PROPOSED METHOD FOR EVALUATING THE EFFECTS OF RESTORING LAKES

by

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INTRODUCTION

An ongoing program to demonstrate methods for restoring polluted lakes and preventing pollution of clean lakes is being funded with EPA/local matching (50/50) money as directed by sections 314/104(h) (Clean Lakes) of PL92-500 (Federal Water Pollution Control Act Amendments of 1972). To aid in evaluating the efficacy of the various restoration techniques, comprehensive limnological evaluations are being conducted on a subset of lakes selected from all those being restored under the 314 program (Porcella and Peterson, 1977).

The evaluation grants are the outgrowth of several questions about lake management. Suppose the quality of a lake is perceived as needing protection or as being undesirable; can objective criteria be related to that perception? How does one change a lake to another specific condition or at least change its water quality? What are the effects of changes that occur in the watershed or in the lake on the water quality of the lake? How do various restoration techniques compare in terms of effectiveness?

Thus, the objectives of these detailed limnological evaluations of lake restoration projects are:

1) To determine the effectiveness of the specific restoration manipulation(s) at a given lake.

2) To compare the effectiveness of various restoration processes on different lakes.

The above questions and objectives reflect a need for predicting lake dynamics and future steady states as related to physical, chemical and biological factors and their interactions. Although it is probably not possible at this time to use sophisticated and precise means of predicting lake, biotic community, and specific organism responses to specific manipulations, it is

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necessary for managers to be able to predict manipulation effects on generalized variables that represent the more detailed and complex interactions of aquatic communities. Such "target" variables must be measured so that the effects of lake restoration projects can be evaluated and then the above questions answered. For the limnological evaluations discussed above, the target variables will be measured over a period of time extending from prior to the application of restoration (baseline) to a significant time after the restoration has been completed.

Two basic approaches will be used in achieving the evaluation objectives: 1) target variables will be based on the concept of nutrient balance similar to Vollenweider's analysis that began in the late 1960's (Vollenweider, 1968, 1976; Dillon and Rigler, 1974); 2) target variables will be selected to represent general lake water quality and combined in a logical fashion to provide an index number (Lake Evaluation Index, LEI).

Data appropriate for determining phosphorus and nitrogen loading of lakes and for estimating the LEI from the individual target variables will be used to compare lake quality before and after application of lake restoration methodology in each lake and to estimate the quantitative effects of the restoration on that specific lake. Then the effects of specific restoration methodology will be evaluated in terms of effects on external and internal loading and the predicted effect of that changed loading as compared to observed values in all lakes being evaluated. Similarly, calculated and observed effects on individual target variables and the LEI will be determined. The individual target variables that compose the LEI will be transformed to produce a scale of 0 to 100 so that comparisons can be made easily.

In this report we describe the basic concepts of lake quality evaluation and the data needed to perform the evaluation. In addition, we describe the concepts relating to the development of a LEI useful in performing the evaluation. We emphasize that we are presenting proposed methods; modifications and refinements no doubt will occur as our experience increases.

EVALUATION VARIABLES

BASIC APPROACHES

Many variables can be and have been measured in lakes; most measurements are fairly costly but results are not all of equal value in assessing lake quality. This is why it is necessary to develop concepts and approaches which limit the number of measurements. It is assumed that the Vollenweider Approach and the LEI are useful concepts for meeting the objectives of EPA's Clean Lakes evaluation program.

VOLLENWEIDER APPROACH

Considerable development of the phosphorus loading concept has occurred (see Vollenweider, 1976; Dillon and Rigler 1975; Lorenzen, et al., 1976; Lung et al., 1976; Larsen and Mercier, 1976; Chapra and Tarapchak, 1976); the necessary measurements are listed in Table 1. This approach seems reasonable because it is relatively simple, has feasible data requirements, considerable

TABLE 1. A LISTING OF MEASUREMENTS NECESSARY TO PERFORM ANALYSES OF LAKE ECOSYSTEMS USING NUTRIENT LOADING CONCEPTS (VOLLENWEIDER APPROACH).

Parameter	Water	Phosphorus	Nitrogen
depth area curves	X		
depth volume curves	X		
evaporation	X		
precipitation	X		
inflow (Q)	X		
outflow (Q)	X		
mean depth (maximum volume and area)	X		
inflow concentration*		X	X
in lake concentration*		X	X
sediment bulk concentrations and/or sediment release rates		X	X

* See Larsen, D. P., this publication pp. 311 for sampling protocol.

research has been done or is in progress, and external inputs are related to watershed activities and thus to possible control strategies.

LAKE EVALUATION INDEX

Various trophic state indices have been proposed (120 separate citations were reviewed by Shapiro, 1977; Uttormark and Wall, 1975; and Brezonik, 1976). The reviews conclude that there is no universal and completely satisfactory index of lake water quality. Generally, indices are designed for specific uses and for a set of regional or local lakes (Table 2). Ideally, a simple index of lake quality should be developed that 1) is not lake specific, i.e., it can be generalized to all lakes, 2) is related to all uses, and 3) is objective, independent of other variables, and easily measured. However, lakes are complex systems having many variables and their waters have many beneficial uses; at our present state of lake understanding an indicator(s) may be inadequate to satisfy all of the above criteria.

The difficulties in achieving these criteria can be seen in the variety of lake classification schemes shown in Table 2. Many critical reviews of the concepts and approaches for lake classification have been published but with little consensus (Bortleson, et al., 1974; Brezonik, 1976; Carlson, 1977a; Donaldson, 1969; Fruh et al., 1966; Hooper, 1969; Inhaber, 1976; Margalef, 1958; Shapiro, 1977; Sheldon, 1972; Stewart, 1976; USEPA, 1974; Uttormark, 1977; Vallentyne, et al., 1969). Some consensus can be gained from observing that the most commonly used variables include Secchi depth, DO, phosphorus, chlorophyll a, and nitrogen compounds.

In this discussion an LEI is proposed that incorporates a minimal set of limnological variables required to evaluate the limnological effects of lake

TABLE 2. THE CLASSIFICATION OF LAKES USING VARIABLES THAT REFLECT THEIR LIMNOLOGICAL CONDITIONS.

Reference	Dependent Variable	Number of Variables	TP	OP	TIN	TON	TN	POC	PP	CA	DO	pH	SD	Morph.	M/A	WQ	Ratios	Other Variables Floral	Other Variables Faunal
Brinkhurst et al., 1960	Trophic state	1																	X
Brook, 1965	Trophic state	1																X	
Carlson, 1977b	TSI	3	X							X			X						
Dillon & Rigler, 1975	Trophic state	3	X							X			X						
Dobson et al., 1974	Trophic state	4	X					X		X			X						
Harkins, 1974	Standards SM	4	X								X	X				BOD_5 alk.			
Hayes, 1957; Hayes et al., 1964	Fish PI	3												Mean depth, cm					
Hutchinson, 1938	Trophic state	1									X								
Jarnefelt, 1958	Trophic state	1																	X
Lueschow et al., 1970	RTSI	5	(X)	(X)	X	X					X		X		Algae				
McColl, 1972	RTSI	9	X	X	X					X	X		X			Alk., Fe, Mn			
Megard et al., 1978	Trophic state	1														Light Trans.			
Michalski & Conroy, 1972	Trophic state	6								X	X		X	Mean depth, Ryder			Fe/P		
Miller et al., 1974	Trophic state	1													Bio-assay				
Mortimer, 1941	Trophic state	1									X								
Neel, 1977	TSI	2												Residence Time			Mg/Ca		
Rawson, 1960	RTSI	8								X			X	Mean depth		Temp., TDS		Plankton	Benthos, fish
Reynoldson, 1958	Trophic state	1																	X
Rodhe, 1958, 1969	Trophic state	1							X										
Ryder, 1965	Fish production	2												X		TDS			
Sawyer, 1947	Trophic state	2		X	X														
Shannon & Brezonik, 1972	TSI	7	X			X			X	X			X			Cond.	Cation		
Skulberg, 1966	Trophic state	1													Bio-assay				
Stockner, 1972	Trophic state	1																Sediment diatoms	
Toerien et al., 1975	Trophic state	1													Bio-assay				
USEPA, 1974	RTSI	6	X	X	X					X	X		X						
Uttormark & Wall, 1975	LCI	4									X		X		X	Fish kills			
Vollenweider, 1968	Trophic state	2	X				X												
Winner, 1972	RTSI	9							X	X			X		Seston	Assimilation	P/B, pigment	Diversity	Diversity
	Frequency of use		8	4	4	2	1	1	3	8	9	2	11	6	5	12	5	4	6

* Abbreviations: TP - total phosphorus, OP - orthophosphate P, TIN - total inorganic nitrogen, TON - total organic N, TN - total N, POC - particulate organic carbon, PP - primary productivity, CA - chlorophyll a, DO - dissolved oxygen, SD - Secchi depth, Morph. - various morphological parameters, M/A - macrophyte and other algal variables, WQ - other water quality variables.

restoration projects. (A discussion of data needs for phosphorus distribution in lake ecosystems is contained in the paper by Larsen, pp. 311 in this publication). The LEI is intended for a specific use although its generality may increase with application to other studies. The concept is simpler than the Vollenweider Approach, but data requirements are quite similar. The measurements relate to previous studies and in some cases conform to perception of lake problems and, therefore, to phenomena the general public can see.

Lake quality variables can be grouped roughly into hydrological, morphological, physical-chemical and biological types (Table 3). In most cases hydrology is not expected to be significantly affected by lake restoration. Changes in mixing patterns and residence times will occur in dilution/flushing projects; mixing can result from some dredging, aeration, and other projects. Some morphological variables will be greatly affected; depth and volume will be changed by dredging and/or outlet structure changes and diversions. Most changes will be seen in terms of physical-chemical interactions (nutrients, other salts, light and temperature) and biological responses to these changes (flora, fauna and dissolved oxygen). Measurement of all factors related to these changes is impractical. Thus it is necessary to select target variables that indicate general water quality.

TABLE 3. CATEGORIES OF MAJOR LAKE RESPONSE PARAMETERS

Hydrologic	Morphologic
Inflows	Shoreline shape
Evaporation-transpiration	Mean depth
Precipitation	Area
Outflows	Volume
Mixing	
Residence time	
Physico-chemical	**Biological Response**
Phosphorus	Chlorophyll a
Nitrogen	Secchi disk
Iron	Macrophyte biomass
Trace Metals	Faunal densities
Carbon	Phytoplankton parameters
Cation/Anions	Dissolved oxygen
pH	
Light*	
Temperature*	

* affect nutrients and growth responses

SELECTION OF TARGET VARIABLES FOR LEI

The basis for the LEI concept is that lake water quality problems are defined as being caused largely by or associated with increased nutrient concentrations in the lake. In most cases, phosphorus will be the nutrient of concern (Bartsch, 1972; Porcella et al., 1974; Schindler, 1977). For example, in Figure 1, a sequence of cause and effect events are shown which would occur under conditions where phosphorus was limiting. An increase in lake phosphorus concentration would cause an increase in primary productivity as measured by chlorophyll a. Simultaneously there would be decreases in Secchi depth (higher turbidity) and hypolimnetic DO (higher BOD from algal growth, i.e., respiration exceeds production). For this scenario, data on Total P (TP), chlorophyll a (CA), Secchi depth (SD), and DO can be used to express changes in lake water quality.

This scheme applies when phosphorus limits primary production of phytoplankton but not when nitrogen is limiting (USEPA, 1974; Miller et al., 1974). Thus it is necessary to measure nitrogen compounds (total nitrogen, TN) as well. Other nutrients can limit primary production of lakes (Goldman, 1965); such an occurrence is infrequent relative to phosphorus and nitrogen limitation and thus those factors will not be included in order to maintain the concept of measuring only the essential variables for developing a reliable LEI.

Macrophytes (MAC) are an important part of lake primary production that are not measured by phytoplankton chlorophyll a or most primary productivity methods and yet have significant effects on nutrients, DO, SD and other water quality parameters and lake beneficial uses. Whenever lakes are relatively deep, primary productivity is dominated by phytoplankton. Sedimentation in lakes decreases lake depth (whether sedimentation is due to settling of organic materials produced in or out of the lake or is due to settling of inorganic materials). Also some lakes are naturally shallow for topographical or geological reasons. In all cases lakes having shallow zones (<6 meter depth contours) usually develop significant macrophyte growth when nutrients are available. Therefore data on macrophytes are required also.

The evaluation phase has been designed to analyze productivity problems. However, lake water quality problems resulting from BOD inputs and suspended solids loadings would affect the target variables DO and SD, also. Additional analyses would be required to determine effects of lake restoration on bacteriological problems as would be required for other non-eutrophication related problems (toxicity, oil spill, salinity). Although investigations at specific lakes need be concerned with those problems where relevant, time and dollar constraints confine this overall evaluation phase to those limnological variables related chiefly to eutrophication problems.

