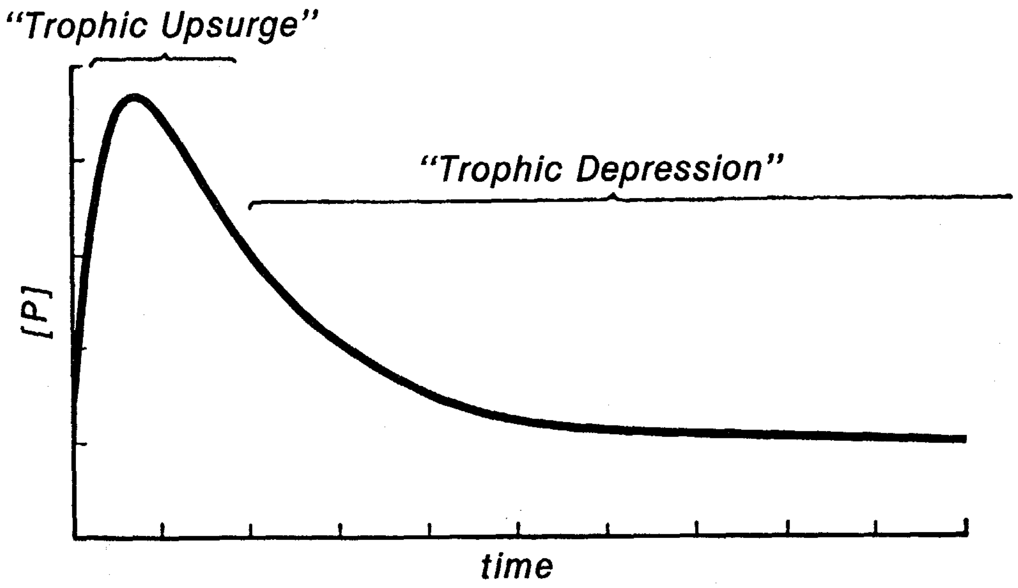

Figure 3.4-3
AMOUNT OF PHOSPHORUS IN A RESERVOIR AS A FUNCTION OF TIME AS PREDICTED BY OSTROFSKY'S TROPHIC UPSURGE MODEL (EQUATION [3])

SOURCE: OSTROFSKY, 1978.

creation and assumes the following form:

$$P_t = \frac{J}{\phi}(1 - e^{-\phi t}) + \frac{B}{(\phi - \alpha)}(e^{-\alpha t} - e^{-\phi t}) + P_o e^{-\phi t} \qquad (2)$$

where: $\phi = \sigma + \frac{1}{\tau_w}$,

σ = **sedimentation coefficient (Vollenweider, 1968),**

J = **mass load of phosphorus entering the reservoir,**

B = **total leachable phosphorus from the submerged basin soils,**

α = **leaching rate coefficient,**

τ = **hydraulic residence time,**

t = **time,**

P_o = **phosphorus concentration in the reservoir at time 0, and**

P_t = **phosphorus concentration in the reservoir at time t.**

As Ostrofsky's model and others indicate (e.g., Sonzogni et al., 1976), the period of time required for reclaimed lakes to recover from this initial period of instability varies inversely with residence time. Thus, lakes with short residence times pass beyond the state of "trophic upsurge" (Figure 3.4-3) within a shorter time frame.

Lake trophic state is also related to Factor 8, which reflects inorganic nitrogen concentrations. Because of the high levels of phosphate typical of reclaimed phosphate pit lakes, nitrogen availability may be hypothesized to limit primary production (see Section 6.5 for further discussion of the relationship between primary production and nitrogen levels). A substantial portion of the dispersion in the inorganic nitrogen factor can be accounted for by the morphometric/hydrologic variables FLTOT, TIME and Z. Multiple linear regression of the factor against these variables yields r^2 equal to 0.42 ($p<0.0001$) (Table 3.4-2).

The sign of the coefficients in the multiple regression model indicates external nitrogen inputs increase with the hydraulic loading rate and residence time (Table 3.4-2). The relationship of the hydraulic loading rate, FLTOT, in the model strongly suggests that inorganic nitrogen levels in reclaimed lakes result primarily from allochthonous sources. In addition, the positive relationship of residence time in the model for the inorganic nitrogen factor agrees with the model developed for the trophic state factor and provides further evidence that reclaimed lake water quality is in a transitional state. This should not be construed that, ceteris paribus, lakes with long residence times will necessarily have higher inorganic nitrogen (or phosphorus) concentrations than rapidly flushed lakes. As reclaimed lakes mature and approach steady state conditions, lakes with longer residence times will characteristically have lower nutrient levels because of the nonconservative behavior of nitrogen and phosphorus (Yeasted and Morel, 1978). Biological uptake of nitrogen and phosphorus results in a net loss of these substances from the water column to the sediments. Apparent settling velocities are on the order of 5.5 and 8.5 m/y for nitrogen and phosphorus, respectively (Baker et_al., 1981); thus, net removal of nutrients increases with lake detention time.

Multiple regression analysis indicates that ionic content or salinity in reclaimed lakes, as represented by Factor 2 (Table 3.4-2), is largely controlled by in-lake processes. F statistics for this model, which accounts for 77 percent of the dispersion in the salinity factor, indicates that significance in the model is primarily attributable to mean depth and the wind stress index. The positive correlation of mean depth with the salinity factor suggests that penetration of the lake basin into the calcareous bedrock underlying the surficial unconsolidated layer of sands controls the ionic character of the water column. This is supported by inspection of the components that comprise the salinity factor. This factor is dominated by the positive associations of Mg ($r = 0.97$) and Ca ($r = 0.94$), which are derived primarily from the bedrock. Furthermore, cation balances show that the reclaimed lakes contain primarily Ca and, to a lesser extent, Mg. Na, which is derived principally from atmospheric inputs, and K are considerably less prevalent (Section 6.4). It is important to note that unlike inorganic nitrogen, the ionic constituency of reclaimed lakes is not controlled to an appreciable extent by hydraulic residence time.

Somewhat more difficult to interpret is the influence of maximum depth on variability in the salinity factor. In the desired statistical model (Table 3.4-2), the effect of ZMAX is negative--opposite in sign to mean depth. This dichotomy in effect by these two parameters was also observed for the trophic state factor and is apparently indicative of the importance of deep holes as traps or sinks for detrital or easily weathered material. Thus, assuming that weathering within the lake basin dictates the ionic composition of reclaimed lakes, it follows that the wind stress index is positively correlated with the salinity factor. WSIA is a shape factor that weights the configuration and orientation of a lake with the seasonal distribution of wind vectors and, independent of lake area, estimates the relative quantity of energy transferred to the water column because of wind-induced mixing.

The effect of VDI on the salinity factor is difficult to interpret in a manner consistent with other parameters in the model. VDI is a crude indication of the overall bottom configuration and represents the ratio of lake volume to that of a cone with basal surface area (corresponding to lake surface area) and height ZMAX. Consequently, VDI reduces to:

$$\mathrm{VDI} = \frac{3\,\bar{z}}{\mathrm{ZMAX}} \qquad (3)$$

The relationship of VDI in the stepwise regression model implies that for reclaimed lakes, a conical basin configuration (i.e., low VDI) results in higher ionic content than more developed, teacup-shaped basins. This aspect of the model may reflect greater amounts of calcareous bedrock exposure in poorly developed lakes.

