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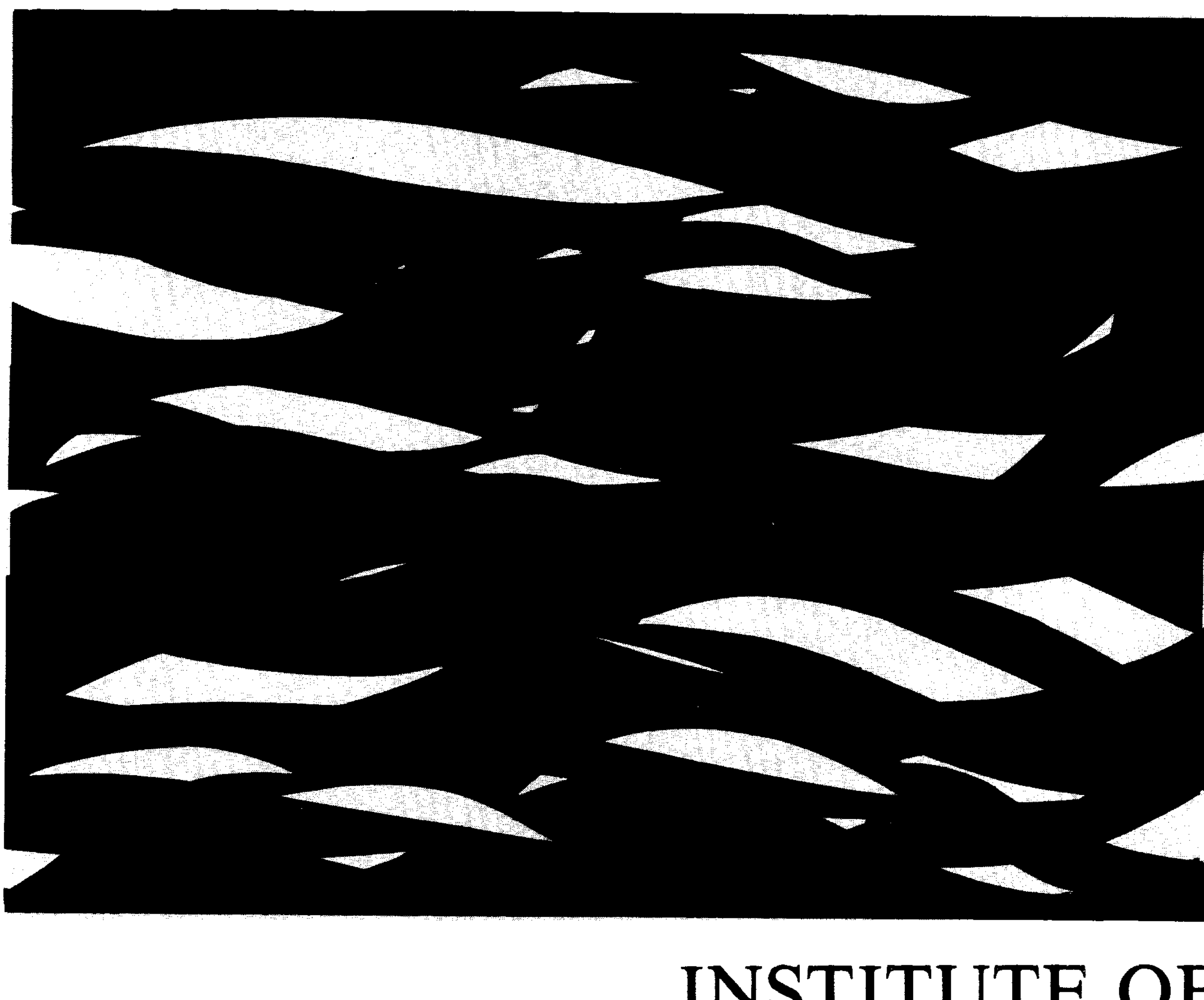

INSTITUTE OF WATER RESOURCES

The University of Connecticut

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Report No. 30 *March 1979*

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PROCEEDINGS:

LAKE MANAGEMENT CONFERENCE

Held June 9, 1977
at The University of Connecticut,
Storrs

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PREFACE

At the time when this Lake Management Conference was planned, it was intended that the proceedings, papers and an inventory of lake information and sources would be published as a single volume. Unfortunately, both the proceedings and the inventory have been delayed by a variety of difficulties, including serious illness, involving authors and editors. In order to go to press without further delay, it has been decided that the papers are to be issued separately as Proceedings. The lake inventory continues to be studied, both by the Connecticut Department of Environmental Protection and the Institute of Water Resources; and it will be issued at a later date.