DEFINITION OF TARGET VARIABLES OF THE LEI

The above rationale suggests that the following target variables are sufficient for the purposes of developing an LEI:

1) Secchi depth (SD)
2) Total phosphorus (TP)
3) Total nitrogen (TN)
4) Chlorophyll a (CA)
5) Dissolved oxygen (DO)
6) Macrophytes (MAC)

These target variables have the following attributes: 1) They span most of the major water quality problems that affect uses of lakes, 2) they duplicate

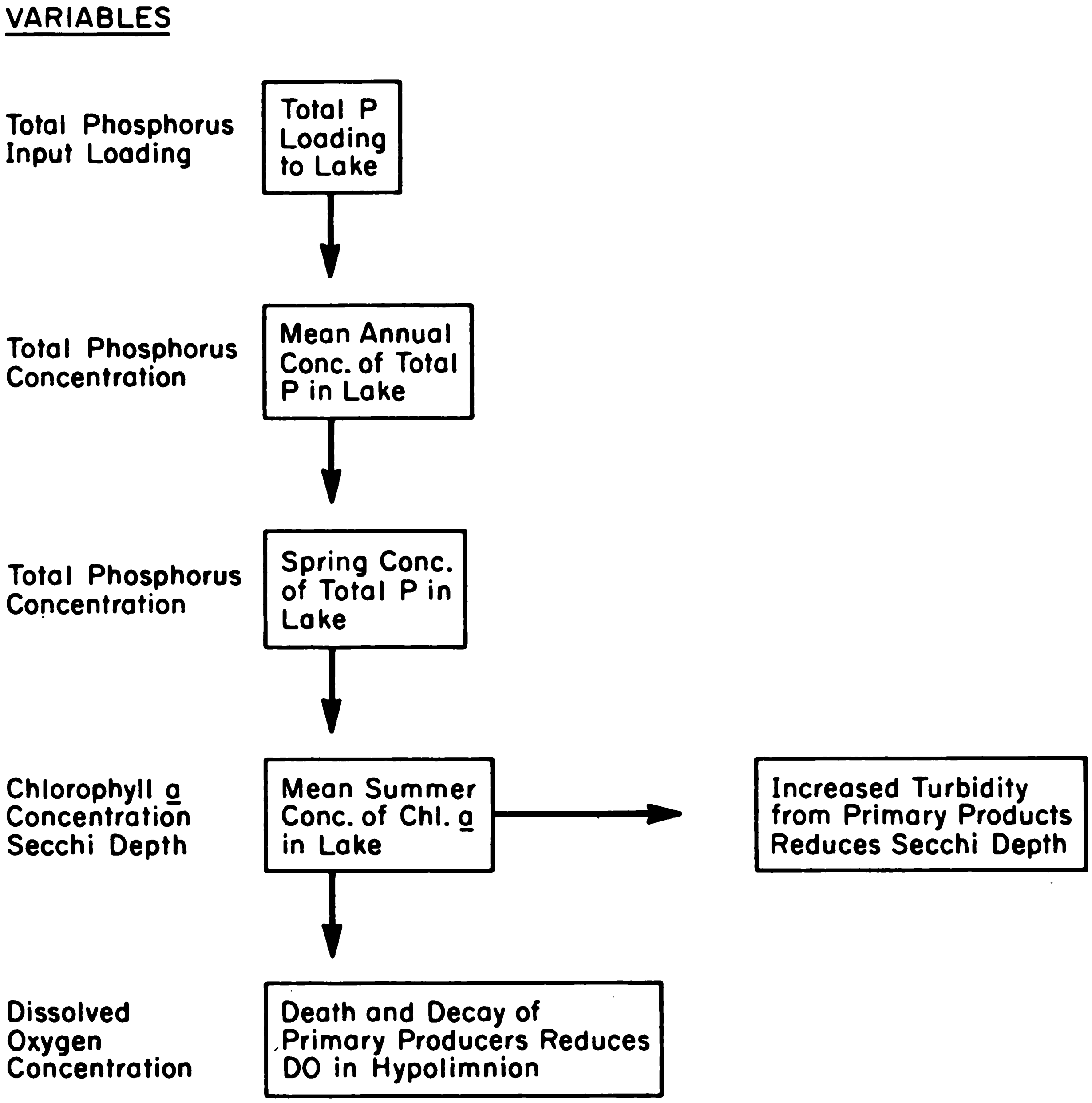


Figure 1. Conceptual sequence of cause and effect relationships in lake eutrophication processes (modified from Chapra and Tarapchak, 1976).

most of the parameters contained in other indices and in the Vollenweider Approach and 3) they are commonly and for the most part, relatively simply measured.

However, the target variables are not mutually exclusive, independent variables. They are interrelated in complex ways. They may be additive, as may be the case for MAC and CA. In other cases there may be a concentration dependent maximum in reference to one variable (CA and DO) and a relatively linear relation in reference to another (CA and TP). Because the LEI is a composite of variables that in specific cases or at different seasons can be unrelated, negatively related, or positively related, interpretability of the LEI will probably be limited. However, the range of lake types to be evaluated will be broader.

Having selected the above target variables, other questions arise:

-When, where and with what frequency are they measured?
-Are other data needed to calculate the target variables?
-Are other data needed to support the development of an LEI?

The following sections provide some answers to these questions. Sampling needs and concepts, previous work on each target variable, and other data requirements are discussed. Methods of analysis are specified in Appendix A.

SAMPLING

For practical reasons, funding will limit the frequency and density of sampling. During critical flow periods (spring runoff, summer low flows) and the growing season (periods of high primary productivity), sampling should be at least biweekly and weekly if possible. Overlap of these periods provides some sampling economy. For uniformity the July-August period is specified for the target variables as used in the LEI. At other periods monthly sampling should be adequate. Generally, time of day is very important and lake measurements should be restricted to 1000 hrs to 1400 hrs standard time, preferably closer to 1200 hrs.

At least 90% of the tributary inflow should be determined by measurements, continuously if feasible (USEPA, 1975a). Estimates of runoff (USEPA, 1975a) and groundwater input (Lee, 1977) should be obtained and their significance to loading assessed to determine if more accurate measurement is necessary (USEPA, 1974).

Sampling for chemical analysis should allow estimation of the total lake loading of TP and TN and in-lake mass at a point in time for TP, TN, DO, and CA. Sampling of the major lake basins and littoral zones should be as judged appropriate by the investigator. Vertical profiles of the variables should be determined at least by a bottom, midpoint and near surface sample at the deep station(s).

Variables such as chlorophyll a, open water primary productivity, and nutrients relate principally to measurements made in the water column in the epilimnetic zone (defined as being the layer enclosed between the water surface and the lake bottom or water depth at the thermocline).

For the LEI, mean epilimnetic zone nutrient and CA concentrations will be used. Mean upper level concentrations (such as 10 meter depth, etc.), photic zone, maximum epilimnetic concentrations, and maximum lake concentrations could be used if necessary. Although loadings, total lake mass (kg/lake), and areal measurements ($mg \cdot m^{-2}$) are useful concepts, they are not used herein for the LEI because such measurements vary greatly and independently with drainage basin, lake volume, area, and residence time. They may be combined at some future time since data can be normalized using various loading equations to relate lakes of differing morphology (Allum, et al., 1977).

SECCHI DEPTH

The depth of light penetration into lakes is controlled by the sun and climate, season, water color and turbidity (Tyler, 1968). Light controls photosynthesis hence primary production in the lake, defining zones that limit the depth of phytoplankton net production and the distribution of macrophytes. The SD is a common and simple method for estimating the maximum depth of light penetration in lake waters. SD needs to be measured at the same time (near noon) as other variables and as often as the lake is sampled; however, SD is measured only at the deepest sampling station.

Because we expect SD to estimate the limit to light penetration during the growing season, the target variable will be the mean SD during the months of July and August. During this period SD will vary chiefly according to the concentration of phytoplankton. Because the highly colored waters of certain lakes affect SD (Shannon and Brezonik, 1972), it may become necessary to separate lakes into classes or types. Although classification will be avoided if possible, color should be noted where observed.

TOTAL PHOSPHORUS

Sawyer (1947, 1966) was the first to rate eutrophication levels based on nutrient concentrations; inorganic phosphorus concentrations of 10 $mg \cdot m^{-3}$ when vertically uniform concentrations exist was defined as the threshold above which nuisance algal blooms could be expected to occur. Vollenweider (1968) used Sawyer's estimate to define eutrophic conditions by relating total phosphorus in the spring and summer to annual loading rates from inflows. More sophisticated mass balance models consider sediment loading (Lorenzen et al., 1976; Lung et al., 1976; Larsen and Mercier, 1976; Vollenweider, 1976) and attempts are now being made to define the role of the different forms of phosphorus. For example, TP includes non-algal P and would introduce some error in interpretation. For purposes of the LEI, summer (July and August) total P (TP) concentration averaged through the epilimnetic zone will be used.

TOTAL NITROGEN

A value of 300 $mg \cdot m^{-3}$ of total inorganic nitrogen similar in concept to phosphorus, was defined by Sawyer (1947, 1966) to relate to incipient eutrophication problems. Leuschow et al. (1970) proposed that total inorganic and total organic N be used as variables for lake characterization. Because total N would include inorganic nitrogen forms (potential growth of primary producers) as well as particulate nitrogen (primary producers), it was chosen as the lake target variable. Unfortunately total N also includes detrital N and soluble organic forms of N that might or might not be available for growth; in addition there is considerable analytical error in the Kjeldahl measurement and this plus its difficulty and cost often lead to its exclusion as a measured parameter. For purposes of the LEI, the summer (July and August) TN concentration averaged through the epilimnetic zone will be used even though these disadvantages exist.

CHLOROPHYLL A

Many investigators have correlated chlorophyll a and phosphorus loading and thereby related a level of eutrophication to chlorophyll levels (NAS-NAE, 1973; Jones and Bachmann, 1976; Dillon and Rigler, 1974; Porcella et al., 1974; USEPA, 1974). These approaches have a logarithmic functional relationship in common; thus, loss of beneficial use occurs with increasing chlorophyll a concentrations, but detriment increases more rapidly at low concentrations and less rapidly at higher concentrations.

Dobson (1974) defined chlorophyll a as a function of clarity using the inverse of SD in meters: $CA = 1.14\ (30/\overline{SD})$. Similarly, a non-linear approach was used by Carlson (1977b): $\ln SD = 2.04 - 0.68 \ln (CA)$.

Because CA concentrations are a function of other variables and like SD, can be related to a perception of the quality of a lake system, epilimnetic zone concentrations can be used to define levels of quality for the other target variables. For this reason it is an important variable. However, CA does not provide the dimension of the composition of the phytoplankton population. Consequently, it is necessary to characterize the algal species comprising the phytoplankton community. To minimize effort and costs associated with this task, only the three dominant genera and their numerical concentration in a single epilimnetic zone composite sample collected in conjunction with the CA sample need to be determined. The CA target variable is defined as were TP and TN: the summer (July and August) CA concentration averaged through the epilimnetic zone.

DISSOLVED OXYGEN

Several approaches have been used for analyzing DO data: hypolimnetic DO has been used to characterize lake trophic status (Uttormark and Wall, 1975); DO deficit (Hutchinson, 1938) and deficit rates (Mortimer, 1941) have been suggested (Hutchinson, 1957); hypolimnetic concentrations (Lueschow, et al., 1970; Michalski and Conroy, 1972), a transformed minimum DO (USEPA, 1974), and DO concentration (Harkins, 1974) have been used.

These approaches all have disadvantages. Hypolimnetic DO represents a water layer which has a continuous demand due to heterotrophic breakdown of organic matter (excess production) but little or no replenishment from other sources (atmosphere, diffusion processes, inflow, primary productivity). Almost all of the demand for hypolimnetic DO comes from organic material settling through the hypolimnion or contained in the sediments (Lasenby, 1975). Consequently, oxygen demand by the sediments represents previous history of the lake system and changes in lake nutrient and productivity status may not be reflected in a change in DO demand without a significant time lag. Significant changes in nutrient inflow that are applied over a long period of time and/or changes in existing sediment chemical composition would be required before hypolimnetic DO patterns would be significantly affected.

Epilimnetic DO increases during the day due to photosynthesis and decreases at night from respiration. Sampling times must be uniform or, preferably, determined over diel cycles.

