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TABLE OF CONTENTS

List of Tables

ABSTRACT

Long-standing concerns about water quality in Lake Matoaka were heightened in 1989 when elevated concentrations of bacteria belonging to the *Aeromonas hydrophila* group were observed. Densities and generations times of these bacteria are reported to be highly correlated with several indicators of lake eutrophication, including total phosphorus concentrations.

Prior studies have shown that several important measures of water quality can be predicted if the phosphorus load entering the lake each year is known, along with information on lake geometry and hydrology. Consequently, land use data and other information were collected for Lake Matoaka and its drainage basin. The statistical model suggests that present land use patterns produce a phosphorus load that will result in less than desirable water quality conditions. Major reductions (>50%) in phosphorus loads are needed for water quality to improve to acceptable conditions. Although this approach has a number of subjective elements and is general in nature, the analysis suggests that lake water quality will continue to deteriorate until substantial efforts are undertaken to reduce the amount of phosphorus that is delivered to the lake in runoff.

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INTRODUCTION

For a number of years, students and faculty members at the College of William & Mary have been concerned about Lake Matoaka. One concern, the in-filling of the lake in the region called "the delta", was attributed by some to runoff from construction sites. Another concern was the abundant plant growth, especially in the shallow fringes of the lake. Both of these concerns relate to a process called eutrophication.

One way to classify lakes and reservoirs is by their trophic state or degree of nutrient enrichment (see for example, Clapham, 1973). Oligotrophic (poorly-fed) lakes are poor in nutrients, whereas eutrophic (well-fed) lakes are highly enriched. At both extremes, the lakes can be dystrophic (ill- fed). The nutrients of concern are those that support plant growth.

Eutrophication results from the natural, geological in-filling of lakes (Reid & Wood, 1976). As sediments in streamflow and runoff settle lakes become shallower. The sediments often include nutrients, either incorporated in organic matter or sorbed to mineral particles. The shallow depths and available nutrients promote the growth of plants - rooted aquatic vegetation, phytoplankton, and benthic algae. Eventually a lake becomes a swamp or bog.

This natural process can be, and often is, accelerated by human activity and is sometimes referred to as cultural eutrophication. Sediments and nutrients arise from the so-called point and non-point sources of pollution. Point sources are industrial and municipal wastewater treatment plants and other sources which discharge wastewaters to a water body at discrete points, often the ends of pipes. Non-point sources are diffusely distributed and include atmospheric deposition, groundwater inputs, and runoff from land.

In 1989 a group of students who had been collecting plants and animals in and around Lake Matoaka developed pustules where the skin had been broken. Subsequent testing of the lake waters showed high numbers of bacteria belonging to the *Aeromonas hydrophila* group. These bacteria occur naturally in waters but were at elevated concentrations in Lake Matoaka. Aeromonads are not perceived to be a major health risk for healthy individuals, but pose significant risks to persons with a compromised immune system. These bacteria can produce a variety of diseases, both gastrointestinal and extraintestinal infections, the latter including skin lesions. Consequently, in the fall of 1989 recreational use of the lake was prohibited to minimize public health risks.

Researchers have found that the densities and generation times of *Aeromonas hydrophila* are highly correlated with several indices of lake eutrophication, including total phosphorus concentrations (Rippey & Cabelli, 1985). This is an important additional reason to give attention to eutrophication of Lake Matoaka.

The purpose of the present study is to assemble information necessary to predict the trophic state of Lake Matoaka given current land use patterns. The approach also allows one to estimate the degree to which nutrient loadings must be reduced to achieve more desirable lake conditions. In the following section, the state of the art in understanding eutrophication processes will be reviewed briefly. Next, the results of recent field measurements will be presented and then used to project steady state trophic conditions. Those findings will be discussed in the final section of the report.

A REVIEW OF THE STATE-OF-THE-ART

The Organization for Economic Cooperation and Development (OECD) organized a large project under the direction of Dr. R. A. Vollenweider to gather and summarize information on eutrophication (Vollenweider, 1968). Rast & Lee (1978) have summarized the U.S. portion of the OECD data. These efforts to organize the data and show the relationships between phosphorus loadings and lake water quality (e.g. Vollenweider, 1975) were successful. The resulting method, often referred to as "the Vollenweider approach," has two major premises. First, phosphorus is the nutrient of concern, and second, statistical models can allow future lake conditions to be predicted from a normalized phosphorus loading rate.

Nutrient Limitation: If some environmental factor is shown to limit or control population density, then it is referred to as a limiting factor. For example, plant growth may be limited if water is turbid, reducing the amount of light available or if one or more essential nutrients are in short supply. The three primary macro-nutrients necessary for plant growth are carbon, nitrogen, and phosphorus. From a water quality management perspective, however, carbon and nitrogen have been found to be of little importance in controlling freshwater algal populations.

