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Trophic State of Lakes in North Central Florida

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ABSTRACT

TROPHIC STATES OF LAKES IN NORTH CENTRAL FLORIDA

General limnological and trophic conditions of 55 lakes and ponds in north and central Florida were established over an extensive one year sampling period. Florida lakes are typically shallow and in a sandy terrain. Most of the lakes have soft water, and high organic color is a common but variable property. Trophic conditions range from ultraoligotrophy in the sand-hill lakes of the Trail Ridge region to hypereutrophy in some large drainage lakes in Alachua County and in the Oklawaha River Basin.

Trophic data were analyzed by multivariate techniques, and logical trophic groups derived by cluster analysis. A quantitative index of trophic state (TSI) was derived using 7 trophic indicators, and the TSI values were used to establish quantitative relationships between lake trophic conditions and watershed characteristics. Nitrogen and phosphorus budgets were calculated for the lakes based on land use and population patterns in the watersheds, and critical loading rates were estimated from the budgets and the trophic conditions.

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CHAPTER 1. EUTROPHICATION AND FLORIDA LAKES

A. INTRODUCTION

Although Florida has more than 7500 lakes (Florida Board of Conservation 1969), limnological investigations of these lakes have been few and limited to special interests. Most detailed studies have been centered on a few unusual or recreationally important lakes; for example, Mud Lake (Marion County) (Bradley and Beard, 1969; Iovino and Bradley, 1969), Lake Mize (Alachua County) (Brezonik and Harper, 1969; Keirn and Brezonik, in press) and Lake Apopka (Orange and Lake Counties) (for a review, see Sheffield and Kuhrt, 1970). Yount (1963) has reviewed most pre-1960 limnological studies in discussing some general features of Florida lakes.

However, as a group Florida lakes are almost limnologically unknown. Threatening of the recreational assets of Florida lakes by cultural encroachment and consequent nutrient enrichment has stimulated studies on these lakes. In 1968 the University of Florida Department of Environmental Engineering initiated an extensive survey of the physical, chemical and biological characteristics of 55 lakes in north and central Florida. The investigation had five main objectives: i) to determine the basic limnological features of lakes in the region; ii) to assess the present water quality (trophic state) characteristics of the lakes and provide baseline data for future studies; iii) to evaluate the applicability of the common trophic state indicators to sub-tropical lakes; iv) to provide necessary data to develop an index of trophic state for sub-tropical lakes; v) to study the relationships between lake trophic state and lake watershed conditions influencing trophic state.

B. NATURE OF EUTROPHICATION

Cultural lake eutrophication is an undesirable consequence of the interaction between man and his environment. Many of his agricultural, industrial, domestic and recreational activities are introducing excess nutrients into surface waters, causing significant water quality deterioration. Since fresh water is vital to the total well-being of the environment, man has an obligation to protect his valuable lacustrine resources. However, progress in solving the problem has been retarded by the inherent complexity of the eutrophication process, and considerable vagueness still exists concerning the definition of cause and effect relationships in the overall process (Brezonik, 1969; Putnam, 1969).

It is generally agreed that eutrophication involves nutrient enrichment, and a lake in time responds to this enrichment. This response is reflected in a lake's trophic state (eutrophic condition). However, few efforts have been devoted to quantifying the relationship of eutrophication to trophic state.

One of the problems in the study of lake eutrophication is of a semantical nature; i.e. distinguishing between and defining the causes, symptoms and effects. Considerable literature has been devoted to discussing these concepts. The meaning of the term "eutrophication" has been stated by Hasler (1947) as being, simply, the enrichment of water, be it intentional (cultural) or unintentional (natural). This nutrient enrichment is generally considered as the causal mechanism in the overall eutrophication process. As originally suggested by Naumann (1919) perhaps primary consideration should be given to nitrogen and phosphorus nutrients. The concept of trophic state (degree of eutrophy) is difficult to define. Eutrophic conditions are the consequences or effects of a lake's nutrient enrichment, but there is no way to express this state in simple, quantitative terms. Much of the conceptual difficulty with the idea of trophic state could have been avoided long ago had limnologists defined trophic state in precise terms as a measure either of a lake's productivity or of a lake's nutrient status. Instead the term has been used to refer to both characteristics. While correlated to a degree, productivity and nutrient status are both also functions of other independent phenomena (e.g. hydrology and climate).

Adequate description of a lake's trophic state requires consideration of several different physical, biological and chemical characteristics. For this reason the concept of trophic state is not only multi-dimensional but hybrid, as suggested by Margalef (1958). The trophic state of a lake cannot be measured directly because of its multi-dimensional nature. However, it is evidenced by various symptoms called trophic state indicators. A list of common indicators of trophic state is in Table 1. Reviews of trophic state indicators have been compiled by Fruh *et al*. (1966), Vollenweider (1968), Hooper (1969) and Stewart and Rohlich (1967).

There has been no scarcity of lake classification schemes and a review of such is beyond the scope of this report. Birge and Juday (1927) made a fundamental distinction concerning the origin of dissolved organic matter in lakes. Lakes dependent on internal sources (primary production) were autotrophic and lakes dependent on external sources were allotrophic. Later Aberg and Rohde (1942) related the classical trophic types of lakes in a two-dimensional concept of autotrophy and allotrophy. This general approach was used for the classification purposes in this study and the idealized two-dimensional relationship is shown in Figure 1. Organic color measurements were assumed to be indicative of external-

Table 1. Trophic Indicators and Their Response to Increased Eutrophication[1]

Physical	Chemical	Biological[2]
Transparency (d) (Secchi disc reading)	Nutrient concentrations (I) (e.g. at spring maximum)	Algal bloom frequency (I)
Morphometry (D) (mean depth)	Chlorophyll *a* (I)	Algal species diversity (D)
	Conductivity (I)	Littoral vegetation (I)
	Dissolved solids (I)	Zooplankton (I)
	Hypolimnetic oxygen deficit (I)	Fish (I)
	Epilimnetic oxygen supersaturation (I)	Bottom fauna (I)
	Sediment type	Bottom fauna diversity (D)
		Primary production (I)

[1](I) after parameter signifies value increases with eutrophication: (D) signifies value decreases with eutrophication.

[2]Biological parameters all have important qualitative changes, i.e. species changes as well as quantitative (biomass) changes as eutrophication proceeds.

From Brezonik (1969)

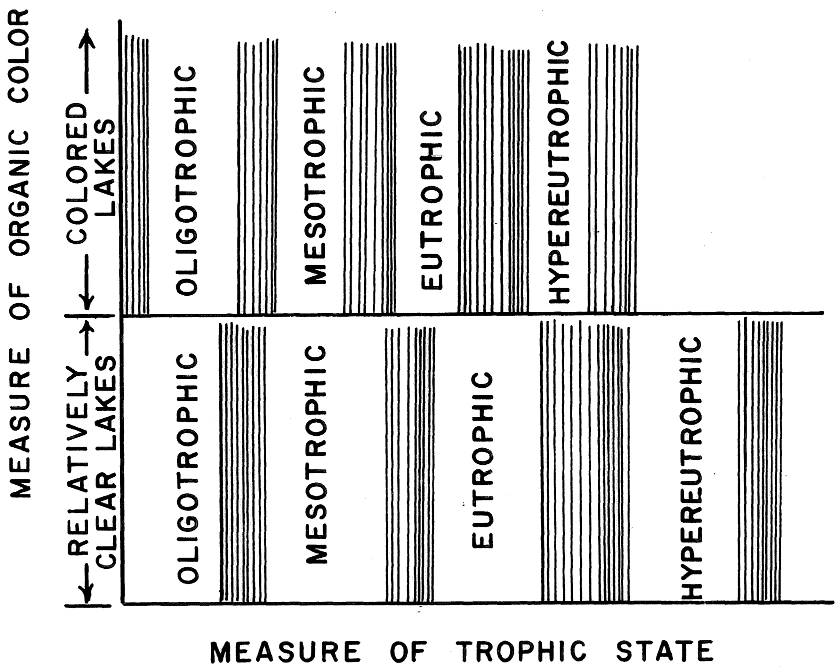

Figure 1. Two-Dimensional Concept of Lake Classification Based on Autotrophy (Internal Organic Production) and Allotrophy (External Organic Input)

source dissolved organic matter and thus denote lake allotrophy. As originally suggested by Hansen (1962), colored and relatively clear lakes were recognized as two fundamentally different lake types. Within each of these types, oligo-, meso-, and eutrophic state subdivisions could occur as determined by some measure of lake trophic state.

C. QUANTIFYING EUTROPHICATION

From a qualitative viewpoint the phenomenon of eutrophication is now fairly well understood. However, for lake management eutrophication control qualitative facts are seldom sufficient. For example, it is generally recognized that increased nitrogen and phosphorus input to a lake will generate increased plant production. But information concerning the precise nutrient loading rates that stimulate excessive production and scum-forming algal blooms is sorely lacking. Lakes are highly complex ecosystems, and the factors controlling nutrient cycling and primary and secondary production in them are at best poorly understood. Furthermore, lakes cannot be regarded as isolated entities, but the interactions of the entire watershed with the lake itself must be taken into account (Hutchinson, 1969). The general significance of various land use patterns and cultural activities as nutrient sources are largely unknown, and in particular the total nutrient loading rates for specific lakes of varying trophic conditions are known with accuracy for only a few cases.

The complexities of the eutrophication problem suggest the utility of systems analysis techniques and of mathematical modeling in properly defining the problem and simplifying it to the extent that solutions become feasible. The theory and nature of mathematical ecosystem models have been discussed in several recent papers and books (Moreau, 1969; Patten, 1969; Watt, 1968; and Thomann, 1971). In general mathematical models can be divided into two types. Analytical or mechanistic models consist of a series of equations (algebraic, or in ecosystem models more commonly, differential) which attempt to explain the fundamental (functional) relationships between certain parameters. For example, differential equation models of primary production have been developed (Patten, 1968) in terms of the basic relationships between photosynthesis and light intensity, nutrient levels, etc. Empirical or statistical models are composed of approximate parameter relationships which are derived by such techniques as regression, multi-variate, or time series analyses. Such models are attractive in management of complex systems where cause-effect relationships are unknown. Empirical models can be useful in predicting system response to changes in environmental conditions, and they can give clues to the significance of the relationships (i.e. the dependency) between variables. However their lack of foundation in causal relationships renders empirically developed models susceptible to misuse and over-extension (to conditions in which they may not be applicable).

The inherent complexities of nutrient enrichment and its attendant effects on lakes imply that a purely deterministic approach is beyond our present capabilities. While functional relationships are known for various lacustrine phenomenon, and relatively sophisticated analytical (i.e. differential equations) models have recently been formulated for even as complicated a process as planktonic production (Chen, 1970; DiToro et al., 1970; Patten, 1968), the much larger scope of the eutrophication problem precludes such approaches at the present time, especially in the general case. For particularly unique and valuable resources like Lake Tahoe or the St. Lawrence Great Lakes, the manpower and time expenditures required for development of such models may be justified. This seems not to be the case for the thousands of smaller and locally important recreational lakes in the U. S. and elsewhere. A simpler, less costly approach is required for these lakes.

Where large numbers of lakes must be managed an attractive possibility is the development of empirical models based on data from a representative sample of the lakes in question. Such management tools as critical nutrient loading rates can be developed by empirical manipulation of basic limnological and watershed information. While empirical models are perhaps not the ultimate answer to eutrophication problems, they can provide direction for further studies and models while simultaneously providing interim predictive capacities required for proper water quality management.

Eutrophication is a multivariable problem and thus lends itself to analysis by multivariate statistical techniques. Beneficial applications of empirical multivariate models can be anticipated in three major areas of eutrophication research, and Table 2 summarizes potential applications in each area. Because of the broad, multi-dimensional concept of trophic state, multivariate techniques seem especially appropriate for the long standing problem of rational lake classification. Trophic classification systems can be useful in several ways: a) for identification [a certain class (name) calls to mind certain distinctive characteristics]; b) for organization of our knowledge concerning the objects (lakes) being classified; c) as the basis for development of theories regarding causes of phenomena associated with a particular class (e.g. what do lakes in a class have in common that might induce their similar behavior), and d) for management purposes (different classes of lakes may have different "best uses" and require different land use and water management controls).

The ill-defined concept of trophic state is in reference to both a lake's general nutrient status and its productivity,

Table 2. Applications of Empirical Models to Quantification of Eutrophication

1. Lake Classification

   a. formation of logical lake groups according to multi-dimensional concept of trophic state

   b. delineation of the set of conditions (ranges for indicator values) defining different trophic groups

   c. determination of redundancy and uniqueness among various trophic indicators

2. Quantification of Trophic State

   a. development of uni-dimensional quantitative trophic state index (TSI)

   b. correlation of classical trophic indicator values with water quality problems

3. Relationship between Lake Trophic State and Causative Factors

   a. regression models of TSI vs. N and P loading

   b. regression models of trophic state vs. population and land use patterns (including basin hydrology and morphometry).

which are not always correlated. The circumstances defining a given state (e.g. eutrophy) are not at all agreed upon by limnologists. No single measure of nutrient status or productivity is satisfactory or sufficient, and the results one obtains depend on which indicators are used. Thus the limnologist is left with the difficult task of subjectively deciding which indicators to use and which to disregard or weigh less heavily.

Reviews on trophic state indicators have been published elsewhere (Fruh et al., 1966; Vollenweider, 1968; Hooper, 1969). Selection of appropriate indicators is a difficult task, but consideration of the following criteria should facilitate the decision: a) an indicator should be quantifiable in order to permit numerical differentiation between lakes of varying trophic states, b) each indicator should be unique (i.e. not measure the same lake characteristic as another indicator), c) an indicator should have fundamental significance in terms of the concept of trophic state (as a general measure of a lake's nutrient and productivity status), and d) an indicator should be sensitive to levels of enrichment and relatively simple to measure. The uniqueness of trophic indicators can be studied by several multivariate statistical methods, including factor analysis (Shannon, 1969; Lee, 1971), principal component analysis (Lee, 1971) and cluster analysis (Goldman et al., 1968; Shannon, 1969). While different geographical regions may require somewhat different treatment, indicators should be widespread properties of aquatic environments in order to insure general interpretability of the generated classes.

The subjectivity involved in forming logical trophic classes from conflicting indicator data can be minimized with certain multivariate techniques such as cluster analysis (Sokal and Sneath, 1963). Another important classification problem is the assignment of lakes outside the original sample group into appropriate pre-established classes. The method of discriminant function analysis (Shannon, 1970; Lee, 1971) is useful in this regard.

In order to predict and evaluate the consequences of watershed management practices on trophic conditions in a lake, trophic state must somehow be quantified. As discussed above, this has heretofore been obviated by the multidimensional nature of the trophic concept. Development of a single numerical index of trophic state from a combination of several important indicators avoids the misleading and fragmentary situation arising when only one indicator is used and the confusion which results when several indicators are considered individually. An index also allows quantitative interpretation of trophic state not otherwise feasible. At least five applications and advantages derive from development of a trophic state index: 1) a numerical index would be valuable in conveying lake quality information to the non- and semi-technical public; 2) an index would be useful in comparing overall trophic conditions between lakes; 3) in the dynamic process of lake succession and trophic change, an index would provide a means to evaluate the direction and rate of changes; 4) an index would facilitate development of empirical models of trophic conditions as a function of watershed "enrichment" factors for predictive and management purposes; 5) a properly developed index would be highly relevant to (i.e. identified with) water quality from a human (or user's) perspective. In contrast to the last point, many indicators (especially qualitative species composition indicators) are largely of academic or research interest.

On the other hand an index can be criticized as having no real physical meaning and as improperly combining diverse parameters (the "can't add apples and oranges" syndrome). However, the first argument is irrelevant; a relative index of trophic state, in so far as it reflects the trophic concept, has value regardless of its interpretability in actual physical terms. With proper selection of indicators and rational development of an index, the second criticism can be largely overcome, but it must be realized that no index can or should be expected to supply the detailed information available in the individual parameters.

Proper selection of indicators is a vital consideration in developing an index of trophic state. Criteria discussed previously with regard to trophic classification apply equally here; that the individual indicators be quantifiable is of course essential. The number of indicators desirable in an index bears some discussion. Generally an index should include sufficient indicators to account for the essential attributes denoted by the broad trophic concept. As fewer variables are used, the index becomes more unstable, i.e. a large deviation from "normal" for a given indicator will tend to affect an index incorporating few variables more than one incorporating many. Use of only one variable could result in very misleading rankings of lake "trophic states." For example if plankton biomass (expressed as packed cell volume, numbers per ml, or chlorophyll a) were the sole measure, lakes with a dense and active macrophyte and periphyton population but low phytoplankton levels would be misranked as oligotrophic. Similar criticisms apply to any other single indicator, and to a lesser extent when only a few indicators are used. However, redundant indicators (i.e. those that measure essentially the same phenomenon as another indicator) should be avoided to prevent biasing the index, i.e. weighing it too heavily toward that aspect or phenomenon. For example, specific conductance and dissolved solids should not both be used in an index since they measure nearly the same thing.

The multivariate statistical method of principal component analysis represents one means of deriving a single numerical trophic state index from a number of indicators. Given such an index, empirical models of trophic state as simple functions of nutrient loading rates or other watershed enrichment factors can then be developed by multiple regression analysis or other appropriate means.

D. COMPOSITION OF THE LAKE STUDY GROUP

Fifty-five lakes from three different areas of north-central Florida were selected for the study (Figure 2). Table 3 lists the lakes by name and code number and gives the surface area and mean depth of each. The study originated in early 1968 with a survey of 33 lakes within Alachua County, in which Gainesville and the University of Florida are located. This group, comprising all accessible and potentially important recreational lakes in the county, exhibits considerable diversity in trophic conditions. Most of the lakes are very shallow, and moderate to high organic color is common, reflecting the large expanses of pine forest in the county. The small lakes typically have outlets only during periods of extended rain whereas the large lakes have permanent outlets. General physical features of the Alachua County lakes and initial chemical and biological measurements were summarized by Brezonik et al. (1969); Clark et al. (1962) have described the geological formations and general land forms which affect the lakes.

In early 1969 lakes from two important north-central Florida lake regions outside of Alachua County were included in the study. Sixteen lakes in the Trail Ridge region of the Central Highlands (east of Alachua County) comprise one of these groups. This scrub-oak, sand-hill region is richly endowed with lakes, most of which are clear and lie within small drainage basins. Lakes in the Trail Ridge area are naturally low in nutrients and subject to only light cultural influence. While still shallow and typically unstratified, these lakes are generally deeper than lakes in the other two groups. Anderson-Cue and McCloud Lakes are being used as model lakes in a separate eutrophication study (Brezonik and Putnam, 1968; Brezonik et al., 1969). Artificial nutrient enrichment of Anderson-Cue Lake has been proceeding since 1967, and the relevant chemical, biological and physical characteristics of both lakes have been monitored since 1966.

The final group consists of six lakes in the upper Oklawaha River Basin northwest of Orlando, Florida. Five of the Oklawaha lakes are joined by watercourses with the general pattern of flow being from Lake Apopka through Lake Dora to Lake Eustis which drains into Lake Griffin. The effluent

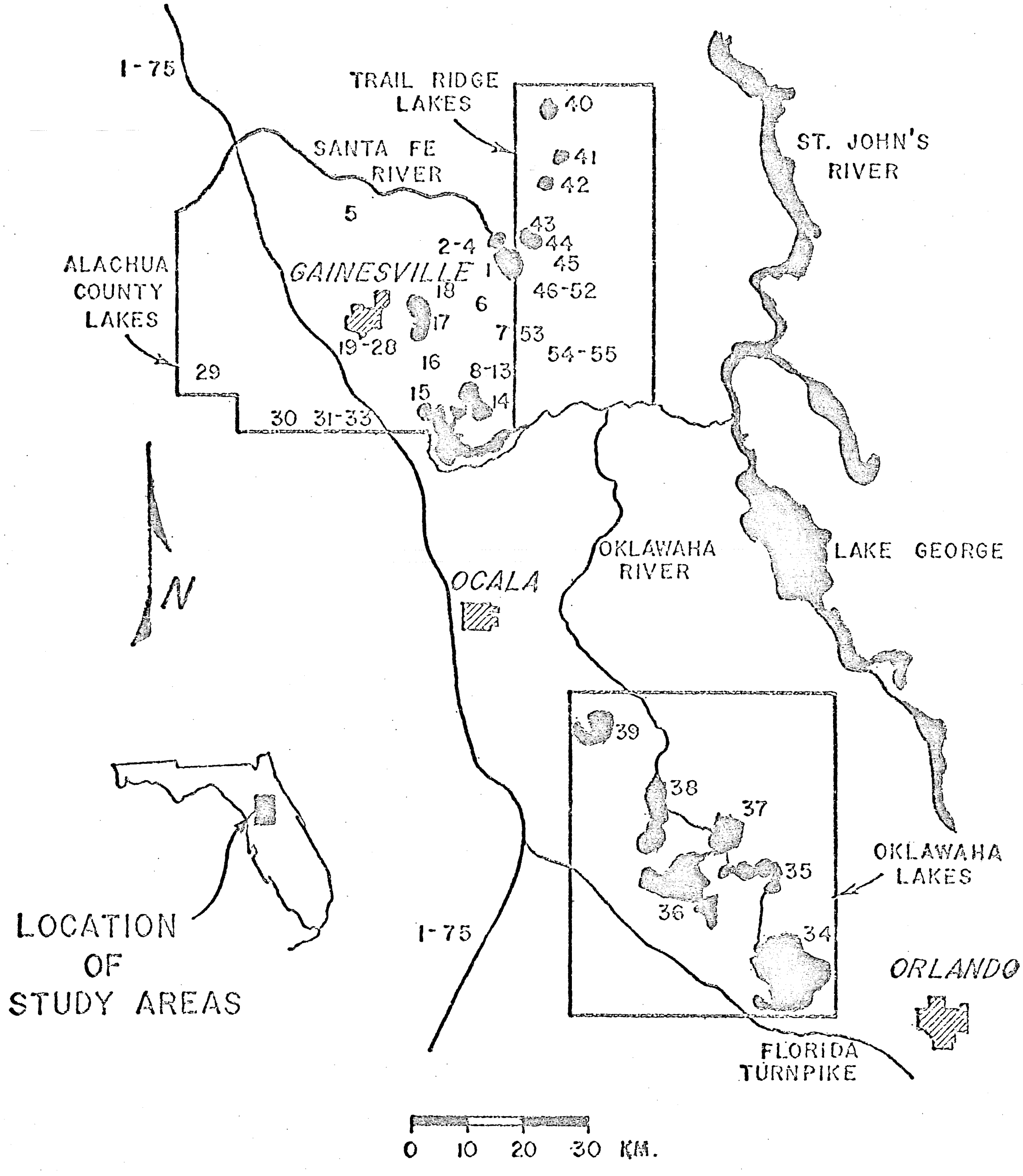

Figure 2. Location of 55 Lakes in Study Areas of North-Central Florida

Table 3. North-Central Florida Lakes in this Study

Lake Number	Lake Name	Mean Depth (meters)	Surface Area (hectares)
(1) ALACHUA COUNTY LAKES			
1	Santa Fe*	5.5	1674
2	Little Santa Fe	4.8	467
3	Hickory Pond	3.4	27
4	Altho	3.6	222
5	Cooter Pond	2.2	86
6	Elizabeth	1.5	27
7	Clearwater	1.5	5
8	Hawthorne*	2.8	20
9	Little Orange	2.8	314
10	(Unnamed) Ten*	3.2	29
11	Moss Lee	3.6	52
12	Jeggord	3.0	64
13	Still Pond	1.1	5
14	Lochloosa	2.9	2235
15	Orange*	1.8	3324
16	Palatka Pond	0.8	4
17	Newnan's*	1.5	2433
18	Mize*	4.0	1
19	Calf Pond	1.6	11
20	(Unnamed) Twenty*	1.9	4
21	Meta	1.6	2
22	Alice*	.9	29
23	Bivin's Arm*	1.5	58
24	Clear*	1.6	3
25	(Unnamed) Twenty-Five	1.0	6
26	Beville's Pond	3.1	2
27	(Unnamed) Twenty-Seven	3.8	4
28	Kanapaha	0.7	82
29	Watermelon Pond	1.5	213
30	Long Pond	1.2	5
31	Burnt Pond	2.2	22
32	Wauberg*	3.8	101
33	Tuscawilla	1.3	162

(cont'd).

Table 3 (cont'd).