Total lake DO is the sum of these two layers and 1) could exceed calculated temperature limited equilibrium DO levels if photosynthesis is relatively high or 2) fall short of the saturation levels where respiration is relatively high. Ideally hypolimnetic DO would be the most useful indicator of respiration and respiration would be relatively independent of time and space effects on sampling. Unfortunately the volume of the hypolimnion of many lakes, particularly the lakes being restored in the Clean Lakes program, is small relative to the lake bottom area or is nonexistent. Thus many of the approaches described in the literature cannot be used due to morphological differences in lakes (Lasenby, 1975).

As a first step in developing a target variable based on DO, we have assumed that it is possible to estimate the instantaneous total lake equilibrium DO (EDO, mg/lake) from atmospheric pressure and the temperature-depth profiles. This value (EDO) is defined as the reference value for a clean water lake. A comparison of this value with the calculated instantaneous total lake DO (CDO, kg/lake) allows analysis of the relative quality of the lake ecosystem with respect to physical processes and respiration/photosynthesis. However, in highly productive lakes that stratify during the summer, DO supersaturation can occur in the surface waters while zero DO or undersaturation occurs in the bottom waters. Addition of these quantities (a positive and a negative) to obtain total DO could result in essentially no difference in comparison with EDO. Thus, for analysis of DO the incremented absolute values of the net difference with depth between EDO and CDO will be utilized to evaluate lakes:

$$\text{net DO} = \frac{1}{V} \sum_{i=0}^{i=ZM} \left| (\text{EDO} - \text{CDO})_i \right| \Delta V_i$$

where ZM is maximum depth, ΔV is the volume at a selected and convenient depth increment, and i is the increment. Determination of EDO and CDO would require measurement of DO and temperature profiles with depth at sufficient sampling sites to estimate total lake DO. Measurements should be based on average summer (July and August) values. Significant ($\leq$5%) inflow/outflow or volume changes would require adjustment of EDO estimates.

MACROPHYTES

So far we have defined variables that relate principally to the pelagic area of lakes, i.e., the deeper zone of open waters. Most eutrophic lakes are relatively shallow, but even deep lakes have shallow regions (the littoral zone) typical of neither the pelagic zone nor the drainage basin (watershed) which nourishes the lake. The littoral zone contains macrophytes which mark the transition from rooted upland or terrestrial producer organisms to planktonic producers of the open water ecosystem. Because macrophytes have not been used to a great extent for lake indexing, we present more background information on macrophytes than the other target variables.

Our concern is to develop a relationship between macrophyte biomass and nutrient variables (water concentrations, sediment concentrations, loadings) within the littoral zone because macrophyte problems occur in approximately 1/3 of the funded Clean Lakes demonstration projects. Generally, we define that high quality lakes have few macrophytes and lower quality lakes have more macrophytes in the littoral zone. Kettelle and Uttormark (1971) listed more than 40% of U.S. problem lakes as having macrophyte problems. Uttormark and Wall (1975) indicated that more than 20% of all the lakes they surveyed in Wisconsin had observable macrophytes and 40% of their problem lakes (Lake Condition Index $\geq$10) had severe macrophyte problems. Also, macrophyte productivity in the littoral zone can be a major fraction of organic matter to the lake system (Wetzel, 1975) and may be a significant source of nutrients as well (Howard-Williams and Lenton, 1975; Klopatek, 1975; Cooke and Kennedy, 1977). Hence, characterization of macrophytes generally is necessary to assess eutrophication processes in most lakes in addition to the analysis of watershed and open water processes and, for the lake restoration program, to estimate littoral zone areal distribution and biomass of macrophytes.

Macrophytes (algae, mosses, and vascular plants or weeds) may be attached emergent, submerged, submerged with floating leaves, or free-floating forms. These plants obtain nutrients in part from the water but also from the bottom sediments where many are anchored; thus they mark a second interface within the lake ecosystem, that between the lake bottom and the water. Among other physiological differences, vascular plants differ from algae and mosses because they are sensitive to pressure, probably because of the presence of gas containing tissues necessary for maintenance of the life cycle (Wetzel, 1975), and are thus physiologically depth limited to no more than approximately 10 meters. Most are limited to much shallower depths due to light attenuation.

The littoral zone can be divided into three different regions on the basis of macrophyte distribution zones (zones slightly modified from Hutchinson, 1975; Wetzel, 1975): 1) shallow zone ($\leq$1 meter deep); emergent, rooted macrophytes; these include swamps, marshes, and shallows, and can be classified as wetlands; 2) mid zone (1 to 3 meters); floating leaf vegetation ("usually are perennials that are firmly rooted with extensive rhizome systems"; Wetzel, 1975; p. 335); 3) deep zone (0.5 to 10 meters for weeds and deeper to the limits of the photic zone for mosses and macroalgae). Macrophyte dynamics include community and nutrient interactions and flux with time and among water, sediment and biotic components. Wetlands (shallow zone macrophytes) are excluded from evaluation because we are interested principally in the response of definable lake systems to restoration (Hutchinson, 1975). However, significant inputs of materials from wetlands should be assessed, if possible. The lake area itself will still extend to the typical boundary of the lake margin (water-land interface). Wetlands in freshwater ecosystems are defined as the area enclosed by the emergent (throughout most of life cycle), rooted, aquatic vegetation line on the deepening slope and by the line on the upland slope where vegetation requires saturated soils for growth and reproduction (Federal Register: 40/173: 41297, September 5, 1975).

Evaluation of macrophytes excludes wetlands but considers that the biomass of a lake ecosystem is the result of allochthonous inputs (tributaries, wetlands, direct runoff from terrestrial systems) and autochthonous plant growth (macrophytes, benthic and attached algae, and phytoplankton). Defining the area of macrophyte growth is the first step in developing an approach for evaluating macrophyte productivity.

The distribution of macrophytes in a lake, where no other growth requirements are limiting, is controlled largely by light. Consequently, denser macrophyte growth occurs on the surfaces of water by essentially free-floating plants (water hyacinth, duckweed) and throughout littoral zones of lakes where rooted plants receive sufficient light. Turbidity derived from allochthonous particles, turbulence, or due to phytoplankton or self-shading, can decrease light penetration and reduce the depth to which macrophyte communities extend. Thus, watershed activities or eutrophication effects which cause increases in phytoplankton may cause changes in macrophyte density. It may be feasible to relate SD to vascular plant distribution limits, because of its relationship to light penetration (e.g., 2 times SD; Dillon and Rigler, 1974; 2-5 times SD; Mackenthun, 1969; p. 30). Thus, the vascular plants of interest for evaluation are restricted to the littoral zone bounded by the shoreline, wetland or an upper limit maintained by mechanical disruption of life cycles by wave action or shearing by ice and bounded in deeper water by pressure or light limitation (e.g., defined by mean SD during the growing season, July-August).

The variables for relating macrophyte populations to nutrients and lake condition are obviously complex and interrelated with other variables. For example, it is possible for macrophyte problems to occur in lakes that have no algal blooms and vice versa. This complication arises because of differing nutrient sources and interaction with the phytoplankton community. Macrophytes obtain nutrients directly from the water column and from the lake sediments (via the roots) but phytoplankton obtain nutrients only from the water column. Also, in contrast to algal communities, primary production in macrophyte communities might be limited by nitrogen. There is no documentation of aquatic macrophytes' ability to fix nitrogen as occurs with terrestrial legumes or in lakes with heterocystous blue-green algae. Also, development of shallow water zones will be increased by the presence of macrophytes due to increased siltation rates as a result of their dampening effect on water velocities in specific areas of lakes.

Population density of macrophytes may or may not be related to changes in Secchi depth or DO and needs to be estimated as a separate parameter. Because of the dearth of management-oriented information on macrophytes, an arbitrary approach has been taken for macrophytes; based on experiences of the State of

Minnesota (Jessen and Lound, 1962) and the State of Wisconsin (Dunst, Wisconsin Dept. Natural Resources, 1976; personal communication), the following parameters of macrophyte communities have been defined as requiring measurement: Species present, density (plants/unit area), percent of lake surface area covered, water depth and substrate type for the type of plant, percent of theoretically available substrate determined on the basis of the 10 meter contour line or the light-limited macrophyte growth contours, whichever is least. The specific approach has been prepared in step-by-step fashion in Appendix B.

Using this approach and obtaining synoptic data from a large number of lakes, several hypotheses that relate macrophyte distribution and population density to light (turbidity) and nutrients in sediments and/or the water column could be tested:

1) total macrophyte biomass and/or density is related to light input and nutrient availability;

2) the light-limited distribution of macrophytes is a function of a Secchi Depth parameter;

3) the composition of nutrients is very important to macrophyte successional sequences;

4) nutrient availability is governed by sediment interstitial water and/or water column nutrient concentrations;

5) total macrophyte biomass in a lake system is relatively independent of the species composition and diversity;

6) the transport of sediment interstitial water nutrients into the water column by macrophytes is dependent on water column concentrations primarily and sediment concentrations secondarily.

In summary, the analysis of aquatic vascular plants (predominantly angiosperms) would allow 1) evaluating lake restoration techniques and 2) assessing whether certain functional relationships exist between light/nutrients and macrophytes. Thus, the study of macrophyte distribution is expected to integrate the effects and interactions of many environmental variables on macrophyte growth and distribution, namely light (season, latitude and turbidity), nutrients (sediment, water sources and nutrient type), and other variables (bottom substrate type, cations and anions, temperature, toxicants).

OTHER REQUIRED DATA

In addition to the above target variables and data required for the Vollenweider Approach (Table 1), the following data are required for all lakes although they are not part of any specific lake index (rather they are independent variables): area and volume relationships with depth, pH and temperature depth profiles with time, identification of 3 predominant algal genera and macrophyte genera, and total macrophyte biomass. This is a minimum program for evaluation.

Other analyses of specific research interest and specific to the particular problems of the region or locality are not precluded and in fact attention to those problems is needed. The data needs described in this report are designed to meet the overall objectives of the limnological evaluation projects and have been selected to minimize duplication and unnecessary additional work; thus, the collection of these data should not preclude other methods of evaluating lakes. In addition it may be important to establish relationships between certain variables as necessary for the specific problems of a specific lake. For example, measurements of SD relate closely to other variables, particularly turbidity. Suspended solids (SS, $mg \cdot l^{-1}$) relate to turbidity and hence SD. If inorganic solids settle out and are not resuspended, SS and SD relate to phytoplankton biomass and should have some relationship to chlorophyll a and primary productivity. Where data are available, primary productivity ($mg \cdot cm^{-2} \cdot yr^{-1}$) and algal biomass estimates ($mg \cdot l^{-1}$) from cell counts are useful for developing relationships to chlorophyll a concentrations.

TRANSFORMATION OF VARIABLES

In order to use the target variables in a meaningful way, they must be transformed to represent a scalar quantity which represents a value judgment (e.g., good or bad, best or worst, beneficial or damaging, etc.). The range of true scalar quantity must be the same for all target variables to allow variables to be combined and to allow comparisons between variables for different restoration projects. The approach suggested here derives from Carlson's (1977b) method of transforming SD data.

Carlson's approach was to take the greatest and least expected values for SD and assign a rating scale of 0 to 100. Then the functional shape of the curve relating the ratings was described mathematically. Conceptually, this can be accomplished for SD where 100 can be assigned to essentially no light transmission, 0 can be assigned to the light transmission of pure water and the Beer-Lambert Law can be assumed to apply to the functional relationship for the ratings. For the other variables the functional relationships that transform measured values to rating values are not as clearly defined even though a reasonable range of minimal (0) to maximal (100) impact can be assigned. These other variables are not as simply related to a single target as SD is for clarity (light penetration). Carlson avoided this problem in part by relating TP and CA to SD.

SECCHI DEPTH (SD)

To relate lake trophic state to a measurable variable, Carlson assumed that light intensity (I/I_o) as measured by Secchi disk disappearance decreases with depth (Z) according to the Beer-Lambert Law:

$$\ln I/I_o = -nZ$$

Increased turbidity owing to phytoplankton and other suspended material would increase the value of the extinction coefficient (n) and cause the disk to disappear at shallower depths. Carlson felt that using a logarithmic base of

2 instead of the natural logarithm would be more useful for translating the rating to the public.

Using a maximum limit for SD of 64 m (41.6 m was the maximum reported in Hutchinson, 1957; 43.25 m was reported for Lake Tahoe by Goldman, 1974), Carlson developed a trophic state index (TSI) for SD:

$$TSI = 10(\log_2 (64) - \log_2(SD))$$
$$TSI = 10 (6 - \log_2 (SD))$$

Carlson's TSI was equated with the scalar rating value, XSD, for use in the LEI as follows:

$$XSD = 60 - 14.427 \ln (SD)$$
$$\text{and } XSD \leq 100.$$

(All rating values are confined to the range 0 to 100 to prevent undue weighting of single variables on the LEI.) Comparison of SD and the rating values are shown in Table 4.