Sedimentation dynamics in reclaimed lakes are principally represented by Factors 1 and 4, which comprise inorganic and organic components, respectively. The stepwise regression approach yielded very weak relationships (r^2 = 0.14) for the inorganic sediment factor versus morphometric features (see Table 4.2-1).

Only ZMAX satisfied the 0.15 confidence level for inclusion into the model. The model for organic sediment factor represented a substantial improvement in terms of explaining factor variability (r^2 = 0.42) with inclusion of VDI and VOL (Table 4.2-1).

Because of the sampling bias involved in the limited sediment sampling program (see Section 6.1), caution should be applied before extrapolating these results to indicate basin depositional trends for all the reclaimed lakes. Sediment samples were derived from essentially two locations, deep and shallow stations, and do not cover the continuum of substrate types that lie between. In fact, the relatively clean separation of sedimentary parameters into two major factors attests to the fact that only two sediment types were sampled. With these conditions in mind, it is apparent that the presence of inorganic sediments at either deep or shallow stations is reduced in lakes with deep holes, presumably because of focusing of detrital clay particles. This, however, does not imply that reclaimed lakes with deep holes do not have appreciable quantities of inorganic sediments but indicates that the presence of deep holes influences the redistribution of inorganic sediment particles.

F statistics indicate that VOL is by far the most important component for the regression model for the organic sediment factor. The influence of VOL on organic matter deposition may reflect a greater likelihood for selective size sorting processes to redistribute sedimentary material.

Another factor of considerable interest is Factor 10, which is mainly the result of the positive correlation of dissolved oxygen and the negative correlation of dissolved Ra-226. This factor was weakly correlated with only one variable, FLTOT. The coefficient of determination (r^2) was only 0.04 and provides evidence that controllable morphometric or hydrologic features in reclaimed lakes have virtually no influence on the dynamics of either dissolved oxygen or Ra-226.

3.5 BIOTIC CHARACTERISTICS

3.5.1 Interpretation of Components

A set of 17 descriptors of biological community structure and standing crop were subjected to principal component analysis to extract those components which account for the greatest amount of variability. Four major trophic types were included in the analysis: phytoplankton, zooplankton, benthic invertebrates; and fish. The structure of each class was delineated with respect to density, species diversity, richness, and evenness. In addition, chlorophyll *a* was included as an estimate of algal standing crop. Table 3.5-1 lists the loadings of each variable with each factor as well as the respective eigenvalues for each factor.

Factor 1, fish biomass and phytoplankton density, accounted for 17.0 percent of the total variability in the biotic data, representing primarily the positive loadings of fish diversity and richness and phytoplankton population totals. In addition, areal fish biomass was weakly correlated with the factor. This factor essentially represents a process or series of processes that promote increasing algal densities and fish species diversity and standing crop. Conspicuously absent is fish evenness, which is implicitly included in the Shannon-Weaver diversity index and did not load highly on any component. The association of phytoplankton concentration with Factor 1 may be reflective of the predatory pressures of planktivorous fish, such as the bluegill, on large herbivorous zooplankton, thus indirectly promoting higher standing crops of algae (Shapiro, 1979; Lynch and Shapiro, 1981).

Table 3.5-1. Eigenvalues, Percent Variance Explained, and Loadings for PCA for Reclaimed Lake Biotic Parameters

Variable	Factors					
	1	2	3	4	5	6
Fish Biomass	0.67					
Phytoplankton Totals	0.77					
Fish Diversity	0.86					
Fish Richness	0.86					
Phytoplankton Diversity		0.96				
Phytoplankton Richness		0.83				
Phytoplankton Evenness		0.93				
Zooplankton Diversity			0.98			
Zooplankton Richness			0.78			
Zooplankton Evenness			0.89			
Benthos Evenness				0.83		
Benthos Diversity				0.97		
Benthos Richness				0.72	0.59	
Benthos Totals					0.87	
Zooplankton totals						0.77
Chlorophyll *a*						0.56
Eigenvalue	2.88	2.84	2.60	2.41	1.63	1.30
Percent Variance	16.97	16.69	15.28	14.15	9.57	7.67
Cumulative Variance	16.97	33.66	48.94	63.09	72.66	80.33

Source: ESE, 1983.

The second factor extracted from the analysis is highly correlated with phytoplankton diversity, evenness, and richness and may be interpreted as indicative of the stability of the phytoplankton community. Total dispersion in the data set accounted for by Factor 2 was approximately 16.7 percent.

In a similar fashion, Factors 3 and 4 are indicators of community stability or structure, for zooplankton and benthic invertebrates, respectively. As with Factor 2, Factors 3 and 4 increase both with the number of species at a particular trophic level and with the evenness or equality of distribution of individuals per species. Conversely, values for these three factors are reduced for systems that show a strong dominance structure of high abundance among a few species.

Factor 5 was comprised of two benthic population variables, richness (r = 0.59) and total density (r = 0.78). Both species richness and total density were skewed toward higher values in shallow lake zones.

Factor 6 reflects primarily a construct between zooplankton concentration (r = 0.77) and chlorophyll *a* (r = 0.56). The weak association of chlorophyll a suggests that the same factors that tend to promote phytoplankton standing crop induce a concomitant increase in zooplankton densities. It is interesting to note that the two estimates of algal standing crop, chlorophyll *a* and phytoplankton totals, were most highly correlated with different factors. This result reflects the subtle difference between these two variables; phytoplankton total may be a poor surrogate of biomass because it constitutes a count of a population of individuals that may be skewed in size distribution while chlorophyll *a* is relatively independent of such bias.

3.5.2 Relationship Between Biotic Factors and Lake Morphometry

Stepwise MLR analysis was performed on the biotic factors extracted from principal component analysis to determine their relationship with lake morphometric and hydrologic features. The results, which are summarized in Table 3.5-2, show that a satisfactory model which sufficiently accounts for variability in the biological community was developed for the fish biomass/diversity factor (Factor 1) alone. The model judged the best predictor for this factor included one hydrologic function (TIME), one size function (AREA), three configuration functions (SDI, WSIA, and HYPCO), and one depth function (z).

An evaluation of F values from the stepwise regression indicates the order of importance of the morphologic and hydrologic variables to be AREA > TIME > SDI > WSIA > HYPCO > Z (see Table 3.5-3). Increases in fish biomass and diversity, as related to the factor were concomitant with increases in lake surface area, hydraulic retention time, and shoreline development index. Overall, the regression model indicates that reclaimed lakes with major orientations away from prevailing winds, with large surface areas comprised of highly irregular shorelines, with relatively shallow mean depths, and with long residence times will generally yield higher fish biomass and phytoplankton totals.

The coefficient of determination for the fish biomass/diversity factor regression model was 0.68 ($p<0.0001$). Although the stepwise procedure developed more extensive multiple linear models for the factor, accounting for a greater portion of the dispersion, this model yielded the highest regression F statistic, and it was felt that further increases in the complexity of a relatively unwieldy model were not justified by improvements in the predictive capabilities for this factor.