> "(I)f phosphorus were supplied in excess of algal demands relative to nitrogen and carbon, algae would call upon atmospheric and sedimentary carbon and nitrogen sources to balance their nutrient accounts, fixing enough of the elements to produce the proportions of nutrients which algae prefer (known as the Redfield numbers to estuarine and marine workers). The net effect of these interactions is to keep the growth of freshwater phytoplankton in most lakes proportional to the supply of phosphorus." (Schindler, 1981)

Controlling the amount of nitrogen in lake and reservoir waters is possible, but this may lead to undesirable results. Some cyanobacteria (formerly called blue-green algae) are able to "fix" nitrogen and include noxious forms that (1) accumulate to dense concentrations because few zooplankters feed on them, (2) give water a bad taste and odor, (3) often rise to the surface creating surface scums and unsightly conditions, and (4) can accumulate on the shoreline. Thus, control of nitrogen can "backfire" if it favors these less desirable forms. (See NAS-NAE, 1972 for a review of the aesthetic problems associated with eutrophication.)

Vollenweider Model: The Vollenweider model is based on a number of related hypotheses. First, the phosphorus loading to a lake depends on the land use characteristics of the drainage basin. For a given set of land use patterns, an average annual phosphorus load can be estimated. Second, phosphorus concentrations in the lake are related to the phosphorus load. And last, but not least, the concentrations of phosphorus in lake waters determines the trophic state of the lake.

Vollenweider assembled data from a large number of lakes. With judicious choice of factors to normalize the data, statistical models were developed that relate phosphorus loadings to lake responses such as summer mean chlorophyll concentration, Secchi depth, and hypolimnion oxygen depletion rate.

Geographical Information Systems (GISs): Much of the data needed for the Vollenweider approach is geographical in nature. While it is possible to work with maps, computer based GISs allow manipulations to be completed quickly and easily (Bylinsky, 1989). Data are stored in "layers" that conceptually are similar to the clear overlays often used with maps. Example layers would be the lake drainage basin (and sub-basins), land use, streets, and lake shoreline. Once information has been entered into a GIS, calculations can be made easily. For example, areas in a particular land use category can be determined for the basin, or for sub-basins separately. Additionally, data from various layers can be combined and maps drawn to virtually any scale desired. The GIS used in the present study is the ARC/Info software package. (ARC/Info is a registered trade mark of ESRI, Inc. of Redlands, California.)

RESULTS OF LAKE MATOAKA STUDIES

The purpose of the present investigation was to apply the Vollenweider approach to Lake Matoaka so that the trophic state corresponding to present phosphorus loadings could be determined. Once that has been established, the load reduction necessary to achieve some other trophic state can be estimated. A number of activities have been undertaken to complete this assessment.

Aerial Photography: Aerial photographs of the Lake Matoaka drainage basin were made on January 30, 1990 using the VIMS de Havilland "Beaver" and a 70 mm camera. A photo-mosaic of the entire drainage basin was prepared (Figure 1).

Land use: The aerial photographs were used to map land use onto U.S. Geological Survey (USGS) topographic maps and the data entered into the GIS. For the purpose of this study, only three land use categories were used: urban, rural/agriculture, and forest (Figure 2). The application of such broad land use categories involves considerable subjectivity. Areas classified as urban included the Monticello Shopping Center and other commercial lands along Richmond Road, Chambrel, Berkeley High School proper, and most of the main campus of the College of William & Mary. Low density residential areas were classified as rural, along with a large open area near Berkeley School.

The land use statistics were used to estimate the annual phosphorus load (Table 1), using nutrient export coefficients suggested by Rast & Lee (1983).

One difficulty, which shows up on Table 1 and subsequent tables, is that of units. Several U.S. agencies continue to report data in English units, for example, river flow is reported in cubic feet per second. Most scientific studies use metric units. Consequently, conversions are required when calculations are made. Both English and metric values have been provided in the tables.

Table 1. Land Use Statistics for Lake Matoaka

	Area (acres)	Area (m^2)	Runoff Coefficient ($g\ P/m^2/yr$)	Load (kg/yr)
Forest	929.5	3,761,700	0.01	37.6
Urban	326.1	1,319,700	0.10	132.0
Rural	176.1	712,700	0.05	35.6
Lake	40.2	162,700	0.025 *	4.1
Total	1,471.9	5,956,800		209.3

* Atmospheric deposition onto lake surface.

Lake Morphometry: The lake shoreline was taken from the aerial photographs and enlarged for field measurements of the lake geometry. A fathometer deployed on a small jon boat was used to measure water depths along more than forty transects, most across the channel but some along the channel. Depths at points along the transects were read from the strip charts and transferred to the map. Lines of equal depth were then contoured by hand. The 5, 10, 15, and 17 contours, and part of the 2 foot contour were entered into the GIS (Figure 3) and lake areas and volumes for various depth intervals determined (see Table 2). If the nominal or median depth is used for each area, the mean depth is 8.27 feet (2.5 meters). The lake surface area is 1.75 million square feet or 40.2 acres (1.63 hectare) and lake volume is 14.5 million cubic feet (410,000 cubic meters).