Lake Number	Lake Name	Mean Depth (meters)	Surface Area (hectares)
(2)	OKLAWAHA RIVER BASIN LAKES		
34	Apopka	1.3	12412
35	Dora*	3.0	2237
36	Harris	4.2	5580
37	Eustis	4.1	3015
38	Griffin	2.4	3533
39	Weir*	6.3	2301
(3)	TRAIL RIDGE LAKES		
40	Kingsley*	7.3	667
41	Sumter-Lowry	4.8	508
42	Magnolia	8.0	83
43	Brooklyn	5.7	253
44	Geneva*	4.1	692
45	Swan*	4.8	227
46	Wall	2.1	31
47	Santa Rosa	8.1	42
48	Adaho	3.5	41
49	McCloud*	2.0	6
50	Anderson-Cue*	2.0	5
51	Suggs*	2.5	47
52	Long	3.4	104
53	Winnott	5.2	85
54	Cowpen	3.7	240
55	Gallilee	3.5	34

*lakes in 19 lake sub-sample group (see text) from Lake Griffin forms the Oklawaha River. Lake Harris also flows into Lake Eustis. Lake Weir, although in the Oklawaha River basin, does not discharge directly into the Oklawaha River. All six lakes in this group are important recreational lakes; in the past Lake Apopka was among the best known bass fishing lakes in the country. However, considerable cultural eutrophication (and consequently water quality impairment) has occurred in the five connected lakes within recent years. The watersheds of these lakes are utilized primarily for citrus farming, but a large area on the north shore of Lake Apopka is devoted to vegetable farming of muck soils (recovered marshland).

CHAPTER 2. EXPERIMENTAL PROCEDURES

A. SAMPLING METHODS

The sampling schedule used in this study was designed to provide information on the average chemical, biological and physical characteristics of the 55 lakes over a one-year period. Systematic sampling of all lakes began in June, 1969, and all 55 lakes were sampled at four-month intervals up to June, 1970. In order to obtain greater detail on seasonal trends, a 19 lake sub-group from the 55 lakes was sampled at two-month intervals during this same time period. The 19 lakes (denoted by asterisks in Table 3) were selected on the basis of being representative of the different trophic types present in the 55 lake group. It was felt that this subgroup adequately reflected seasonal trends in lake characteristics without sampling all 55 lakes on a closer time interval.

Water samples taken from the lakes for chemical and biological analysis were composites. The small lakes (surface area less than 10 hectares and maximum depth less than 4 meters) were sampled at two stations over depth (surface, middle, and bottom). These samples were combined into a composite sample from which aliquots were taken for major chemical characteristics, for nutrient analyses (preserved with mercuric chloride), for primary production and chlorophyll analysis, and for plankton identification and counts (preserved with formalin). For the larger lakes that were relatively shallow (maximum depth <10 meters) the procedure of sample collection was the same except that three stations were sampled and composited. For the few deep lakes in which stable stratification was evident, samples were composited from the euphotic zone (estimated as twice the Secchi disc reading) for biological analyses and from the entire water column for major chemical analyses, and nutrient analyses were done in profile on uncomposited samples taken at regular depth intervals. Sediment samples were taken by Ekman dredge from the deepest region of the lake.

B. PARAMETERS EVALUATED AND EXPERIMENTAL TECHNIQUES

A total of 6 morphometric, 2 physical, 29 chemical and 6 biological parameters were evaluated for each lake during the project. In addition 11 parameters were evaluated for the lake sediments. Six land use and three population characteristics were evaluated for each lake drainage basin. Table 4 lists all the parameters measured at various times during the project. The physical parameters were measured *in situ*; biological and chemical parameters were determined on the composite samples using standard limnological procedures (see Brezonik *et al*. 1969 for details). Primary production was measured in the laboratory with a "light box" procedure rather than *in situ* in order to standardize light and temperature conditions and offer a more uniform basis of comparison among the lakes.

Bathymetric maps were available for about 20 of the lakes (Kenner, 1964); the remainder were sounded and mapped with a Heath Co. depth sounder as part of the project. Basic morphometric parameters such as volume, mean depth, volume development index and shoreline development index were computed from the bathymetric maps by methods described in Hutchinson (1957).

Land use patterns in the lake watersheds were determined by aerial photograph and topographic map interpretation. Lake watershed areas were outlined and planimetered from United States Geological Survey (Scale: 1/24,000) topographic maps. Recent (1965-1968) aerial photographs (Scale: 1" = 1667') were obtained for each watershed from the Florida Soil Conservation Service Office. Using photogrammetric techniques, areas of various types of land use patterns were delineated and measured. Lake surface areas were also determined from the aerial photographs.

The population in each watershed was characterized in four categories. Residences on a shoreline were classified as immediate cultural units (ICU). Other residences within the lake watershed were categorized as remote cultural units (RCU). The ICU's and RCU's were evaluated from aerial photographs. Residences served by sanitary sewer facilities were not included in the two previous categories. Recent population figures were obtained for all of the municipalities served by sewage treatment plants within each of the lake watersheds. These figures were converted to equivalent cultural units by dividing by a factor of 2.5, which represents the average population of a single rural family residence in

Table 4. Lake and Basin Parameters Evaluated for this Study

Land Use	Population Characteristics
Watershed	
Fertilized cropland	Cultural units[1] on lake shore
Pastured area	Cultural units in rest of basin
Forested area	Sewage treatment plant
Urban area	Cultural units
Unproductive cleared area	
Total watershed area	
Morphometric	
Bathymetric map	Lake surface area
Mean depth	Maximum depth
Shoreline development	Volume development
Physical	
Temperature profile	Secchi disc transparency
Turbidity	
Chemical	
Acidity	Organic nitrogen
Alkalinity	Ortho phosphate
Ammonia	pH
Calcium	Potassium
Chloride	Silica
C.O.D.	Sodium
Color	Specific conductance
Copper	Strontium
Dissolved oxygen	Sulfate
Fluoride	Suspended solids
Iron	Total phosphate
Magnesium	Total solids
Manganese	Zinc
Mercury	
Nitrate	
Nitrite	
Biological	
Chlorophyll *a*	Primary production
Total carotenoids	Algal species diversity
Algal identification and counts	

(cont'd).

Table 4 (cont'd).

Sediments

Ammonia	Volatile solids
Organic nitrogen	C/N ratio
Total phosphate	Iron
Sediment type (visual classification)	Manganese
Benthic organisms	Chlorophyll derivatives
	Total carotenoids

[1]See text for explanation of this term.

the State of Florida (U.S. Bureau of Census, 1961). Cultural units of municipalities discharging sewage effluent directly into a lake were classified as immediate sewage treatment plant cultural units (ISPU). Cultural units of municipalities discharging sewage effluent somewhere else in the watershed were classified as remote sewage treatment plant cultural units (RSPU). The total cultural units (TCU) in the watershed was obtained by summing the cultural units in each of the four categories. Estimates of total watershed population could in turn be obtained by multiplying the TCU by 2.5.

C. MULTIVARIATE ANALYTICAL METHODS

Relationships among the several trophic indicators and watershed eutrophication factors were investigated by a variety of multivariate statistical techniques. This term is used to describe statistical methods concerned with analyzing data collected on several dimensions (variables) on a set of objects or individuals. Some dependency is assumed among the variables so that they are considered as a system. Because of their multi-dimensional nature, these techniques are most conveniently described using vector and matrix notation. Theoretical aspects of these techniques are discussed by Morrison (1967), Sokal and Sneath (1963), and Lee (1971). The applications and computational aspects of the techniques used in this study are described below; see Appendix for a description of the terminology used for vectors, matrices, and multivariate statistics.

1. Cluster analysis is concerned with the problem of classifying N objects (e.g. lakes) into groups based on p variables measured on each object, when the number of groups that best fit the data is not predetermined. Expressed geometrically, the method attempts to distinguish logical groupings of objects in the p-dimensional hyperspace described by the p data attributes of the objects. Figure 3 illustrates a simple bivariate cluster problem involving groups formed by hypothetical data for color and productivity in lakes (cf. Figure 1). Cluster analysis of objects is referred to as a Q-type analysis; a second type which clusters the variables measured on a set of objects is referred to as R-type cluster analysis. Cluster analysis was used in this study to find natural groupings of lakes, i.e. those with similar trophic states or chemical characteristics, as measured by several limnological parameters (indicators) considered simultaneously and weighed equally. Cluster analysis progressively combines a set of objects into a smaller and smaller number of groups according to the degree of similarity among the objects; objects (lakes) with the greatest similarity are joined first.

The starting point for any cluster analysis is the N x

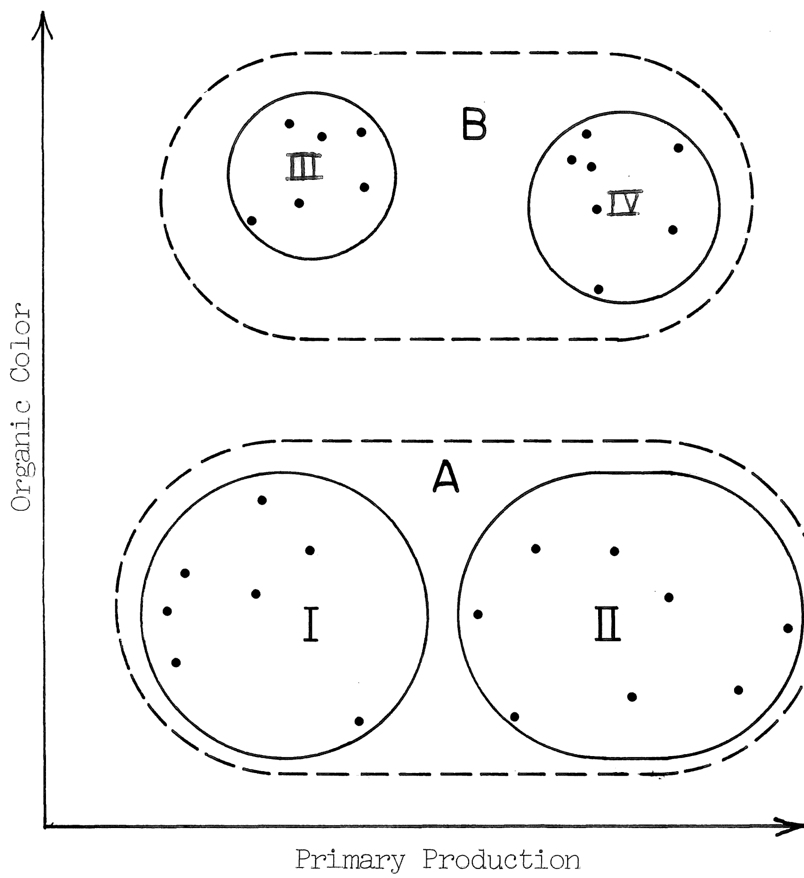

Figure 3. Hypothetical bivariate plot showing clusters formed by data for organic color and primary production in lakes. Solid circles represent clusters formed around 4 groups with good in-group similarity: I. low color, low production; II. low color, high production; III. high color, low production; IV. high color, high production. Dashed lines represent less similar clusters of (A) low color and (B) high color lakes formed later (at higher objective function values).

p raw data matrix X. If it is desired to group objects, the matrix X is normally transformed to the matrix of standardized variates Z since the variables may have been measured in quite different sized units. The standardized data are used to calculate product-moment correlation coefficients for all possible pairs of objects. The resultant N x N symmetric matrix is called the similarity matrix Q, with general element q_{ij} being the correlation between objects i and j considering the p variables measured on each object. The Q matrix represents the starting point of the cluster analysis.

The three basic elements of a cluster analysis are the between-object distances, the clustering criterion and the computational procedure (Padron, 1969). A multitude of methods are available to evaluate the between object distance (see Sokal and Sneath, 1963, for a review); popular distance measures include the correlation coefficient between objects and simple functions of the Euclidean distance. The distance measure used in this project was proposed by Gower (1966):

$$d_{ij} = [2(1-q_{ij})]^{1/2}, \qquad (1)$$

where d_{ij} is the distance between the i-th and j-th objects and q_{ij} is the correlation coefficient or measure of similarity between objects i and j.

Clustering criteria (a measure of the goodness of any given allocation of objects into groups) usually include a measure of within group similarity. In some cases, good within group similarity implies good between group dissimilarity. The clustering criterion used was minimization of an objective function (OF):

$$OF = 500\ (WBAR-BBAR), \qquad (2)$$

where WBAR is the average within group distance and BBAR the average between group distance for any given allocation. The constant is an arbitrary number used to scale the objective function into a convenient range. Using the distance measure in Eq.(1), the minimum value of the objective function in Eq. (2) is -1000, implying complete similarity within groups and complete dissimilarity between groups. A value of zero represents a random grouping of the lakes (where the mean within group and between group distances are equal). Consideration of the OF value for any allocation and its change from a previous allocation offers a means of determining the relative degree of similarity between the two groups or objects joined. Computational procedures are usually heuristic in the interest of solving large problems with an economy of computer time. A clustering algorithm in Fortran IV developed by Padron (1969) was used in the cluster analyses.

2. Discriminant function analysis is a multivariate classification procedure which can be used to assign objects into appropriate pre-established classes. Figure 4 illustrates a simple example involving two groups formed by two variables. Discriminant functions are linear combinations of variables for which the separation between groups is a maximum. The functions contain as many variables as there are dimensions to the objects. When the population is divided into two mutually exclusive groups, one discriminant function is sufficient to determine the group to which an object belongs.

Fisher (1936) first formulated the method for the separation of two groups of objects. This technique was later generalized by Anderson (1958) so that linear discriminant functions could be evaluated for distinguishing between multiple groups.

Let $\pi_1, \pi_2 \ldots. \pi_m$ be the m populations under consideration. In this study the populations, π_i, represented the different trophic states to which a lake may belong. Associated with each population are the multivariate probability density functions $p_1(\underline{x})$, $p_2(\underline{x}) \ldots. p_m(\underline{x})$ ($\underline{x}$ is an observation vector of p variables). It is desired to divide the space of observations into m mutually exclusive and exhaustive regions $P_1, P_2 \ldots. P_m$. If an observation falls into P_i it is assumed to be a member of population π_i. Assume the distribution of π_i to be normal with mean vector $\underline{\mu}_i$ and covariance matrix Σ. The covariance matrix Σ is assumed to be common for all i populations. If the costs of misclassification are equal and the a priori probabilities q_i of drawing an observation from π_i are known, the region P_i is defined by those $\underline{x}$ satisfying

$$P_i: \mu_{ik} \geq \log \frac{q_k}{q_i}, \; k=1,2,\ldots.,m; k \neq i, \qquad (3)$$

where μ_{ik} is the linear discriminant function related to the i^{th} and k^{th} populations. The a priori probabilities of $\underline{x}$ being in population i or k are given by q_i and q_k, respectively. The discriminant function μ_{ik} is given by

$$\mu_{ik} = \frac{\log P_i(\underline{x})}{\log P_k(\underline{x})} = [\underline{x} - \tfrac{1}{2}(\underline{\mu}_i + \underline{\mu}_k)]' \Sigma^{-1} (\underline{\mu}_i + \underline{\mu}_k). \qquad (4)$$

Usually $\underline{\mu}_j$, $\underline{\mu}_k$ and Σ are not known and $\underline{\bar{x}}_i$, $\underline{\bar{x}}_k$ and S are used as their estimates ($\underline{\bar{x}}_i$ is the vector of sample means of the p variables and S is the sample covariance matrix). The linear

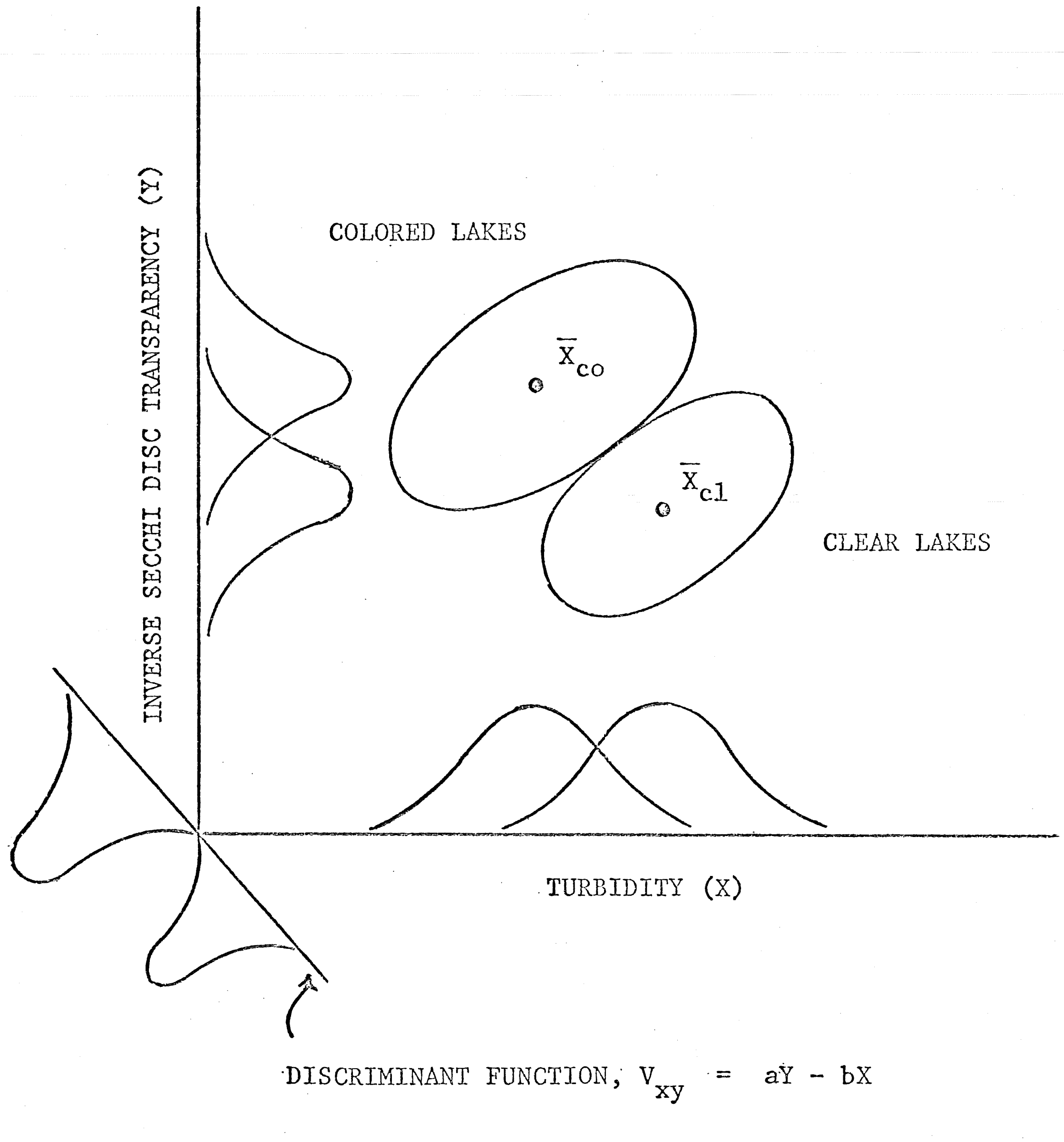

Figure 4. Hypothetical Two-Dimensional Plot Showing Relationship Between Discriminant Function and Two Clusters of Inverse Secchi Disc Transparency and Turbidity Data.

Clusters represent the envelopes of points (not shown) for colored and clear (uncolored) lakes. Color decreases Secchi disc visibility; hence colored lakes tend toward higher (1/SD) values for a given turbidity. Bell-shaped curves represent idealized distribution on a given axis for data points within each cluster.

discriminant function then becomes v_{ik} and is given by:

$$v_{ik} = [\underline{x} - \tfrac{1}{2}(\underline{\overline{x}}_i+\underline{\overline{x}}_j)]'S^{-1}(\underline{\overline{x}}_i+\underline{\overline{x}}_k) \qquad (5)$$

For sufficiently large samples v_{ik} is considered to be a good estimator of μ_{ik}. If the a priori probabilities q_k and q_i are equal in Eq. 3, the region P_i is defined for $\mu_{ik}>0$.

The method used to calculate the linear discriminant functions in this study was the stepwise procedure (BMD07M) described in Biomedical Computer Programs (Dixon, 1968). In the stepwise procedure variables are brought into the discriminant function one at a time based on an 'F' test for significance. In essence, the most powerful discriminatory variables are entered into the discriminant function first and less important variables at later stages.

3. Principal component analysis is used to examine the dependence structure of multivariate data and reduce the dimensionality of the data by expressing the original observation variables in terms of fewer component variables, which are linear functions of the observation variables. A simple bivariate example of principal component analysis is shown in Figure 5. Principal component analysis was used to derive indices using the first principal components extracted from trophic state correlation matrices of trophic indicators measured on the lakes. When the variables are expressed in different units, the matrix of sample correlations (R) between all possible pairs of variables is used as the starting point in the analysis. If p variables are involved, R is a p x p symmetric matrix.

The first principal component y_1 of the correlation matrix R is the linear combination

$$y_1 = \underline{a}_1'\underline{z}, \qquad (6)$$

where $\underline{a}_1'$ is the transpose of the first characteristic vector (eigenvector) of R associated with the largest characteristic root λ_1 (eigenvalue) of R, and $\underline{z}$ is the vector of standardized variables. The variance of y_1 is given by λ_1. The j^{th} principal component y_j is given by

$$y_j = \underline{a}_j'\underline{z}, \qquad (7)$$

where $\underline{a}_j$ is the transposed eigenvector associated with the j^{th} largest eigenvalue λ_j of R.

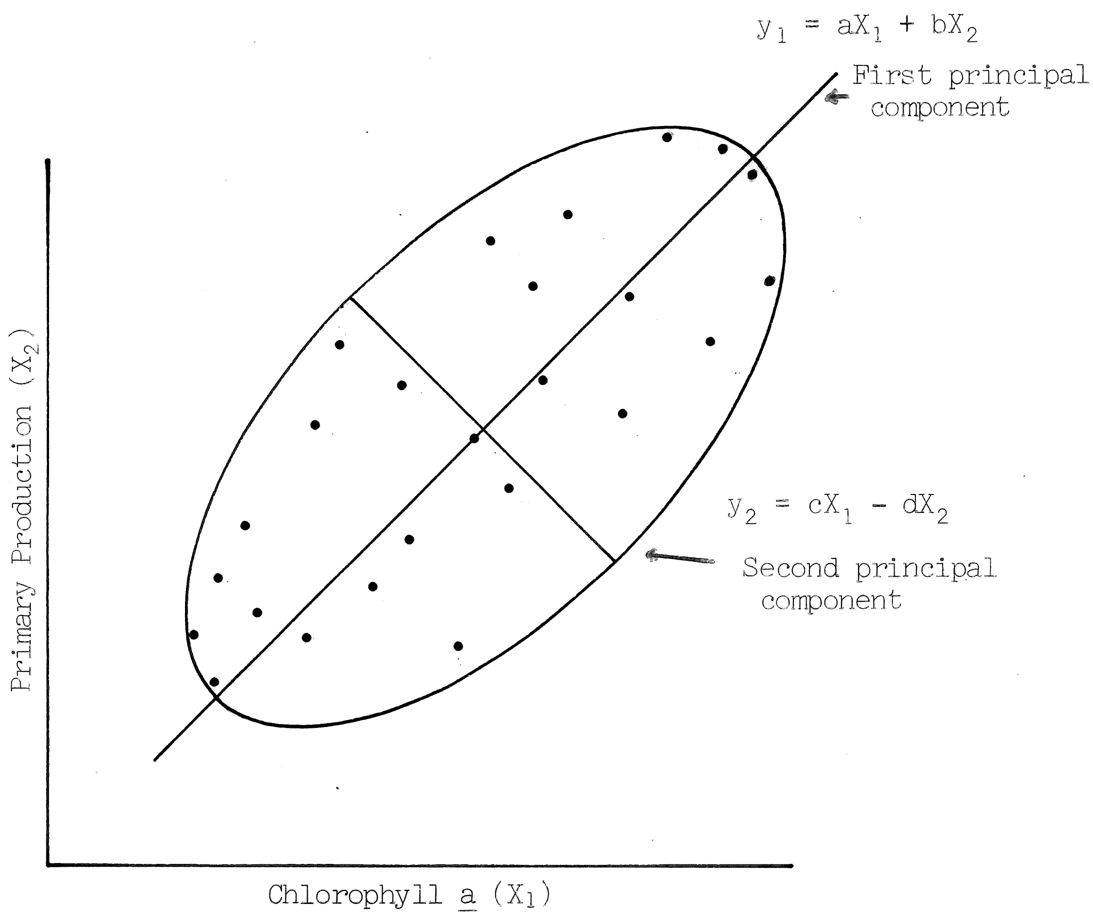

Figure 5. Hypothetical bivariate plot of primary production and chlorophyll data showing relationship of first and second principal components to original variables. First component is defined to pass through long axis of elliptical sample cluster configuration, giving maximum variance of the cluster; second component passes through short axis of sample cluster, giving maximum variance in that direction.