Carlson's relationships for SD are based on surface concentrations of TP and of CA. The LEI target variables are defined for epilimnetic zone concentrations. Different slope values would be expected for rating curves of epilimnetic zone concentrations as compared to surface samples. Correlation of TP and CA using surface samples (Carlson, 1977b) or epilimnetic zone samples (Dillon and Rigler, 1974) indicated that differences in equation coefficients were minimal. Although SD coefficients could vary significantly, Carlson's will be used for the target variables in the LEI as defined for the photic zone concentrations, until new data show that significant differences occur.

TOTAL PHOSPHORUS (TP)

The shape of the curve relating the scalar value (XTP) to TP July-August average epilimnetic zone concentration is based on relationships between chlorophyll a and TP (e.g., Carlson, 1977b; Dillon and Rigler, 1974; Jones and Bachmann, 1976) and chlorophyll a and SD (Edmondson, 1972; Carlson, 1977b). These relationships suggest that TP is logarithmically related to the quality of lake water; higher TP results in greater algal populations and lesser transparency but the impact of the rate of concentration increase is less at higher concentrations.

The limits of Carlson's scalar values include the lower TP measurements but the higher values ($\geq$ 768 $mg \cdot m^{-3}$) must be defined as equal to 100. Oligotrophic lakes have lower values on the order of 1 $mg \cdot m^{-3}$ (Waldo Lake, OR; Malueg *et al.*, 1972; Lake Tahoe, CA-NV, 0.9 $mg \cdot m^{-3}$; Goldman, 1974). Eutrophic lakes exhibit a wide range of maximum values of springtime orthophosphate P or summer TP (150 $mg \cdot mg^{-3}$, Jones and Bachmann, 1976; 330 $mg \cdot m^{-3}$, Miller *et al.*, 1974; up to 3660 $mg \cdot m^{-3}$ of median TP, USEPA, 1974).

TABLE 4. RATING SCALE FOR LAKE WATER QUALITY PARAMETERS.

Rating (X)	Secchi Depth meters	Total P $mg \cdot m^{-3}$	Total N $mg \cdot m^{-3}$	Chlorophyll a $mg \cdot m^{-3}$	Net DO $mg \cdot l^{-1}$	Macrophytes % available lake area covered
0 (minimally impacted)	64.	0.75	5.2	0.04	0.0	0
10	32.	1.5	10	0.12	1.0	10
20	16.	3.0	21	0.4	2.0	20
30	8.0	6.0	42	0.94	3.0	30
40	4.0	12	83	2.6	4.0	40
50	2.0	24	170	6.4	5.0	50
60	1.0	48	330	20.0	6.0	60
70	0.50	96	670	56.0	7.0	70
80	0.25	190	1300	150.0	8.0	80
90	0.125	380	2700	430.0	9.0	90
100 (maximally impacted)	≤0.062	≥770	≥5300.	1200.0	≥10.0	100

Carlson's equation transformed for use in the LEI is:

$$XTP = 4.15 + 14.427 \ln TP$$
$$\text{and } XTP \leq 100$$

TOTAL NITROGEN (TN)

The formulation of TN July-August average epilimnetic zone concentration in the rating scale (XTN) was determined in relation to TP. The N/P ratios for phytoplankton average about 16/1 (mole/mole) or 7/1 (weight/weight) (Bartsch, 1972; Stumm and Morgan, 1970; p. 429). Thus TN is equivalent to 7.0 TP and the scalar rating is:

$$XTN = 14.427 \ln TN - 23.8$$
$$\text{and } XTN \leq 100.$$

Equivalent values of XTN and TN are shown in Table 4.

Oligotrophic lakes show values of TIN (TN data incomplete) to be about 1-50 $mg \cdot m^{-3}$ (Waldo Lake, OR, 50 mg $N \cdot m^{-3}$, Malueg et al, 1972; Lake Tahoe, CA-NV, 0.9 mg $N \cdot m^{-3}$ (NH_4^+ assumed to be 0.0); Goldman, 1974). Values for eutrophic lakes vary widely (710 mg $TIN \cdot m^{-3}$, Miller et al., 1974; median value 7355 mg $TIN \cdot m^{-3}$, USEPA, 1974), and XTN must be restricted to 100 when including values greater than 5330 $mg \cdot m^{-3}$.

CHLOROPHYLL A (CA)

The average July-August epilimnetic zone concentration of chlorophyll *a* (corrected for pheophytin; see Holm-Hansen et al., 1965; APHA, 1975 for analytical methods and Fee, 1976 for discussion of sampling problems for chlorophyll *a*) is related to the scalar value (XCA) as a logarithmic function as was discussed for TP, above. Concentrations of chlorophyll *a* in oligotrophic and eutrophic lakes are encompassed by Carlson's equation (Table 5):

$$XCA = 30.6 - 9.81 \ln (CA)$$
$$\text{and } XCA \leq 100.$$

Equivalent values of XCA and CA are listed in Table 4.

DISSOLVED OXYGEN (DO)

The net DO calculated as an average over the principal summer months (July-August) is based on what the DO would be in a pure water lake and what is actually measured (see section on defining target variables). Without contrary information the scalar value (XDO) is assumed to be a linear function of the net DO. The best situation (XDO = 0) would occur if net DO was zero, and a very poor quality (XDO $\geq$100) would exist if net DO is $\geq$10:

$$XDO = 10 \text{ (net DO)}$$
$$\text{and } XDO \leq 100.$$

Equivalent values of XDO and average net DO are listed in Table 4.

TABLE 5. SOME MAXIMUM AND MINIMUM CHLOROPHYLL A VALUES MEASURED IN LAKES.

Reference	System or Lake	Chlorophyll a*, $mg \cdot m^{-3}$ Maximum Values	Chlorophyll a*, $mg \cdot m^{-3}$ Minimum Values
Dobson, *et al.*, 1974	Great Lakes	25.4	0.4
Jones & Bachmann, 1976	16 Iowa Lakes	262.2	6.8
" " " "	" " " and compiled data**	400.0	0.3
USEPA, 1974	209 lakes in National Eutrophication Survey	381.0	1.0
Winner, 1972	5 Colorado Lakes	34.1	1.0
Shannon & Brezonik, 1972	55 Florida Lakes (mean)	39.1	1.8
Fee, 1976	ELA lakes	327	<1.0**
Malueg, *et al.*, 1972	Waldo Lake, OR	1.64	0.13 (Mean, 0-60 m deep)
Holm-Hansen, 1976	Lake Tahoe, CA-NV	<1.0	0.1
Extremes		400	0.1

* not all data corrected for pheophytin *a*

** estimated from graphical data

MACROPHYTES (MAC)

The area of the lake subject to growth of macrophytes can be defined as the area encompassed by the lake margin and either the 10 m line or the depth at which light becomes limiting to vascular plant distribution and growth (2 times SD) whichever is shallower. The percent of this area that is actually covered by vascular plants is defined as the target variable. Only relatively crude surveys during the growing season (July-August) are needed to assess the percent of that area that is actually covered by the vascular plants. The target variable, percent macrophyte area covered (PMAC), could be assessed in terms of a rating value (XMAC) as a simple percentage:

$$XMAC = PMAC$$

The least impacted system would be defined as having zero percent cover and the most impacted system as having 100 percent cover. Equivalent values of XMAC and PMAC are listed in Table 4.

A PROPOSED FORMULATION OF THE LEI

RATING VALUES AND TROPHIC LEVELS

The target variables used for evaluation are not mutually exclusive or independent variables and their comparison as a rating value for a given lake will not necessarily agree. Furthermore, each measures slightly different lake functions. Thus, the rating values are not expected to agree among themselves for a lake or set of lakes. This is apparent when comparing rating values for complementary variables such as macrophytes and chlorophyll a; however, the relationship between these variables, SD and the other target variables is sequential where one is a function of another.

The most difficult target variables to relate to problems or perceptions of problems are the nutrients nitrogen and phosphorus because they are causes, not effects. Also, nitrogen may be considered limiting on the basis of nutrient ratios (see USEPA, 1974; Miller, *et al*., 1974), but be supplied from atmospheric nitrogen by nitrogen fixing blue-green algae (Bartsch, 1972; Horne and Goldman, 1972; Schindler, 1977). Although ratios of nitrate to orthophosphate concentrations in lakes can be constant (Stumm and Morgan, 1970), the ratio does not allow interpretation of possible effects of nutrients directly. Loading and mass balance models (Vollenweider Approach) seem to offer the best approach to determining the effect of nutrient changes on lake quality and will be used to define trophic levels in relation to nutrient concentrations.

Morphological (depth) and hydrologic (flow through rate) factors affect significantly the nutrient, DO, macrophyte and chlorophyll a concentration in lakes. For these reasons it is important to look at the individual variables in terms of meeting the evaluation objectives, i.e., a comparison of the effects of specific lake restoration projects.

Various suggested levels of chlorophyll a concentrations have been related to trophic levels and Chapra and Tarapchak (1976) averaged these values to obtain reasonable quantitative definitions of trophic state (Table 6). Similar values have been estimated, for SD, inorganic nitrogen (TIN) and orthophosphate (TIP) as well as other parameters.

Good agreement with the values in Table 6 was obtained when the USEPA (1974) ranked 209 NES lakes and, by summing percentile rankings for 6 separate parameters, provided a breakpoint of 500 for oligotrophic lakes and 420 for mesotrophic lakes. These totals correspond to average percentile limits of 83.3 and 70.0 for eutrophy and oligotrophy, respectively. Values of parameters corresponding to these percentiles (Table 7) indicated very narrow ranges "defining oligotrophic and eutrophic" over the rather broad spread of actual concentrations shown in Table 5 for the rating value. The values in Table 4 were plotted and then the levels associated with different trophic states (Table 7) were noted for comparison (Figure 2). The variables that define different trophic states agree surprisingly well and in defining selective limits, show that rating values of less than 45 indicate oligotrophy and values greater than 50 indicate eutrophy.

TABLE 6. SOME ESTIMATES OF EUTROPHICATION LEVELS ASSOCIATED WITH SPECIFIC VARIABLES THAT MEASURE LAKE QUALITY.

	OLIGOTROPHIC	EUTROPHIC	REFERENCE
Variables in LEI			
Chlorophyll *a* photic zone mean, $mg \cdot m^{-3}$	<4	>10	NAS-NAE, 1972
	0.3-2.5	5-140	Sakamoto, 1966
	<4.3	>8.8	Dobson, *et al.*, 1974
	<1	>6	Carlson, 1977b
Overall average	<2.75	>8.7	Chapra and Tarapchak, 1976
peak photic zone, $mg \cdot m^{-3}$	<3	>20	Landner, 1976
Secchi Depth, m	>6	<3	Dobson, *et al.*, 1974
TIN, $mg \cdot m^{-3}$		>300	Sawyer, 1947
TIP, $mg \cdot m^{-3}$		>10	
Non-LEI variables			
PRIMARY PRODUCTIVITY-$^{14}CO_2$ uptake			
mean daily, mg cm^{-2} day^{-1}	30-100	300-3000	Rodhe, 1969
total annual g cm^{-2} day^{-1}	7-75	75-700	
mean daily, mg cm^{-2} day^{-1}	<200	>750	Landner, 1976
HYPOLIMNETIC DO DEFICIT			
rate, mg $O_2 \cdot m^{-2}$ day^{-1}	<250	>550	Mortimer, 1941
NUTRIENT LOADING (at mean depth, $\bar{z}$)			
TP, $g \cdot m^{-2}$ yr^{-1}		>0.3 (20 m)	Vollenweider, 1968
		>0.8 (100 m)	
TN, $g \cdot m^{-2}$ yr^{-1}		>4 (20 m)	
		>1 (100 m)	
ALGAE, $number \cdot ml^{-1}$	<2000	>15,000	Landner, 1976
BIOMASS, mg l^{-1}	<1	>10	
CELL VOLUME, $mm^3 \cdot l^{-1}$	<5	>30	
ROTIFERS, $number \cdot l^{-1}$	<10	>250	
MICROCRUSTACEA, $number \cdot l^{-1}$	<1	>25	
SPECIES DIVERSITY	low (high is mesotrophic) low		