Table 2. Bathymetric Information for Lake Matoaka

Depth range (feet)	Nominal Depth (feet)	Area (ft^2)	Volume (ft^3)
0 - 2	1.0	107,000	107,000
2 - 5	3.5	567,000	1,985,000
5 -10	7.5	433,000	3,251,000
10 - 15	12.5	347,000	4,340,000
15 - 17	16.0	253,000	4,044,000
17	17.1	44,000	750,000
TOTAL		1,751,000	14,477,000

Surface area = 1.75×10^6 ft^2 = 1.63 hectare.
Volume = 14.5×10^6 ft^3 = 410,000 m^3.
Mean depth = Volume/Area = 8.27 ft. = 2.5 m.

Flow and Residence Time: Streamflow records (Prugh et al., 1989) for several nearby gaged streams were examined. The typical, long-term mean flow per area is 1 cubic foot per second per square mile of drainage area (1 cfs/mi^2 is equal to about 1,000 cubic meters per day per square kilometer; see Table 3). When this is applied to the entire drainage basin and all conversions are made, the average annual flow to Lake Matoaka is estimated to be slightly over two million cubic meters (2,050,000 m^3/yr). The mean hydraulic residence time then is 0.2 years or 73 days. The statistics for Lake Matoaka are summarized in Table 4.

Table 3. Mean Stream Flow and Drainage Area Statistics for Nearby Gaged Streams (Data from Prugh et al.; 1989).

Station	Years of Record	Mean Flow (ft^3/s)	Drainage Area (mi^2)	Flow per Unit Area (ft^3/sec/mi^2)
Ware Creek	8	6.25	6.29	0.99
Beaverdam	40	7.06	6.63	1.06
Totopotomy Cr	11	28.8	26.2	1.10
Po	26	74.8	77.4	0.97
Deep Creek	42	150.0	158.0	0.95
Chickahominy	46	262.0	248.0	1.06

1 ft^3/mi^2 = 944 m^3/km^2

Table 4. Vital Statistics for Lake Matoaka

Drainage area 1,472 acres = 5.96 km^2 = 2.30 mi^2

Land Area 1,432 acres
Lake Surface area 40.2 acres = 163,000 m^2

Mean flow to lake = 2.3 cfs (ft^3/s)
= 5,630 m^3/day
= about 2.05 million cubic meters per year, assuming a long-term average flow rate of 1 $ft^3/s/mi^2$ (see Table 3).

Mean residence time = Volume/Mean flow = 0.20 years = 73 days

L(p) = areal annual phosphorus load = 1.28 $g/m^2/yr$

Calculated Values and Projections:

L(p) = annual areal phosphorus load (see Table 1)
= {209 kg-P/yr} / 163,000 m^2 = 1.28 $g/m^2/yr$
q_s = mean depth/hydraulic residence time = 12.6 m/yr
t_w = residence time = 0.2 years
$1 + (t_w)^{0.5}$ = normalizing factor = 1.45
Normalized phosphorus loading rate = $\{L(p)/q_s\}/\{1 + (t_w)^{0.5}\}$ = 70.2 mg/m^3

When the figures from Jones & Lee (1982; Figures 4 and 5) are used to project steady state conditions for presental land uses, these yield the values in Table 5: Chlorophyll a is used by many to characterize the amount of algae. Summer values are used because growth is greatest during the warmer months. Furthermore, summer average concentrations correlate reasonably well with peak concentrations (Figure 5). If Vollenweider's model is accurate, the phosphorus loading factor (1.28 $g/m^2/yr$) would have to be reduced by about 80% to reach the acceptable range (Figure 6).

Table 5. Projected Values (and 95% Confidence Intervals) for Several Indicators of Eutrophication.

Water Quality Measure	Value	95% Confidence Interval
Mean chlorophyll a	15 ug/l	3.7 to 50 ug/l
Maximum chlorophyll a	25 ug/l	0 to 100+ ug/l
Mean Secchi depth	1.7 m	0.6 to 4.5 m

DISCUSSION

The Vollenweider approach provides a means to estimate trophic state for a lake with a minimum amount of data. The approach gives projections for the steady state achieved over the long term. It does not provide an estimate of the differences between wet and dry years or differences due to other factors. It would not apply to a basin in which land use patterns were changing rapidly. (It also would not apply to a reservoir for which the volume and residence time changed, but these do not change appreciably for Lake Matoaka.)

Despite these reservations, the approach does provide much useful information. The monitoring program that is being conducted by the Virginia Institute of Marine Science includes microbiological, physical, and chemical measurements. These observations can, and will, be compared with the estimates from the Vollenweider approach. Preliminary results for 1990 suggest that chlorophyll levels are higher and Secchi depths lower that those projected, indicating that the Vollenweidder approach provides a conservative estimate of the eutrophication problems in Lake Matoaka.