In principal component analysis the main objective is to explain as much of the variance in the original observations as possible with a minimum number of components. The first principal component is that linear combination of variables which explains the maximum variance in the original data; the second principal component is the linear combination of variables explaining as much of the remaining variance as possible, and so on. As many component variables as original variables can be derived, at which point all the variance is explained, but this subverts the purpose of the procedure (i.e. reducing the dimensionality of the data). The proportion of the total variation that any one component y_j explains is given by

$$\frac{\lambda_j}{tr(R)} \quad \frac{\lambda_j}{p}, \tag{8}$$

where λ_j is the j^{th} eigenvalue of R and tr(R) is the trace of R (sum of the diagonal elements). The trace of R is also equal to p (the number of variables) since each diagonal element of R has a value of unity.

Theoretical and computational aspects involved in calculating principal components from covariance or correlation matrices are presented by Morrison (1967). The BMDX 72 program from the Biomedical Computer Programs Library (Dixon, 1968) was used to perform the analyses in this project.

4. Canonical correlation is used to analyze the statistical relationships between two sets of variables considered in vector form. In this project canonical analysis was used to study the relationships between a trophic state vector consisting of seven trophic indicator variables, and a eutrophication factor vector, consisting of several land use and population characteristics of the lake watersheds. The advantage of canonical correlation over conventional multi-regression analysis is that the former allows one to study relationships between two sets of variables without defining any one variable as dependent and without assuming orthogonality (independence among the variables). This method determines the linear combination of the variables within each set which produces the maximum correlation coefficient between the two sets. Thus canonical analysis can be used to determine the dependency structure, i.e. the nature and extent of covariation, between two sets of variables.

Consider a random vector $\underline{x}$ composed of observations on p variables with a covariance matrix Σ. This vector $\underline{x}$ may be partitioned into two subvectors $\underline{x}_1$ and $\underline{x}_2$ with p_1 and p_2 components, respectively. Usually the variables of each subvector will have some common feature, e.g. let $\underline{x}_1$ consist of several trophic state indicators for a lake and the variables $\underline{x}_2$ be various eutrophication factors that influence trophic state. For convenience, it is assumed that $p_1 \leq p_2$. From the population, N independent observation vectors are drawn and the p x p sample covariance matrix S calculated. It is assumed that $N \geq (p_1 + p_2 + 1)$ and S is the unbiased estimator of Σ. The covariance matrix may be partitioned into submatrices in a manner similar to $\underline{x}$ where

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{12} & S_{22} \end{bmatrix}, \tag{9}$$

where the dimensions of S_{11}, S_{12} and S_{22} are $p_1 \times p_1$, $p_1 \times p_2$ and $p_2 \times p_2$, respectively. Once a testing procedure (described by Morrison, 1967) indicates a significant dependence between $\underline{x}_1$ and $\underline{x}_2$, the method of canonical correlation may proceed.

In canonical correlation analysis the following question is proposed. What are the linear compounds

$$\begin{aligned} \mu_1 &= \underline{b}_1' \, \underline{x}_1, \ldots\ldots, \mu_t = \underline{b}_t' \, \underline{x}_1 \\ v_1 &= \underline{c}_1' \, \underline{x}_2, \ldots\ldots, v_t = \underline{c}_t' \, \underline{x}_2 \end{aligned} \tag{10}$$

with the property that the sample correlation of μ_1 and v_1 is greatest, the sample correlation of μ_2 and v_2 greatest among all linear compounds uncorrelated with μ_1 and v_1 and so on for $t = \min(p_1, p_2)$ possible pairs? These pairs of linear compounds are called canonical variates. It should be noted that the correlation matrix R could have been partitioned in a similar manner to S resulting in similar canonical correlations. However, canonical variates based on the correlation matrix are dimensionless and are expressed in terms of the standardized variables. The BMDO6M program (Dixon, 1968) was used to perform the canonical correlation analyses.

5. Multiple regression analysis may be described as a method to predict the value of one variable (Y) from the values of other variables (X_i). Variable Y is assumed to be dependent on the values of the independent variables X_i. Strictly speaking multiple regression analysis is not a method of multivariate analysis since variates are considered interdependent in the latter, and no single variable can be considered as the "dependent variable." The general model of (linear) multiple regression may be written as

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \ldots b_p X_p, \qquad (11)$$

where Y is the dependent variable, $X_1, X_2, \ldots X_p$ are independent variables, b_0 is the intercept value, and $b_1, b_2, \ldots b_p$ are regression coefficients. The variables may be raw data values or may be transformed values of the raw data. The principle value of multiple regression analysis lies in its predictive capacity (i.e. prediction of Y values from a measured set of X_i). The technique was used to evaluate statistical relationships between the trophic state index (TSI) and eutrophication factor (land use and population) variables. The BMDO2R program (Dixon, 1968) was used with the zero intercept (i.e. $b_0 \equiv 0$) option. This option was used since it is desirable to have a situation where the TSI is equal to zero when all the eutrophication factors are zero. The computer program is a stepwise multiple regression procedure and adds the variables to the equation in decreasing order of their statistical significance (i.e. their partial correlation with the dependent variable).

CHAPTER 3. LIMNOLOGICAL RESULTS

Detailed descriptions of the morphometry and physical features of the lakes in the study group are the subject of another report in this series. Similarly the chemical and biological limnology of the lakes will be described in detail in a third report (Brezonik, in preparation). This chapter will describe the limnological results in general terms as background information for analysis of eutrophication factors and lake trophic conditions in the following chapters.

A. MORPHOMETRIC AND PHYSICAL FEATURES

The geology of Florida is dominated by a limestone substratum underlying the entire peninsula. In north-central Florida the upper limestone deposits are of Eocene to Miocene age and are covered by more recent deposits of sand and clay. Thickness of the overlying formations ranges from a meter or so (e.g. in southern Alachua County) to over 30 meters. The limestone deposits give rise to a karstic topography throughout the peninsula with artesian springs, sink holes and solution lakes as prominent features of the landscape.

The morphometry and physical features of Florida lakes are to a large extent determined by the geological structure and resulting topography. Table 5 summarizes these features for the 19 lakes sampled bimonthly. In general the lakes are shallow, and maximum depths of more than 10 m are uncommon.

Table 5. Morphometric Features of Selected Florida Lakes

LAKE	SURFACE AREA (hectares)	MAXIMUM DEPTH (z_m) (m)	MEAN DEPTH ($\bar{z}$) (m)	D_V [a]	D_L [b]
Santa Fe	1674	8.8	5.5	1.88	1.24
Hawthorne	20.4	4.3	2.8	1.95	1.10
#10	29.3	4.6	3.2	2.09	1.10
Orange	3324	3.0	1.8	1.80	1.63
Newnan's	2433	4.0	1.5	1.13	1.20
Mize	0.86	25.3	4.5	0.53	1.19
#20	3.7	3.4	1.9	1.68	1.28
Alice	28.6	1.5	0.9	1.80	1.66
Bivin's Arm	58.4	1.9	1.5	2.37	1.48
Clear	3.4	2.7	1.6	1.77	1.40
Wauberg	101	5.2	3.8	2.19	1.13
Dora	2237	4.9	3.0	1.84	2.24
Weir	2301	9.8	6.3	1.93	1.70
Kingsley	667	22.9	7.3	0.96	1.01
Geneva	692	8.8	4.1	1.40	1.58
Swan	227	9.4	4.8	1.53	1.37
McCloud	5.6	3.7	2.0	1.62	1.17
Anderson-Cue	4.5	4.6	2.0	1.30	2.12
Suggs	47.2	3.7	2.5	2.03	1.22

[a]Development of volume index = $3\bar{z}/Z_m$.

[b]Development of shoreline index = $L/2\sqrt{\pi A}$.

Mean depths for all 55 lakes range from about 0.7 to 8.1 m, and maximum depths range from about 1.0 to 25 m. Most of the shallow lakes have U-shaped basins; i.e. the lake basin walls are concave toward the water. The deeper lakes generally are more cone-shaped; in the deepest lake of the survey, Lake Mize, the lake basin walls are considerably convex toward the water. The trend can be seen by examining the volume development indices (D_V) in Table 5. Index values less than 1.0 indicate a convex (toward the water) lake basin while values greater than 1.0 are indicative of U-shaped basins. Lakes with a D_V of 1.0 have a basin similar in form to that of a cone (Hutchinson, 1957; Zafar, 1959).

Many small Florida lakes are hydraulically perched; i.e. their connection to groundwater is with a perched water table located above and not directly connected to the principal aquifer in the peninsula, the Floridan aquifer. Most of the small Alachua County and Trail Ridge region lakes are seepage (Birge and Juday, 1934) with no visible outlets or permanent inlets, and water levels may vary as much as several meters between dry and wet periods. Thus few lakes have a definite land-lake interface, and the shorelines may be intermittently submerged land. Water levels in the larger drainage lakes (e.g. Newnan's, Orange and Lochloosa Lakes, Alachua County) frequently are structurally controlled so that water level variations are much smaller. Some of the Trail Ridge lakes (e.g. Kingsley, Swan, Brooklyn), because of their occurrence in a region of very sandy soil, do possess fine natural sandy beaches in spite of the periodically wide fluctuations in water levels.

Nearly all the natural lakes in Florida have been derived or substantially modified by limestone solution processes. Numerous lakes are situated in sink-hole depressions formed by dissolution of underlying limestone (Stubbs, 1940; Hutchinson, 1957). In some cases lake basins have originated by other mechanisms (e.g. fluviatile action) but solution activity has substantially modified the original basin (e.g. Lake Tsala Apopka in Citrus County; Cooke, 1939). Many small and some larger lakes are simple dolines which tend to have simple circular basins. Perhaps the best example is Kingsley Lake (Clay County), an almost perfectly circular basin (shoreline development index, S_D=1.01) about 3 km in diameter. Lake Santa Rosa (S_D=1.09), a lake 0.8 km in diameter in Putnam County, is another example. S_D is defined as the ratio of the actual length of a lake's shoreline to the minimum length (i.e. the circumference of a circle) which would enclose an area equal to that of the lake surface. Other lakes are complex dolines with more irregular shorelines. For example, Lake Brooklyn (Clay County) consists of at least 9 separate solution basins and has an S_D=2.37, and Cowpen Lake (Putnam County) with an S_D=1.80 consists of at least 5 basins.

The shallowness of Florida lakes suggests that thermal stratification would be unimportant in these lakes, and indeed most lakes do not exhibit classical Birgean thermoclines with stagnant hypolimnia as is common in temperate lakes. Eight lakes are sufficiently deep to develop stable stratification and oxygen deficient bottom waters; these are Lakes Mize (Brezonik and Keirn, in press), Kingsley, Magnolia, Moss Lee, Santa Rosa, unnamed lakes numbered 20 and 27, and Beville's Pond. Climatic circumstances favor a long period of stratification; for example Lake Mize is stratified from February or early March till November. The surprising feature of some of the lakes is the shallowness at which stable thermal stratification can occur. Lake No. 20 is only about 4 m deep but the temperature in the bottom meter is several °C cooler than the minimum temperatures in the region during summer. Lake No. 27 is only about 7 m deep, yet it has a pronounced thermocline between 2.7 and 4.2 m (9-12 ft), and the bottom water was 11.4°C in June, 1969, which is only 1°C warmer than the mid-winter bottom temperature. Clearly morphometric factors are important in producing the thermal stability of these lakes. Both are fairly small (1.5-4.5 ha), are in a rolling terrain and are surrounded by high pine forest. Thermal stratification is not limited to the summer months; temporary stratification can develop as a result of the highly changeable weather that occurs during January and February. While none of the lakes are meromictic, low to zero, dissolved oxygen values in the bottom waters of Beville's Pond, Lake No. 27, and Lake Mize throughout the year indicate the bottom waters circulate rather incompletely even during winter.

At least 6 other lakes among the 55 exhibit incipient thermal stratification. Typical of these are Lake Wauberg and Hickory Pond. Stratification develops only near the bottom in these shallow lakes, preventing the formation of a distinct hypolimnion, but the bottom water temperatures during summer are at least as cool as the nocturnal minima in the region so that fairly stable conditions can be assumed. Low dissolved oxygen values in the bottom waters of these lakes also imply stable stratification. These lakes are somewhat larger or less wind protected by forest than the small lakes discussed previously. Size is obviously an important factor in determining whether stratification will occur in a lake. For example, neither Lake Santa Fe (surface area = 1650 ha, Z_m = 8.8 m) nor Lake Weir (surface area = 2300 ha, Z_m = 9.8 m) have shown any evidence of stratification on any sampling date.

Many other shallow lakes show signs of stratified conditions even in the absence of a typical thermocline. Temperature differences of 4-5°C from top to bottom in lakes that are only 2-4 m deep are common during summer, but the decline is continuous with depth rather than confined to a narrow layer (also see Yount, 1961). At surface temperatures of

25-30°C, temperature differences of a few degrees are sufficient to impart considerable stability to the water column (Hutchinson, 1957). Bottom temperatures are greater than regional nocturnal air temperatures during summer, and stratification thus is not highly stable. However, oxygen depletion in the bottom waters of several lakes implies a metastable circumstance (i.e. mixing is not a daily phenomenon).

B. GENERAL CHEMICAL CHARACTERISTICS

In order to determine general patterns in chemical composition among the lakes (i.e. classify the lakes into distinct chemical types), a cluster analysis was performed on data for six basic chemical parameters for the 55 lakes. The parameters considered were pH, alkalinity, acidity, conductivity, color and calcium, and mean values for each lake over the sampling period were used for the analysis. The resulting cluster diagram is shown in Figure 6.

The 55 lakes fall into four easily interpreted groups: (i) acid colored lakes, (ii) alkaline colored lakes, (iii) alkaline (hardwater) clear lakes; and (iv) soft, clear lakes. A comparison of the six chemical characteristics in these 4 lake types is shown in Table 6. Assuming the 55 lakes are a reasonable cross-section of the lakes in north-central Florida, several conclusions derive from the results in Figure 6. Slightly less than 50 percent of the lakes are classified as colored, and the bulk of these are also acidic. Thus color would appear to be a common feature of Florida lakes. However, all but three of the colored lakes lie in Alachua County, which fact both implies a rather heterogeneous geography in the region and suggests that caution should be observed in extrapolating the statistics of the sample group to the population of Florida lakes.

Several other regional differences can be noted. The alkaline-colored group is composed entirely of lakes from Alachua County. Three (Newnan's, Orange, Lochloosa) are large connected drainage lakes; the other two are seepage or semi-drainage. All five lakes are moderately enriched. The alkaline clear group includes the five culturally enriched lakes of the Oklawaha chain plus the small eutrophic lakes of Alachua County. The soft water clear lakes are located primarily in the Trail Ridge region and eastern Alachua County, which geographically comprise one topographic unit.

One conclusion that seems a valid extrapolation is that Florida lakes generally have soft water; only the 12 alkaline clear lakes can be considered to exhibit hardness, and even here the degree is moderate. This may seem contradictory in

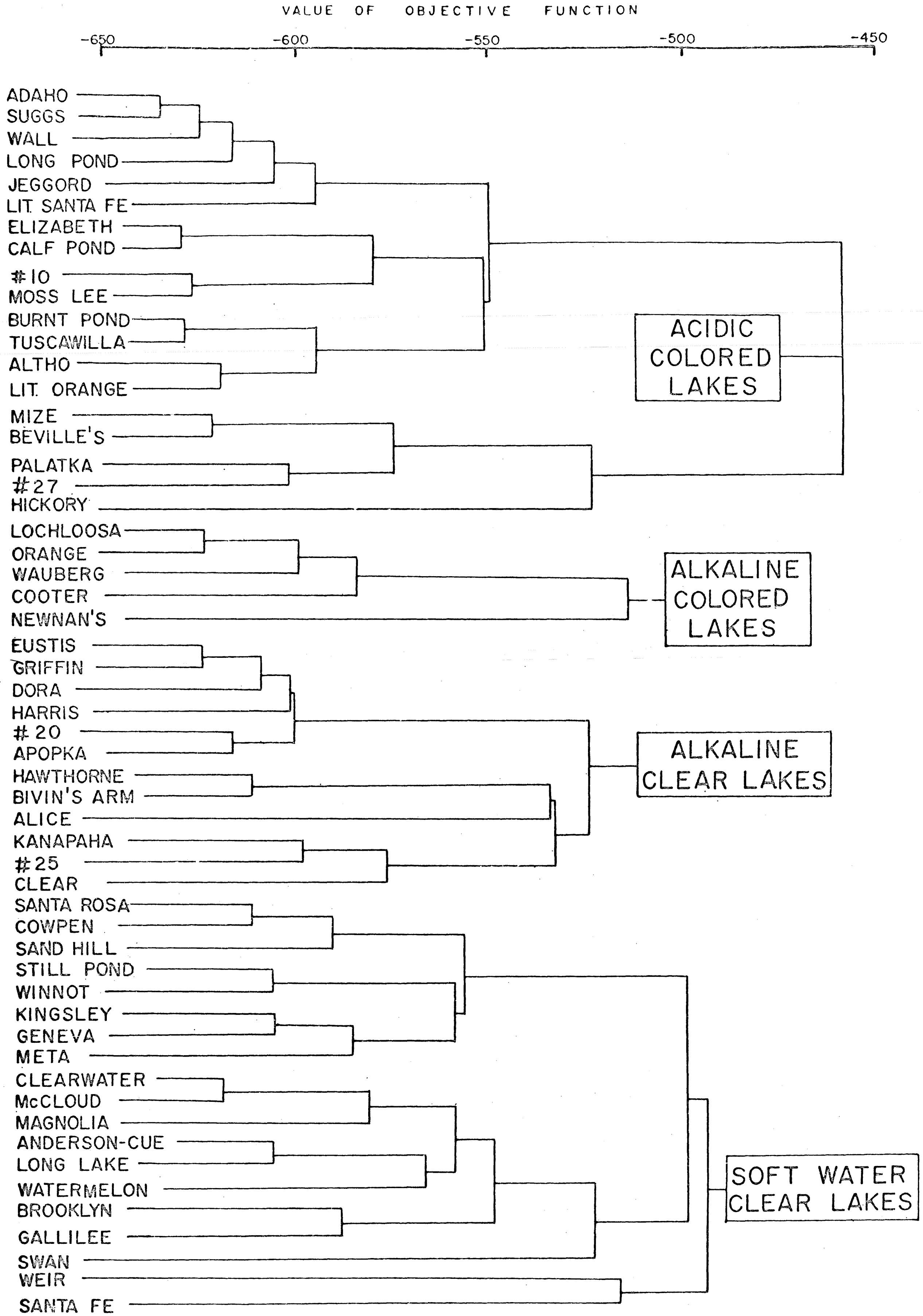

Figure 6. Clustering Diagram of Fifty-Five Florida Lakes Considering Six Chemical Characteristics

Table 6. Selected Chemical Characteristics of Four General Lake Types

Characteristics	Colored-Acidic	Colored-Alkaline	Clear-Alkaline	Clear-Soft Water
pH	5.66[a]	7.63	8.38	5.83
Acidity (mg/l as $CaCO_3$)	7.31[b] 6.64[c]	1.18 .47	1.00 1.27	2.00 .96
Alkalinity (mg/l as $CaCO_3$)	2.36 3.37	11.69 6.04	92.14 39.91	2.80 6.42
Conductivity (μmho/cm)	45.8 10.1	70.0 11.9	249 123	48.2 25.6
Color (mg/l as Pt)	220 121	114 45	60 30	17 19
Calcium (mg/l)	3.3 1.6	6.9 1.5	36.8 16.2	3.0 2.2

[a]denotes median value

[b]denotes mean value

[c]denotes the standard deviation

view of the solution origin of the lakes and the abundance of hard water springs in Florida, but few Florida lakes are spring fed. Rather, most of the lakes receive the bulk of their water either directly from precipitation or by surface and subsurface runoff from the sandy, low calcareous soils. In fact several of the hard water lakes are not naturally calcareous but have hard water because of cultural effects, i.e. the influx of ground water as treated sewage or septic tank drainage.

The mean and median values of the chemical parameters in Table 6 indicate highly distinct and readily apparent differences among the 4 lake types, perhaps much greater than when the lakes are considered individually (as the large standard deviations for some parameters would suggest). The acidic-colored lake group has a much higher mean color than the alkaline-colored group (220 to 114 mg/l as Pt), and the high color probably contributes to the low pH values. Color concentrations as high as 700 mg/l have been found in some lakes (e.g. Lake Mize). Color certainly contributes to acidity (cf. acidity values of the acidic-colored and clear-soft water groups, both of which have acid pH values). Color is the only parameter which has a significantly different value in each of the 4 types and as such appears to be an important chemical characteristic for distinguishing between the lake types.

C. PHYTOPLANKTON AND MACROPHYTE CHARACTERISTICS

Algal identification and enumeration was done on all 55 lakes at each sampling. Because of year-round favorable growth conditions (solar radiation and temperature), some of the fertile lakes such as Apopka, Bivin's Arm and Dora exhibit virtually continuous algal blooms. However maximum bloom conditions usually obtain during summer. Lake Apopka has exhibited phytoplankton blooms of 88,000 cells/ml or higher, predominated by blue-green genera such as *Lyngbya* and *Microcystis* and green genera such as *Pediastrum* and *Scenedesmus*. Blooms of 32,000 cells/ml or more have been found in Lake Dora. Newnan's Lake, a colored eutrophic lake, has summer populations predominated by blue-green algae (*Microcystis*, *Anabaena*, *Spirulina*). In winter this lake usually produces an extremely dense bloom of *Aphanizomenon*, which fixes nitrogen at high rates (Brezonik and Keirn, unpublished data). However this alga is not present in the lake during other seasons of the year and is not a common constituent of the phytoplankton in other eutrophic lakes. *Microcystis* and *Anabaena* are the summer bloom formers in Bivin's Arm. The latter organism is found in all lakes in which nitrogen fixation has been detected, and seems to be the primary algal agent for this process in all the lakes except Newnan's Lake.

Oligotrophic lakes have typically low algal populations. For example, in Swan Lake (a clear soft water, oligotrophic type) a summer 1969 population of about 36 organisms/ml was dominated by the diatoms *Synedra* and *Navicula* and the green alga *Sphaerocystis*. *Dinobryon* and *Synura* (class Chrysophyceae) are common in the low pH, low ionic strength waters of the soft water clear (oligotrophic) lakes as are a variety of Desmidaceae (e.g. *Staurastrum*, *Closterium*, and *Cosmarium*).

Diatoms are comparatively rare in the plankton of Florida lakes, especially in the oligotrophic soft water lakes. Low silica concentrations in Florida lakes may in part account for this distribution. An exception to this general trend is Lake Apopka, which normally supports a high (although not usually dominant) population of diatoms, including *Melosira*, *Tabellaria*, and *Navicula*, and perhaps not coincidentally has one of the highest silica concentrations (3.7 ppm) of the 55 lakes. Bivin's Arm with a mean silica content of 1.8 ppm also supports a spring bloom of diatoms (Maslin, 1970).

The dominant primary producers in a number of the 55 lakes are floating macrophytes. For example, Lake Alice, on the University of Florida campus was until recently covered almost entirely by a dense crop of water hyacinth (*Eichornia crassipes*). While a faculty-student effort succeeded in mechanically clearing this lake (at least temporarily), the plant is common in canals and other lakes (e.g. Lakes Tuscawilla and Apopka). Chemical spraying is used to control the plant in a number of lakes including Bivin's Arm and Lake Apopka. Duckweed (*Lemna minor*) partially covers the surface of Lake No. 27 throughout the year, while perhaps one-third of Beville's Pond is covered by *Salvinia* during the summer months. Such growths limit light penetration, drastically reducing phytoplankton populations, and under severe conditions may inhibit oxygen transfer from the atmosphere to the water.