All remaining biotic factors yielded rather weak statistical models from multiple linear regressions. Coefficients of determination from these analyses were below 0.20, indicating variables other than lake morphology and/or hydrology as keys to population growth and stabilization in these aquatic communities. Perhaps the overall lack of stable chemistry in these lakes (as discussed earlier) and the relative age of the systems are reflected in these results.

Table 3.5-2. Multiple Linear Regression Relationships Between Abiotic PCA Factors and Lake Morphometry/Hydrology

Factor Characteristic	Factor No.	Significant Morphologic Features	R^2
Fish Biomass, Diversity, and Richness; Phytoplankton Concentration	1	= 9.15 + 2.42 (TIME) + 0.0216 (AREA) + 9.40 (HYPCO) - 6.01 (SDI) - 4.04 (WSIA) - 1.36 (Z)	0.68
Phytoplankton Diversity, Richness, and Evenness	2	= 0.860 + 0.00153 (VOL) - 0.130 (Z MAX)	0.20
Zooplankton Diversity, Richness, and Evenness	3	= -0.546 + 0.131 (FLTOT)	0.16
Benthos Diversity, Richness, and Evenness	4	= 0.531 - 0.436 (VDI)	0.03
Benthos Concentration	5	= 0.360 - 0.0864 (FLTOT)	0.07
Zooplankton Concentration and Chlorophyll _a_	6	= 0.127 - 0.00248 (AREA)	0.06

Where: TIME = Hydraulic residence time.
AREA = Lake surface area (ha).
HYPCO = Lake area to lake depth relationship.
SDI = Shoreline development index.
VDI = Volume development index.
WSIA = Annual wind stress index (lake orientation to prevailing winds).
Z = Mean depth.
ZMAX = Maximum lake depth.
Vol = Lake volume (m^3).
FLTOT = Hydraulic loading rate.

Source: ESE, 1983.

Table 3.5-3. F Values for Stepwise Regression Relationships of Morphometric/Hydrologic Variables with Biotic Factors

Varible	Factor					
	1	2	3	4	5	6
AREA	366					15.7
VOL		52.4				
Z	185					
ZMAX		29.9				
VDI				7.06		
HYPCO	209					
FLTOT			49.1		19.3	
TIME	314					
WSIA	246					
SDI	261					
R^2	0.68	0.20	0.16	0.03	0.07	0.06

Source: ESE, 1983.

3.6 DISCUSSION

Multivariate statistical analyses were used to delineate parametric relationships within the abiotic and biotic data sets, with each data type considered as a distinct or separate group. Under natural conditions, the abiotic and biotic are, of course, interrelated. Factors defined through this process minimize confounding relationships and allow greater sensitivity in overall data analyses. Only those parameters that provided statistically significant results were used for further multiple regressions. Utilizing this approach in an iterative fashion allowed an evaluation of lake design-controllable features to determine which of these features, if any, control lake chemical or biological processes. Physical, chemical or biological data used in these analyses were from reclaimed phosphate pit lakes only. Data from the four natural or unmined lakes were specifically excluded from these multivariate statistical procedures.

From a water quality perspective, two factors were separated for further evaluation. One factor represents lake trophic state indicators (total nitrogen, total phosphorus) and another represented water column inorganic nitrogen concentration. Maximum lake depth was negatively correlated with trophic state indicators and was also the most important morphometric relationship. Interpretation of this relationship would indicate that as maximum depth increased, concentrations of indicators declined. Sedimentation of detrital material may be the process involved in removing nutrients from the trophogenic or biologically active zone. In contrast, mean depth was positively correlated with trophic state indicators. This relationship may be confusing at first; however, it does present a situation where deep holes can be a vital component of lake design while keeping the overall mean depth in line with natural or unmined lakes. Sediments throughout the basins for each reclaimed lake are periodically disturbed and resuspended, with net deposition and removal occurring only in deep holes. Irregular bottom contours, consisting of intermittent deep holes, require greater wind energy to induce mixing than smooth bottom lakes. Since reclaimed phosphate pit lakes are either mesotrophic or eutrophic, the reduction of surplus nutrients by sedimentation to deep water zones with minimal recirculation potential can be a major factor in lake design.

The inorganic nitrogen factor provided indications that reclaimed lake water quality is in a transitional state, dependent upon inorganic nitrogen from allochthonous sources. This factor was negatively correlated with lake mean depth. Since phosphorus is in sufficient supply within these lakes, nitrogen supply is critical to maintain high productivity levels. Increasing mean depth would remove nitrogen from the trophogenic zone. This factor was also strongly correlated with lake residence time (+) and hydraulic loading rate (+).

The dissolved oxygen/radium-226 factor did not yield a strong statistical relationship with either morphometric or hydrologic variables. From a lake design viewpoint it is obvious that controllable lake design features have virtually no influence on the dynamics of either dissolved oxygen or Ra-226.

The strongest statistical relationship was with the water column ionic content factor. These results indicated that penetration of the lake basin into the calcareous bedrock underlying the surficial unconsolidated layer of sands controls the ionic character of the water column. Both mean depth and orientation to prevailing wind stress were primary lake design features relative to water column ionic strength. Maximum depth was also significant, indicating the importance of deep holes as traps or sinks for detrital or easily weathered material. Since ionic content is governed by internal processes, lake orientation to wind can aid in redistribution and recirculation of ionic constituents.

Only the water quality factors yielded highly significant results for controllable lake design features. Statistical relationships between sediment factors and the dissolved oxygen/radium-226 factor did not indicate lake design features that could control or modify their concentrations.

Biotic parameters also provided poor statistical relationships between population data and lake design parameters. The highest coefficient of determination within the biotic data set was for an association of fish biomass, fish diversity and richness, and phytoplankton concentration. Six morphologic features comprised the regression model for this factor, indicating a lack of clear control between the physical environment and the biological community in reclaimed phosphate pit lakes. Lake area and hydraulic residence time appear to be the principal parameters in the fish biomass factor model and suggest that increasing area and residence time in reclaimed lakes results in increase in fish biomass and diversity.

The overall effect of a particular morphometric or hydrologic design variable can be evaluated relative to other variables by considering its significance in each factor relationship (as determined by its F value), the amount of overall variability accounted for by each factor, as well as the strength or explanatory power of each model given by the coefficient of determination.

This approach indicates overall data variability appears most strongly influenced by the two depth variables, ZMAX and Z, followed by lake volume and volume development. Lake hydrology embodied as the hydraulic loading rate and residence time was somewhat less important, as was lake orientation (WSIA). The remaining morphometric/hydrologic variables were not particularly effective in accounting for overall variability in reclaimed lakes. These results are dominated by contributions from the abiotic data set; this, of course, is a direct result of the considerably greater success achieved in constructing regression models for the abiotic factors while the biotic factor models generally were quite poor. Considering the biotic factors alone suggests that the most important variables to be controlled are AREA and FLTOT.

A final word of caution is perhaps in order. Implications of cause and effect have been intended to account for the correlations between the various morphometric/hydrologic variables and the biological and chemical attributes of the reclaimed lakes. For example, supporting mechanisms have been hypothesized to account for the statistical relationship between ZMAX and the lake trophic state and salinity factors. However, correlations between variables do not confirm cause and effect and the possibility that ZMAX may be correlated with some other (unmeasured) parameter that is essentially the true cause of the observed effect cannot be discounted. Further research is necessary to confirm the cause and effect implication.