The Vollenweider approach suggests that major reductions in the phosphorus loading are needed in order to restore Lake Matoaka to "acceptable" conditions. Certainly the land use categories are broad and there is considerable leeway in applying the method to this basin. Similarly, what constitutes "acceptable" conditions and "permissible" loadings is subject to interpretation. Nonetheless, the results indicate that significant changes are needed, despite the preponderance of forested land in the watershed.

Noting that the nutrient export coefficient for urban land uses is larger than the others and an order of magnitude larger than the coefficient for forested land, it is clear that emphasis should be placed on the most highly developed portions of the basin. It is interesting to note that the estimated annual phosphorus load for a totally forested drainage basin is about 60 kilograms. In other words, if the basin were all forest, the adjusted loading would be about at the "permissible" line in Figure 6.

If an aggressive campaign to reduce phosphorus loadings is deemed appropriate, then it might be worthwhile to improve the land use definitions and to monitor the runoff from "typical" plots in each category. The U. S. Environmental Protection Agency has manuals available to guide the establishment of nonpoint source control programs (Maas et al, 1987; Maas et al., 1987; U.S. EPA, 1987, EPA, 1987) and lake and reservoir restoration (Moore and Thornton, 1988). Given the success that other communities have acheived by reducing phosphorus loads (e.g., Chapra and Tarapchak, 1976), there is a reasonable chance for success for Lake Matoaka if the appropriate political commitments are made by the citizens and businesses in the basin.

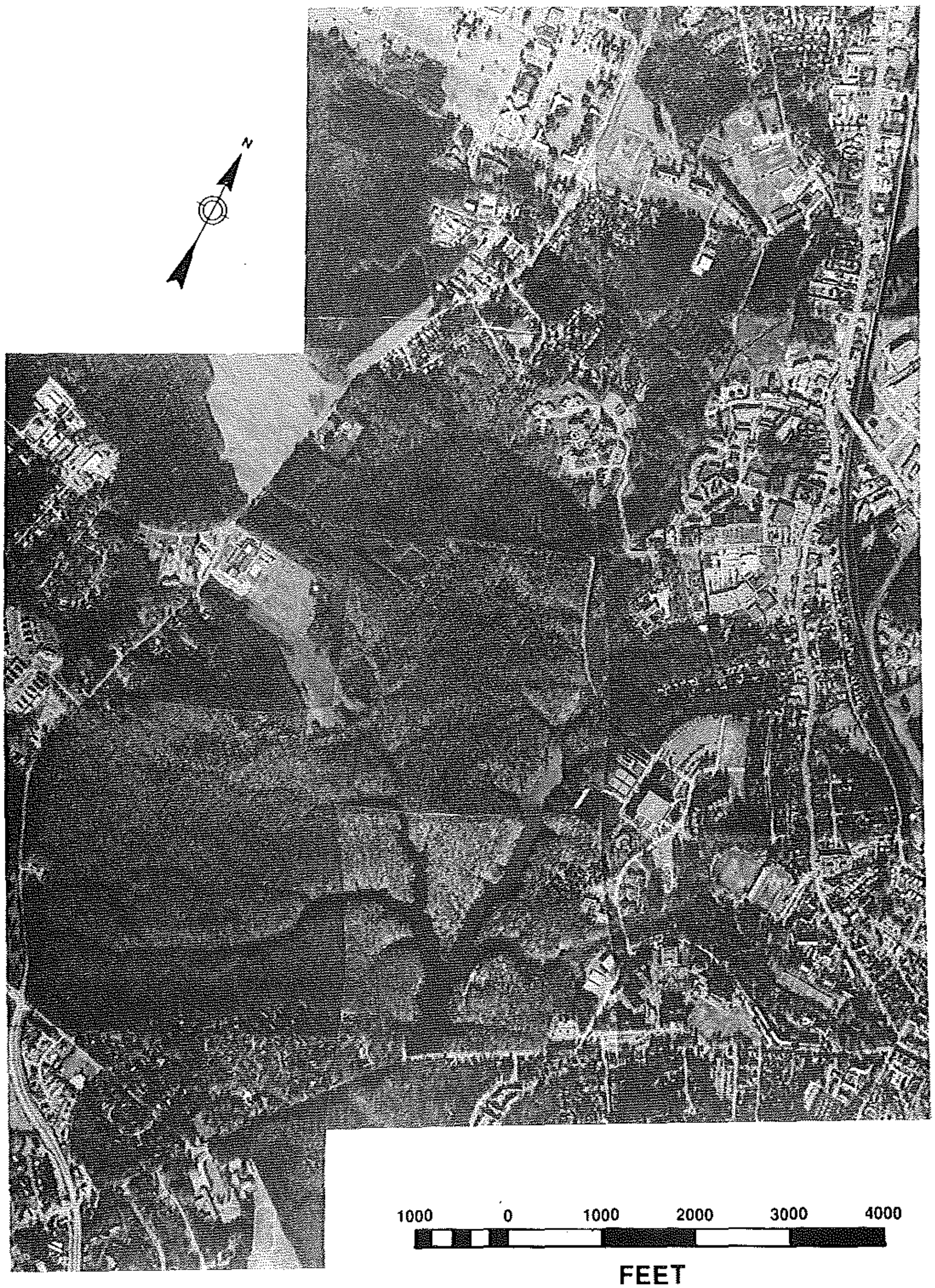

Figure 1. Photo-mosaic of the Lake Matoaka drainage basin. (January 30, 1990)