D. SEDIMENTS

Florida lakes have a wide variety of sediment types, including sand, peat, and sludge-like (ooze) deposits. In some of the oligotrophic lakes a light nearly pure sand bottom occupies most of the lake bottom, suggesting the geological newness of these lakes. Organic deposits in the lakes range in color from light brown (peat) to nearly black (ooze) and the sediment consistency similarly covers a wide range with large fragments of plant remains evident in peat sediments and very fine, slowly settling particles in some of the oozes. In many of the lakes there is no defined sediment-water interface. Rather a gradation from thin suspensions of sediment to more compact strata occurs often over depths of a meter or more. This characteristic makes sampling of bottom water (and surface sediments) rather difficult. In shallow lakes the suspended sediments undoubtedly become mixed with the overlying water during periods of wind stress, and considerable nutrient exchange is thus effected. The carbon: nitrogen ratios in nearly all the sediments are greater than 10 indicating a "dy" type of sediment in Hansen's (1962) terminology. A crude correlation also exists between C/N ratio and trophic conditions. The most eutrophic lakes have C/N ratios in the range 10-15 and oligotrophic lakes have generally higher ratios, but considerable scatter occurs when all 55 lake sediments are considered.

CHAPTER 4. CLASSIFICATION AND QUANTIFICATION OF TROPHIC CONDITIONS IN FLORIDA LAKES

As discussed in Chapter 1, eutrophication and trophic state are extremely complex, multivariable phenomena. At present our understanding of them and their interrelationships is primarily qualitative. A broad effort to quantify these relationships was made using the statistical techniques described in Chapter 2 and the collected limnological and watershed data. The analyses were applied to three major aspects of eutrophication research listed in 1) the long standing problem of rational classification of lakes according to trophic state, 2) quantification of the presently nebulous term "trophic state," and 3) delineating the relationships between lake trophic conditions and watershed enrichment factors. This chapter presents results for the first two aspects; Chapter 5 discusses the third.

A. DEVELOPMENT OF A TROPHIC CLASSIFICATION SYSTEM FOR FLORIDA LAKES

The multi-dimensionality of the trophic state concept has heretofore obviated objective and consistent classification of lakes according to their trophic states. In an attempt to minimize subjectivity in delineating trophic classifications for Florida lakes, similarity (cluster) analyses were performed on trophic indicator data from the 55 lakes. Seven indicators; viz., primary production (PP), chlorophyll a (CHA), total organic nitrogen (TON), total phosphorus ($\overline{\text{T}}$P), Secchi disc transparency (SD), conductivity (COND), and a cation ratio (CR) due to Pearsall (1922) were chosen as the dimensions describing the hybrid concept of trophic state and were considered simultaneously in the cluster analysis to derive logical lake groups according to their trophic states (at least as defined by the 7 indicators).

The main considerations in selecting the first six indicators are that (i) they are quantitative, (ii) they are fundamentally significant as measures of trophic state, (iii) they satisfy Hooper's (1969) criteria for useful trophic indicators reasonably well, and (iv) they apply to Florida lakes. The first six indicators have all been used with some degree of success in various lake classification schemes.

The selection of Pearsall's cation ratio $\frac{(Na + K)}{Mg + Ca}$ was a somewhat subjective attempt to incorporate information on the major cations into the concept of trophic state without adding each cation as an individual indicator. Pearsall (1922) reported that English lakes with high nitrate and silica and a $\frac{Na + K}{Mg + Ca}$ ratio less than 1.5 had periodic algal blooms. Thus this ratio should be inversely related to increasing eutrophy. Parenthetically it might be noted that many workers have suggested a general correlation between high productivity and water hardness (Ca and Mg concentrations). This ratio has not been used to any extent in other investigations, but it was suggested as a potentially effective parameter for differentiation between lake trophic types by Zafar (1959). For Florida lakes the cation ratio appears to be a reasonably good indicator of trophic state with high values of the inverse cation ratio being indicative of eutrophic conditions.

Averages of the lake parameters over the one year sampling period would seem the most appropriate values for the purposes of statistical analysis. In some respects extreme values (e.g. maximum nutrient concentrations, algal densities at the height of bloom conditions, etc.) are more critical determinants of a lake's water quality and may thus be better and more sensitive indicators of trophic state. But extreme values are less reproducible, and their magnitude depends greatly on the vagaries of sampling frequency and climatic circumstances. Since the breadth of this project precluded detailed (e.g. weekly) sampling, it is felt that mean values are more appropriate in the ensuing analysis. In order not to bias the means toward summer conditions, the June, 1970, values were not included in the computations. Means of the trophic indicators, color, and turbidity for the 55 lakes are listed in Table 7. So that each indicator would denote trophic state in a positive sense (an increase in indicator value denotes an increase in trophic state) the Secchi disc and cation ratio indicators were inversely transformed. Obviously there are many more possible indicators of trophic state that could be included. Alternatively, it may be that fewer trophic indicators will eventually prove sufficient to describe the concept of trophic state. The selection of 7 indicators was a somewhat arbitrary attempt to incorporate as much information into the concept of trophic state as possible without getting into a proliferation of secondary or redundant indicators.

Because of the basic typological differences caused by

Table 7. Trophic State Indicator, Color and Turbidity Data[1]

Lake Number	1/SD	Color Scaled 1/SD	Cond	TON	TP	PP	CHA	1/CR	COL	TUR
1	0.43	0.52	53.2	0.50	0.021	9.3	5.6	1.24	59.0	1.9
2	0.66	0.46	53.7	0.61	0.015	1.8	4.5	0.90	149.0	1.5
3	0.56	0.52	45.7	0.70	0.027	4.1	7.6	0.64	62.0	1.9
4	0.73	0.58	53.3	0.59	0.023	12.4	5.9	0.65	133.7	2.3
5	1.16	0.92	59.7	1.26	0.165	29.6	22.6	1.01	83.3	4.5
6	1.66	0.89	47.7	0.81	0.036	6.9	8.0	0.85	236.7	4.3
7	0.41	0.39	40.0	1.32	0.012	0.5	2.3	0.53	21.3	1.0
8	1.41	0.91	167.7	1.86	0.079	96.6	56.8	1.88	58.3	4.4
9	1.06	0.54	50.7	0.94	0.105	20.8	9.8	0.55	165.7	2.0
10	0.65	0.53	50.4	0.86	0.064	18.2	12.6	0.47	123.7	1.9
11	0.70	0.53	43.0	0.77	0.036	25.4	8.1	0.49	98.3	1.9
12	1.23	0.77	55.7	0.47	0.087	6.8	7.0	0.39	192.7	3.5
13	0.50	0.47	38.0	0.63	0.013	0.5	3.1	0.61	26.0	1.5
14	1.15	0.81	87.0	1.42	0.058	20.9	23.3	1.41	116.3	3.8
15	1.00	0.74	77.4	1.07	0.063	27.4	15.6	1.01	107.1	3.3
16	0.81	0.44	25.0	1.22	0.024	8.5	15.6	0.78	93.3	1.3
17	1.91	0.88	59.8	1.41	0.110	102.5	47.4	0.85	188.9	4.2
18	1.83	0.47	53.0	0.85	0.113	11.2	33.9	0.62	433.4	1.5
19	1.41	0.42	43.7	1.41	0.184	12.7	23.5	0.83	404.0	1.2
20	2.87	2.88	314.3	2.06	0.410	262.8	92.8	4.04	68.5	17.4
21	0.45	0.49	93.3	0.81	0.030	2.4	3.3	1.50	25.0	1.7
22	0.67	0.46	552.2	0.50	0.900	7.9	4.4	3.42	25.5	1.5
23	1.65	1.79	253.8	1.88	0.546	251.7	56.00	2.48	42.1	10.2
24	1.33	1.17	136.4	1.27	0.392	87.4	26.4	2.91	85.4	6.1
25	0.66	0.57	92.7	0.73	0.028	2.6	3.5	9.88	36.0	2.2
26	0.46	0.39	39.7	0.65	0.087	1.8	23.7	0.54	181.7	1.0
27	0.71	1.37	47.0	0.58	0.325	1.2	30.1	1.21	92.0	7.5
28	2.81	2.27	121.7	2.20	0.422	158.7	42.7	5.12	120.7	13.8
29	1.04	1.08	37.7	0.86	0.052	17.0	9.0	0.73	74.0	5.6

(cont'd.)

Table 7 (cont'd.)

Lake Number	1/SD	Color Scaled 1/SD	Cond	TON	TP	PP	CHA	1/CR	COL	TUR
30	1.01	0.61	31.0	1.00	0.052	1.4	7.6	0.77	253.5	2.4
31	1.64	0.89	63.0	1.69	0.478	86.8	29.0	1.63	351.7	4.3
32	1.13	0.88	66.2	1.67	0.169	103.8	37.3	1.23	74.8	4.2
33	1.04	0.62	51.8	1.19	0.292	20.2	8.5	1.50	434.5	2.5
34	4.54	4.39	314.7	4.45	0.380	337.7	60.4	3.85	78.0	27.3
35	2.66	3.13	313.0	3.33	0.384	310.7	50.4	3.45	96.4	19.0
36	0.94	0.68	210.0	1.18	0.037	30.1	14.5	3.68	38.7	2.9
37	1.31	1.65	251.7	2.22	0.167	92.8	23.8	3.34	47.0	9.3
38	1.50	1.91	255.3	2.63	0.183	218.3	47.3	3.12	36.0	11.0
39	0.51	0.53	135.8	0.82	0.019	12.3	6.5	0.51	8.8	1.9
40	0.21	0.39	52.8	0.35	0.011	2.9	1.8	1.15	10.6	1.0
41	0.30	0.45	28.0	0.19	0.011	0.8	1.3	0.63	7.7	1.4
42	0.27	0.40	26.0	0.18	0.012	1.0	1.5	0.64	10.7	1.1
43	0.23	0.45	30.3	0.28	0.011	0.8	1.9	0.81	9.3	1.4
44	0.32	0.50	49.2	0.35	0.016	2.6	1.5	0.61	9.8	1.7
45	0.31	0.45	44.3	0.27	0.011	3.5	1.6	0.51	5.7	1.4
46	0.73	0.37	42.0	0.67	0.025	6.8	5.1	0.47	151.0	0.9
47	0.16	0.37	37.0	0.19	0.011	0.6	1.7	0.48	2.0	0.9
48	1.16	0.37	37.7	0.72	0.027	7.1	5.3	0.60	336.0	0.9
49	0.21	0.41	34.8	0.30	0.017	0.9	2.4	0.59	4.1	1.1
50	0.27	0.39	38.2	0.29	0.018	1.1	3.2	0.63	3.0	1.0
51	1.09	0.48	46.2	0.69	0.036	6.7	3.4	0.58	280.7	1.6
52	0.24	0.40	52.0	0.09	0.012	0.3	1.4	0.61	10.0	1.1
53	0.30	0.54	41.3	0.56	0.023	1.3	2.6	0.61	23.3	2.0
54	0.21	0.46	45.7	0.25	0.010	0.4	1.6	0.59	5.0	1.5
55	0.29	0.43	38.0	0.36	0.014	1.9	1.9	0.65	12.3	1.3

[1] 1/SD (Secchi disc transparency)$^{-1}$ in m^{-1}; Cond in µmho cm^{-1}; TON and TP in mg N or P/l; PP in g C/m^3-hr; CHA in mg/m^3; 1/CR (cation ratio)$^{-1}$ dimensionless; COL (color) in mg/l as Pt; TUR (turbidity) in Jackson Turbidity Units. See text for explanation of column 3 (color scaled 1/SD).

organic color (Figure 6 and Table 6), it seemed best to consider clear and colored lakes as separate classes in each of which a range of trophic subclasses could exist. In fact, a cluster analysis of the 55 lakes considering the 7 trophic indicators plus color divided the lakes into essentially the same 31 clear and 24 colored lakes shown in Figure 6. (Lakes Wauberg and Kanapaha, which are in the alkaline colored and alkaline clear groups, respectively, in Figure 6, are the only lakes which fall into the opposite groups in the color plus trophic indicator cluster analysis.) The lakes in the colored group had mean color levels greater than about 75 ppm, whereas the clear lakes had color levels less than this value. Thus the horizontal line separating clear and colored lakes in Figure 1 would appear to have a value of about 75 ppm for Florida lakes.

The lakes within each of the main classes were grouped into subclasses of similar trophic state by performing cluster analyses with the 7 trophic indicators. The clear lakes (Figure 7) formed three apparently natural groups which can be interpreted in the classical (oligotrophic-mesotrophic-eutrophic) sense. Nearly all the lakes of the Trail Ridge region comprise the oligotrophic Group A. These demonstrate a good within-group similarity as denoted by the low objective function values at which they are joined. The mesotrophic Group B includes a few lakes from the Trail Ridge region (e.g. Kingsley and Winnott) which have been subjected to some cultural influence. As a whole the lakes in Group B (especially those from the Trail Ridge) are perhaps closer to being oligotrophic than eutrophic, but nonetheless they are distinctly (if slightly) more productive than the Group A lakes. The lakes of the eutrophic Group C include the 5 Oklawaha chain lakes plus the small eutrophic and hypereutrophic lakes in Alachua County. The latter are located primarily in urbanized areas, especially around Gainesville, and cultural sources seem to exert a heavy influence on their trophic states. The mesotrophic and eutrophic groups exhibit greater diversity in values for the individual trophic indicators and consequently are joined at higher objective function values.

The colored lakes exhibited considerable diversity, and the results were not as interpretable in terms of classical trophic groupings. Perhaps this reflects a basic difference between colored and clear lakes; in this regard it should be noted that the position of dystrophic lakes in the usual trophic (i.e. nutritional state) classification has long been a subject of contention (Hansen, 1962; see Brezonik et al., 1969 for further discussion). As previously mentioned, we have considered color (roughly equivalent to dystrophy) as a major lake type parallel to a clear lake type (as proposed by Hansen, 1962, and Stewart and Rohlich, 1967), and a range of nutrient states was considered possible for both. However the results of the cluster analysis imply that a simple har-

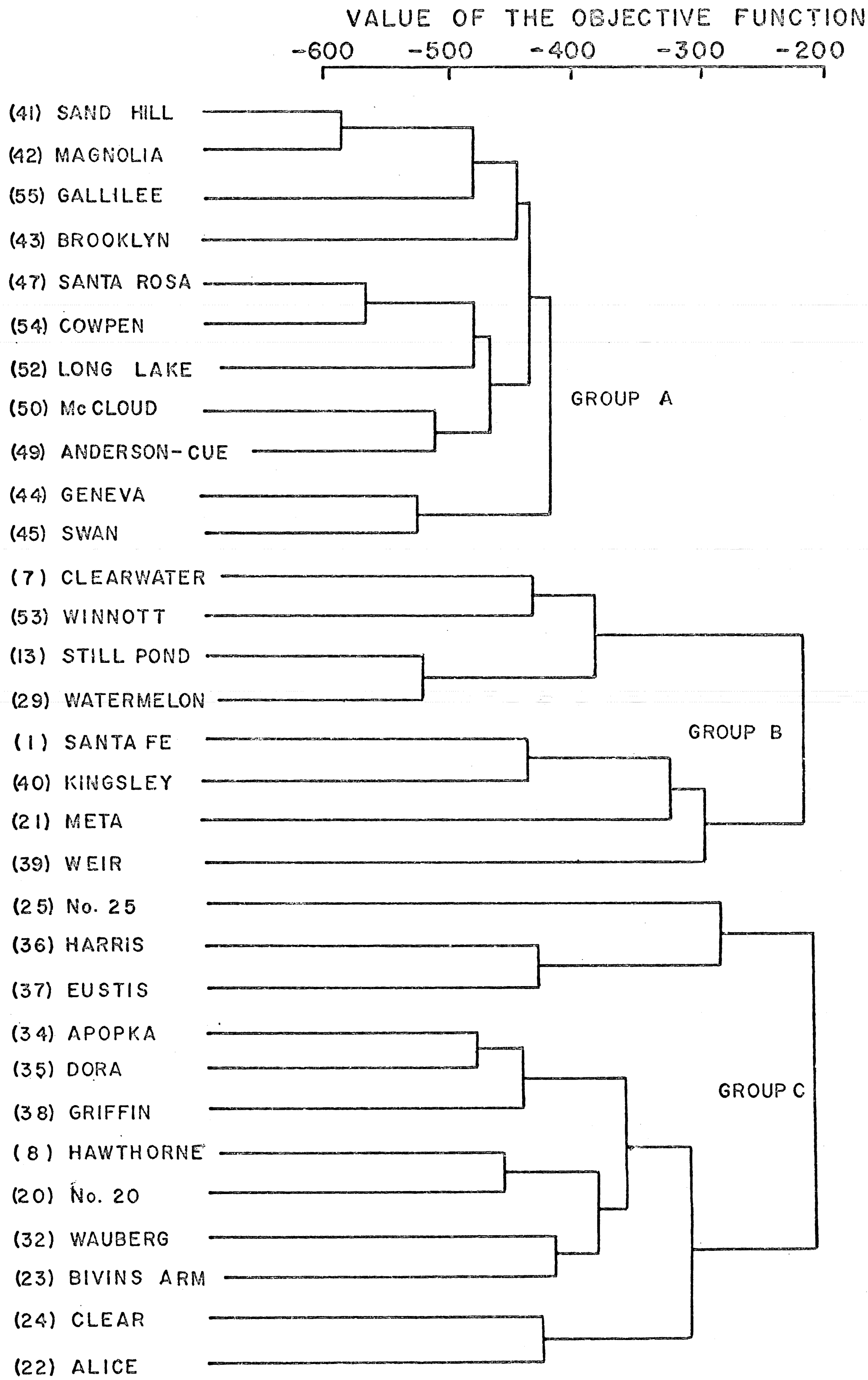

Figure 7. Cluster Analysis of 31 Low-Color (Clear) Lakes Considering 7 Trophic Indicators

monious oligo - to eutrophic gradation may not occur in highly colored lakes. Depending on where the vertical line is drawn through the colored lake cluster diagram (Figure 8) one can obtain classifications containing anywhere from 2 to 6 or more groups. However none of these systems are completely satisfactory with regard to interpretability of the groups.

Similarity cut-off line A in Figure 8 delineates a 5-group classification for the purpose of the present discussion; this system gives good within group similarity for groups 1, 2 and 3, and moderate within group similarity for group 4. Group 5 would appear to be a residual group whose lakes are similar only to the extent that they are different from the other groups. Lake Kanapaha is the most dissimilar of the colored lakes since it was the last lake to be incorporated into a group, and a seven group classification could also be drawn which would leave this lake in a group by itself. The five groups can be interpreted and labeled as follows: 1. oligotrophic, 2. meso-eutrophic, 3. oligo-mesotrophic, 4. dystrophic, 5. residual. Group 4 is labeled dystrophic because the lakes in this group are moderately to highly acidic and have high organic color and low dissolved solids. However pH was not one of the indicator variables, and dystrophy is not a lake type parallel to oligotrophy and eutrophy. Several of the lakes in this group are very shallow (mean depths of .1-1.5 meters) and are partially covered with emergent and floating macrophytes (e.g. water hyacinths). These lakes (Palatka Pond and Tuscawilla, for example) could more accurately be described as senescent (bordering on extinction), but again this is not a recognized trophic state comparable to oligo- and eutrophy. The remaining lakes (Group 5) would appear to be a residual group whose members (except for Beville's Pond and Lake No. 27, which are in fact similar) are alike only in being different from the other groups. Apparently there were not enough pairs or groups of lakes of nearly adjoining trophic characteristics to form groups with good within-group similarity.

At a higher objective function value (i.e. lower degree of similarity) (line B in Figure 8), three groups can be drawn: 1. oligotrophic, 2. mesotrophic, 3. eutrophic-dystrophic. In this scheme Lakes Lochloosa and Orange would appear misclassified and some of the dystrophic (i.e. low pH, high color) lakes like Palatka and Calf Ponds are classified with obviously eutrophic lakes like Newnan's Lake in spite of the low productivities and algal standing crop in the former. The latter apparent misclassifications result from low Secchi disc transparencies (caused partly by high color) and in some cases from fairly high nitrogen and phosphorus levels, which, because of high color and low pH, do not produce algal blooms and high productivity. At a still lower level of similarity (line C in Figure 8) two colored lake groups can be formed: 1. oligo-mesotrophic and 2. eutrophic-dystrophic.

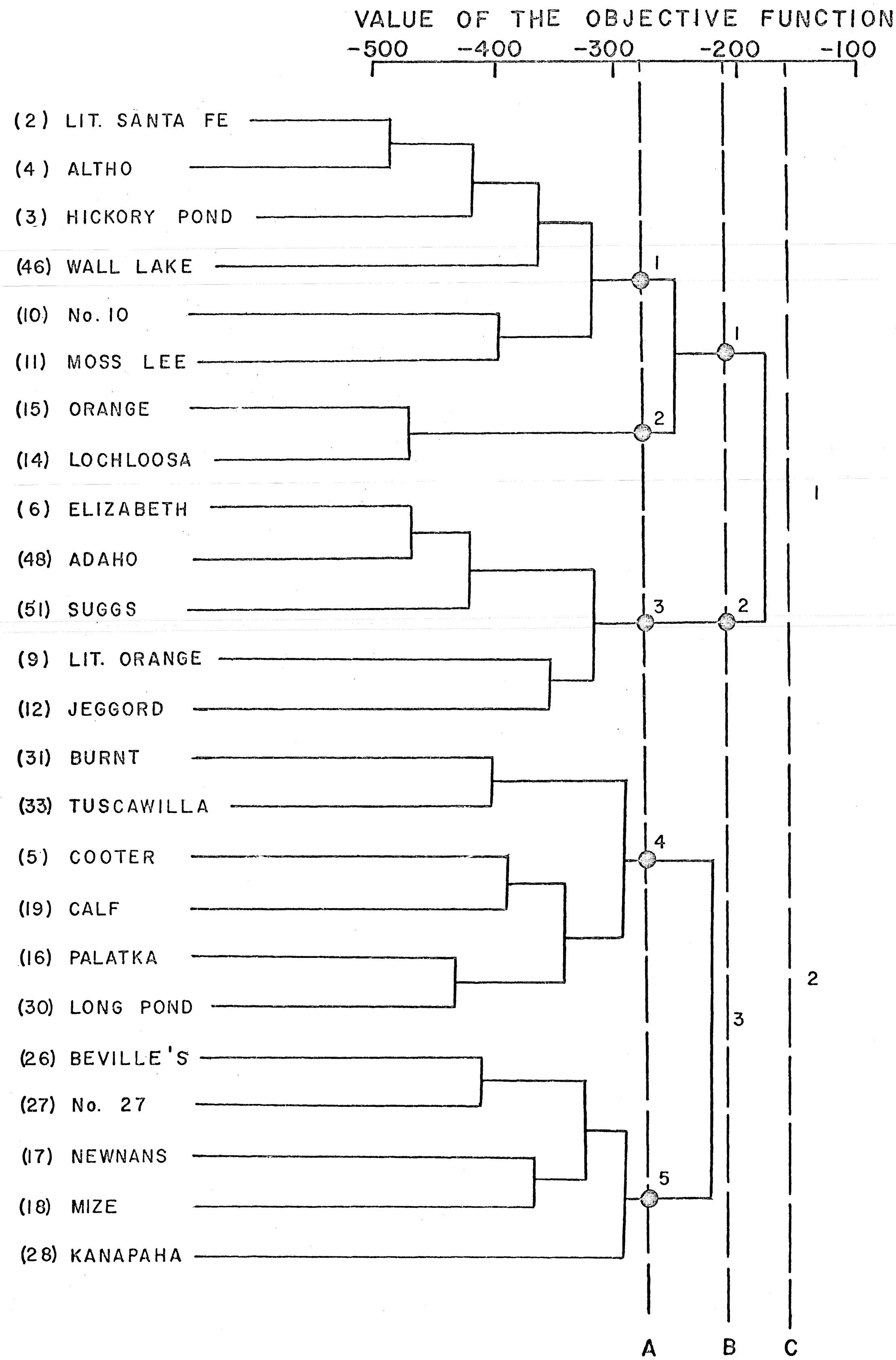

Figure 8. Cluster Analysis of 24 Colored Lakes
Considering 7 Trophic Indicators

This is not a very useful classification since the groups then contain highly dissimilar lakes and are not easily interpreted in terms of classical trophic groups. It is apparent that none of the colored lake classifications is ideal. The five group classification is not readily interpretable in terms of classical trophic groups, and the two group system has groups that are too broad to be of much use. The three group classification has some advantages in terms of interpreting classical trophic states, but some obvious misclassifications occur in this system.