4.0 LAKE DESIGN

Prior to initiation of this investigation in 1981, data on reclaimed phosphate pit lakes were minimal. Since that time, only one other study (Boyd and Davies, 1982) has added information on the physical, chemical and biological characteristics of these by-product lakes produced by surface strip mine reclamation.

A substantial database on a cross-section of reclaimed phosphate lakes in Central Florida has been obtained through this study. In this document descriptive analyses of the chemical (Section 6), physical (Section 5) and biological (Section 7) data, as well as analyses of statistical interactions (Section 3) between these data sets, have been provided. Each descriptive chapter provides statistical results for potential factors which may be controlling lake productivity. One end product of this investigation has been the development of a matrix of lake design features based on the relationships between lake productivity (eutrophication) controlling factors and controllable lake design features.

A discussion of mine reclamation rules (Chapter 16C-16, FAC) and water quality standards (Chapter 17-3, FAC) indicating relative impacts of lake design on either water quality or fish and wildlife by lake depth, size, hydrology, or configuration is included in this section. It should be specifically noted by those reviewing this text that all statistical observations for lake design were based solely upon reclaimed lake data, i.e., no natural lake data were permitted to bias these conclusions. Natural lakes included in this investigation were utilized as points of reference between this and other aquatic ecology/water quality studies.

4.1 RECLAIMED PHOSPHATE PIT LAKES--A DESIGN MATRIX

Lake design in a traditional sense relates to the creation of a new water body to suit either specific or multiple functions. Common examples include reservoirs for electric power generation, potable water resources, storm water retention lakes, farm ponds for fish production, irrigation or livestock watering, and recreational activities. In contrast, phosphate pit lakes are the by-product of surface strip mining, with an excavated area remaining after removal of phosphatic ore. Lake design in this sense is specific to returning the surrounding mine site to an aesthetically pleasing, safe area through reclamation. Beyond the surface complexion, long term uses such as recreation, community development, and water resources are not a primary concern when lake reclamation begins. Short term (2-3 years) objectives to "complete" reclamation generally take precedence from both a mine operation and regulatory viewpoint.

Creating a water body requires consideration of both short-term and long-term benefits which can be derived from the reclaimed lake system. The goal of this investigation was to provide necessary background information and to utilize this information to derive a list of lake design criteria relative to desired use objectives. A prescription for the "ideal" lake design that satisfies all areas of local and regulatory concern was not the objective of this investigation.

Reclaimed lakes evaluated in this project were all found to be eutrophic or borderline mesotrophic. Unlike many natural systems that have direct nutrient inputs and discharges creating eutrophic conditions, the enriched trophic state of reclaimed lakes is principally due to their origin. Like the majority of Florida's natural lakes, reclaimed phosphate pit lakes have the potential to be ecologically productive. Many of Florida's natural lakes are overly productive, supporting large aquatic plant communities and/or undesirable fish or algal species in nuisance proportions. Lake restoration of natural lakes, through such measures as dredging or discharge diversion, is an attempt to reverse the effects of advanced lake trophic condition. With reclaimed phosphate lakes, appropriate lake design can be utilized to minimize problems due to their potential eutrophic condition. Although maximizing lake design characteristics to reduce eutrophication effects undoubtedly will not result in the creation of oligotrophic lakes, it will potentially prolong the derived benefits of the water body.

Statistical analyses of the reclaimed lakes physical data set provided the following major categories of controllable lake design features:

- Depth - Maximum and Mean;
- Size - Total Lake Area and Total Lake Volume;
- Hydrology - Hydraulic Loading Rate and Hydraulic Residence Time; and
- Configuration - Shoreline Development Index, Volume Development Index, Lake Orientation to Prevailing Annual Wind Stress, and Depth versus Area Relationships.

Lake depth and hydrology were the two most important controllable components when statistically evaluated with the chemical and biological data base.

As identified in Section 2.0, lake depth is a critical component in the ontogeny of lakes and lake eutrophication. Florida's natural lakes are characteristically both shallow and mesotrophic to eutrophic. Data from this investigation indicated reclaimed lakes to be in the same category: shallow and mesotrophic to eutrophic. Statistical analyses revealed that reclaimed lakes with a greater maximum depth generally exhibit reduced trophic state factors. The data also indicated that, since mean depths for reclaimed and natural lakes were similar, lakes whose basins are interspersed with deep pockets allowed the creation of persistent stratification below a 2-1/2 to 3 meter depth. This combination of greater maximum depth, relatively deep pockets and stable stratification appears to provide a nutrient sink, which may diminish the availability of N and P to the biological community.

From a lake design viewpoint, an irregular lake bottom punctuated with deeper pockets appears to remove nutrients from the water column, short-circuiting the nutrient regeneration cycle and reducing lake productivity. Such a design feature, of course, assumes the philosophical perspective that highly productive or eutrophic lakes are not desirable. One concern with this design feature would be the incipient thermal stratification and potential anoxia that invariably accompanies such a bottom configuration. During this study, all shallow lake areas, less than 2-1/2 to 3 m, had surface oxygen levels above water quality standards (Chapter 17-3; see Section 4.3). However, no significant adverse impacts were observed during this investigation due to low dissolved oxygen levels. Rather, it appears that anoxic zones serve as potential nutrient removal areas through sedimentation of biogenic material, which may be considered beneficial to the lake system.

Inorganic nitrogen concentrations were also correlated with both controllable hydrologic functions and lake mean depth. Consequently, reclaimed lakes with shorter residence times, lower loading rates, and greater mean depths should have reduced inorganic N levels, thereby promoting an improvement (i.e., reduction) of trophic state.

Fish populations were found to be relatively unaffected by most controllable lake design features. Lake morphometric features did not appear as important factors in principal components analysis, and very few negative or positive correlations resulted between fisheries data and lake morphometric variables. Neither total fish catch (CPE) or bluegill biomass showed any correlations with morphometric variables. Total fish biomass showed a positive correlation with lake volume. Bluegill catch showed a negative correlation with lake residence time. Both largemouth bass catch and biomass were positively correlated with the lake volume development index. Biomass also had a positive correlation with the hypsographic coefficient.