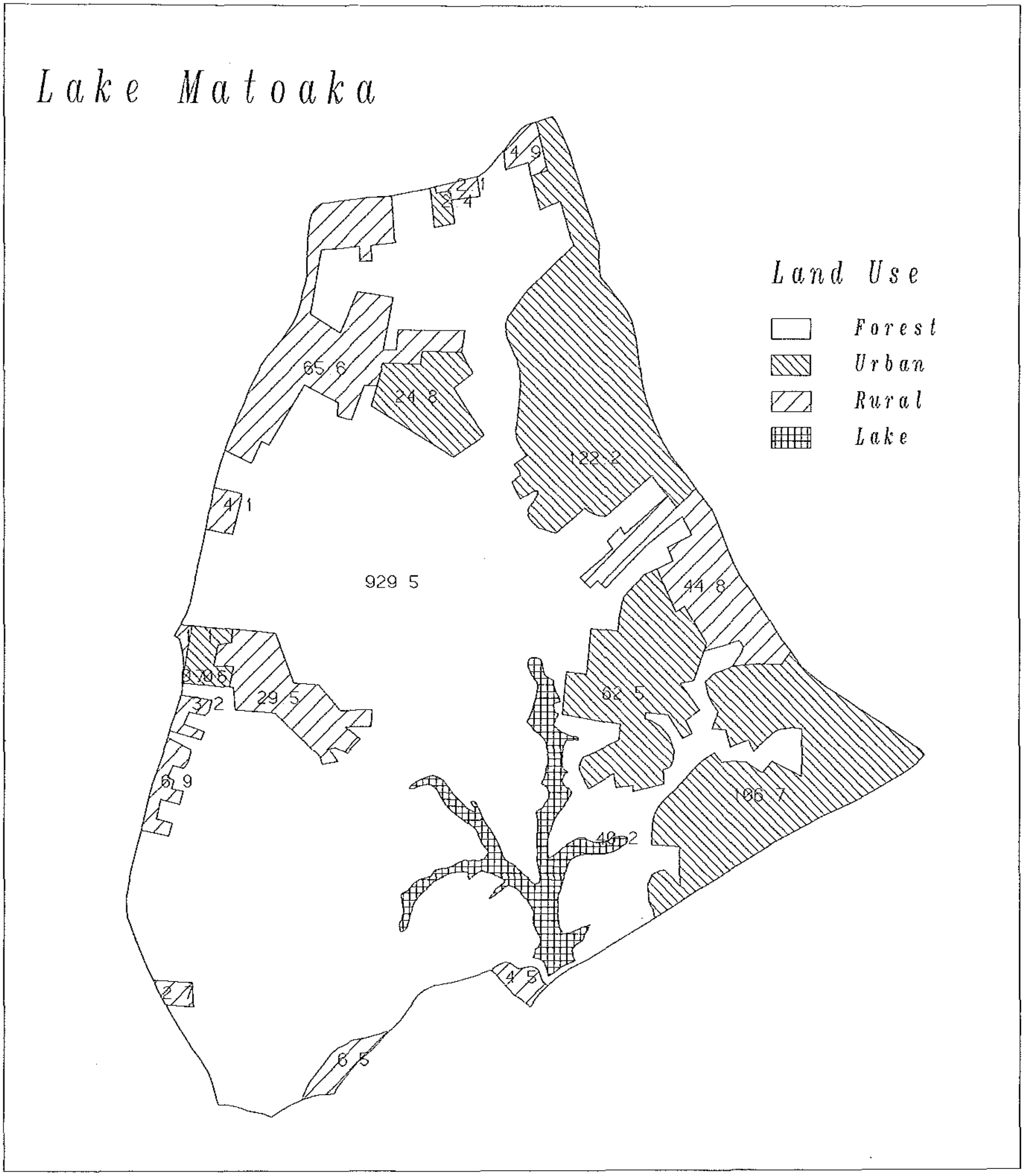

Figure 2. Land use in the Lake Matoaka drainage basin (areas in acres).