Mean values and standard deviations of the trophic indicators within the 3 clear lake subgroups and 5 colored lake subgroups delineated by the cluster analyses (Figures 7 and 8) are presented in Table 8. All seven indicators appear to reflect trophic levels reasonably well. Among the clear lakes indicator mean values without exception increase in each succeeding trophic group (from oligotrophy to eutrophy). Among the colored lakes the same trend is noted although some exceptions occur. There is little difference between mean values for the colored oligotrophic (Group 1) and oligo - mesotrophic (Group 3) groups; primary production and chlorophyll means are actually somewhat higher in the former than in the latter. The high values for the residual group derive from the hypereutrophic conditions in Newnan's and Kanapaha Lakes; the other lakes in this group have varied indicator values.

It is interesting to note that the colored lakes have a much smaller range of values for most of the indicators compared to the clear lakes. Thus the clear oligotrophic lakes reflect much greater nutrient impoverishment than the colored oligotrophic lakes, and similarly the apparent degree of eutrophy is greater in the clear lakes. For example, the range of mean primary production values in the clear lakes is 1.3 to 150 mg C/m^3-hr, while in the colored lakes the range is 9.7 to 55.

B. DEVELOPMENT OF DISCRIMINANT FUNCTIONS TO CLASSIFY LAKES OUTSIDE THE ORIGINAL SAMPLE GROUP

Discriminant functions were derived for the three trophic classes delineated by cluster analysis of the 31 low-color lakes and are presented in Table 9. In addition, the 55 lakes were grouped into five trophic categories ranging from ultra-oligotrophic to hypereutrophic based on the trophic state index described in the next section. Discriminant functions were derived for these classes and are shown in Table 10. The colored lake group was too small and diverse to form meaningful discriminant functions. Using the criterion de-

Table 8. Mean Values and Standard Deviations of Trophic State Indicators Within Trophic State Groups

Trophic State Indicators

Group	Primary Production (mg Cm^3-hr)	Chlorophyll <u>a</u> (mg/m^3)	Total Phosphate (mg-P/l)	Total Organic Nitrogen (mg-N/l)	Inverse Secchi Disc (m^{-1})	Conductivity (µmho/cm)	Cation Ratio
(a) Clear Lakes							
A. Oligotrophic	1.3[a]	1.8	.013	.25	.25	38.5	.61
	1.0[b]	.5	.003	.08	.05	8.5	.08
B. Mesotrophic	5.8	4.3	.023	.73	.47	61.5	.86
	6.3	2.5	.014	.30	.24	35.1	.38
C. Eutrophic	150.2	39.5	.306	1.98	1.72	244.0	3.61
	119.5	26.3	.251	1.10	1.12	129.0	2.13
(b) Colored Lakes							
1. Oligotrophic	11.4	7.3	.032	.70	.67	48.0	.60
	9.0	3.0	.017	.10	.06	5.1	.17
2. Meso-Eutrophic	24.1	19.5	.060	1.24	1.07	82.2	1.21
	4.6	5.5	.003	.25	.11	6.8	.28
3. Oligo-Mesotrophic	9.7	6.7	.058	.72	1.24	47.6	.60
	6.2	2.5	.035	.17	.25	6.6	.16
4. Dystrophic	31.6	21.1	.213	1.36	1.59	46.0	1.36
	230.0	24.5	.278	1.45	2.41	49.0	1.57
5. Residual	55.1	35.6	.211	1.13	1.54	64.2	1.67
	71.9	9.5	.152	.68	.96	33.0	1.95

[a]denotes mean value

[b]denotes standarddeviation

Table 9. Discriminant Functions
for Trophic Groups Delineated in Table 8[a]

$$V_{AB}{}^{b} = 16(1/SD) + .27(PP) + .04\,(COND) - 62(TP) - 34(TON)$$
$$- 4.4(1/CR) - .74(CHA) + 14.3$$

$$V_{AC} = 65(1/SD) + .77(PP) + .10(COND) - 230(TP) - 108(TON)$$
$$- 20(1/CR) - 2.9(CHA) + 126$$

$$V_{BC} = 49(1/SD) + .51(PP) + .06(COND) - 167(TP) - 75(TON)$$
$$- 16(1/CR) - 2.2(CHA) + 112$$

---

[a] Indicator abbreviations: 1/SD = inverse Secchi disc, PP = primary production, COND = specific conductance, TP = total phosphate, TON = total organic nitrogen, 1/CR = inverse of Pearsall's cation ratio, CHA = chlorophyll _a_, all indicators in units given in Table 8.

[b] Subscripts of discriminant functions indicate the groups (from Table 8) being compared.

Table 10. Discriminant Functions for Five Groups of Lakes Determined from Trophic State Indicator Ranges (From Table 18)

$$V_{HE}^{b} = 23.99(1/SD)^{a} + .47(COND) + 15.17(TON) + 148.76(TP4) + .38(PP) - .04(CHA) + 8.19(1/CR) - 289.10$$

$$V_{HM} = -22.44(1/SD) + .53(COND) + 35.93(TON) + 289.93(TP4) + 91(PP) + .77(CHA) + 11.11(1/CR) - 369.94$$

$$V_{HO} = -34.88(1/SD) + .59(COND) + 74.56(TON) + 427.32(TP4) + .59(PP) + 2.45(CHA) + 23.39(1/CR) - 451.87$$

$$V_{HU} = -44.33(1/SD) + .64(COND) + 111.06(TON) + 490.95(TP4) + .33(PP) + 3.27(CHA) + 26.56(1/CR) - 475.42$$

$$V_{EM} = -46.43(1/SD) + .06(COND) + 20.77(TON) + 141.17(TP4) + .53(PP) + .81(CHA) + 2.92(1/CR) - 80.85$$

$$V_{EO} = -58.87(1/SD) + .12(COND) + 59.40(TON) + 278.56(TP4) + .21(PP) + 2.49(CHA) + 15.19(1/CR) - 162.78$$

$$V_{EU} = -68.32(1/SD) + .17(COND) + 95.90(TON) + 342.20(TP4) -.05(PP) + 3.31(CHA) + 18.37(1/CR) - 186.32$$

$$V_{MO} = -12.44(1/SD) + .07(COND) + 38.63(TON) + 137.39(TP4) -.32(PP) + 1.68(CHA) + 12.28(1/CR) - 81.93$$

$$V_{MU} = -21.88(1/SD) + .12(COND) + 75.13(TON) + 201.03(TP4) -.58(PP) + 2.50(CHA) + 15.45(1/CR) - 105.48$$

$$V_{OU} = -9.45(1/SD) + .05(COND) + 36.50(TON) + 63.64(TP4) -.26(PP) + .82(CHA) + 3.18(1/CR) - 23.55$$

[a] Key to indicator abbreviations identical to Table 9

[b] Subscripts of discriminant functions refer to groups labeled in Table 18: hypereutrophic (H), eutrophic(E), mesotrophic (M), oligotrophic (O), ultraoligotrophic (U).

scribed in Chapter 2, a lake belongs to Group A (oligotrophic) if V_{AB} and V_{AC}, the respective discriminant functions between the subscripted groups in Table 9, are both greater than or equal to zero.

To demonstrate the application of this technique to lake classification, trophic indicator data for three well known North American lakes (Table 11) were assembled from various sources, and the lakes were classified according to the discriminant functions of Tables 9 and 10.

Data for Lake Tahoe was taken from Ludwig et al. (1964) and Goldman and Armstrong (1968). Data for the two great lakes was obtained from Saunders (1964), Putnam et al. (1966) and Beeton (1969). As expected, Lakes Tahoe and Superior were assigned to the oligotrophic class and Lake Erie to the eutrophic class using the discriminant functions for the clear lakes (Table 9). The discriminant functions of Table 10 derived from all 55 lakes classified Lake Tahoe in the ultra-oligotrophic group (U), Lake Superior with the oligotrophic lakes (O), and Lake Erie in the mesotrophic group (M).

It should be emphasized that use of these three lakes is for illustrative purposes only. The validity of assigning large temperate lakes into classes delineated from a sample of small sub-tropical lakes has not been tested. Certainly the general effects of eutrophication are similar in all "normal" lakes, and in this sense the examples are not inappropriate. However, if geographically broad (or universal) trophic groups are to be delineated, the original sample group should be similarly broadly based, which of course the Florida lakes used to develop the discriminant functions are not. A further word of caution regarding this method is the deleterious effect of small sample size on the probability of misclassification (Wallis, 1967). For good differentiating power the functions should be based on sample groups of 50 or more.

C. FORMULATION OF TROPHIC STATE INDICES

The multivariate statistical method of principal component analysis (Chapter 2) represents one means of deriving a single numerical index from a number of indicators, and this technique was used to derive indices from the trophic indicator data for the 55 lakes.

As seen in Figure 6, organic color can be used to separate lakes into the two fundamentally different classes of colored and clear lakes. Nutrient enrichment may cause different effects in each class, i.e., various trophic indicators may respond differently to nutrient enrichment in clear vs. colored

Table 11. Trophic Characteristics and Classification of Three Well-Known North American Lakes by Discriminant Functions in Tables 9 and 10[a]

Lake	1/SD m^{-1}	PP mg C/m^3-hr	COND µmho/cm	TP mg P/l	TON mg N/l	1/CR	CHA mg/m^3	Trophic Class (Table 9)	Trophic Class (Table 10)
Tahoe	.04	0.5	83	.007	.09	1.4	1.5	A (oligotrophic)	U (ultraoligotrophic)
Superior	.10	8.0	79	.014	.14	5.1	2.5	A (oligotrophic)	O (oligotrophic)
Erie	.29	59	313	.060	.48	4.7	27.5	E (eutrophic)	M (mesotrophic)

[a]Indicator abbreviations as in Table 9.

lakes, and a single trophic index for all lakes could possibly be inappropriate. Consequently separate trophic state indices were developed from the correlative relationships of indicators within each of the two basic classes defined previously by cluster analysis. The annual mean values for each lake (Table 7) were used in the derivation of the indices. Table 12 lists the means and standard deviations of each indicator for all 24 colored lakes and all 31 clear lakes, and Table 13 presents the respective correlation matrices. The first principal components, y_{co} and y_{cl}, extracted from the colored and clear lake correlation matrices, respectively, are shown in Table 14. The first principal components extract a good portion of the information from the R's since y_{co} and y_{cl} explain 72 and 71% of the total variances in their respective correlative matrices.

The principal components are simple linear functions of the 7 trophic state indicators with weighting factors for each indicator. The indicator values are standardized values (i.e. the actual raw value from Table 7 minus its mean value and divided by its standard deviation from Table 12). The trophic state index for each group of lakes, i.e. TSI_{co} and TSI_{cl}, was derived by slightly modifying the respective first principal components. The modification consisted in adding a constant value to the principal component so that the TSI would always be greater than zero. The constant was obtained by evaluating the first principal component with raw data values of zero for each indicator. A zero raw data value results in a negative standardized value and hence a negative value for y, which value was then added to y to produce the TSI (see Table 14). Hence a hypothetical lake with zero productivity and zero values for the other indicators would then have a TSI of zero. (In actuality this would never occur since even pure water has a finite Secchi disc transparency, and all natural waters have a non-zero cation ratio.) In general, lakes with increasingly positive indicator values will exhibit correspondingly higher TSI's.

The TSI's of the lakes in each group were calculated by substituting the standardized indicator values into the appropriate TSI formula, and Table 15 presents the results for each group ranked in descending order of TSI value. Thus the above analysis indicates that Lake Kanapaha is the most eutrophic colored lake and Wall Lake is the least eutrophic in this group; similarly Lake Apopka (eutrophic) and Lake Santa Rosa (oligotrophic) represent the extremes of trophic state within the clear lake group.

The results of the cluster analyses (Figures 7 and 8) are also included in Table 15 for comparative purposes. Rankings of the clear lakes according to their TSI's are in excellent agreement with the clear lake groups formed by cluster analysis. The first 12 lakes (in order of decreasing TSI)

Table 12. Means and Standard Deviations of Trophic Indicators Within the Colored and Clear Lake Groups[a]

Group	1/SD	COND	TON	TP	PP	CHA	1/CR
Colored Lakes	1.13[b]	53.2	.99	.119	25.0	16.7	.99
	.53[c]	20.2	.42	.130	37.8	12.6	.94
Clear Lakes	.88[b]	124.0	1.04	.129	60.1	17.0	1.83
	.97[c]	126.1	1.04	.209	102.7	24.2	1.94

[a]See Table 7 and text for explanation of symbols and units of expression.

[b]Denotes the mean.

[c]Denotes the standard deviation.

Table 13. Correlation Matrices of Seven Trophic Indicators for Colored and Clear Lake Groups

(a) Colored Lakes:

	1/SD	COND	TON	TP	PP	CHA	1/CR
1/SD	1.000	.630	.720	.534	.782	.646	.697
COND		1.000	.627	.484	.733	.517	.792
TON			1.000	.643	.818	.658	.764
TP				1.000	.640	.596	.685
PP					1.000	.705	.800
CHA						1.000	.529
1/CR							1.000

(b) Clear Lakes:

1/SD	1.000	.643	.931	.559	.962	.858	.464
COND		1.000	.621	.888	.638	.603	.522
TON			1.000	.481	.915	.813	.442
TP				1.000	.586	.543	.396
PP					1.000	.910	.402
CHA						1.000	.392
1/CR							1.000

Table 14. First Principal Components (y_{co} and y_{cl}) and Trophic State Indices (TSI_{co} and TSI_{cl})

(a) Colored Lakes:

$$y_{co} = .848(1/SD) + .809(COND) + .887(TON) + .768(TP) + .930(PP) + .780(CHA) + .893(1/CR)$$

Cumulative Percent of Total Variance Explained by y_{col} = 72%

$$TSI_{col} = y_{col} + 9.33$$

(b) Clear Lakes:

$$y_{cl} = .936(1/SD) + .827(COND) + .907(TON) + .748(TP) + .938(PP) + .892(CHA) + .579(1/CR)$$

Cumulative Percent of Total Variance Explained by y_{cl} = 71%

$$TSI_{cl} = y_{cl} + 4.76$$

Table 15. Lakes of Clear and Colored Groups Ranked According to TSI_{cl} and TSI_{co}

a. Clear Lakes

Lake	TSI_{cl}	Cluster Group	Lake	TSI_{cl}	Cluster Group
Apopka	18.1	C	Santa Fe	1.9	B
Twenty	15.1	C	Still Pond	1.6	B
Dora	14.6	C	Winnott	1.4	B
Bivin's Arm	12.0	C	Kingsley	1.3	B
Griffin	10.7	C	Geneva	1.2	A
Alice	9.2	C	Gallilee	1.2	A
Eustis	8.2	C	Swan	1.1	A
Hawthorne	7.9	C	Anderson-Cue	1.1	A
Clear	7.3	C	McCloud	1.0	A
Wauberg	6.3	C	Brooklyn	1.0	A
Harris	5.3	C	Cowpen	1.0	A
Twenty-five	5.1	C	Long	0.9	A
Watermelon	2.9	B	Sumter-Lowry	0.9	A
Weir	2.7	B	Magnolia	0.9	A
Meta	2.4	B	Santa Rosa	0.8	A
Clearwater	2.1	B			

b. Colored Lakes

	TSI_{co}			TSI_{co}	
Kanapaha	27.9	3	Ten	6.9	1
Burnt	17.0	3	Palatka Pond	6.9	3
Newnan's	15.3	3	Jeggord	6.7	2
Lochloosa	12.0	1	Moss Lee	6.3	1
Cooter	11.0	3	Beville's Pond	6.2	3
Calf Pond	10.6	3	Suggs	6.2	2
Mize	10.5	3	Adaho	6.1	2
Tuscawilla	10.4	3	Long Pond	6.1	3
Orange	9.9	1	Altho	6.0	1
Twenty-seven	9.2	3	Little Santa Fe	5.8	1
Little Orange	8.0	2	Hickory Pond	5.6	1
Elizabeth	7.9	2	Wall	5.3	1

correspond to the lakes in eutrophic group C of Figure 7; the next 8 lakes are in mesotrophic group B, and the last 11 lakes comprise oligotrophic group A. Thus the TSI for clear lakes can be used to separate classical trophic states quantitatively. A TSI_{cl} of about 5.0 would appear to be the dividing line between mesotrophy and eutrophy, and a value of about 1.2-1.3 separates mesotrophy and oligotrophy. Qualitative inspection of other trophic indicators for Lakes Kingsley and Winnott suggests these lakes are more typically oligotrophic than mesotrophic and the TSI dividing line should perhaps be raised to 1.5. The colored lakes ranked according to TSI_{co} are in general agreement with the cluster analysis (Figure 8), but some discrepancies are noted. For example, Lakes Lochloosa and Orange have a high degree of similarity; however, the lakes have high but somewhat dissimilar TSI values, and four lakes have TSI rankings between the values for the two lakes. Also Beville's, Palatka and Long Ponds were clustered into eutrophic groups although their TSI values indicate oligotrophy. The discrepancies in comparing the two analyses probably arise within the cluster analyses since the colored lakes exhibited considerable diversity and did not form groups with good within-group similarity.

For management and identification purposes it would be desirable to have a single trophic state index to rank all lakes regardless of color. Large differences in the specific conductance, primary production and cation ratio mean values for the two groups (Table 8) and the cluster analysis of basic chemical parameters (Figure 6) suggest a basic difference which could possibly cause different trophic indicator responses in the two types. On the other hand, that the two groups can be viewed as two samples of one (larger and more diverse) population, and a single TSI to rank all 55 lakes was developed under this assumption.

Of the seven indicators used to assess trophic state in this study, the one most directly affected by organic color is Secchi disc transparency. This parameter is essentially a function of color and turbidity, and a multiple regression of inverse Secchi disc reading as dependent variable vs. color and turbidity as independent variables produced the following relationship:

$$1/SD = 0.003(Col) + 0.152(Tur) \tag{12}$$

Data for the analysis were from Table 7, and the zero intercept option was used in the regression analysis. The relationship is significant at the 99% confidence level, and the percent of variation in 1/SD explained by Eq. 12 is 96%. Using Eq. 12, a color value of 75 mg/l, and turbidity values from Table 7, new color-scaled inverse Secchi disc values were calculated for each of the 55 lakes; the results are listed in Table 7. A color value of 75 mg/l was chosen for the scaling purposes because it represents the dividing line between clear and colored lakes and is also in the middle range (zone of best prediction) of the regression equation.

Once the Secchi disc values had been color scaled, the correlative relationships between the seven trophic indicators for all 55 lakes were subjected to a principal component analysis, and the means, standard deviations and the correlation matrix are given in Table 16. The first principal component y_t extracted from R is given by

$$y_t = .919(1/SD) + .800(COND) + .896(TON) + .738(TP) + .942(PP) + .862(CHA) + .634(1/CR) \quad (13)$$

y_t extracts a good portion of the information from R and explains 70% of the total variation in R. The TSI is given by

$$TSI = y_t + 5.19, \quad (14)$$

where the value of 5.19 was determined as described previously in the derivations of TSI_{co} and TSI_{cl}.

TSI's were calculated for each of the 55 lakes by substituting the standardized indicator values (computed from Tables 7 and 16) into Eqs. 13 and 14. The lakes are ranked in descending order of TSI in Table 17. Using the cluster analyses of Figures 7 and 8 as a guide, the 55 lakes were separated in terms of classical trophic state terminology into five groups as follows: 1. Hyper-eutrophic ($TSI>10$), 2. Eutrophic ($10\geq TSI\geq 7$), 3. Mesotrophic ($7>TSI\geq 3$), 4. Oligotrophic ($3>TSI\geq 2$), 5. Ultra-oligotrophic ($TSI<2$). These groups are delineated and labeled in Table 17. The relative rankings of the lakes in the TSI_{cl} and TSI_{co} formulations of Table 15 are also shown in Table 17. Comparison shows that the clear lakes are ranked in almost identical order according to the total (55 lake) TSI (excluding the interspersed colored lakes) as they are by the TSI_{cl}. Further it is obvious that the clear lakes as a group are more extreme in their trophic behavior than are the colored lakes; all but one of the hypereutrophic lakes and all the ultraoligotrophic lakes in Table 17 belong to the clear lake group. Nearly all the colored lakes are included in the oligotrophic and mesotrophic categories. Comparison of the colored lake rankings according to the 55 lake TSI and the TSI_{co} also indicates a general correspondence. The lake most out of order is Lake Twenty-seven, which is the fourth listed colored lake in Table 17 and the tenth ranked lake according to the TSI_{co}. Many of the other colored lakes are "misranked" by one or two places, but there are no major discrepancies. Most of the changes in relative rankings between Tables 15 and 17 probably

Table 16. Means, Standard Deviations, and Correlation Matrix of Trophic State Indicators for 55 Lakes

Indicator	Mean	Standard Deviation
1/SD	.84	.77
COND	93.1	101.3
TON	1.02	.82
TP	.125	.177
PP	44.8	82.3
CHA	16.9	19.8
1/CR	1.47	1.63

Correlation Matrix R:

	1/SD	COND	TON	TP	PP	CHA	1/CR
1/SD	1.000	.617	.880	.542	.927	.784	.502
COND		1.000	.582	.762	.654	.540	.560
TON			1.000	.500	.890	.788	.474
TP				1.000	.576	.553	.440
PP					1.000	.859	.478
CHA						1.000	.402
1/CR							1.000

Table 17. Fifty-five Florida Lakes Ranked According to Trophic State Index (TSI)

Lake	TSI	Rank in Table 15[1]
1. Hypereutrophic group		
Apopka	22.1	1A
Twenty	18.5	2A
Dora	18.5	3A
Bivin's Arm	14.7	4A
Griffin	13.7	5A
Kanapaha	13.5	1B
Alice	10.7	6A
Eustis	10.5	7A
2. Eutrophic group		
Hawthorne	9.1	8A
Clear	8.8	9A
Burnt Pond	8.3	2B
Wauberg	7.4	10A
Newnan's	7.1	3B
3. Mesotrophic group		
Twenty-five	6.4	12A
Harris	6.3	11A
Twenty-seven	5.8	10B
Cooter Pond	5.3	5B
Lochloosa	5.2	4B
Tuscawilla	4.8	8B
Calf Pond	4.6	6B
Orange	4.3	9B
Mize	4.2	7B
Watermelon Pond	3.6	13A
Little Orange	3.4	11B
Weir	3.3	14A
Elizabeth	3.2	12B
Ten	3.2	13B
Palatka Pond	3.2	14B
Beville's Pond	3.1	17B
Meta	3.1	15A
4. Oligotrophic group		
Jeggord	2.8	15B
Moss Lee	2.8	16B
Long Pond	2.8	20B
Clearwater	2.6	16A
Altho	2.5	21B
Hickory Pond	2.5	23B
Santa Fe	2.5	17A

(cont'd.)

Table 17 (cont'd.)

Lake	TSI	Rank in Table 15[1]
Suggs	2.3	18B
Little Santa Fe	2.3	22B
Adaho	2.2	21B
Wall	2.1	24B
Winnott	2.0	19A
5. Ultra-oligotrophic group		
Still Pond	1.9	18A
Kingsley	1.9	20A
Geneva	1.8	21A
Gallilee	1.6	22A
Swan	1.5	23A
Anderson-Cue	1.5	24A
McCloud	1.5	25A
Brooklyn	1.5	26A
Cowpen	1.5	27A
Long	1.3	28A
Sumter-Lowry	1.3	29A
Magnolia	1.3	30A
Santa Rosa	1.3	31A

[1]Rank from Table 15 according to TSI_{cl} (A values) and TSI_{co} (B values).

result from the use of color-corrected Secchi disc transparencies for the TSI values in Table 17, which presumably should produce a more accurate relative ranking of the lakes according to their trophic states.