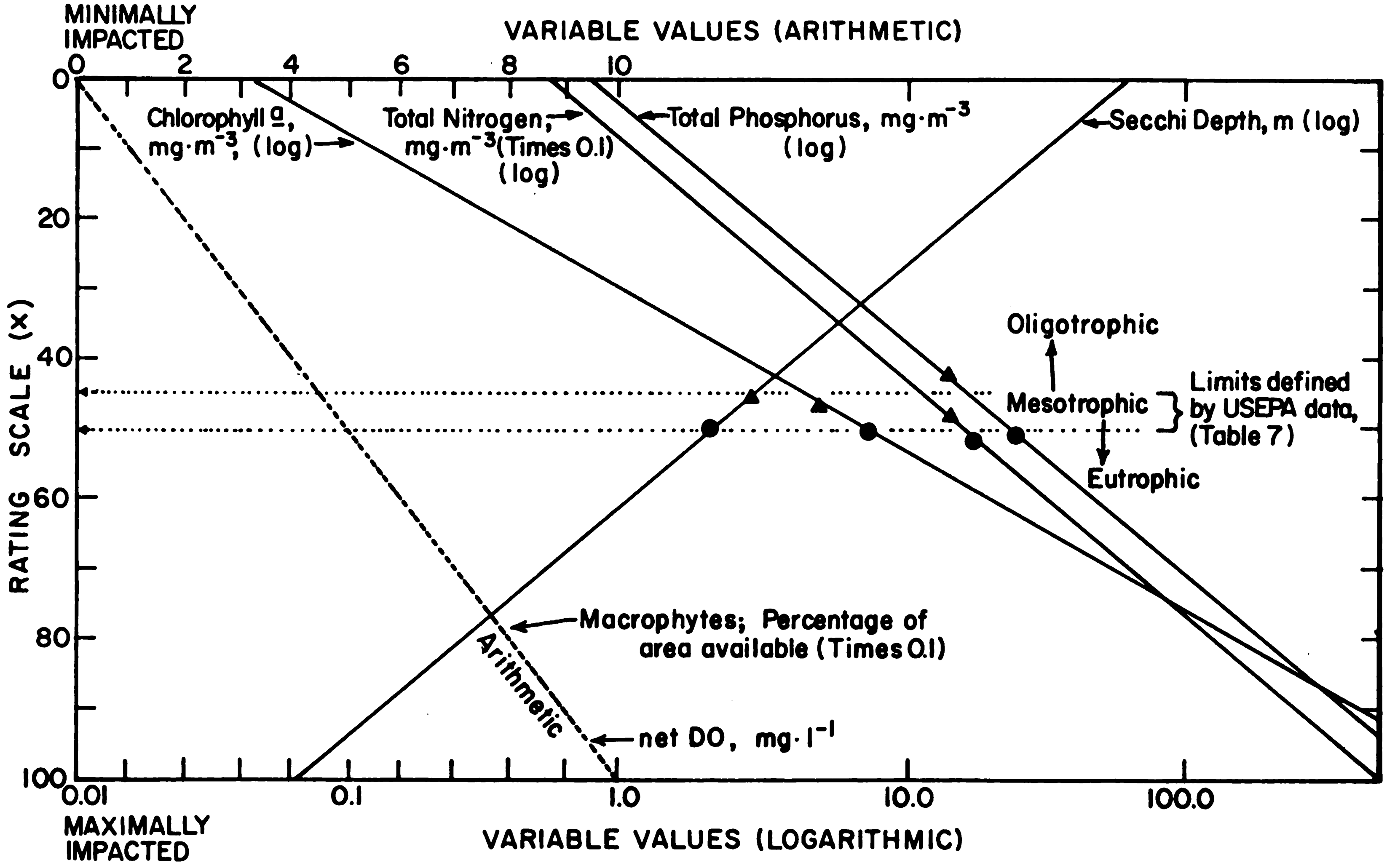


Figure 2. Relation between rating values and variable values compared to eutrophication levels.

TABLE 7. CONCENTRATIONS ASSOCIATED WITH TROPHIC STATE DEFINED BY A RELATIVE RANKING OBTAINED FROM NES DATA ON 209 LAKES (USEPA, 1974).

Parameter	Oligotrophic [percentile <83.3]	Eutrophic [percentile >70]
median total P, $mg \cdot m^{-3}$	<14	>25
median dissolved P, $mg \cdot m^{-3}$	<8	>11
median total N, $mg \cdot m^{-3}$	<140	>180
median chlorophyll a, $mg \cdot m^{-3}$	<4.8	>7.4
minimum observed DO, $mg \cdot l$	>7.2	<6.2
mean Secchi depth, m	>2.8	<2.0

* Estimation based on three sampling times (spring, summer, and fall) and 1 or more sampling sites and more than 1 sampling depth.

LEI

The formulation of the LEI was based on a number of assumptions, limited data, and as yet relatively untested concepts of the authors. The formulation of the LEI is hypothetical, and to a certain extent, arbitrary. It is proposed as an hypothesis that will be tested by applying synoptic data obtained from the evaluation grants or from literature data or NES data (USEPA, 1975b). The LEI is not intended to be unalterably structured. It is anticipated that testing the concept may result in some alteration of the LEI formulation.

The LEI has a range of 0 to 100 and was obtained by averaging specific target variables. Primary productivity in lakes is the sum of phytoplankton productivity and macrophyte productivity, therefore, the rating values of these two variables (XCA, XMAC) were summed and averaged; XSD and XDO were included directly; the nutrient variable was assumed to be XTP because of its typical importance but XTN could be (and will be for testing the hypothesis) substituted. Generally, if phosphorus is limiting, lower rating values for TN will be obtained than for TP. This comparison (XTP vs. XTN) is one way of determining whether to use XTP or XTN; i.e. the higher rating value of either XTP or XTN will be used. This resulted in the following equation:

$$LEI = 0.25 [0.5 (XCA + XMAC) + XDO + XSD + XTP]$$

As defined, the LEI is a simple number that ranges from 0 to 100 (minimal to maximal) and is related primarily to clean water uses as a function of eutrophication. Obviously, uses dependent on lake productivity such as fishing or largely unaffected by lake productivity such as irrigation storage are not related to the LEI. The formulation of such relationships will require utility functions. These utility functions would be cost/benefit functions, primarily but not exclusively. Utility functions for the LEI and lake use would include 1) optimality relationships (fishing, wildlife habitat), 2) linearly decreasing relationships (aesthetic, swimming, water supply, industrial uses), and 3) non-productivity affected relationships (irrigation, waste disposal, flood control, navigation). These would be influenced by the availability of such factors as alternative lake sites or water supplies and alternative activities or resources.

Also the LEI does not reflect other conditions such as toxicants (pesticides, heavy metals), salinity, inorganic sedimentation problems, spills. It is limited to productivity problems, i.e., eutrophication. Application to such problems would require modification and/or the development of other concepts.

SUMMARY

Two basic approaches, the Vollenweider or mass balance loading models and a lake evaluation index (LEI), are proposed to evaluate restoration manipulation(s) applied to a specific lake and to evaluate specific restoration techniques by studying a set of lakes. Although the Vollenweider Approach appears reasonable for phosphorus to a certain extent and has been accepted for managing lakes, a review of the literature reveals that little consensus exists on the development of indices for evaluating lake quality.

The LEI as proposed herein has a conceptual basis and includes the most commonly used target variables for limnological analysis of lakes: Secchi Depth (SD), Total Phosphorus (TP), Total Nitrogen (TN), Chlorophyll a (CA), net Dissolved Oxygen (net DO), and Percent Macrophytes (PMAC). Recommended sample collection and analysis appropriate to the LEI, the Vollenweider Approach, and associated necessary data are listed in Appendix A. Some of the target variables and associated data will be utilized in a quality assurance program to insure that comparable data are obtained.

Investigators on the evaluation grants will perform analyses appropriate for developing an understanding of lake limnology and the effects of restoration and analyses necessary to calculate the LEI and nutrient loadings. These will be used to assess treatment effects on individual lakes and to compare similar treatments on different lakes to achieve the objectives cited in the Introduction and to modify the LEI so that the most accurate and reproducible interpretation of lake response can be obtained. As the first step in this latter process a set of data for 28 lakes from the state of Washington have been evaluated using the LEI (Appendix C).

APPENDIX A

TABLE A-1. SAMPLING AND ANALYSIS FOR VOLLENWEIDER APPROACH

Variables	Min. Freq. of Sample Collection Season Spring	Summer	Fall-Winter	Time of Sampling	Sample Location	Data Source Or Analytical Method	References
I. Vollenweider Approach							
A. Water							
Precipitation	Continuous if Possible			Continuous	within lake margins	Class I weather station - nearest or most appropriate	USEPA, 1975a
Evaporation/Transpiration	"	"	"	"	" " "		
Inflow							
Tributaries	"	"	"	"	≥ 90% of inflow	USGS, irrigation, etc.	" "
Groundwater (±)	Accumulative or estimate			"	" " "	Lee, 1977	
Direct Runoff	Measure if possible or estimate			As Occurs	" " "	Wiers, precip/runoff, balance	" "
Outflow	Continuous if possible			Continuous	Outflow(s)	USGS, irrigation, etc.	" "
B. Nutrients							
Inflow Conc. (NO_2+NO_3-N, HN_4-N, TON, SRP, Total P)	Biweekly	Biweekly	Monthly	0900-1200	≥ 90% of inflow	See Table B-2 "	See Table B· "
Inlake Conc. (same as inflow)	"	"	"	1000-1200	" " "	"	
II. LEI							
A. Secchi depth	"	"	"	1000-1200	deepest water at	"	"
B. TP (see I.B.)	"	"	"	"	≥ 3 depths; 0.5 m, mid, bottom	"	"
C. TN "	"	"	"	"	" " "	"	"
D. CA	"	"	"	"	" " "	"	"
E. DO and Temperature Profiles	"	"	"	diurnal cycles if possible	profile at deepest point and in littoral zone	DO meter, thermistor	"
F. Percent area covered by macrophytes	"~August 15"					survey. (Appendix C)	"
III. Associated and Optional Data							
A. Visual Observations - notes (weather, incident light (Weather stat, I.A.), climatic and lake conditions, any unusual situations, wildlife and human uses of lake and basin, air temp. lake evaluation)	each sampling event			1000-1200	Basin		
B. Morphometric: max. depth, depth area, depth volume curves, perimeter	once			-	within lake margins		
C. Surficial Sediments (< 15 cm)							
Bulk concentrations (Tot. N, Tot. P Avail. P, TOC, pH, Eh).	One period			any	" " "		
Release Rates (DO use, PO_4 release)	" "			Accumulative	" " "	SOD chambers	Sonzongni et al. 1977
D. Product. Data - C uptake, DO/CO_2 bottles	As appropriate			1000-1200	(as CA, II.D)		
E. 3 major algae and 2 major macrophytes	As in LEI			1000-1200	(as CA, MAC; II.D. & F.)		
F. Other variables	As appropriate			as approp.	within lake margins	As appropriate	
Pop. Surveys (macroinverts, fish zooplankton, bacteria)							
Other nutr. (inorgan. C. trace metal)							
Other cations and anions, organics, particulates (TDS, SS, VSS, etc.)							

APPENDIX B - MACROPHYTE EVALUATION

The following description has been adapted from the Wisconsin Department of Natural Resources guidelines for macrophyte surveys (Dunst, pers. comm.).

Evaluation of macrophytes as a target variable for use in the LEI.

Example (Pine Lake, WI) is included.

1. Obtain or draw a bathymetric graph in meters of the lake.

   Example. Figure B-1.

2. Divide lake surface into 100 sections (A/100) and draw squares with appropriate dimensions to form a grid over the lake surface. Label the North-South and the East-West axes numerically.

   Example. $\frac{6{,}070{,}000 \text{ m}^2}{100} = 60{,}700 \text{ m}^2/\text{quadrat}$

   $\sqrt{60{,}700} = 246.4 \text{ m} \cong 250 \text{ m}$ on a side.

   NOTE: There are more than 100 squares defined; on Figure B-1, the grid pattern is indicated along the margins of the bathymetric map.

3. Define sections within the 10 m depth contour line. For this example all sections fall within the 10 m contour since the lake is shallower than 10 m. Select randomly 50 percent of these sections. For lakes smaller than 25 hectares, select a grid pattern which produces sections 50 m on a side; select randomly 50 percent of these sections.