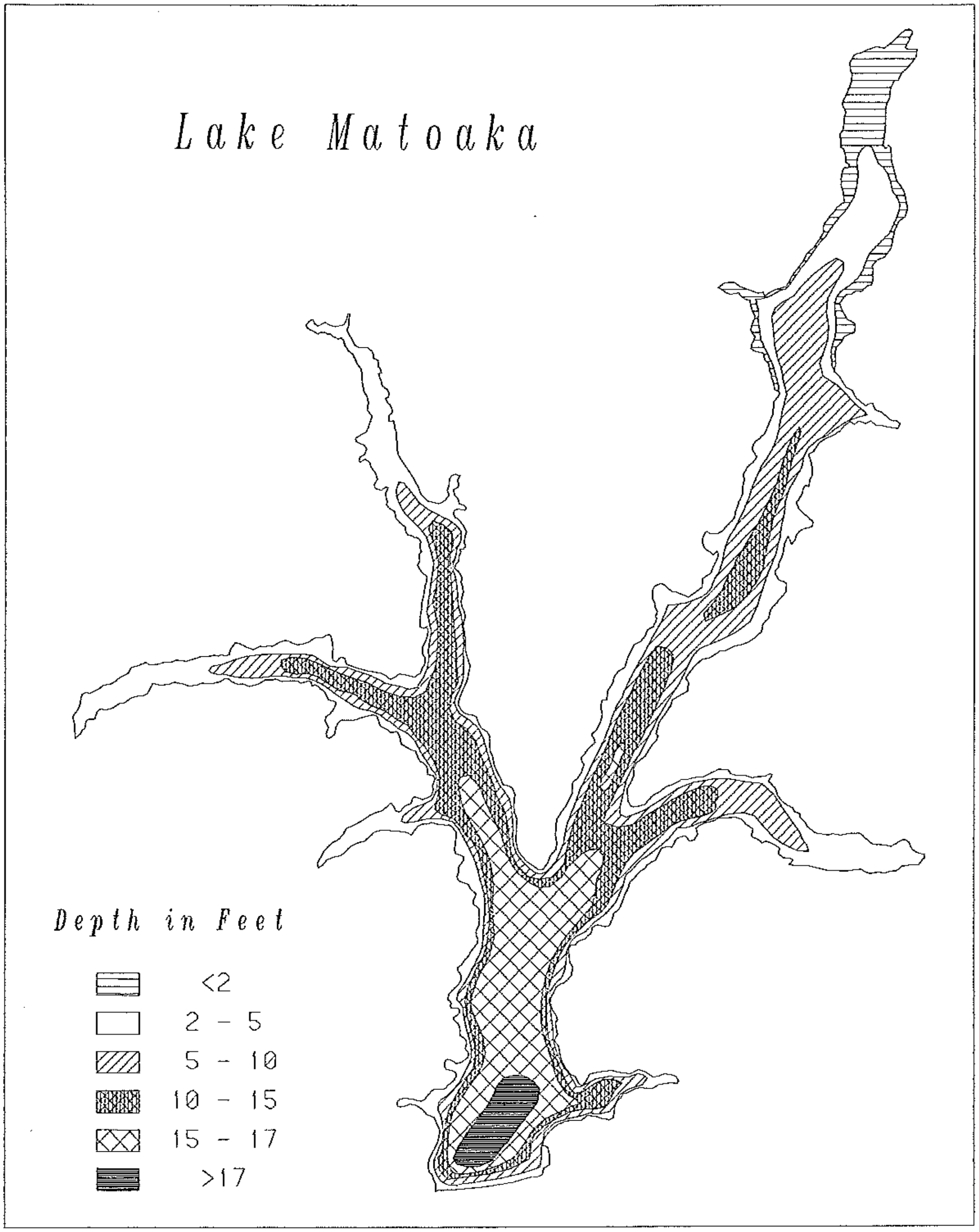

Figure 3. Lake Matoaka bathymetry.