The question concerning the soundness of one TSI for both clear and colored lakes remains. A definitive answer is perhaps impossible. However, the first principal component on which the 55 lake TSI is based accounts for about as much of the variance (70%) in the correlation matrix of trophic indicators for all lakes as do the first principal components for the clear and color groups, which accounted for 71 and 72% of the variances in their respective correlation matrices. Further, there appear to be no obvious misclassifications or misrankings in the 55 lake TSI's. One of the major values of the TSI concept is the possibility of ranking rather diverse objects (lakes) in a logical and objective manner. Obviously if the sample is too diverse, the rankings will have little or no meaning. Thus extrapolation of the TSI concept to development of a single, universal index for all lakes is not suggested. To rank Arctic bogs, acid volcanic lakes, tropical ponds and the Great Lakes on the same scale would be pointless and meaningless. On the other hand, the more "harmonious" the sample, the more meaningful and logical (and easier) it will be to rank the objects. The relatively harmonious series of clear lakes is easily and logically ranked (Table 15). Inclusion of the colored lakes produces a more diverse sample with an inevitable loss in clarity in interpretation of the resulting TSI. Nevertheless, it is felt that the 55 lake TSI is a useful, interpretable and logical means of ranking Florida lakes.

Some interesting features of the TSI rankings deserve mention. Lake Alice has been ranked in the hypereutrophic group although it might be classified oligotrophic on the basis of plankton productivity alone. Lake Alice has extremely high nitrogen and phosphorus concentrations and supports a profuse growth of water hyacinths, which along with a short hydraulic detention time (in the order of 2-3 days), have restricted plankton productivity. In this case, the other trophic state indicators (nitrogen, phosphorus, and conductivity) have been sufficiently high to counteract the low primary production and chlorophyll <u>a</u> values. Lake Twenty-seven was also ranked higher than it would be on the basis of plankton production alone. This lake is almost completely covered with duckweed (<u>Lemna</u> <u>minor</u>), and as with Lake Alice the other indicators have counteracted the low primary production value.

The usefulness of the trophic state index can be best determined by its application, e.g. in practical (e.g. management and control) situations or in development of empirical models relating trophic state to watershed enrichment factors (see the next section). However, the validity of the approach can be inferred from closer inspection of the TSI and its component parameters. Table 18 presents the means and 95% confidence intervals for the 7 trophic indicators in each of the classes delineated in Table 17. In nearly every case the mean parameter values increase in progressing toward more eutrophic classes. However the large confidence intervals for most parameters implies considerable overlap between the classes delineated by any single indicator. These facts demonstrate three important points. First, because of the overlap, any single parameter is inadequate to define trophic state or trophic classes. Second, the wide and overlapping ranges of indicator values preclude easy placement of lakes into appropriate trophic classes since the values for a lake could fit within the confidence intervals of the parameters in two adjacent classes. Finally, the increasing mean values in progressing toward eutrophic conditions imply that the TSI provides at least an objective means of placing lakes into appropriate trophic classes and suggests that the relative ranking of the lakes by their TSI values is reasonable.

The TSI described above reflects the general trophic conditions of Florida lakes; whether it is the best index that can be developed will have to be answered by further work comparing its attributes with those of other indices that might be developed. The seven indicators in the present index reflect the major limnological consequences of eutrophication with the exception of macrophyte problems. Indices with fewer variables would reflect a narrower concept of trophic state and would be more likely to yield misleading results.

Specific water quality problems resulting from eutrophication are not directly considered by the index, but some of the indicators are indirectly related to such problems. For example, chlorophyll a, a biomass parameter, might be correlated with taste and odor problems arising from algal blooms; Secchi disc transparency is associated with water turbidity, which should be correlated with the length of sand filter runs in water treatment plants. Perhaps other indices could be developed which would be directly related to water quality problems, but it is not always a simple matter to find appropriate quantitative indicators for such purposes.

The index described above should be practical for routine assessment of general trophic conditions since the individual parameters are commonly and rather simply measured. The only exception possibly is primary production. This parameter, while of fundamental significance to the trophic state concept, also suffers from the fact that measured values are highly variable in a given lake and are greatly dependent on physical factors such as light and temperature. Perhaps a simpler TSI not incorporating this parameter would prove

Table 18. Confidence Intervals for Trophic Indicators in Five Lake Groups Delineated by Trophic State Index Values[a]

Parameter	Ultraoligotrophic	Oligotrophic	Mesotrophic	Eutrophic	Hypereutrophy
TSI Range	1.3-1.9	2.0-2.9	3.0-6.9	7.0-9.9	>10.0(10.0-22.1)
Number of Lakes	13	12	17	5	8
Primary Production mg C/m^3-hr	1.3 ± .7	8.6 ± 3.3	17.3 ± 8.5	95.4 ± 10	205 ± 94
Chlorophyll <u>a</u> mg/m^3	1.9 ± .4	7.7 ± 2.3	19.5 ± 7.5	39.4 ± 15.8	42.7 ± 21.7
Total Phosphate mg P/l	0.13 ± .002	.040 ± .012	.141 ± .085	.246 ± .221	.424 ± .192
Total Organic Nitrogen mg N/l	.29 ± .08	.78 ± .10	1.08 ± .23	1.58 ± .29	2.41 ± .96
$(\text{Secchi Disc})^{-1}$ m^{-1}	.43 ± .02	.55 ± .08	.73 ± .22	.94 ± .16	2.31 ± .98
Specific Conductivity μmho cm^{-1}	39.6 ± 5.3	50.6 ± 11.5	80.2 ± 39.8	98.6 ± 62.2	297 ± 101
$\frac{[Ca] + [Mg]}{[Na] + [K]}$	.65 ± .10	.69 ± .13	2.35 ± 2.27	1.70 ± .97	3.60 ± .64

[a]Values represent means ±95% confidence interval.

more useful to governmental agencies faced with evaluating the trophic characteristics of large numbers of lakes.

CHAPTER 5. RELATIONSHIPS BETWEEN TROPHIC STATE AND WATERSHED ENRICHMENT FACTORS

A. INTRODUCTION

Empirical relationships between lacustrine trophic conditions and watershed conditions can be developed by regression analysis using the TSI as dependent variable and appropriate conditions in the watershed as independent variables. A general model for eutrophication can be written as:

$$TS = \int(N, M, H, S, t \ldots), \qquad (15)$$

where TS is the trophic state resulting from nutrient (N) loading (nitrogen, phosphorus and other essential nutrients), M represents morphometric characteristics such as mean depth, H represents hydrological conditions (e.g. water detention time), S is a sedimentation factor, and t is time. The relationships among these parameters is presently too vague for the development of functional relationships. However, simplified empirical approximations of Eq. 15 can be developed.

As a first approach models of the type

$$TSI = g(N,P) + C, \qquad (16)$$

were developed, where the TSI described in Eq. 14 represents the trophic state parameter of Eq. 15, N and P represent annual nitrogen and phosphorus loading rates, and C is an uncertainty term. Although nitrogen and phosphorus are not the only nutrients required for algal growth, it is generally agreed that they are the two main nutrients involved in the lake eutrophication process. In spite of current controversy over the role of carbon (Bowen, 1970; Legge and Dingeldein, 1970; Kerr *et al*., 1970), researchers as a whole regard phosphorus as the most frequent limiting nutrient in lakes. Vollenweider (1968) and others have emphasized the importance of nutrient (particularly nitrogen and phosphorus) supply in determining a lake's trophic state. Although various lake factors, such as mean depth, detention time, basin shape, and sedimentation rate, affect the amounts of nutrients a lake can assimilate, nutrient budget calculations represent a first step in quantifying this dependence.

A few lacustrine nitrogen and phosphorus budgets have been reported in the literature, e.g. Rohlich and Lea (1949) for Lake Mendota, McGauhey *et al*. (1963) for Lake Tahoe and Edmondson (1968) for Lake Washington. Vollenweider (1968, 1969) has summarized most of the budget calculations for American European Lakes. Comprehensive evaluation of the nutrient balance for a lake requires measurement of all potential nutrient sources and sinks (Table 19) over an extended period in order to assess seasonal and other effects. Some sources and sinks, e.g. groundwater, nitrogen fixation and denitrification, require elaborate sampling and experimental procedures to be adequately evaluated. Consequently, manpower and time constraints have resulted in very few complete nutrient balances being attempted. An alternative and simpler method is to use literature estimates for nutrient exports from various sources and information on the various land use and population characteristics of the lake watershed. This approach was used by Lee *et al*. (1966) for nitrogen and phosphorus budget calculations for Lake Mendota. While perhaps not as accurate as actual measurement, there is no other realistic alternative when evaluating budgets for a large number of small lakes.

B. NITROGEN AND PHOSPHORUS BUDGETS

Partial nitrogen and phosphorus budgets for the 55 lakes in the study group have been computed by this latter approach. The budgets are referred to as partial since no attempt was made to account for such sources as nitrogen fixation, leaves and pollen and groundwater. Adequate data were not available to evaluate most sinks, and consequently none were considered. The partial budget calculations therefore estimate gross supply or loading.

The morphometric, land use, and population figures for each lake were determined according to the methods described in Chapter 2. Watersheds were divided into forest, urban, pasture, fertilized cropland, and cleared unproductive areas. Table 20 lists the pertinent watershed and morphometric data for each lake.

Literature figures for the expected contributions of nitrogen and phosphorus from the various sources were compiled, and the values used in this study are summarized in Table 21. Where applicable, each value is accompanied by the literature reference. Literature estimates were not available for two sources. Muck (recovered marshland) and citrus farm contributions were calculated from average fertilizer composition and application rates, assuming that 10 percent of the applied nitrogen and one percent of the applied phosphorus was exported from the soil to the lake. The figures for percentage

Table 19. Potential Nitrogen and Phosphorus Sources and Sinks for Lakes

(a) Sources

Natural	Cultural
Precipitation on Lake Surface	Domestic and Industrial Waste Waters
Swamp Runoff	Agricultural Runoff
Virginal Meadowland Runoff	Managed Forest Runoff
Forest Runoff	Urban Runoff
Soil Erosion	Septic Tanks
Aquatic Bird and Animal Wastes	Landfill Drainage
Leaf and Pollen Deposition	
Groundwater Influxes	
Nitrogen Fixation*	
Sediment Recycling	

(b) Sinks

Outlet Losses	Denitrification*
Fish Catches	Volatilization*
Aquatic Plant Removal	Ground Water Recharge
	Sediment Losses

*Applies to nitrogen alone.

Table 20. Population and Land Use Data for 55 Florida Lake Watersheds

Name/No.		Mean Depth (m.)	Forested Area (ha.)	Urban Area (ha.)	Fertilized Cropland (ha.)	Pastured Area (ha.)	Unproductive Cleared Area (ha.)	Immediate Cultural Units	Remote Cultural Units	Population Served by STP[a] Facilities
Santa Fe	1	5.5	4424	191	60.6	206	137	209	91	0
Lit. Santa Fe	2	4.8	842	0	61.3	109	72.8	34	24	0
Hickory	3	3.4	95.5	0	29.3	119	0	0	6	0
Altho	4	3.6	666	73.8	17.1	21	21	13	58	0
Cooter	5	2.2	487	0	0	627	0	0	19	0
Elizabeth	6	1.5	156	0	0	5.2	0	6	3	0
Clearwater	7	1.5	18.1	0	0	0	0	0	0	0
Hawthorne	8	2.8	53.6	38.0	0	0	26.8	10	120	0
Lit. Orange	9	2.8	525	0	108	524	786	4	109	0
Unnamed	10	3.2	70.0	0	7.7	0	0	0	0	0
Moss Lee	11	3.6	148	0	0	7.7	5.2	0	0	0
Jeggord	12	3.0	207	0	0	23.2	15.5	4	0	0
Still	13	1.1	10.4	0	0	5.2	0	0	0	0
Lochloosa	14	2.9	17766	81.6	201	1232	1232	96	371	0
Orange	15	1.8	26405	182	488	1499	2298	54	381	0
Palatka	16	0.8	18.2	0	0	0	13.0	0	0	0
Newnan's	17	1.5	22136	876	71.3	1549	2324	79	792	0
Mize	18	4.0	15.5	0	0	0	0	0	3	0
Calf	19	1.6	100	8	0	0	8.1	0	29	0
Unnamed	20	1.9	38.4	16.5	0	0	2.1	3	11	0
Meta	21	1.6	8.2	4.9	0	0	8.4	0	0	0
Alice	22	0.9	56.8	288	129	0	0	0	0	5100
Bivin's Arm	23	1.5	378	256	72.8	85.4	0	16	91	0
Clear	24	1.6	15.9	15.2	0	0	0	11	7	0
Unnamed	25	1.0	9.3	1.6	0	0	34.0	0	1	0
Beville's	26	3.1	12.5	5.2	0	0	9.4	3	27	0
Unnamed	27	3.8	26.3	0	0	0	20.2	0	7	0
Kanapaha	28	0.7	4043	1087	0	821	821	6	679	0
Watermelon	29	1.5	979	0	0	106	70.5	3	4	0

(cont'd.)

Table 20 (cont'd.)

Name/No.		Mean Depth (m.)	Forested Area (ha.)	Urban Area (ha.)	Fertilized Cropland (ha.)	Pastured Area (ha.)	Unproductive Cleared Area (ha.)	Immediate Cultural Units	Remote Cultural Units	Population Served by STP[a] Facilities
Long Pond	30	1.2	43.7	0	0	20.2	17.8	0	0	0
Burnt	31	2.2	129	0	0	55.4	38.8	2	18	0
Wauberg	32	3.8	258	16.1	0	123	0	6	4	0
Tuscawilla	33	1.3	963	66.3	0	154	103	1	59	0
Apopka	34	1.3	2384	467	17508	0	0	274	1157	6950
Dora	35	3.0	1233	931	6762	0	0	342	507	6500
Harris	36	4.2	5979	675	8672	0	3612	438	690	0
Eustis	37	4.1	1683	722	5271	0	900	355	554	7740
Griffin	38	2.4	5157	679	9605	0	1187	415	239	13850
Weir	39	6.3	320	139	1168	0	0	274	105	0
Kingsley	40	7.3	503	328	0	0	96.8	266	120	0
Sand Hill	41	4.8	1689	0	0	0	0	0	0	0
Magnolia	42	8.0	484	0	0	0	0	0	0	0
Brooklyn	43	5.7	667	32.3	0	0	0	167	24	0
Geneva	44	4.1	741	205	0	0	270	165	388	0
Swan	45	4.8	460	0	0	0	97.5	107	7	0
Wall	46	2.1	401	12.1	0	73.2	114	0	25	0
Santa Rosa	47	8.1	122	0	0	0	0	26	15	0
Adaho	48	3.5	369	0	0	41.3	0	1	0	0
McCloud	49	2.0	40.5	0	0	0	11.3	0	0	0
Anderson-Cue	50	2.0	48.9	0	0	0	8.1	0	0	50
Suggs	51	2.5	658	0	24.9	23.2	34.8	0	6	0
Long	52	3.4	547	0	0	0	0	10	5	0
Winnott	53	5.2	216	0	15.5	23.8	45.0	48	26	0
Cowpen	54	3.7	712	0	0	0	211	65	110	0
Gallilee	55	3.5	213	0	0	0	150	13	18	0

[a]Sewage Treatment Plant

Table 21. Expected Quantities of Nitrogen and Phosphorus from Various Sources

Source	Reference	Quantity of Nitrogen	Quantity of Phorphorus
Domestic Sewage	Vollenweider (1968)	3940[a]	795[a]
Fertilized Area			
Citrus Farms	-	2.24[b]	.018[b]
Muck Farms	-	.11[b]	.135[b]
Pastured Area	Miller (1955)	.85[b]	.018[b]
Unproductive Cleared Area	Brink (1964)	.18[b]	.006[b]
Forested Area	Sylvester (1961)	.24[b]	.008[b]
Urban Area	Weibel (1969)	.88[b]	.110[b]
Rainfall	Brezonik _et_ _al_. (1969)	.58[c]	.044[c]
Septic Tanks			
Immediate	-	2420[d]	138[d]
Remote	-	970[d]	13.8[d]
Domestic Ducks	Paloumpis & Starret (1960)	480[e]	90[e]

[a]grams/capita - year

[b]grams/square meter of land use area - year

[c]grams/square meter of lake area - year

[d]grams/septic tank - year

[e]grams/duck - year

fertilizer losses were reported by Vollenweider (1968) and, although approximate, probably represent lower limits. Septic tank contributions were estimated using a similar procedure. An average septic tank was assumed to have a daily effluent volume of 475 liters with total nitrogen and phosphorus concentrations of 35 mg/l and 8 mg/l, respectively (Polta, 1969). For septic tanks associated with immediate cultural units, it was estimated that 25 percent of the nitrogen and 10 percent of the phosphorus in the effluent were exported to the lake. For remote cultural unit septic tanks it was estimated that 10 percent of the nitrogen and 1 percent of the phosphorus discharged eventually reached the lake.

Contributions from domestic sewage are expressed in Table 21 as the amount per capita per year. These sewage figures were used only when effluent records for the individual plants were not available. One lake (Mize) harbors a colony of 50 domestic ducks; estimated nitrogen and phosphorus contributions from ducks are thus listed in Table 21. Several large lakes, e.g. Griffin and Apopka, receive nitrogen and phosphorus via citrus processing plant effluents. The magnitude of the contributions were determined from average plant flow rates and concentrations (Environmental Engineering, Inc., 1970).

The calculated nitrogen and phosphorus loading rates for each of the 55 lakes are presented in Table 22 expressed as grams per cubic meter of lake volume per year. Loadings expressed per unit lake surface may be obtained by simply multiplying the volumetric loading by lake mean depth (from Table 20). In Florida lakes mean depths rarely exceed 5 meters and most lakes are completely mixed year round. Consequently most of the analyses reported here pertain to the volumetric loading rates.

In general, the results indicate a positive correlation between nitrogen and phosphorus supply and trophic state as quantified by the TSI, but several discrepancies are evident. Lakes Alice (22) and Kanapaha (28), although demonstrating hypereutrophic characteristics, have nitrogen and phosphorus loadings at least an order of magnitude higher than any of the other hypereutrophic lakes. This can be attributed to the fact that both lakes have had their natural watersheds increased by cultural activities, which have resulted in very short detention times for the lakes. Lake Alice receives 1 to 2 million gallons per day of sewage effluent and 10 to 12 million gallons per day of cooling water from University of Florida facilities. Lake Kanapaha, which is connected with a sinkhole draining an urbanized stream, has had its watershed enlarged 2 to 3 fold by drainage diversion schemes. Thus the hydraulic characteristics of these two lakes separate them from the remainder of the study lakes, which receive runoff from natural watersheds. In order to prevent severe bias in the statistical analyses, these two lakes were excluded

Table 22. Calculated Nitrogen and Phosphorus Supplies for Fifty-Five Florida Lakes

	Lake	Type[a]	TSI[b]	N[c]	P[c]
1	Santa Fe	O	2.5	.28	.015
2	Lit. Santa Fe	O	2.3	.32	.014
3	Hickory Pond	O	2.5	2.25	.051
4	Altho	O	2.5	.53	.031
5	Cooter Pond	M	5.3	3.72	.101
6	Elizabeth	M	3.2	1.45	.064
7	Clearwater	O	2.6	1.01	.051
8	Hawthorne	E	9.1	1.62	.130
9	Lit. Orange	M	3.4	2.58	.082
10	Unnamed	M	3.2	.54	.021
11	Moss Lee	O	2.8	.39	.020
12	Jeggord	O	2.8	.57	.027
13	Still Pond	U	1.9	1.73	.072
14	Lochloosa	M	5.2	1.15	.044
15	Orange	M	4.3	1.85	.071
16	Palatka Pond	M	3.2	2.70	.121
17	Newnan's	E	7.1	2.61	.118
18	Mize	M	4.2	2.05	.183
19	Calf Pond	M	4.6	2.42	.132
20	Unnamed	H	18.5	3.99	.335
21	Meta	M	3.1	3.00	.250
22	Alice	H	10.7	106.00	18.000
23	Bivin's Arm	H	14.7	6.86	.424
24	Clear	E	8.8	4.31	.405
25	Unnamed	M	6.4	2.07	.113
26	Beville's Pond	M	3.1	2.89	.187
27	Unnamed	M	5.8	.77	.032
28	Kanapaha	H	13.5	48.30	2.950
29	Watermelon Pond	M	3.6	1.45	.062
30	Long Pond	O	2.8	5.94	.183
31	Burnt Pond	E	8.3	2.27	.092
32	Wauberg	E	7.4	.63	.028
33	Tuscawilla	M	4.8	2.60	.124
34	Apopka	H	22.1	2.23	.161
35	Dora	H	18.5	3.00	.127
36	Harris	M	6.3	1.10	.029
37	Eustis	H	10.5	1.46	.077
38	Griffin	H	13.7	3.69	.183
39	Weir	M	3.3	.29	.010
40	Kingsley	U	1.9	.18	.015
41	Sandhill	U	1.3	.29	.015
42	Magnolia	U	1.3	.25	.011
43	Brooklyn	U	1.5	.26	.016
44	Geneva	U	1.8	.31	.022
45	Swan	U	1.5	.26	.015
46	Wall	O	2.1	3.27	.124
47	Santa Rosa	U	1.3	.18	.009
48	Adaho	U	2.2	1.03	.039
49	McCloud	U	1.5	1.35	.058
50	Anderson-Cue	U	1.5	3.10	.187
51	Suggs	O	2.3	2.24	.071
52	Long	U	1.3	.55	.026
53	Winnott	M	2.0	.41	.016
54	Cowpen	U	1.5	.42	.021
55	Gallilee	U	1.6	.86	.036

[a]Key to Symbols: U - Ultraoligotrophic; O - Oligotrophic; M - Mesotrophic; E - Eutrophic; H - Hypereutrophic.

[b]Trophic State Index

[c]In g/m^3-yr

from the sample group.

Anderson-Cue Lake (50) has a nitrogen and phosphorus loading comparable to hypereutrophic Lake Dora (35), but a TSI typical of ultraoligotrophic lakes (1.5, see Table 17). Two reasons may be responsible for this discrepancy: (1) the lake has not had sufficient time to equilibrate with its nutrient supply and (ii) the TSI has not been sensitive to the lake response. This lake has been artificially enriched with nitrogen and phosphorus at approximately the present loading rates since 1967 as part of a study of eutrophication factors in Florida lakes (Brezonik and Putnam, 1968; Brezonik et al., 1969). Prior to 1967, the lake was ultraoligotrophic and similar in most aspects to the control, McCloud Lake (49). Both lakes are still ultraoligotrophic according to their TSI's although some increased growths of attached algae have recently been noted in Anderson-Cue Lake. Since the TSI accounts for phytoplankton production and biomass alone, this response is not reflected in the TSI.

C. RELATIVE IMPORTANCE OF VARIOUS NUTRIENT SOURCES

Budgets for six representative lakes are shown in Table 23 in order to compare the percentage contributions of the various nutrient sources to the overall nitrogen and phosphorus budgets. In order to illustrate general trends occurring in the transition from ultraoligotrophic to culturally hypereutrophic conditions, one lake from each of the five trophic groups is presented. In addition, Newnan's Lake is included as an example of a naturally eutrophic lake. For the ultraoligotrophic and oligotrophic lakes, the natural nutrient sources of rainfall and runoff from forested regions are dominant, although Lake Santa Fe receives a small portion of its nitrogen and phosphorus supply (21%) from cultural sources. Orange Lake could perhaps be classified as naturally mesotrophic since most of its nitrogen and phosphorus supply is derived from natural sources.

Lakes Hawthorne and Dora have obviously been influenced by the cultural activities in these watersheds. The former receives the major portion of its nitrogen and phosphorus supply from urban runoff and septic tanks while sewage effluent and agricultural runoff have played a significant role in the deterioration of Lake Dora. Newnan's Lake has a large, heavily forested watershed, and the associated runoff appears to be the predominant factor in the eutrophication of this shallow lake. Eutrophication of this sort is virtually impossible to control, whereas measures can be taken to control the cultural sources degrading lakes like Hawthorne and Dora.

Table 23. Percentage Contributions From Various Cultural and Natural Sources for Selected Lakes

Lake and Type[a]	Nutrient	Sewage	Urban Runoff	Fertilized Area	Pasture Area	Unproductive Cleared Area	Forest Area	Septic Tanks	Rainfall on Lake Surface	% Cul-tural
Santa Rosa (U)	N	0	0	0	0	0	47	13	40	13
	P	0	0	0	0	0	30	11	59	11
Santa Fe (O)	N	0	7	5	7	1	41	2	37	22
	P	0	15	1	3	N.S.	25	2	54	21
Orange (M)	N	0	1	10	11	4	57	N.S.	17	21
	P	0	5	2	6	3	49	N.S.	35	13
Newnan's (E)	N	0	8	2	14	4	56	1	15	25
	P	0	22	N.S.[b]	7	3	41	1	26	30
Hawthorne (E)	N	0	36	N.S.	N.S.	5	14	32	13	68
	P	0	57	N.S.	N.S.	2	6	23	12	80
Dora (H)	N	13	4	74	N.S.	N.S.	1	2	6	93
	P	60	12	14	N.S.	N.S.	1	1	12	87

[a]See Table 4 for key to symbols.