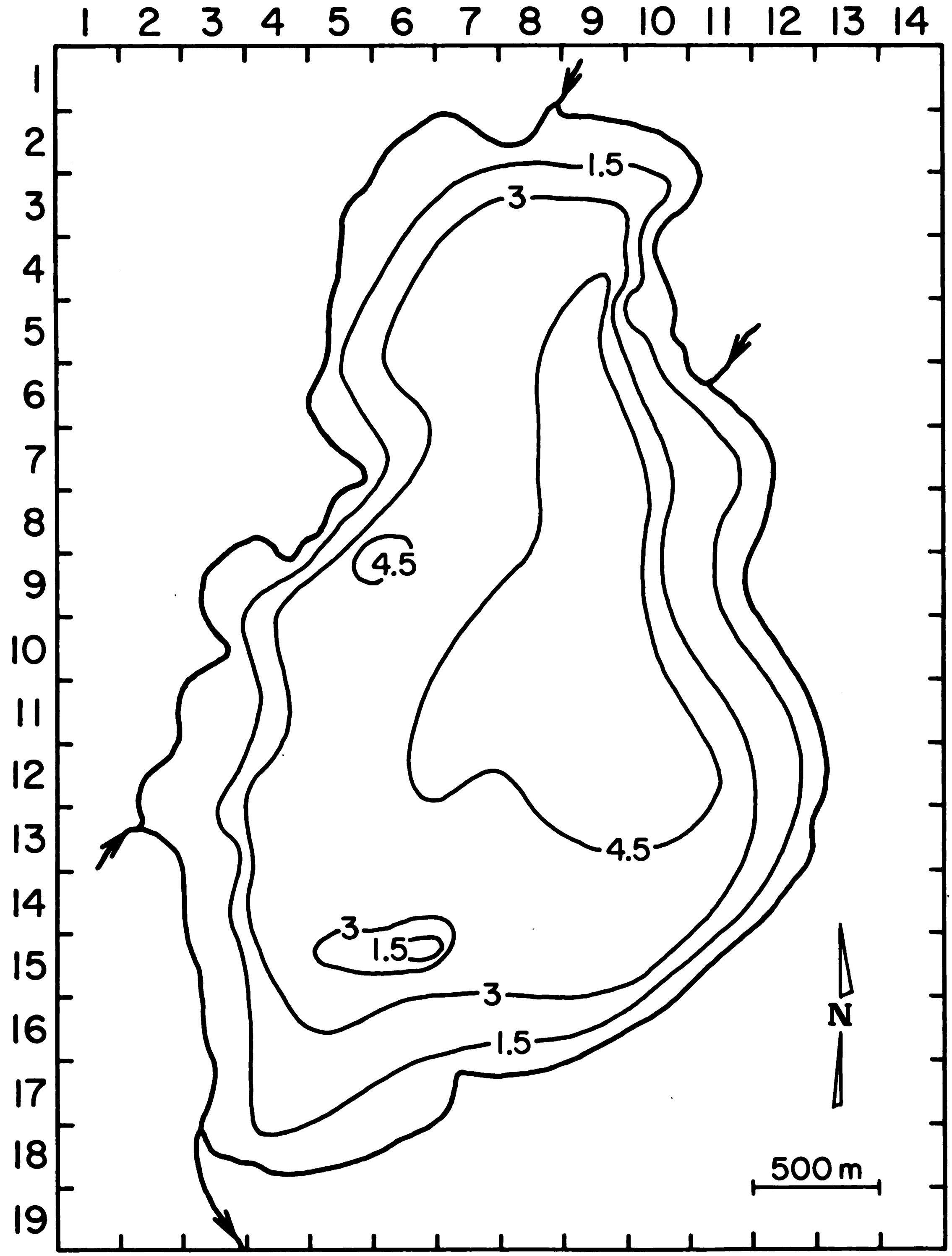
   Example. Figure B-1.

4. Mapping: Visually survey the lake and mark on the map the major community types: emergent, floating leaved and submergent plants.

   Example. Figure B-2.

   A = abundant
   C = common
   S = sparse

Indicate the boundaries of single species stands within the more general community type.



PINE LAKE, WISCONSIN

Figure B-1. Bathymetric map of Pine Lake, Wisconsin, with grid pattern for selecting sections for macrophyte survey.

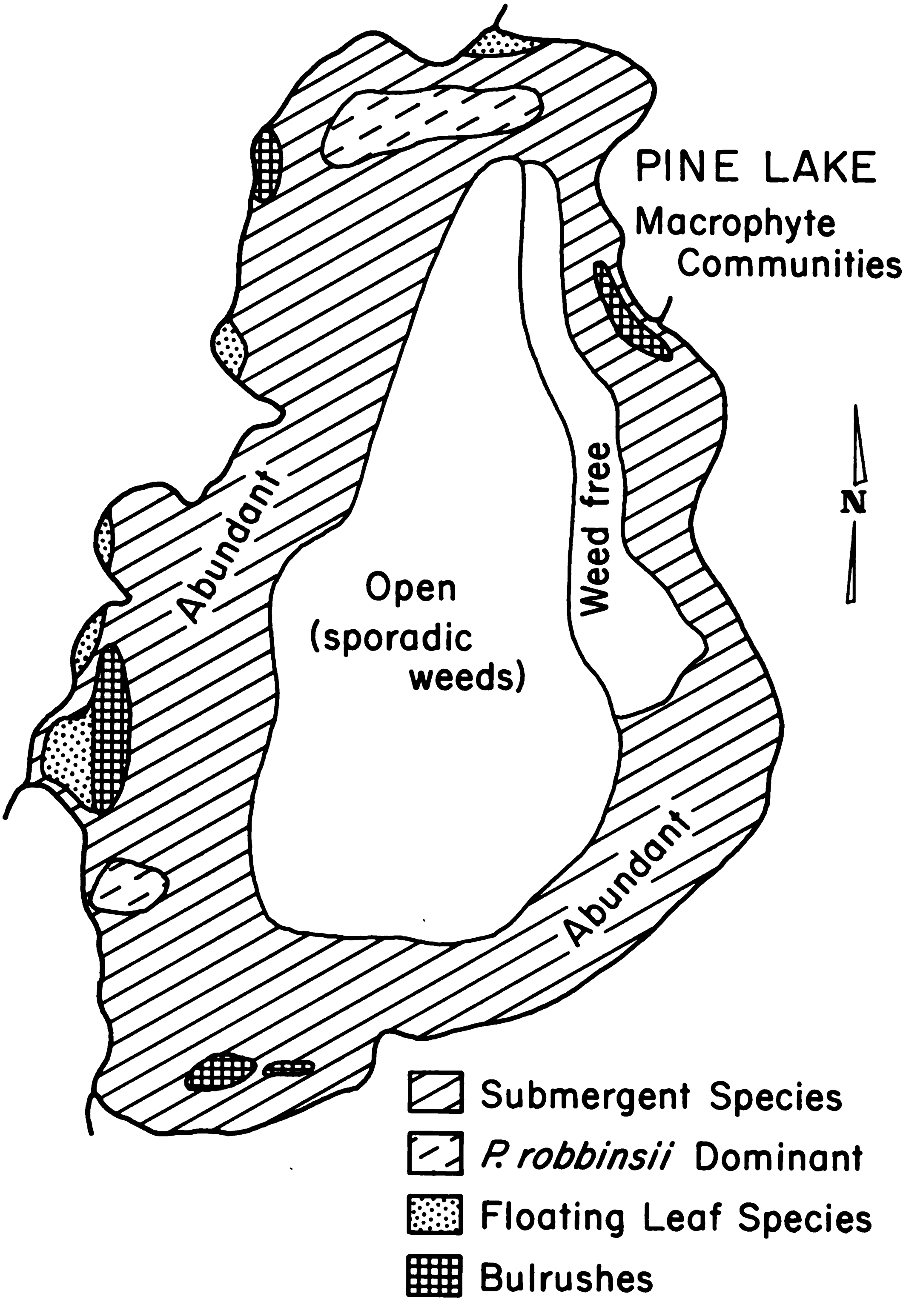


Figure B-2. Map of Pine Lake, Wisconsin indicating distribution of major macrophyte types.

Show this information on a bathymetric lake map (Lind, 1974). The map should show distribution of the communities and a species list with the appropriate abundance symbol for each location (Fassett, 1960).

5. Density, frequency and depth. This analysis is applied to the selected sections as defined in steps 2 and 3.

Follow the grid pattern as much as possible using a compass and shoreline reference points, being reasonably precise.

Within the center of each selected section will be an imaginary circle with a six foot radius. Mentally divide the circle into quadrants and using an underwater viewer (Lind, 1974) determine the density of growth for each species according to:

1 = present in one quadrant
2 = present in two quadrants
3 = present in three quadrants
4 = present in four quadrants
5 = very abundant in all four quadrants

Visual determinations should be possible in most instances; however, a garden rake can be utilized if necessary to provide more reliable results. Additional measurements at each stations shall include:

a. Water depth (lake water level at the time of sampling should also be recorded),

b. percent of open surface area within the six foot radius,

c. sediment type (include combinations),

    i. rock
    ii. gravel
    iii. sand
    iv. muck--decomposed organic materials
    v. detritus--undecomposed organic materials (e.g., leaves, sticks, peat, etc.)
    vi. marl--whitish in color, fizzes profusely when muriatic acid is applied.

Reporting. In the report compute frequency occurrence, average density rating, and depth of growth for each species during each sampling period for the lake as a whole; however, furnish all of the original data. Numerically identify the approximate location of each sampling station on a map.

Indicate the total area available for macrophyte growth (10 m depth line and/or the contour line for 2 times mean Secchi depth for July-August), and the percent total lake surface covered by macrophytes.

APPENDIX C

APPLYING THE LEI (LAKE EVALUATION INDEX) TO WASHINGTON LAKES THAT ARE OF VARYING MORPHOLOGY AND TROPHIC LEVEL.

The LEI was developed for evaluating the effects of lake restoration techniques. Data adequate for illustrating the use of the LEI were obtained for a set of Washington lakes (Bortleson, *et al*., 1976). Four separate reports written by the Washington DOE and US Geological Survey on Washington lakes have been published; a single report was selected at random (Part 3) and all 28 lakes therein were evaluated. Data from the 28 lakes do not meet the specifications for the LEI described previously; they are reconnaisance data and were used only to illustrate the method for determining the LEI.

MORPHOMETRY (DEFINITIONS AS IN HUTCHINSON, 1957)

Areas (A), volume (V), perimeter (P), mean (ZB) and maximum (ZM) depth, and dissolved oxygen (DO) and temperature (T) relationships with depth were obtained along with Secchi depth (SD), total phosphorus (TP), total nitrogen (TN), chlorophyll *a* (CA), and percent area of the total lake covered by macrophytes. These data were used as input to a simple computer program for estimating the LEI. The development ratio (DL) was calculated as the ratio of the true perimeter to the circumference of a circle having the measured area of the lake. The diameter (D) of the lake can be determined assuming that the lake surface is a circle with area, A (Table C-1). The diameter can also be determined by assuming a geometric shape for the lake and by using the dimensions of this geometric shape to calculate D.

The calculation of various components of the LEI (particularly net DO) requires information about lake volumes which correspond to particular depth increments. If these volume increments are not available, they can be calculated by the method outlined below. The method assumes a lake to correspond to a particular geometric shape.

A cone shape has been suggested as a possibility (Hutchinson, 1957) but analysis of lake data indicated that a paraboloid would provide a better approximation of lake volume. The idealized relationships for conic and parabolic shapes compared to a hypothetical vertical plane of a lake can be visualized as in Figure C-1; certain types of morphometric configurations would produce ratios of the empirically determined area (Ae) to such volume-based areas (Av) that vary from unity depending on whether the actual plane was less or greater than the idealized planes shown in Figure C-1.