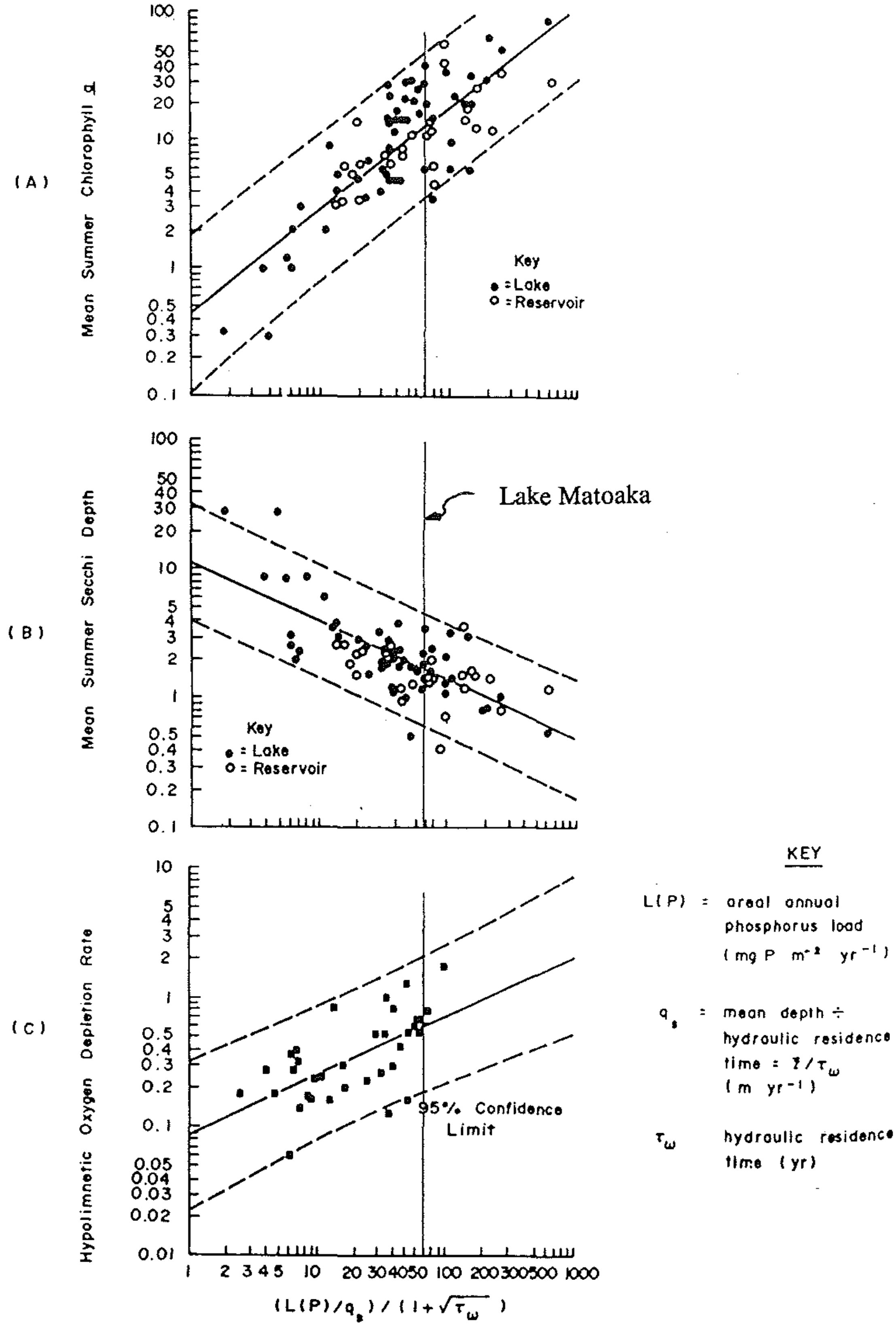

Figure 4. Graphical representations of the Vollenweider approach showing the relationships between a normalized phosphrous loading rate and (1) mean summer chlorophyll (b) mean summer secchi depth and (c) hypolimnion oxygen depletion rate. The estimated loading rate for Lake Matoaka is indicated by the vertical line. (Figures from Jones and Lee, 1982)