[b]Not significant (less than 1%).

D. STATISTICAL ANALYSIS OF TSI vs. NITROGEN AND PHOSPHORUS LOADING RATES

Results of the statistical analyses are summarized in Table 24. Several regression relationships were tested using both additive and multiplicative models. All the regression results presented in Table 24 were significant at the 99% confidence level. Using the magnitude of the multiple correlation coefficient (R) as a criterion for choosing among the regression equations, an additive equation (A) in Table 24 (b), including simple, interaction and quadratic terms, explains the largest percentage of variation in TSI (R=.830). However, equations B and C incorporating only the simple loadings give comparable significance (R~.80), and inclusion of the interaction terms thus provides only marginal increases in R. The multiplicative model (Equations D and E) is the least significant, and comparison of the additive and multiplicative equations suggests that the functional relationship between TSI and nitrogen and phosphorus loadings may itself be additive with one nutrient being more significant; i.e. limiting. In Florida lakes it appears that the phosphorus loading is the limiting factor since it is the first independent variable incorporated by the stepwise procedure into the regression equations, and it has the highest simple correlation [.786, Table 24 (a)] with the TSI. However, too much significance should not be placed on the above interpretations. Regression analysis is inherently empirical, and its primary value lies in its predictive abilities rather than in any analytical potential.

Canonical correlation analysis [Table 24 (c)] derived a canonical variate of the seven trophic indicators that was significantly correlated (.723) with the canonical variate of nitrogen and phosphorus loadings. In general, the analysis corroborates the regression results. For instance, phosphorus loading is the more significant of the two loadings based on the weighting factors in the canonical variate (1.19 for P vs. -0.23 for N). The most heavily weighted trophic indicator in the indicator canonical variate is total phosphorus concentration (TP). Thus, the larger weightings associated with P and TP illustrate the dependence of average total phosphorus concentration upon the phosphorus loading. Vollenweider (1968) observed a similar correlation between spring total phosphorus concentrations and phosphorus supply for a group of European lakes.

Although the regression and canonical correlation analyses resulted in statistically significant relationships, there is considerable disagreement between the predicted and observed values of TSI. For example, Lake Griffin has an experimental TSI of 13.7 and a predicted TSI, using equation A of Table 24 (b), of 9.6, a 30 percent error. Similar discrepancies exist

Table 24. Statistical Analyses of Relationships Between TSI and N and P Loading Rates

(a) CORRELATION MATRIX:

	TSI	N	P
TSI	1.000	.773	.786
N		1.000	.935
P			1.000

(b) STEPWISE REGRESSION ANALYSES:

Model	Loading Rate Units[a]	Equation[b]	F Ratio[c]	Multiple Correlation Coefficient	Percent Variance Explained by Equation
Additive					
A	V	$TSI = 26.1(P_V)-242(P_V)^2+1.12(N_V)^2 +28.7(N_V)(P_V)+2.37(N_V)$	48.1	.830	68.9
B	V	$TSI = 26.1(P_V)+0.90(N_V)$	43.2	.793	62.9
C	S	$TSI = 0.62(N_S)+10.1(P_S)$	46.4	.804	64.5
Multiplicative					
D	V	$TSI = 1.08(P_V)^{.42}(N_V)^{.04}$	15.6	.620	38.5
E	S	$TSI = 0.84(P_S)^{.48}(N_S)^{.20}$	14.1	.600	36.0

(c) CANONICAL CORRELATION ANALYSIS:

Canonical Variate of Trophic State Indicators[d]	Canonical Variate of N and P Loadings	Canonical Correlation Coefficient
0.69(TP) + 0.64(1/SD) + 0.48(CL) - 0.36(TN) + 0.34(PP) + 0.33(CD) + 0.17(1/CR)	1.19(P) - .23(N)	.723[c]

[a]Loading rates per unit lake volume (V), per unit lake surface area (S).

[b]Abbreviations: TSI=trophic state index (dimensionless); N_S and P_S =nitrogen and phosphorus surface loading rates in g/m^2-yr.; N_V and P_V =nitrogen and phosphorus volumetric loading rates in g/m^3-yr.

[c]All significant at the 99% confidence level.

[d]Key to symbols: TP=total phosphorus (mg/l); 1/SD=inverse Secchi disc (m^{-1}); Cl=chlorophyll a (mg/m^3); TN=total organic nitrogen (mg/l); PP=primary production (mg C/m^3-hr.); CD=specific conductance (μmho/cm); 1/CR=inverse of Pearsall's (1922) cation ratio=[(Ca)+(Mg)]/[(Na)+(K)].

for some of the other lakes with the average error being about ±25 percent. Thus in spite of the strong trends demonstrated by the significant regression relationships, there is substantial scatter of the experimental data about the fitted regression surfaces. Several possible sources of uncertainty will be discussed later.

E. CRITICAL NUTRIENT LOADING RATES: APPLICATION TO LAKE MANAGEMENT

Of great interest in control of cultural eutrophication is the development of critical loading rates, above which eutrophic conditions might be expected to ensue.

Vollenweider (1968) has developed two types of critical loading rates based on information from a number of European and American lakes. Permissible loading rates are values below which no eutrophication problems should occur, and dangerous loading rates are values above which problems can be expected. Loading rates in between these two figures may or may not cause problems depending on other factors. Inspection of various limnological data from the 55 Florida lakes indicates that eutrophic conditions (and attendant water quality deterioration) are associated with all lakes having TSI values greater than 7.0 (i.e. the lakes in the eutrophic and hypereutrophic classes of Table 17), and similarly lakes with TSI values less than 4.0 have essentially no nutrient enrichment problems. Using these as "dangerous" and "permissible" TSI values, respectively, the nitrogen and phosphorus loading rates associated with these values were computed, assuming an N:P molar loading ratio of 15:1 as most appropriate. Critical rates were computed on both areal and volumetric loading bases from appropriate regression equations, and Table 25 compares these results with those of Vollenweider (1968). It appears that Florida lakes can assimilate nutrients at somewhat greater rates without becoming eutrophic than suggested by Vollenweider's critical values, but the uncertainties involved in both analyses prevent detailed interpretation.

Some interesting results were obtained through graphical presentation of the relationships between the TSI and phosphorus and nitrogen supplies, respectively. In Figure 9, the mean TSI for each trophic group is plotted against the corresponding mean phosphorus loading. Figure 10 represents a similar treatment considering mean nitrogen loadings. The horizontal bounded lines represent plus and minus one standard error of the group loading mean. In both graphs the dependence of TSI on nitrogen or phosphorus loading can be adequately described by an exponential function similar to the classical logarithmic growth curve. The least squares equation and correlation coefficients are shown for each figure. That both curves are similarly shaped is to be expected since the

Table 25. Critical Loading Rates for Nitrogen and Phosphorus

Reference	Loading Rate Units	Permissible Loading (up to)		Dangerous Loading (in excess of)	
		N	P	N	P
Shannon and Brezonik, 1971c	Volumetric (g/m^3-yr)	.86	.12	1.51	.22
Ibid.	Areal(g/m^2-yr)	2.0	.28	3.4	.49
Vollenweider (1968)[a]	Areal(g/m^2-yr)	1.0	.07	2.0	.13

[a]For lakes with mean depths of 5 m or less.

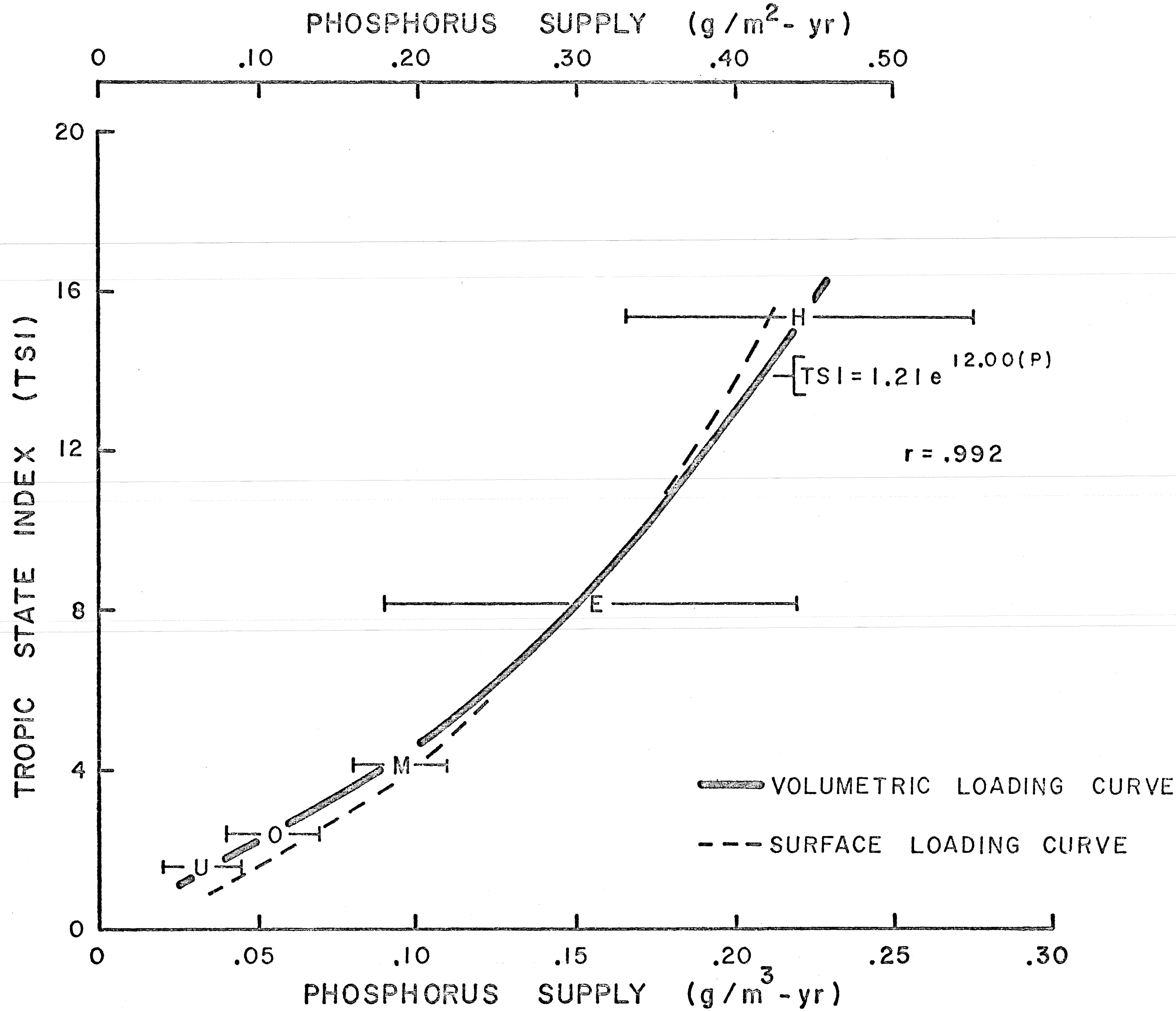

Figure 9. Mean TSI Values for Five Trophic Groups vs. Annual Phosphorus Loading in g/m^3-yr and g/m^2-yr.

Brackets indicate range for one standard error. Symbols of trophic groups are: ultraoligotrophic (U), oligotrophic (O), mesotrophic (M), eutrophic (E), hypereutrophic (H).

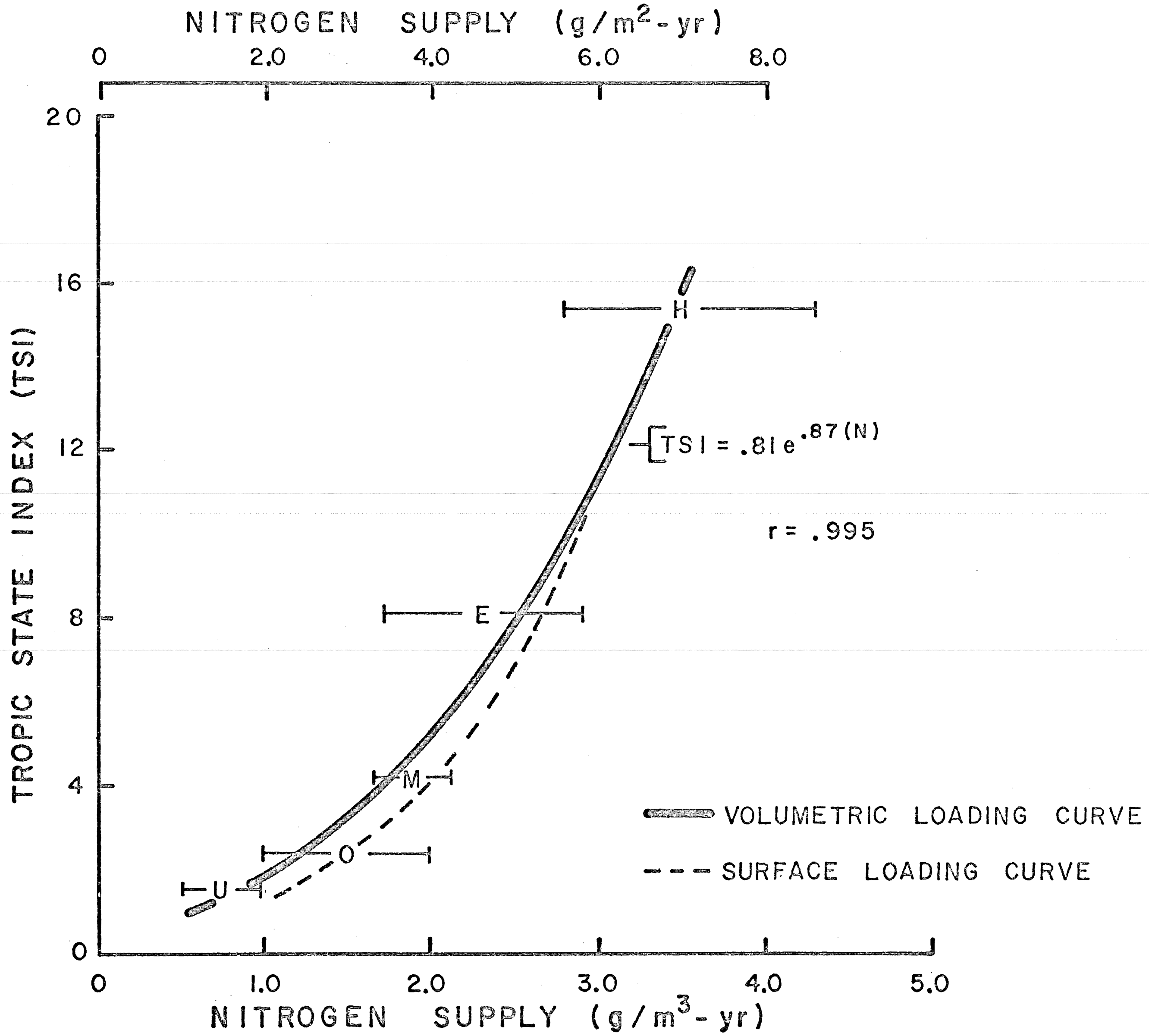

Figure 10. Mean TSI Values for Five Trophic Groups vs. Annual Nitrogen Loading in g/m^3-yr and g/m^2-yr. See Figure 1 for explanation of symbols.

nitrogen and phosphorus loadings are themselves highly correlated [See Table 24 (a)]. The within-group deviation of loadings is considerably more pronounced for the phosphorus relationships, particularly for the hypereutrophic and eutrophic groups of lakes. Such deviations are to be expected when representing the complex process of trophic state change in terms of a single nutrient input. In addition, the hypereutrophic group is essentially unbounded at the upper end and therefore not subjected to artificial boundary constraints as are the other four groups. Quite likely changes in the limiting nutrient will occur over any extended range of trophic state response. Thus, the relationships of Figures 1 and 2 reflect only an average situation, and their major utility probably lies in the area of lake management. For example, given that either nitrogen or phosphorus is limiting and a known or proposed nutrient loading, potential lake response can be determined by consulting the appropriate relationship. It should be emphasized that the graphical relationships in Figures 9 and 10 are most applicable for shallow subtropical lakes, and their use in other situations may be unwarranted.

F. EFFECT OF DEPTH ON LAKE CAPACITY TO ASSIMILATE NUTRIENTS

As our data base expands it should be possible to incorporate other factors of Eq. 15 into empirical eutrophication models. For example, mean depth is probably the most important morphometric factor affecting eutrophication. Figure 11 indicates a slight mean depth-trophic state relationship exists for the 55 Florida lakes, with the most eutrophic lakes having mean depths of 4 m or less and the deepest lakes being the most oligotrophic. As expected a large scatter occurs. The proper relation of mean depth to eutrophication has been confused by many. It is neither a trophic indicator nor a causal factor per se. Rather mean depth affects the rate at which a lake can assimilate nutrients and maintain desirable trophic conditions. The graphical approach taken by Vollenweider (1968) might prove useful in quantifying the effects of depth. The method plots nutrient (N or P) loading rates vs. lake mean depth, and the lines delineating the regions in which oligotrophic and eutrophic lakes occur are estimated by inspection. Figures 12 and 13 illustrate this approach for Florida lakes using phosphorus and nitrogen loading rates, respectively. However it is obvious that insufficient shallow oligotrophic and deep eutrophic lakes occur in the sample group to permit accurate delineation of boundary lines. Perhaps a better approach to evaluating the role of mean depth in the trophic state calculus would be the method of response surfaces (Box, 1954; Goldman, 1967).

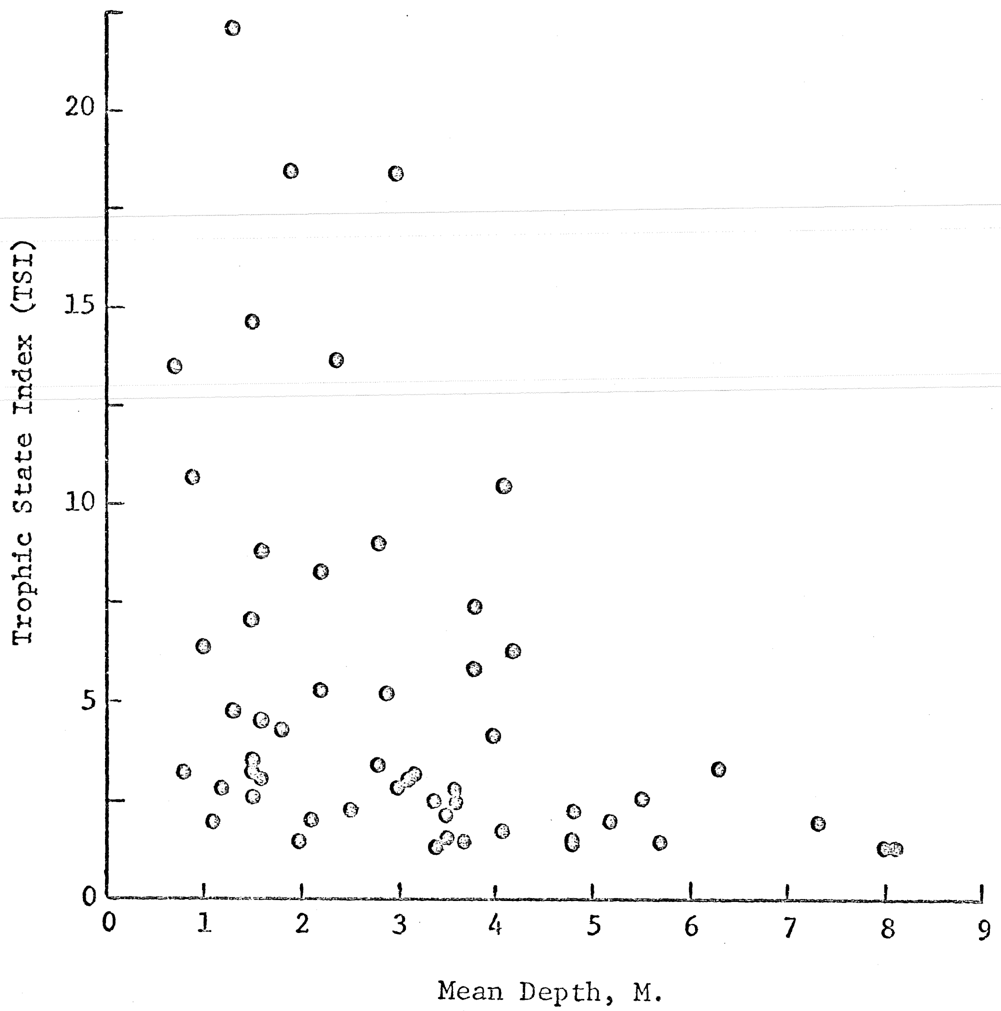

Figure 11. Trophic State Index (TSI) Values vs. Mean Depth for the Florida Lakes

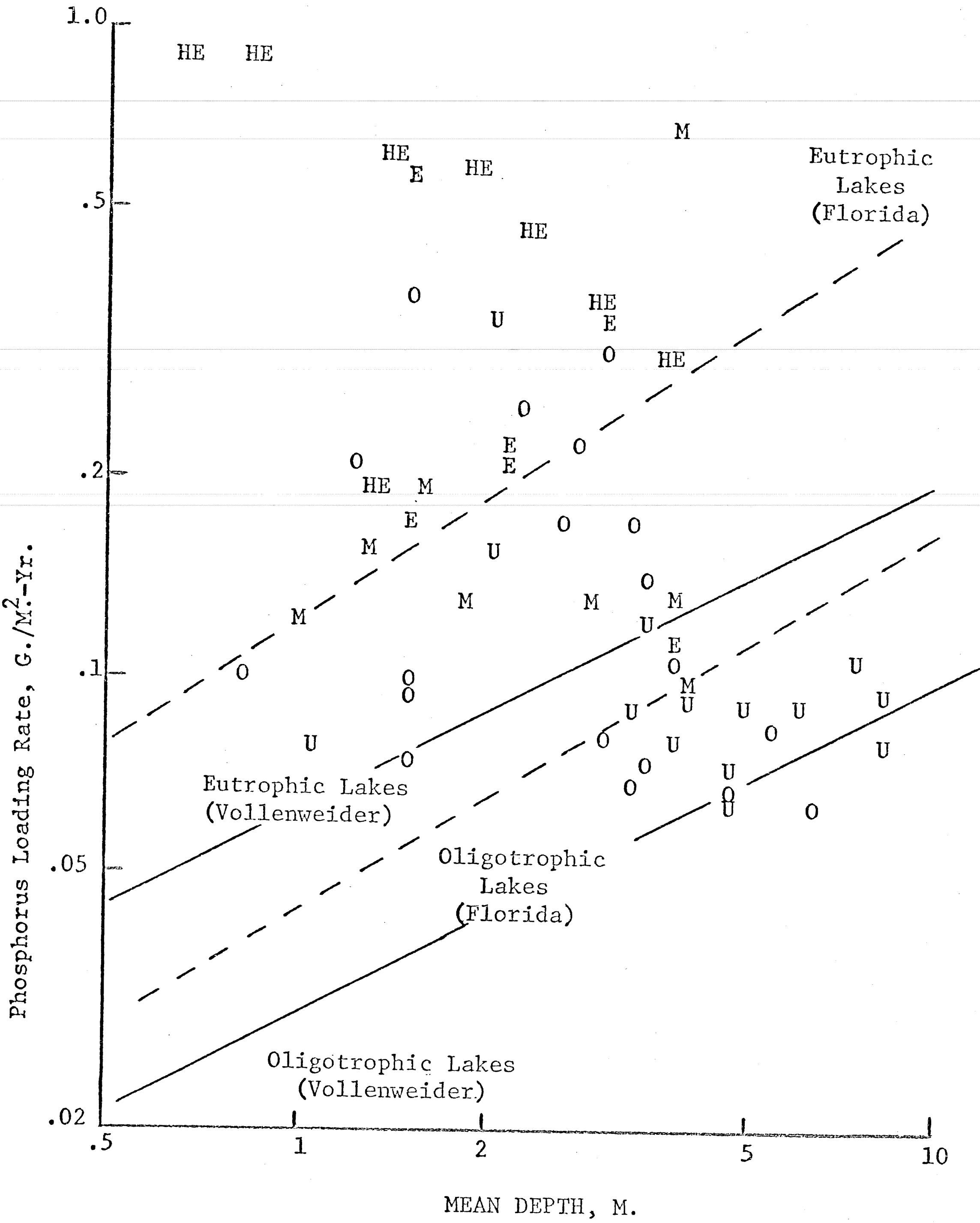

Figure 12. Annual Phosphorus Loading Rate vs. Mean Depth for 55 Florida Lakes.