The lake design matrix, provided in Table 4.1-1, presents an overview of relative impacts on water quality parameters and fish communities for all controllable lake design features. If the desired design goal is water quality improvement, Table 4.1-1 shows that nutrients have a

Table 4.1-1. Controllable Lake Design Features and Their Relative Impact on Either Water Quality or Fish Parameters

	Depth (m)		Size		Hydrology		Configuration			
	Max	Mean	Area	Volume	Loading	Residence	SDI	VDI	WSIA	HYPCO
Water Quality										
Nutrients	-	+	o	o	+	+	o	-	o	o
Physico-Chemical Properties	o	o	o	o	o	o	o	o	o	o
Radiation	o	o	o	o	+	o	o	o	o	o
Major Ions	-	+	o	o	o	o	o	-	+	o
Fish										
Total Catch	o	o	o	o	o	o	o	o	o	o
Total Biomass	o	o	o	+	o	o	o	o	o	o
Bass Catch	o	o	o	o	o	o	o	+	o	o
Bass Biomass	o	o	o	o	o	o	o	+	o	+
Bluegill Catch	o	o	o	o	o	-	o	o	o	o
Bluegill Biomass	o	o	o	o	o	o	o	o	o	o

o No relationship
- Inverse relationship
+ Direct relationship

Area = hectares
Volume = 10^3 meters^3
Areal Loading Rate = meters/year
Residence Time = years

SDI = Shoreline Development Index
VDI = Volume Development Index
WSIA = Wind Stress Orientation
HYPCO = Depth/Area relationship

Source: ESE, 1983.

negative relationship with maximum depth and a positive relationship with mean depth. This indicates that the greater the maximum depth, the lower the nutrient concentration. Also, a greater mean depth would result in higher nutrient concentrations. Therefore, in order to control nutrient levels, overall lake depths, relative to these study lakes, should not be increased; however, a number of deep pockets should be considered in the lake design to act as nutrient sinks. Such a design would result in an irregular lake bottom. Maximum lake depths in this investigation ranged from 5 to 13 meters, and mean depths ranged from 2.6 to 5.6 meters. Based on the observed relationships, maximum depths towards the upper end of this range appear to serve as nutrient sinks. Mean depths in the midrange also appeared to assist in reducing potential lake eutrophication or nutrient conditions.

Lake size was not found to have a significant relationship to water quality conditions in this investigation. However, both total fish biomass and total bluegill biomass were positively correlated with lake size (Table 4.1-1). If higher fish biomass production (particularly bluegill) was a desired lake reclamation goal, lake area and lake volumes as high as those in the larger study lakes should be considered in lake design. Reclaimed lake area measurements in this investigation ranged from 1.6 to 286 hectares (4 to 706 acres) with volumes ranging from 4.7×10^4 to 8.2×10^6 cubic meters. As noted in Table 4.1-1, largemouth bass showed no relationship to either lake size factor (area or volume) and theoretically do not appear to be impacted by increases in lake size which appears to enhance bluegill populations.

Only one controllable design feature, hydraulic loading rate, showed a relationship with lake radioactivity (primarily in the form of Ra-226). Radioactivity levels were not significantly different in reclaimed lakes relative to natural lakes. In addition, the radioactivity levels in both natural and reclaimed lakes were less than state or federal water quality standards (see Section 4.3). However, radium activities were positively correlated with lake hydraulic loading rate. As overall loading rates increased, overall mean Ra-226 levels also increased. This loading rate parameter measures the annual increase in lake level as a function of inflow normalized for average lake area. Hydraulic loading rate ranged from 1.7 to 12.7 meters per year for reclaimed lakes in this investigation. However, there is no evidence that increasing loading rates beyond those found in this investigation would necessarily increase Ra-226 levels above water quality standards. In fact, natural mechanisms within reclaimed lakes appear to be effective in removing soluble Ra-226 from the water column (see Section 6.0). It is important to remember that these assessments have been based on average trends in the observed study data. Projection of data or interpretation beyond the realm of the collected data may be misleading. As an example, the above trend indicates that on an average (all low loading rate lakes versus all high loading rate lakes), Ra-226 will increase as loading rate increases. However, lake-specific data for the upper and lower hydraulic loading rate boundaries, Lakes Brown and Agrico 1, respectively, do not indicate this to be a strong relationship. Lake Brown had a mean Ra-226 activity of 0.25 pCi/l and a maximum activity of 0.60 pCi/l, compared to Lake Agrico 1, which had the lowest hydraulic loading rate and a mean Ra-226 activity of 0.41 pCi/l and a maximum activity of 1.8 pCi/l. A discussion on this relationship in Section 3 confirms that although there is a positive relationship between hydraulic loading rate and radium, the relationship is statistically weak (i.e., low coefficient of determination).

In the context of this report, lake design only pertains to the physical shaping of the land area to create a viable lake ecosystem. These data do not include potential impacts due to future and/or intensified land use in the lake drainage basin. As an example, Table 4.1-1 does not indicate a relationship between water quality and lake size factors. However, when considering the impact of a housing development on a lake, the size of the receiving system is important from a dilution perspective. The difference here is whether or not the source of nutrients is diffuse or from a point source. Lake size does not show a statistical relationship with nutrient concentrations since the general sources of nutrients for reclaimed lakes in this data set are from widespread, diffuse sources that reflect the geochemical characteristics of the watershed and lake basin. Before these data can be effectively used to determine impacts to the lake systems due to future or intensified land use, additional studies will be required.

As mentioned previously, Table 4.1-1 does not provide absolute values for design of the "ideal" reclaimed lake. It only provides an indication of positive, negative or no relationship between design features and design goals. Extrapolation of design criteria beyond the values found within lakes in this study program should be avoided. As additional data on key parameters for reclaimed lakes become available, further refinement of specific lake parameters relative to specific design objectives may be possible.

4.2 REVIEW OF MINE RECLAMATION CHAPTER 16C-16 CRITERIA VERSUS CONTROLLABLE LAKE DESIGN FEATURES

Florida's mine reclamation rules, Chapter 16C-16 (FAC) were first promulgated in October, 1975, under the jurisdiction of Florida's Department of Natural Resources (FDNR), Division of Resource Management. These rules provided for post-mining restoration of Florida's lands, waters and wetlands which were mined after July 1, 1975. Chapter 16C-16 was revised effective October, 1978. FDNR is currently investigating further revisions in Chapter 16C-16 with drafts of the proposed rules published in June 1983 and June 1984. Table 4.2-1 contains excerpts from the current (1972) rule as they pertain to lake reclamation.

One objective of this study was to evaluate the age effects on phosphate pit lakes. Eight of the 12 reclaimed lakes in this investigation were mined prior to July 1, 1975 (see Section 5.2). Therefore, lake age ranged from old unreclaimed lakes (i.e., prior to the current reclamation rules) through lakes governed by the first mine reclamation rules.

Table 4.2-1. Selected Rules Under Chapter 16C-16, F.A.C., Pertaining to Reclaimed Lake Design