As a comparison of the goodness of fit by either the conic or parabolic shape, 1) the surface diameter (D) was calculated from the empirically determined volume using the conic (dvc) and then the parabolic (dvp) equations;

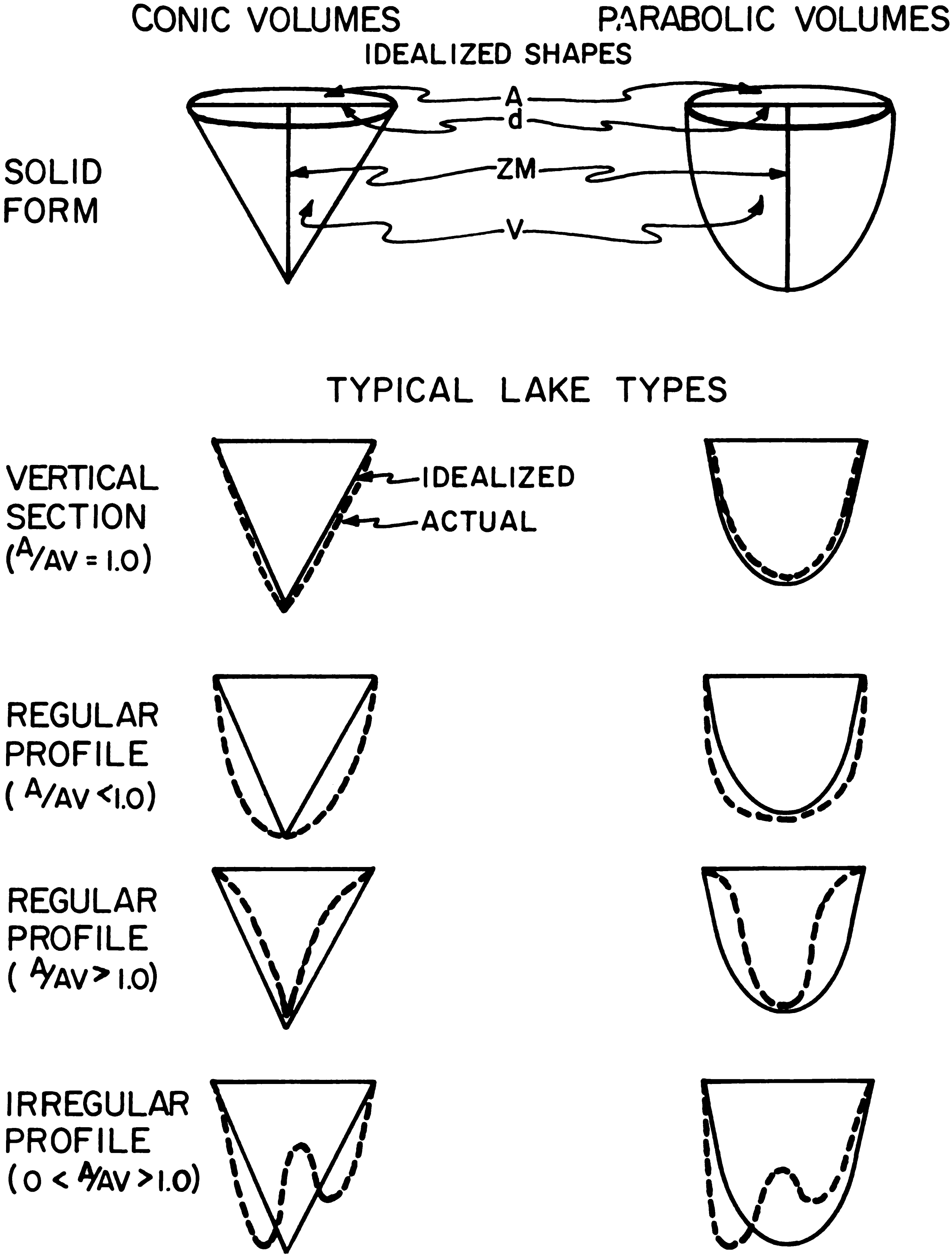


Figure C-1. Use of geometric figures to approximate morphology of specific lake types (vertical dimension exaggerated).

2) the area was calculated from each diameter using the equation of a circle; and 3) these idealized areas were compared to the empirically determined areas using ratios. These ratios (Table C-2) indicate that the paraboloid approximates the set of 28 Washington lakes better than the conic because 1) more ratios of calculated to measured areas for the parabolas are closer to 1.0 (the ideal) than for the cone (20 were better; 3 about the same and 5 were worse); it should be noted that the cone did fit some of the lakes better; 2) based on a t-test the mean ratio of the 28 lakes for the parabola was not significantly different from 1.0 ($p<0.99$) whereas that for the cone was different. Also, note that the cone and parabola ratios were significantly different from each other. Attempts to correlate deviation of the idealized shapes from measured shapes with development ratios (DL) were unsuccessful. Essentially, the ratios of calculated to measured areas for the 28 lakes represent a normally distributed set of data with mean of 1.0 (Figure C-2).

TABLE C-1. MORPHOMETRIC ALGORITHMS FOR USE IN DETERMINING THE LEI.

1. Surface Area (A):

$$A = \pi r^2 = \frac{\pi d^2}{4}$$

2. Perimeter (P) and development ratio (DL):

$$\text{circumference} = \pi d$$

$$d = \sqrt{\frac{4A}{\pi}}$$

$$DL = P/\pi\sqrt{\frac{4A}{\pi}} = P\sqrt{4\pi A}$$

3. Lake volume (V) ratios

   a. Conic

$$V = \frac{1}{3}\pi r^2 h = \frac{1}{12}\pi d^2 h = \frac{1}{12}\pi d^2 ZM$$

$$d_V = \sqrt{\frac{12V}{\pi ZM}}$$

   b. Parabolic

$$V = \frac{\pi\ Y^2}{2a} = \frac{\pi\ ZM^2}{2a}$$

$$a = \frac{\pi\ ZM^2}{2V}$$

$$d_V = 2\sqrt{y/a} = \sqrt{8V/\pi ZM}$$

TABLE C-2. COMPARISON OF 28 WASHINGTON LAKES INDICATES THAT PARABOLOIDS APPROXIMATE LAKE VOLUME BETTER THAN CONES.

	Ratios	
	Conic area/ measured area	Parabolic area/ measured area
	1.590	1.060
	2.080	1.387
	1.396	.931
	1.402	.934
	1.201	.801
	1.200	.800
	1.380	.920
	1.766	1.178
	1.544	1.029
	.969	.646
	1.378	.918
	1.600	1.067
	2.052	1.368
	1.799	1.199
	1.921	1.281
	1.119	.746
	1.380	.920
	.943	.629
	1.309	.873
	1.091	.727
	1.199	.799
	1.024	.682
	1.219	.813
	1.255	.837
	1.722	1.148
	1.777	1.185
	1.446	.964
	1.898	1.266
mean	1.45	0.968
Standard deviation	0.326	0.217
Standard error	0.062	0.041
Range	1.137	0.758
t-value (compare to 1.0)	7.35*	0.78**
t-value (compare conic to parabolic) = 6.54*		

* significantly different at P > 0.99

** not significantly different at P < 0.95

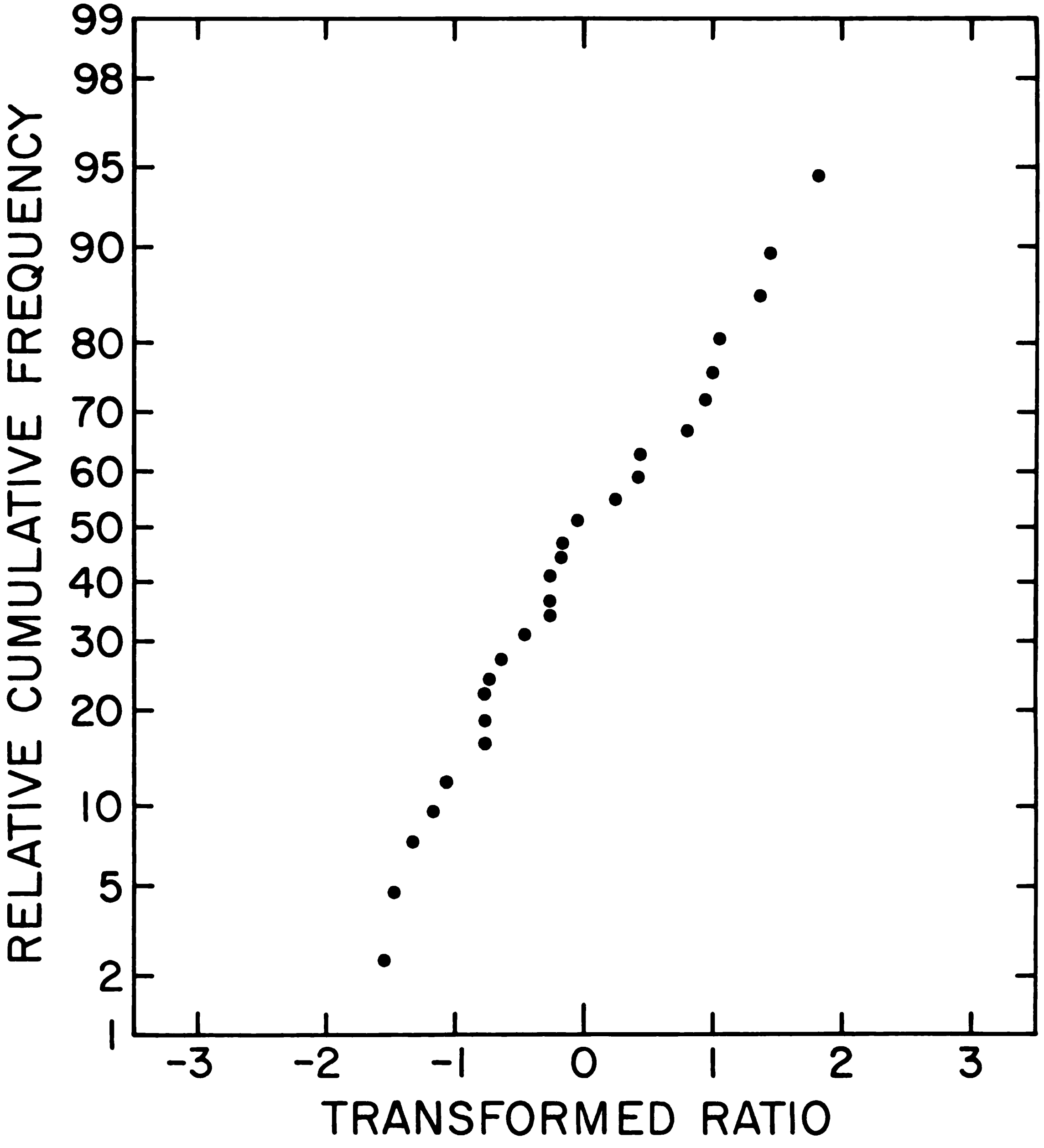


Figure C-2. Relative cumulative frequency of ratios of surface areas calculated (parabolic) to empirical surface areas plotted on probability graph paper. Horizontal axis was obtained from

$$u = \frac{y-\mu}{\sigma}$$

where y = observation, μ = mean of observations and σ = standard deviation. This normalizes the deviations to the standard deviation producing u = 0 for the mean, and each unit on the axis = one standard deviation. A normal distribution plots as a straight line on this graph.

Translating idealized volumes from either cones or paraboloids is simplified by certain definitions (Figure C-3): depth is the positive portion of the axis in the x, y plane; the plane is rotated around the axis to produce the solid figure in the x, y, z dimensions; radius (d/2) is a ±x value for the plane.

Specifically, volume increments (V_i) are calculated as follows: because depth (D) is usually measured from the surface, H = ZM-D. Similar triangles are formed in the cone ($\alpha\beta\gamma$ similar to $\sigma e \gamma$) and thus the ratio of any two sides is a constant ($k = d/ZM = \sigma e/Y$). The diameter (d_i) at any depth (D) would be: $d_i = k(ZM-D)$. Thus, the volume of a cone (Vc) contained below any specified depth (D) can be calculated:

$$V_c = \frac{\pi}{12}[k(ZM-D)]^2(ZM-D) = \frac{\pi}{12}k^2(ZM-D)^3$$

or because $k = \sqrt{\frac{4A}{\pi ZM^2}}$ and H = ZM-D

$$V_c = \frac{\pi}{12}\frac{4A}{\pi ZM^2}H^3 = \frac{AH^3}{3ZM^2}$$

The incremental volume (V_i) is the total volume minus the conic volume:

$$V_i = V - V_c$$

The area for that conic volume is easily calculated assuming a circle for the base of the cone, V_c.