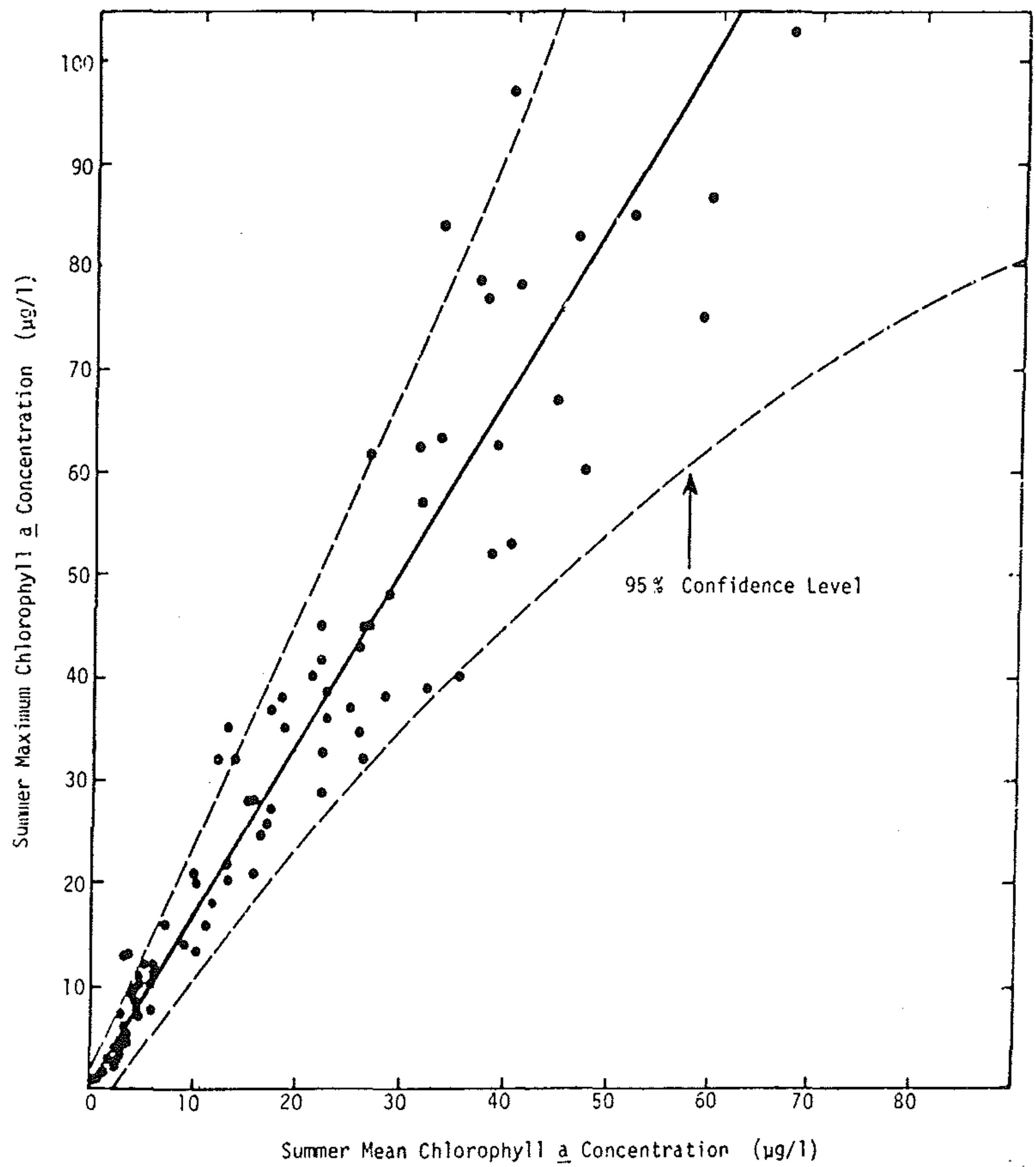

Figure 5. Relationship between summer mean and summer maximum chlorophyll a concentrations (from Jones and Lee, 1982).

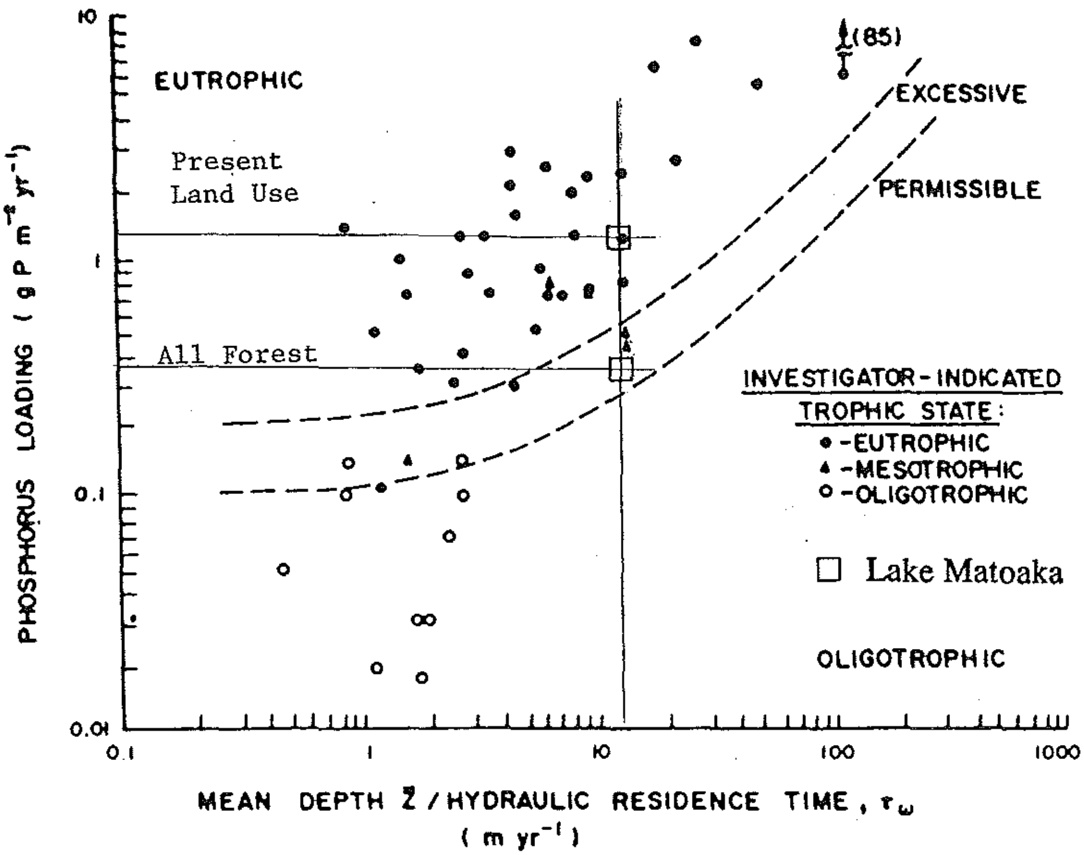

Figure 6. US OECD data applied to Vollenweider phosphorus loading - mean depth/hydraulic residence time relationship (taken from Jones and Lee, 1982).

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