Section	Rule
16c-16.05 Standards	
2. Slopes	
a)	shall be no steeper than 4 ft. horizontal to one ft. vertical to enhance slope stabilization and provide for the safety of the general public. Slopes greater than 4:1 will be approved only where adequate stabilization can be assured.
b)	Slopes of the bottom of artificially created water bodies shall not be steeper than a gradient of 4:1 within 25 feet of the shoreline as measured from the lowest anticipated water line. Where the 4:1 gradient cannot be achieved there shall be a minimum 10 ft. wide perimeter subaqueous bench.
5. Wetlands & Water Bodies	The design of artificially created wetlands and water bodies shall be consistent with health and safety, maximize beneficial contributions within local drainage patterns, provide aquatic and wetland wildlife habitat values, and maintain downstream water quality by preventing erosion and providing nutrient uptake. Water bodies should incorporate a variety of emergent habitats, a balance of deep and shallow water, fluctuating water levels, high ratios of shoreline length to surface area and a variety of shoreline slopes.
a)	At least 25% of the high water surface area of water bodies in a reclamation proposal shall consist of an annual zone of water fluctuation to encourage emergent and transition zone vegetation.
b)	At least 20% of the lake surface will consist of a zone between the annual low water line and -6 feet annual low water to provide fish bedding areas and submerged vegetation zones.
d)	A berm of earth shall be constructed around each waterbody which is of sufficient size to retain at least the first one inch of runoff. The berm shall be set back from the edge of the waterbody so that it does not interfere with the other requirements of Subsection (4).
6. Water Quality a)	All waters of the state on or leaving the property under control of the taxpayer shall meet applicable water quality standards of the FDER Regulation Chapter 17-3, F.A.C.
b)	Water within all wetlands and waterbodies shall be of sufficient quality to allow recreation or support fish and other wildlife.
7. Flooding and Drainage	
b)	The operator shall restore the original drainage pattern of the area to the greatest extent possible. Watershed boundaries shall not be crossed in restoring drainage patterns but shall be restored within their original boundaries.
10. Revegetation	The operator shall develop a revegetation plan adapted to achieve permanent revegetation which will minimize soil erosion, conceal the effects of surface mining, recognize the requirements for appropriate habitat for fish and wildlife.

Source: Rules of the Florida Department of Natural Resources, Division of Resource Management, 1981.

None of the lakes included in this program were designed in accordance with the 1978 revision of Chapter 16C-16.

Chapter 16C-16 is primarily concerned with adjustments in lake morphological features to satisfy the following concerns:

1. Health and safety;
2. Maximization of beneficial contributions within local drainage patterns;
3. Provision for aquatic and wetland wildlife habitat values; and
4. Maintenance of downstream water quality by preventing erosion and providing nutrient uptake.

Changes in the original mine reclamation rules (including changes according to the proposed rules) have concentrated more on Item 3 than on any other area. The major change during 1975 to 1978 was the inclusion of paragraphs 5a and 5b (Table 4.1-1) which can require up to 45 percent of the total lake surface area to be <2 m (-6 feet annual low water). The reason for this change was to provide for greater diversity of aquatic habitat.

In many instances, accommodation of one requirement in Chapter 16C-16 provides simultaneous compliance with other requirements. For example, designing a lake with 4:1 slopes out to the -6 foot annual low water depth contour satisfies the safety requirement for shoreline slopes and provides a littoral zone shelf that extends approximately 6 m from the shoreline (before wind action and erosion settles the shoreline). Another example would include placing a lake in a stream bed or an area that will connect several lakes, thereby reducing overall flow through the system, settling out sediment and nutrients and providing control of water flow.

However, not all requirements of the rule appear to achieve complementary results with other objectives of the rule. For example the requirement for inclusion of a zone of fluctuation and shallow water zones (see Table 4.2-1) apparently was intended to provide more diverse habitats for fish and wildlife. However, water quality standards may be more difficult to meet in predominantly shallow lakes (see Section 2.0) due to their greater potential for nutrient release resulting from wind-wave induced sediment resuspension and bioturbation. In addition, large shallow areas may provide a habitat for pioneer macrophyte species such as cattail which produce considerably more biomass (and, therefore, organic matter) than any other aquatic plant found in reclaimed lakes (see Section 7.2). Since eutrophic lakes generate more organic material than can be effectively decomposed, the provision of a greater surface area for emergent macrophyte growth may only accelerate eutrophic conditions.

Data from this investigation on fish populations (see Section 7.5) indicate that, based on total fish biomass (weight) per acre, the shallow zone was negatively correlated. A negative correlation indicated that, as the percent shallow zone increases, the overall fish population biomass decreases. Morphometric features that were highly correlated (positive) with fish biomass in reclaimed lakes were lake age and total lake volume. Although all reclaimed lake results were included, these results were primarily driven by the largemouth bass catch in Lake Agrico 1 which had both high bass catches as well as high total fish catches. This lake also had the highest fish biomass/acre estimate, which was comprised of 85 percent largemouth bass. Lake Agrico 1 had a total shallow zone (including zone of fluctuation) less than 10 percent of the total surface area.

When evaluating only largemouth bass biomass from reclaimed lakes, the most significant correlations were the depth versus area relationship (positive), percent shallow zone (negative) and volume development index (positive). The depth versus area relationships or HYPCO, relates to an index for overall lake depth contours based on bathymetric surveys. As the HYPCO index increases, the value indicates a system where most of the lake area is close to the maximum depth.

Bluegill are another important component of lake fisheries. Therefore, bluegill were also separated from the overall fish database and statistically correlated with lake morphometric features. This species had significant positive correlations between mean catch per effort (number of fish) and lake percent zone of fluctuation. Bluegill catch was negatively correlated with lake maximum and mean depth as well as lake hydraulic residence time.

Both largemouth bass and bluegill were dominant species in reclaimed lake fish collections. Based on results from this investigation, as presented above and in Section 7.5, an increase in percent zone of fluctuation (i.e., to 25 percent) and shallow zone (i.e., to 20 percent) to 45 percent of the total lake surface area does not appear to improve fish populations. The results of this study do indicate that the habitat provided by irregular shorelines and varying lake depths assist in supporting large fish populations. Thus, these requirements of Chapter 16C-16 (Table 4.2-1) appear to be appropriate for consideration as lake design criteria.

Although an evaluation of wildlife inhabiting reclaimed lakes was not a component of this investigation, sitings of birds and mammals were documented and briefly discussed in Section 7.6. A qualitative review of these wildlife observations only reveals the numbers of different species utilizing habitats surrounding reclaimed lake systems. This study indicates that the reclaimed lakes offer a variety of habitats available for wildlife use, ranging from open water for over-wintering white pelicans and ducks to marshlike fringes occupied by other waterfowl and otters.

Since this investigation and others have shown that reclaimed lakes and the surrounding areas provide valuable fish and wildlife habitat, current lake reclamation practices under both previous and existing rules apparently provide for fish and wildlife needs. Marion et_al. (1981) recommended relaxation of reclamation rules (in certain areas) to foster further conditions which are attractive to wildlife. However, reclaimed phosphate lakes are not without problems or potential problems. The problems appear to be related to the fact that these lakes are inherently eutrophic. In order to improve the long-term benefits derived from lakes, reclamation efforts should probably be directed towards keeping these lakes at the mesotrophic to eutrophic level. This can only be accomplished by management for long term lake status. Further, data from this investigation suggest that rules governing reclamation should also be primarily directed towards water quality/eutrophication considerations. Natural lake aging processes must be incorporated in mine reclamation guidelines in an effort to provide both short-term and long-term benefits from the lakes.

Unlike certain other mining operations, phosphate strip mines are not considered to involve toxic wastes that inhibit plant or animal growth. This is supported by the lack of any adverse effects to fish and wildlife in reclaimed lakes observed during this study. However, unless due consideration is given to lake aging and eutrophication processes, enhancement of excessive productivity during the early stages of a reclaimed lake may create future water quality problems. From the perspective of this investigation, water quality should be the primary consideration for reclaimed lakes. These lakes are highly productive by nature of their origin. If lake designs promote acceptable water quality regimes, then fish and wildlife communities should also be enhanced.