PARABOLIC

The equation describing a parabola with the spatial orientation in Figure C-3 has the form $Y = ax^2$. A parabola rotated around the axis (Y) produces a paraboloid having a volume (V_p):

$$V_p = \frac{\pi Y^2}{2a}$$

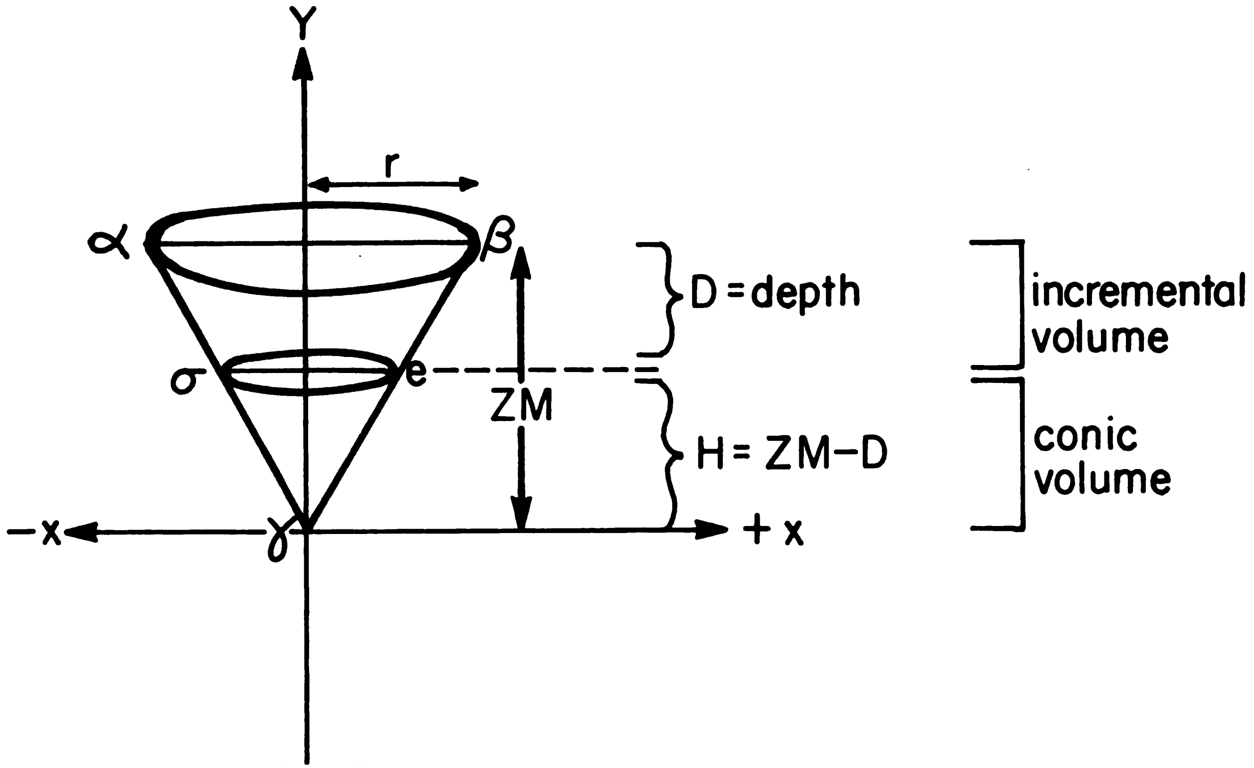
The coefficient, a, is defined for a lake having maximum depth (ZM) and known volume (V) as follows:

$$a = \frac{\pi ZM^2}{2V}$$

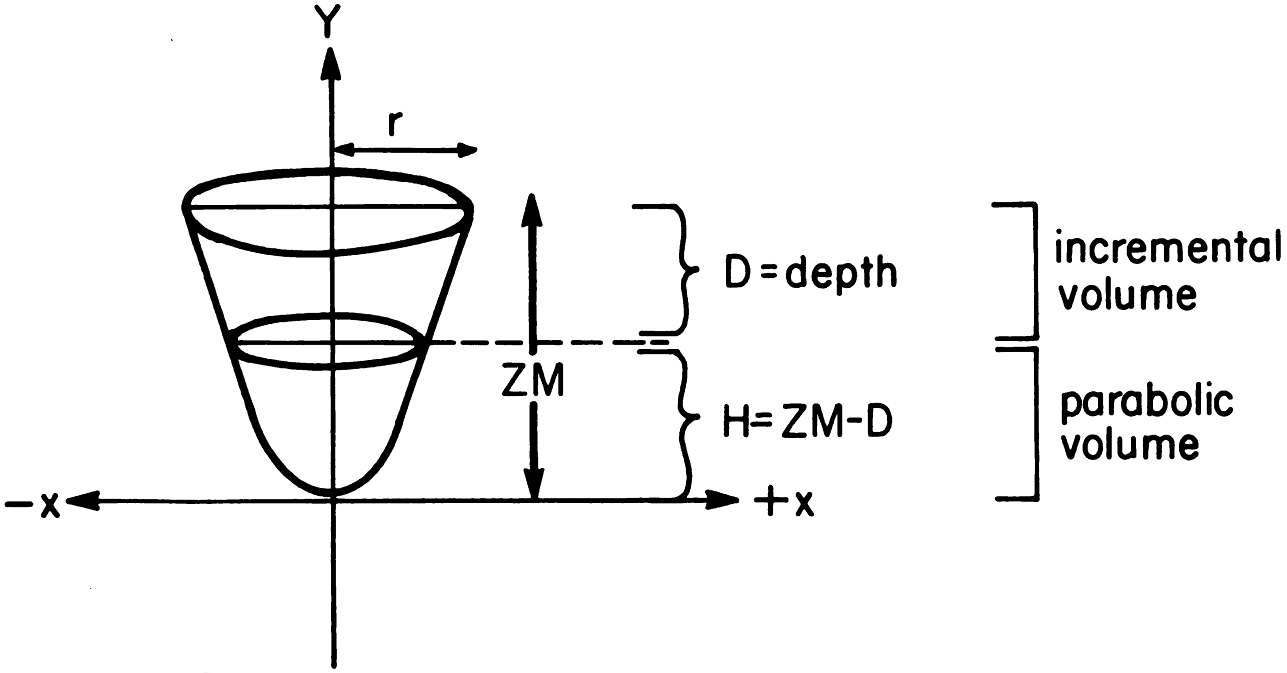
Thus, $V_p = \frac{VY^2}{ZM^2}$

Incremental volumes (V_i) for any depth (D) where Y = H = ZM-D are:

$$V_i = V - V_p = V - \frac{VH^2}{ZM^2} = V(1 - \frac{H^2}{ZM^2})$$



A. CONIC



B. PARABOLIC

Figure C-3. Spatial definitions used to compute idealized volumes of lakes with conic or parabolic basin configurations.

The area for that paraboloid, V_p, is determined from the area of a circle for the base of the parabola (Table C-2).

EXAMPLE

Goodwin Lake, WA is shown in Figure C-4 along with DO and temperature profiles with depth for spring and summer, 1972. Interpolated data for 2 dates for oxygen and temperatures at specific depths are shown in Table C-3. Table C-4 summarizes the data and displays the transformed values calculated with the equations described previously. Although the example data are sparse and do not rigidly meet the requirements listed in the text, they illustrate the process.

LEI values were calculated for each of the 28 Washington lakes mentioned previously, and the lakes were ranked in ascending order. This ranking was then compared with qualitative describers given in Bortlesen *et al*. (1976). Table C-5 demonstrates relatively good agreement between the LEI values and the qualitative describers of trophic character; the low LEI values tend to correspond with lakes of low biological productivity and the higher value with lakes of higher biological productivity.

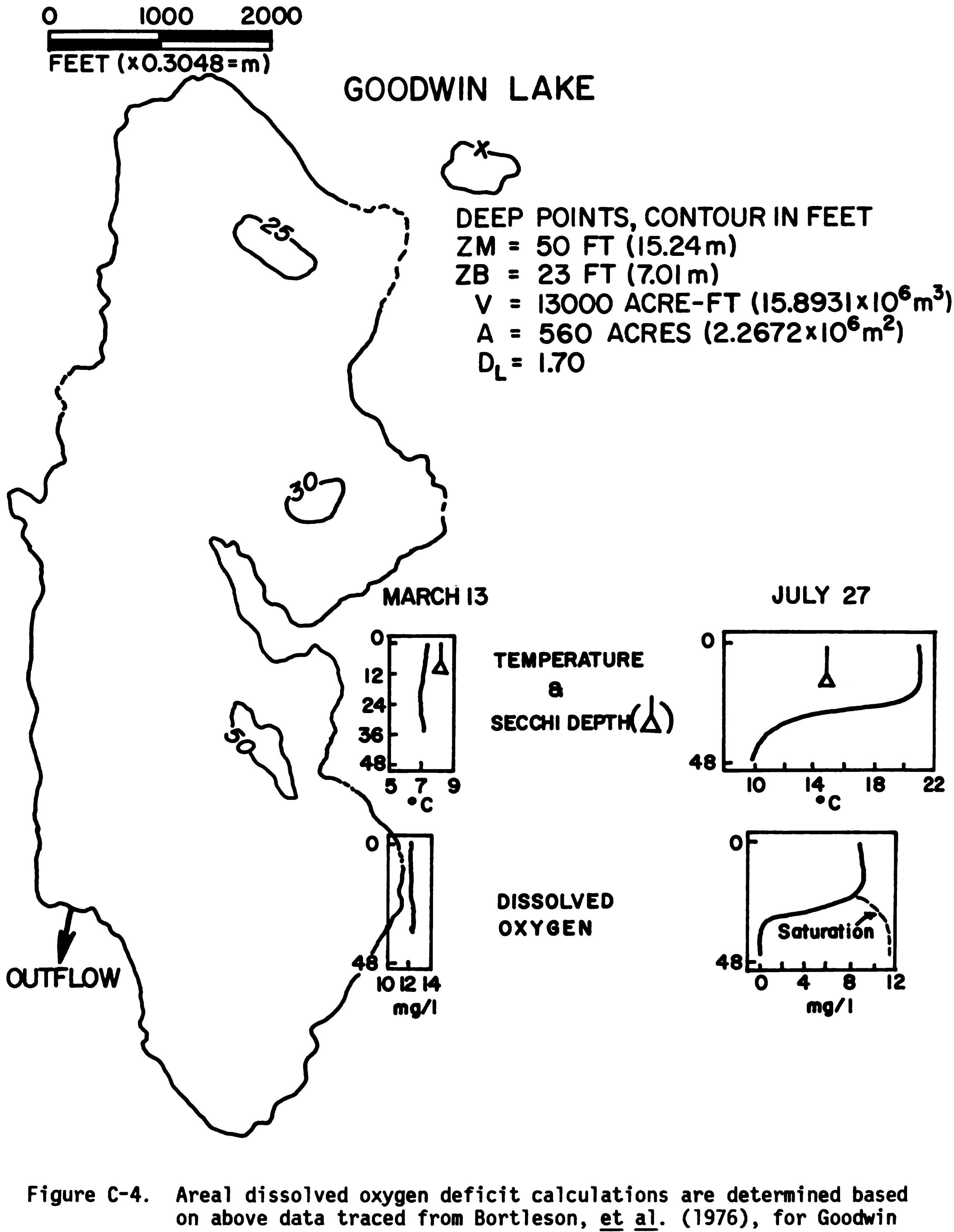


Figure C-4. Areal dissolved oxygen deficit calculations are determined based on above data traced from Bortleson, *et al*. (1976), for Goodwin Lake as an example of 28 other lakes taken from the report.

TABLE C-3. DATA ON GOODWIN LAKE FROM BORTLESON et al., 1976 (See Figure C-3).

	Spring (March 13)		Summer (July 27)	
Depth (m)	DO ($mg \cdot l^{-1}$)	Temp. (°C)	DO ($mg \cdot l^{-1}$)	Temp. (°C)
0 (surface)	12.	7.	8.8	21.
6.4	unchanged		8.8	21.
7.3	to bottom		8.8	19.
9.8			0	12.
13.4			0	10
15.24 (bottom)			0	10

TABLE C-4. DATA NEEDED FOR LEI USING EXAMPLE OF GOODWIN LAKE (FROM BORTLESON et al., 1976).

Variable	7/27/72 Data*	Calculated LEI data (variable)
Secchi Depth (m)	4.27	39 (XSD)
Total P ($\mu g \cdot l^{-1}$)	12.	73 (XTP)
Total N ($\mu g \cdot l^{-1}$)	820.	73 (XTN)
Chlorophyll a, ($\mu g \cdot l^{-1}$)	12.3	55 (XCA)
Net Dissolved Oxygen ($mg \cdot l^{-1}$) [Measured-Saturated from Table C-3]**	2.52	25 (XDO)
Percent total area covered by macrophytes	1.0	1.7 (XPMAC)
LEI		41

* Transform of only one data point; in practice the average of weekly data collected in July and August would be used. For DO, the average of the calculated total differences would be used.

** These data corrected for temperature:

$$DOSAT = 522/(36 + 0.5T).$$

If lake is not at sea level, correction for pressure should be made

$$(f = \frac{\text{actual P}}{\text{760 mm P}})$$

TABLE C-5. COMPARISON OF LEI VALUES FOR 28 WASHINGTON LAKES WITH ESTIMATED TROPHIC STATE (BIOLOGICAL PRODUCTIVITY, BORTLESON *et al*. 1976).

Lake	LEI	Trophic Character (biological productivity)
Wye	27.48	Low
Phillips	29.70	Low
Retreat	31.36	Medium
Goodwin	33.19	Medium
Wallace	33.79	Low
Ward	34.93	Low
Mason	35.10	Low
Walker	35.87	Low to Medium
Offutt	36.64	Medium High
Roesiger (North Arm)	36.97	Low to Medium
Mineral	37.23	Moderate
Echo	37.35	Medium
Stevens	39.88	Medium
Roesiger (South Arm)	40.96	Medium
King	44.25	Medium
Deer	44.92	Low to Medium
St. Clair (North Arm)	47.82	Moderate to High
Diamond	47.84	Medium
Hicks	48.16	Moderately High
Heritage	48.57	High
Boren	49.34	Medium to High
Pierre	50.80	Moderate to High
St. Clair (South Arm)	52.45	Moderate to High
Thomas	53.42	Medium
Leo	53.65	Medium to High
Frater	55.79	Medium to High
Sherry	55.81	Medium
Gillette	63.06	Medium to High

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