Each datum represents a lake in the trophic group denoted by that symbol. U = ultraoligotrophic, O = oligotrophic, M = mesotrophic, E = eutrophic, HE = hypereutrophic.

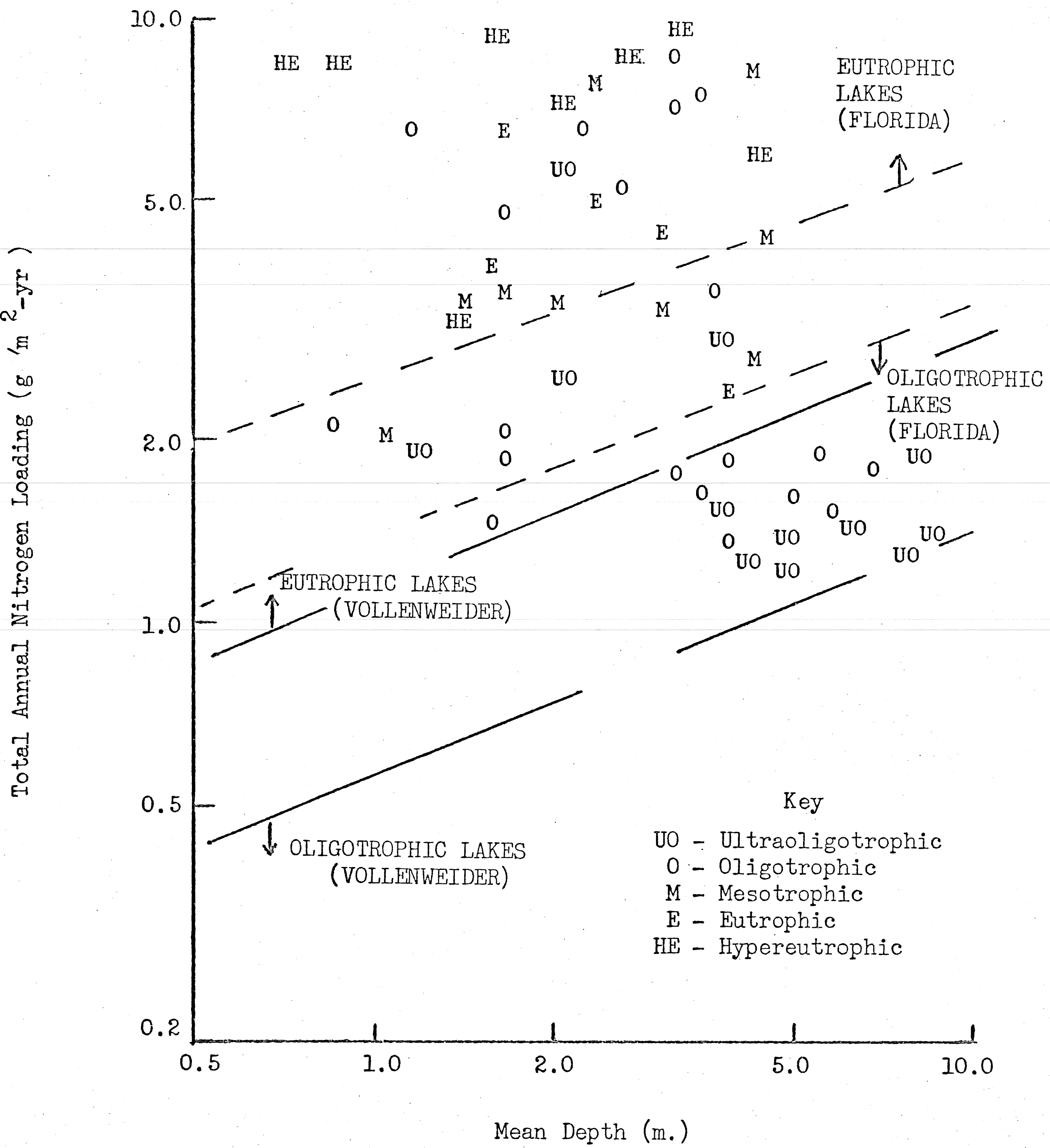

Figure 13. Annual Nitrogen Loading vs. Mean Depth for 55 Florida Lakes

Each datum represents a lake having the trophic state denoted by that symbol.

G. SOURCES OF UNCERTAINTY

The above analysis represents an attempt to approximate the general trophic response function (Eq. 15) by the simple relationship between TSI and nitrogen and phosphorus loadings in Eq. 16. The uncertainty term in Eq. 16 represents the discrepancy between values of TSI predicted by the function g(N,P) and the actual (measured) TSI values, assuming the TSI in fact represents the true trophic status of the lake.

Individual components of the uncertainty term may include the following: (i) g is an approximation of $\int$, (ii) the nitrogen and phosphorus supply calculations are in error, and (iii) the TSI does not represent the concept of trophic state (TS) completely. Approximations of $\int$ were obtained here by using multiple regression techniques. These approximations included only two of a number of potentially important variables, i.e. nitrogen and phosphorus loadings. The loadings were estimated using land use and population characteristics and literature values of individual source contributions, a procedure that contains some inherent uncertainty. The TSI may not completely describe the concept of trophic state in spite of the fact that it incorporates seven of the more significant trophic state indicators. As previously discussed in reference to Anderson-Cue Lake, it does not account for macrophyte and periphyton biomass or primary production, which in some lakes may constitute a significant proportion of total lake primary production.

H. RELATIONSHIPS BETWEEN TROPHIC STATE AND GENERAL WATERSHED CONDITIONS

Another approach to relating trophic state to watershed factors is direct regression of lake conditions (expressed by a TSI) to the extent of various land use practices and population characteristics with the watershed (expressed on a per unit lake volume or area basis). The trophic indicator data (Table 7), the TSI values (Table 17), and the population and land use data (Table 20) were used for these analyses. In addition, the correlative relationship between the seven trophic state indicators and the eutrophication factors was investigated using canonical correlation analysis. The eutrophication factors were expressed on a per unit lake volume basis in the ensuing analyses by dividing the values in Table 20 by the total lake volume. Thus, the units for land use patterns were square meters for a particular land use per cubic meter of lake water, and population characteristics were expressed as number of cultural units per cubic meter of lake water. The eutrophication factors could alternatively have been expressed per unit lake surface area. However, it seems more logical to express eutrophication factors for shallow Florida lakes on a unit volume basis since the entire volume is involved in assimilation and dilution of nutrient influxes. Results considering land use and population factors on a unit surface area basis were similar to the results obtained on a volumetric basis (Shannon, 1970). For the reasons discussed in the section on statistical analysis of the TSI vs. nutrient loading rates, Lakes Alice and Kanapaha were excluded from the following analyses.

Results of regression analyses for TSI (as independent variable) vs. various eutrophication factors are shown in Table 26. Two regression equations are given; the first considers TSI as a linear function of the land use patterns within the watershed plus the immediate and remote cultural units. The second considers TSI as a function of the land use patterns plus total cultural units (TCU), i.e. the sum of remote, immediate and sewage treatment cultural units. The independent variables of the regression equations are written in the stepwise order in which they were incorporated into the equation, i.e. in decreasing order of their partial correlation with TSI. Both equations in Table 26 are statistically significant at the 99% confidence level and both explain about 80% of the total variance in the TSI.

The first independent variable in both equations is the fertilized cropland; other culturally influenced factors such as urban area and immediate cultural units are important variables in explaining the variance in TSI. A natural factor, forested areas, is also important, but other factors like unproductive cleared area, remote septic tanks and pastured areas add little to the predictive abilities of the equations. These results can be interpreted as suggesting that culturally influenced factors (fertilized cropland, urban runoff, septic tank drainage) are among the most important variables determining the trophic states of Florida lakes. However, it should also be emphasized that regression analyses are inherently empirical, and while they may suggest, they never prove cause-effect relationships.

A canonical analysis of the seven trophic indicators (Table 7) and six eutrophication factors (the land use areas and total cultural units) (Table 20) for the 55 lakes is presented in Table 27. The correlation coefficient between the two canonical variates $\int_I$ and $\int_{EF}$ is high (0.94) and significant at the 99% confidence level. In the trophic indicator canonical variate ($\int_I$), primary production is weighted considerably higher than the other indicators, suggesting it is of fundamental importance in the trophic state-eutrophication factor relationship. At the other extreme the cation ratio has a low weight and appears to be of minor importance in the relationship. Cultural factors (urban area and fertilized cropland) carry the heaviest weightings in the eutrophication

Table 26. Stepwise Regression Analysis of TSI vs. Eutrophication Factors Expressed Per Unit Lake Volume[1]

(1) Regression Equation:

$$\mathrm{TSI} = \underset{59.6}{14.95(\mathrm{HFA})} + \underset{73.9}{.64(\mathrm{FOR})} + \underset{80.0}{2.72(\mathrm{ICU})} + \underset{81.2}{1.59(\mathrm{URB})}$$

$$- \underset{81.5}{.35(\mathrm{UCA})} + \underset{81.5}{.06(\mathrm{RCU})} - \underset{81.5}{.02(\mathrm{PA})}$$

F Ratio = 28.98***
Multiple Correlation Coefficient (r) = .903
Percent of total variation explained by the regression equation = 81.5%

(2) Regression Equation:

$$\mathrm{TSI} = \underset{59.6}{14.49(\mathrm{HFA})} + \underset{73.9}{.61(\mathrm{FOR})} + \underset{79.4}{2.23(\mathrm{URB})} + \underset{80.0}{.53(\mathrm{TCU})}$$

$$+ \underset{80.3}{.31(\mathrm{UCA})} - \underset{80.3}{.01(\mathrm{PA})}$$

F Ratio = 31.91***
Multiple correlation coefficient (r) = .896
Percent of total variation explained by the regression equation = 80.3%

Key to Eutrophication Factor Symbols:

HFA = Heavily fertilized cropland (m^2/m^3)
FOR = Forested area (m^2/m^3)
ICU = Immediate cultural units ($\#/m^3 x10^4$)
URB = Urban area (m^2/m^3)
UCA = Unproductive waste cleared area (m^2/m^3)
RCU = Remote cultural units ($\#/m^3 x10^4$)
PA = Pastured area (m^2/m^3)
TCU = Total cultural units ($\#/m^3 x10^4$)

***Denotes significant F value at the 99% confidence level.

[1]Values below symbols in regression equation indicate cumulative percent of total variance explained by independent variables up to that point.

Table 27. Canonical Analysis of the Relationship Between Seven Trophic Indicators and Six Eutrophication Factors[1]

Canonical Variate 1: Linear function of trophic indicators

$$\int_{I} = -0.36(1/SD) + 0.71(COND) - 0.17(TON) + 0.25(TP) + 1.13(PP) - 0.60(CHA) - 0.09(1/CR)$$

Canonical Variate 2: Linear function of eutrophication factors

$$\int_{EF} = -0.10(FOR) + 0.53(URB) + 0.79(HFA) - 0.04(PA) - 0.06(UCA) - 0.16(TCU)$$

Canonical correlation coefficient = 0.94***

***Significant at the 99% confidence level by a testing procedure described in Morrison, 1967.

[1]See Table 26 for key to eutrophication factor abbreviations.

factors canonical variate ($\int_{EF}$); pasture and unproductive cleared areas carry the lowest weightings, which corroborates the regression results of Table 26. Thus in general it appears that the major link between trophic state ($\int_I$) and eutrophication factors ($\int_{EF}$) is one of primary production and the cultural factors of urban and heavily fertilized areas.

Comparing the canonical correlation of trophic indicators vs. nitrogen and phosphorus loadings (Table 24) with the above analysis indicates a higher correlation coefficient was obtained in the latter analysis. There is some inherent error in using literature values of the expected nitrogen and phosphorus contributions from land use patterns in order to obtain nutrient loadings, and this quite likely explains the lower correlation for the analysis using the nutrient loading rates. In other words, the land use and population characteristics in their raw form contain more significant information than the calculated nitrogen and phosphorus loadings.

Empirical relationships such as those in Tables 26 and 27 depend on the fact that runoff from various land use practices has different and to an extent defined nutrient enrichment effects on receiving bodies of water. Similarly the population within a watershed can be divided into a few main groups (e.g. people on sewerage systems, people using septic tanks in the immediate vicinity of a lake, etc.) which have similar (within group) enrichment effects. Refinement of this type of regression relationship could prove beneficial to regional planners and land use (zoning) boards.

In evaluating the statistical relationships between trophic state and eutrophication factors, the time element has not been considered. It has been assumed that lake trophic state as reflected by the TSI or certain trophic state indicators was a result of the eutrophication factors at that time or, in other words, trophic state and the eutrophication factors were in equilibrium at the time they were evaluated. In reality, the trophic state of a lake is the result of the eutrophication factors influence over a period of years. For example, the hypereutrophic conditions of Lakes Apopka and Dora in the Oklawaha group are due to the intense cultural activities around the lake in the past two or three decades. On the other hand, Anderson-Cue Lake has been subjected to a high rate of nutrient enrichment over a period of three years but remains in an oligotrophic condition, presumably because it has not had sufficient time to demonstrate a response. Very little is known about the response time of a lake to nutrient enrichment, and as yet it is impossible to quantify. However, it seems reasonable to assume that the majority of the lakes are in a state of dynamic equilibrium with their environments; the relatively high correlations between causal factors and effects would seem to substantiate this point.

I. RELATIONSHIP BETWEEN TSI AND TOTAL WATERSHED AREA

A simpler relationship between watershed and lake trophic state was recently proposed (Schindler, 1971) for lakes within a similar geological region and in which cultural influences are slight. In a nutrient poor terrain the atmosphere acts as the major nutrient source. Assuming a steady-state exists between nutrient input (via precipitation) and nutrient export to the lake, the rate of lake nutrient enrichment should be directly proportional to the sum of lake area (A_o) plus watershed land area (A_d). Because nutrient influx will be diluted in proportion to lake volume (V), Schindler (1971) hypothesized that lake trophic conditions then should be proportional to $(A_d + A_o)/V$. Many lakes in north-central Florida fit the above conditions, and Figure 14 shows the crude correlation resulting when TSI is plotted vs. the watershed factor for these lakes. Data points in Figure 14 represent seepage and semi-drainage lakes located in similar terrain in the Trail Ridge and Alachua County regions of Figure 2. Drainage lakes and those showing major cultural influences were excluded. The hypothesis seems to have limited applicability under these conditions but the scatter implies poor predictive abilities. Thus the earlier statement that eutrophication is a complicated phenomenon is again borne out, and simple relationships are unlikely to explain more than general trends. From the point of view of eutrophication control and lake management, a compromise between highly complex mathematical models and oversimplified empirical relationships, such as described in the preceding analyses, would seem the most appropriate means of effecting satisfactory results.

CHAPTER 6. CONCLUSIONS

The limnology of north and central Florida is dominated by shallow solution type lakes in a sandy terrain. While thermal stratification is not typical in these lakes, neither is it rare, and stable stratification can occur in small ponds as shallow as 3.5 meters deep. The waters of most lakes are low in dissolved solids, soft and slightly to moderately acid. Organic color is an important but geographically variable feature of the lakes. Both acid and alkaline conditions occur in colored waters, but the former are more prevalent. Apparently few lakes are springfed, accounting for the paucity of hard-water lakes.

Lake trophic state was envisioned as a multi-dimensional or hybrid concept described by several biological, chemical and physical indicators. Groups of lakes with similar trophic state characteristics were formed using cluster analysis, and

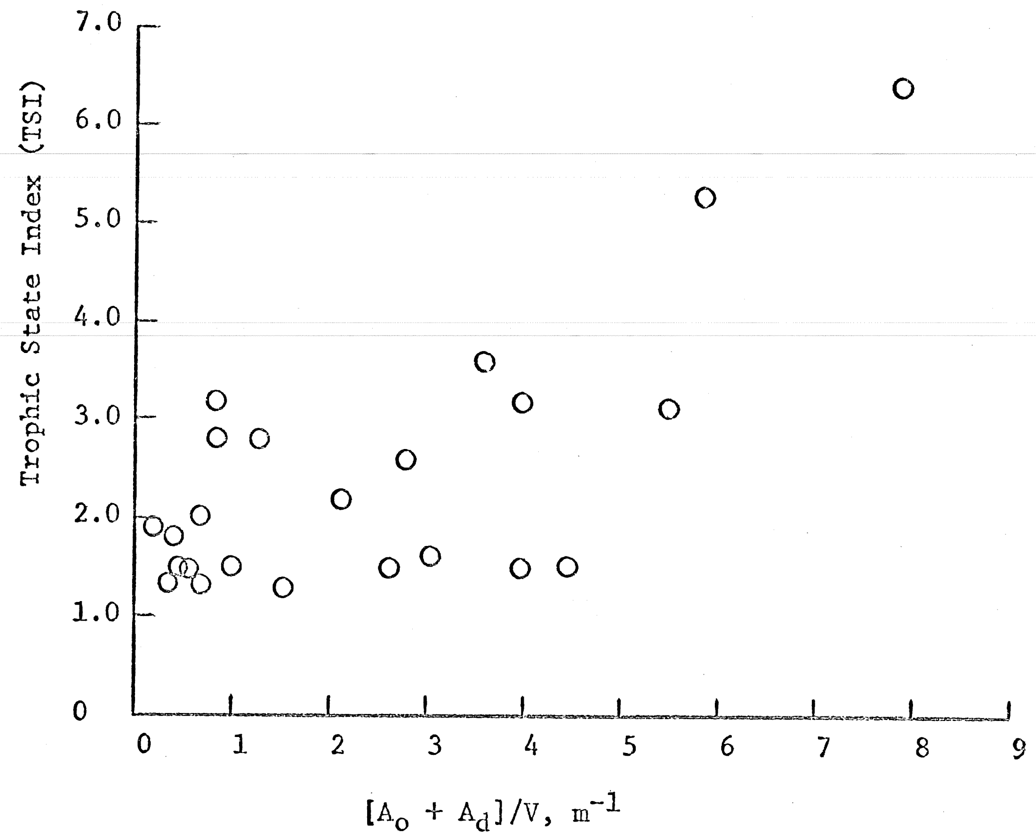

Figure 14. Trophic State Index vs. Total Watershed Area/Lake Volume for Selected Florida Lakes

A_o = lake area, A_d = watershed land area

Only seepage or semidrainage lakes with minimum cultural influences are plotted.

these groups could be interpreted in the classical (oligotrophic-mesotrophic-eutrophic) sense.

A trophic state index (TSI) was formulated using principal component analysis incorporating seven trophic state indicators. The TSI quantified the concept of trophic state on a numerical scale, thus providing a method for ranking and comparing lake trophic states.

The trophic states of Florida lakes are largely dependent on gross nitrogen and phosphorus supplies (loading rates) as evidenced by significant regression relationships between TSI and N and P loading rates and significant canonical correlation between seven trophic indicators and the N and P loadings. Phosphorus loading was the most important variable from a statistical viewpoint in the regression and canonical relationships, and it might be inferred that on an average basis phosphorus is the (most common) limiting nutrient for Florida lakes.

Cultural nutrient sources are relatively unimportant in oligotrophic lakes, but for many eutrophic lakes, cultural sources are by far the most significant. Critical nutrient loading rates were calculated for Florida lakes based on the regression relationships. Florida lakes seem capable of assimilating greater quantities of nutrients than suggested by Vollenweider's critical loading figures, but the two studies are in general agreement.

A positive correlation exists for Florida lakes, between lake trophic state and lake watershed land use and population characteristics. The relationship was verified by statistically significant multiple regression equations using the TSI as the dependent variable and several watershed land use and population characteristics as independent variables. Canonical correlation analysis of several trophic state indicators versus the population and land use characteristics showed high correlation and corroborated the regression results. It appears that cultural influences have played a major role in determining the trophic states of Florida lakes. Regression and canonical analyses results indicate that the most influential eutrophication factor from a statistical viewpoint is fertilized cropland.

In spite of the statistically significant results obtained in this study there are several sources of uncertainty in the methodology. These sources have been discussed in the text and should not be overlooked in studies of a similar nature.

APPENDIX

MULTIVARIATE TERMINOLOGY

The term "multivariate analysis" is used to describe statistical techniques concerned with analyzing data collected for p different variables on N objects. For example, the variables in this study are chemical, biological, and physical characteristics measured on several lakes representing the objects. Some dependency is assumed among the variables so that they are considered as a system, implying that no variable can be separated from the group and considered individually. This feature distinguishes multivariate data and techniques from their multi-dimensional nature multivariate techniques are most conveniently described using vector and matrix notation.

Vector quantities in the text are underscored, for example $\underline{x}_i$ represents the vector of p variables for lake i. Matrix quantities are denoted by capital letters, and scalar quantities are denoted by small letters. Vectors are column vectors unless the transpose is indicated by priming the vector (e.g. $\underline{x}_i'$ is the transpose of $\underline{x}_i$). The inverse of a matrix A is denoted by A^{-1}. The (ij)-th element of a matrix A is denoted by a_{ij}.

Suppose that the assumptions of random and independent sampling have been satisfied and observation vectors of p variables are evaluated for N lakes. The resulting collection of data may be expressed in an Nxp (N rows and p columns) raw data matrix:

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1p} \\ x_{21} & x_{22} & \dots & x_{2p} \\ \cdot & \cdot & \dots & \cdot \\ x_{N1} & x_{N2} & \dots & x_{Np} \end{bmatrix} \tag{A-1}$$

The X matrix is the starting point for most multivariate procedures. Analogous to the univariate situation where a random variable x is considered to be normally distributed with mean μ and variance σ^2, multivariate data are considered to be realizations of a p-dimensional random variable distributed multivariate normal with mean vector $\underline{\mu}$ and covariance matrix Σ. As μ and σ^2 are estimated by the sample mean $\bar{x}$ and the sample variance s^2 in the univariate case, $\underline{\mu}$ and Σ are estimated by the vector of sample means of the p variables $\underline{\bar{x}}$ and the sample covariance matrix S:

$$\underline{\bar{x}} = \frac{1}{N}\sum_{k=1}^{N} \underline{x}_k , \tag{A-2}$$

and

$$S = \frac{1}{N-1}\sum_{k=1}^{N} (\underline{x}_k-\underline{\bar{x}})(\underline{x}_k-\underline{\bar{x}})' . \tag{A-3}$$

S is the p x p matrix of covariance between all possible pairs of variables, i.e. s_{ij} = the covariance between variables x_i and x_j. S is a symmetric matrix, i.e. $s_{ij} = s_{ji}$, except for i=j. The variance of variable x_i is contained in the element s_{ii}.

The matrix of sample correlations between all possible pairs of variables is denoted by the matrix R where:

$$r_{ij} = \frac{s_{ij}}{\sqrt{s_{ii}s_{jj}}} . \tag{A-4}$$

The matrix R can be computed from S by the expression:

$$R = D(\frac{1}{s_i}) \cdot S \cdot D(\frac{1}{s_i}), \tag{A-5}$$

where $D(\frac{1}{s_i})$ denotes a matrix containing the reciprocals of the standard deviations in the diagonal elements and zeros in all other elements of the matrix. The matrix R is also p x p and symmetric.

When the variables under consideration are in different units and ranges it is necessary to transform (or standardize) them to a scale of common origin and units. The Z score method is a commonly used standardization technique. The raw data matrix X is transformed to the standardized matrix Z by

$$Z = (I-\frac{1}{N}E)XD \tag{A-6}$$

where Z and X are the Nxp matrices of transformed and raw variables, respectively. I is the NxN identity matrix with 1's on the diagonal and zeros elsewhere, E is an NxN matrix with 1's in every position and D is a pxp diagonal matrix with reciprocals of the standard deviations on the diagonal elements and zeros elsewhere. The general element of Z is given by

$$z_{ij} = \frac{x_{ij}-\bar{x}_j}{s_j} \quad . \tag{A-7}$$

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ADDENDUM

Publications arising from this project thus far are:

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Shannon, E. E. 1970. Eutrophication - trophic state relationships in north and central Florida lakes. Ph.D. thesis, Univ. Florida, Gainesville, 258 p.

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