4.3 REVIEW OF RECLAIMED LAKE WATER QUALITY VERSUS WATER QUALITY REGULATIONS, CHARTER 17-3

Florida's Department of Environmental Regulation has jurisdiction over water quality standards as described in Chapter 17-3 (F.A.C.). These rules govern all Waters of the State with respect to their

Table 4.3-1. Study Parameters with Regulated Water Quality Standards (Chapter 17-3, F.A.C.) and the Number of Reclaimed or Natural Lakes with Mean Concentrations that Exceeded those levels during 1982.

	General			Class I-A			Class III		
		No. Lakes Exceeding			No. Lakes Exceeding			No. Lakes Exceeding	
Parameter	Stand.	R	N	Stand.	R	N	Stand.	R	N
Alkalinity	—	—	—	<20mg/L	5	2	<20mg/L	5	2
Gross Alpha	15pCi/L	1*	0	—	—	—	—	—	—
Ammonia (un-ionized)	—	—	—	0.02mg/L	1,6*	0	0.02mg/L	1,6*	0
Arsenic	0.05mg/L	0	0	—	—	—	—	—	—
Barium	—	—	—	1.0mg/L	0	0	—	—	—
Cadmium	—	—	—	0.8mg/L	1*	0	0.8mg/L	1*	0
Chromium (Total)	1.0mg/L	0	0	—	—	—	—	—	—
Fluoride	10.0mg/L	0	0	1.5mg/L	2,1*	0	5.0mg/L	0	0
Lead	0.05mg/L	0	0	0.03mg/L	0	1†	0.03mg/L	0	0†
Mercury	—	—	—	0.1ug/L	12	4	0.2ug/L	11	4
Dissolved Oxygen									
24 Hour	—	—	—	<5.0mg/L	0	0	<5.0mg/L	0	0
Anytime	—	—	—	<4.0mg/L	0	0	<4.0mg/L	0	0
Radium-226	5pCi/L	0	0	—	—	—	—	—	—

* Mean value below standard, however maxima may exceed standard
† = lakewide mean approximately equal to standard
— = no standard for this class water
R = reclaimed (12 lakes included in the investigation)
N = natural (4 lakes included in the investigation)

Source: ESE, 1984.

classification, which depends on the intended usage (e.g., potable water, recreation, etc.). Several reclaimed lakes included in this investigation are not Waters of the State due to their isolated nature. However, for discussion purposes, each lake in this investigation was considered to be under Class III criteria (i.e., intended use: recreation and propagation and management of fish and wildlife). Lake Manatee, an unmined natural lake, is a public water supply and is, therefore, covered by Class I-A criteria.

Section 6.0 provides a discussion about each water quality parameter included in this investigation. Table 4.3-1 presents a synopsis of 12 parameters from this investigation which includes listed water quality criteria for either General, Class I-A or Class III classifications. Four parameters are covered by the general criteria only (i.e., gross alpha, arsenic, chromium, and Radium-226); one parameter has Class I-A criteria only (i.e., barium).

Standards for 5 of the 12 parameters listed in Table 4.3-1 were not exceeded in reclaimed or natural lakes based on either mean or maximum values. These parameters were:

- Arsenic
- Barium
- Chromium
- Dissolved Oxygen
- Radium-226

Mean arsenic concentrations were 40 percent lower in natural lakes (9.0 ug/L) than found in reclaimed lakes (15.1 ug/L). Chromium, another "heavy" metal, was only slightly higher in reclaimed (4.53 ug/L) lakes versus natural lakes (3.0 ug/L). Barium was more than twice as high in natural lakes (15.03 ug/L) than found in reclaimed lakes. Barium, combined with sulfate, may be responsible for precipitation of radium-226 from the water column of reclaimed lakes, although removal of Ra by absorption onto hydroxyapatite granules is likely, as well (Murray et al., 1983). Mean radium-226 was approximately the same in both reclaimed (0.38 pCi/L) and natural (0.36 pCi/L) lakes.

Dissolved oxygen (DO) concentrations were found to be approximately 20 percent higher in natural lakes than in reclaimed lakes, 8.06 mg/L versus 6.6 mg/L, respectively. Two factors may be collectively responsible for lower DO in reclaimed lakes. First, algal populations and chlorophyll *a* levels were generally lower in reclaimed lakes than in natural lakes, indicating lower productivity rates. Second, the deep stations in reclaimed lakes were generally deeper than those in natural lakes and, due to lake bottom irregularities which prevented complete surface to bottom mixing, were usually stratified. However, the overall effect of anoxic bottom waters was not sufficient to reduce mean lakewide DO below the 24-hour standard of 5 mg/L. A few reclaimed lakes had lakewide DO levels less than 5 mg/L shortly after fall overturn, a natural limnological process in monomictic lakes. DO was between 3 mg/L and 4 mg/L in these lakes for a short period of time. The only impact was on threadfin shad, which appeared to be a thermal response rather than oxygen stress. No other species were observed in stressed condition. during the overturn period.

The standard for one regulated parameter, mercury, was exceeded in all lakes, based on Class I-A criteria. Only one reclaimed lake did not have mean or maximum mercury concentrations that exceeded Class III criteria. All natural lakes exceeded Class III standards for mercury. The overall mean mercury concentration in reclaimed lakes was 0.44 ug/L, whereas the overall mean mercury concentration in natural lakes was 1.49 ug/L. The highest mercury concentrations were found in Lake Hollingsworth, a natural lake.

Water quality standards for alkalinity, un-ionized ammonia, cadmium and lead are the same for both Class I-A and Class III waters. On the average, reclaimed lakes had alkalinities (as $CaCO_3$) of 43.4 mg/L and natural lakes had alkalinities of 40.8 mg/L. Two of the five reclaimed lakes that fell below the alkalinity standards (20 mg/l as $CaCO_3$) had mean concentrations greater than 18 mg/L and maximum values greater than 20 mg/L. One of the two natural lakes which did not have sufficient alkalinity to meet the standard, had a mean greater than 18.0 mg/L and a maximum value greater than 20 mg/L. Since there are no discharges into these lakes, their levels are due to chemical properties of the lake watersheds.

Total ammonia levels were highest in reclaimed lakes. Calculated concentrations for un-ionized or free ammonia, typically exceeded Chapter 17-3 criteria in one lake, with a potential to exceed criteria existing in six other lakes. The concentration of un-ionized ammonia present in aqueous solutions is highly dependent upon pH, concentration of total ammonia and temperature. As pH increases at a given temperature, the un-ionized fraction of the total ammonia concentration increases. Similarly, as the temperature increases at a given pH, the percent free ammonia increases. In highly alkaline waters, the free ammonia fraction can reach toxic levels (U.S. EPA, 1976). However, the mean pH for reclaimed lakes was 6.87, near neutral but slightly acidic. High ammonia concentrations are typically found in man-made reservoirs as a result of decomposition of terrestrial vegetation deposited prior to inundation. This investigation provides evidence that regeneration of nitrogen is an important component of the nutrient cycle in reclaimed lakes. High numbers of threadfin shad attract large numbers of fish-eating birds to the reclaimed lakes. Excrement from shad, birds and other provides organic nitrogen which is mineralized to ammonia by bacteria. Having excess inorganic nitrogen, as ammonia, in the presence of excess phosphorus indicates that neither N nor P is limiting algal growth. Low levels of another nutrient or micronutrient prevents full utilization of the ammonia. Several lakes with high total ammonia also had nesting avian communities, particularly herons and cormorants.

Two trace metals, lead and cadmium, were above water quality standards in at least one lake. Mean lead concentrations for all lakes, except Lake Hunter, a natural lake, were below standards. Lake Hunter had mean (30.2 ug/L) and maximum (38.4 ug/L) concentrations above both Class I-A and Class III standards. Mean cadmium concentrations were all below standard criteria. However, one reclaimed lake (Lake Bradley) had a maximum value of 1.4 ug/L which was greater than the Florida water quality standard. Based on an estimated hardness of 61.4 mg/L as $CaCO_3$ in reclaimed lakes, the federal criterion (U.S. EPA, 1981b) for acute cadmium toxicity to aquatic life is 1.81 ug/L. None of the lakes in this investigation exceeded this value.

The most stringent criterion for fluoride is applicable for drinking water while general water quality standards are less restrictive (Table 4.3-1). Two of the 12 reclaimed lakes had mean fluoride concentrations which exceeded Class I-A levels. One additional reclaimed lake had a maximum that was greater than 1.5 ug/L. Fluoride levels in either reclaimed or natural lakes did not exceed other applicable water quality standards.

Gross alpha activity was the only radiation parameter that exceeded standards. None of the lakes had mean alpha activity levels which exceeded the 15 pCi/L general standard. However, one reclaimed lake, Lake Bradley, had an alpha activity maximum (21 pCi/L) that exceeded these criteria.

Overall, water quality in reclaimed lakes was within the boundaries described by Chapter 17-3 for waters under Class III categorization. Mercury levels above criteria appeared to be ubiquitous within at least the area of this investigation and did not appear to be a problem specific to phosphate mining or mine reclamation. Other trace metals were usually below limits set by either Florida or USEPA standards and did not present themselves as being harmful to native fish or wildlife.

Both ammonia and alkalinity concentrations are a result of the reclaimed lake habitat. Low alkalinity levels are an indication of low mineral content in the water column. Nearly half of the reclaimed and half of the natural lakes had alkalinities lower than standards. Canfield (1981) estimated that 60 percent of the natural lakes in his investigation of 165 Florida lakes had alkalinities less than 20 mg/L as $CaCO_3$.

Ammonia as the un-ionized fraction does not appear in concentrations that are potentially toxic to warm water fish species. Since none of the reclaimed lakes are associated with waste water return from beneficiation facilities (where organic nitrogen compounds are used), the source of ammonia is probably internal to the lakes. High total ammonia concentrations are probably the result of a combination of factors. First and foremost would be the regeneration of ammonia from organic nitrogen products from plants and animals through bacterial decomposition. A second potential source would be the decomposition of terrestrial material in the soil, accumulated prior to inundation. A third source would be the continued decomposition of organic matter once it leaves the trophogenic zone, entering the the anoxic hypolimnetic waters. This source of ammonia would not be readily available to the majority of the biotic community unless stratification broke down during either a wind event or typical fall overturn periods.

One reclaimed lake, Medard Reservoir, included in this current investigation was evaluated during a two-year study by the Southwest Florida Water Management District as a potential water resource (Attardi and Dooris, 1982). This lake is currently being used as a county park with fishing, swimming, hiking, camping and picnic facilities. Attardi and Dooris (1982) concluded that, although certain biological and chemical parameters would be problematical, existing technology would allow treatment of these parameters to meet FDER Class I-A criteria. Since water quality parameters found in Medard Reservoir were comparable to the ranges found for parameters in the other 11 reclaimed lakes, the conclusions of Attardi and Dooris (1982) could also be extended to these other lake systems.

A comparison of water quality conditions in reclaimed lakes with those found in Lake Manatee, a Class I-A water body, indicates that the majority of lakes included in this investigation had nutrient, trace element and radiation levels which were not statistically significantly different from Lake Manatee.

4.4 RECOMMENDATIONS

Potentially harmful conditions sometimes associated with strip-mine operations for certain other ores were not evident during this one-year investigation of 12 reclaimed phosphate lakes. From a nutrient, water quality, radiation and fish and wildlife perspective, reclaimed lakes were found to be equivalent with Florida's natural lakes both within this investigation and as reported in available literature. Phosphate lakes are productive systems with a diversity of habitats. Efforts to exploit the multiple use recreational capabilities of reclaimed lakes, such as found at Medard Reservoir in Hillsborough County and Lake Teneroc in Polk County should be expanded, particularly in areas where unmined or natural lakes are not available.

In order to enhance long-term benefits of reclaimed lakes, reclamation efforts should probably consider lake design features which reduce rather than enhance productivity (i.e., eutrophication). By nature of their origin, reclaimed systems have an abundance of the necessary growth nutrients--nitrogen and phosphorus. Being highly productive, reclaimed lakes attract a variety of waterfowl and other wildlife which provide additional nutrient resources. Significant lake management practices would probably be needed to improve these lakes to a mesotrophic state.

Regulations for lake reclamation should focus not only on improving fish and wildlife protection, but also on water quality conditions to enhance the long-term benefits derived from lakes. Many private and public lake restoration projects currently involve the removal of organic material and, perhaps, making a lake deeper by dredging. The current and proposed rules for mined land reclamation require that reclaimed lake systems have extensive shallow zones, with up to 40-45 percent of the lake area less than 2 m (6 ft.) in depth. Reclamation rules which mandate large, shallow areas (without provision for deeper nutrient sinks) do not appear to be supported by this investigation. In this study, lakes with less than 9 percent surface area less than 2 m in depth had exceptional fish populations (predominantly largemouth bass) and, by observation, afforded a varied habitat for birds and other wildlife. Current and proposed rulings should more adequately consider the circumstances of natural lake eutrophication and the natural aging processes which are well documented for other man-made systems (Ackermann_et_al. 1973). Natural lakes have had thousands of years to develop a basin through the processes of erosion and sedimentation. Reclaimed lakes could also be created for long-term usage, with proper consideration of the physical processes that shape a lake and control its aging process. Although shallow features may be the desired outcome, a lake that is designed to be uniformly shallow will have an abbreviated life span because of sedimentation, erosion and encroachment of aquatic plant communities.

In summary, this study provides support for lake design guidelines. These include relatively deep pockets, creating an irregular lake bottom to provide natural mechanisms for nutrient removal from the water column. Further, reduction of either N or P below inherent levels are not likely without significant increases in the scale of lake management practices. Mine reclamation rules which provide for shoreline slopes, irregular shoreline configuration along with a mixture of relatively deeper and shallower areas would provide for productive fish and wildlife habitat. Shallower lakes with uniform bottom contours do not appear to be the most appropriate for providing for long-term beneficial uses of these water resource areas. Both quantitative and qualitative data from this investigation indicate that reclaimed lakes do not produce or contain harmful or toxic substances which would warrant their isolation from Waters of the State. Thus, integration of reclaimed lakes into other streams, marshes, and wetland systems would not appear to degrade water quality standards nor endanger Waters of the State due to exposure to toxic substances.