The purposes of this meeting are sufficiently described in the Welcoming Remarks and in the Opening Remarks, so that no further comment is required here.

The Institute of Water Resources is very pleased to be able to present this set of papers to the participants in the conference and to the general public. We wish also to express our sincere thanks to the authors for very fine presentations and for their patience in working with us and waiting for this publication to appear.

- Victor E. Scottron*

*Director of the Institute of Water Resources, U-37, The University of Connecticut, Storrs, Connecticut 06268.

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WELCOMING REMARKS

by

Victor E. Scottron*

As Director of the Institute of Water Resources, it is my privilege to welcome you to this conference on Lake Management. The University of Connecticut is very pleased that you are here today.

Many of you know that our Institute has been a participant in a study of New England Lakes which was initiated by the Office of Water Research and Technology about four years ago. We have been trying to discover the connections among urbanization and land use and the deterioration of lake quality. More importantly, this research has been taking a careful look at the institutional and interagency relationships which can lead to more effective lake management. In the past two years, we have received many inquiries from concerned citizens and lake associations seeking advice about individual lakes. As we explored the situation in the state, we discovered that a great many different agencies were looking at pieces of this problem; and it occurred to us that it might be to our mutual advantage to try to bring the questioners together with some of those who have been seeking solutions. This conference is the result.

The following sets of objectives and commentary were sent to the speakers for guidance:

Objectives:

1. To determine the present state of knowledge concerning the eutrophication of Connecticut lakes.
2. To relate such knowledge to the decision-making needs of planners and managers.
3. To consider future directions for research and data collection, particularly with respect to the institutional approach to land use development.

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Commentary:

1. What sort of technical information is needed to make planning and management decisions on the preservation and improvement of lakes?
2. What information is now available? (Extent of coverage both geographically and technically within Connecticut.)
3. Who can provide this information?
4. Who can help the local agencies?
5. What should we be doing and what steps can be taken to implement a program?
6. What approaches have other regions found to be effective?

To further these objectives, we have sent a short questionnaire to the state, federal and local groups who have been working on lake problems. The results of this questionnaire plus the talks and discussions which you will hear today will be published in separate proceedings. The latter will be sent out to all of you and to other interested people. In this way, we hope to carry out our objectives.

We are very pleased that so many of you have come here and hope that you will enjoy the meeting.

OPENING REMARKS

by

Melvin Schneidermeyer*

It is a privilege and an honor to welcome you here. We are, I think, justifiably proud of our clean water program in Connecticut. One of our remaining difficult problems is dealing with lake eutrophication and lake management issues in general. You from the local lake associations and local governments are on the front lines of many of these decisions relating land use to water use and getting the best benefit out of both for a better environment in Connecticut. The bringing together here at this conference by the Institute of Water Resources of data, concepts, and personalities is a very important achievement. Two major benefits of today's meeting are new information as well as some personal contacts - getting to know the people who have some of the information and have background in managing lakes.

When I came to my job a couple of years ago, one of the first meetings was after a long, hot drive to northwestern Connecticut to meet with a group of vitally interested citizens regarding Lake Waramaug. That meeting not only pointed out to me that lakes management involves technical matters, but it also involves very interesting issues such as the goose population, pollutant loading on the lake and its ramifications. I have since considered various management decisions regarding the controlling of goose natural functions but I have come up with very little. Maybe this conference will strive forward to come up with some further new directions in goose management.

Finally, I'd just like to say that the Department of Environmental Protection sincerely appreciates the valuable inputs of the Institute of Water Resources, particularly this conference. A number of our staff members are here today. We don't have all the answers, but we can tell you what we've learned thus far. I am sure that we're going to learn alot from today's conference. More importantly, the conference will be

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*Deputy Commissioner, Division of Environmental Quality, Connecticut Department of Environmental Protection, Hartford, Connecticut.

of great benefit to state and federal agency representatives and the local lake associations. We're all striving towards the objective of better lakes management.

Welcome, and I look forward to a very informative and interesting day.

THE ROLE OF GROUNDWATER IN LAKE-WATER BALANCES

by

Thomas C. Winter*

Abstract. Understanding groundwater flow systems associated with lakes is basic to understanding nutrient and other chemical fluxes between lakes and the groundwater system. This is a factor in nutrient budget studies that is often ignored or relegated to a residual term in the budget equation, with little attention given to its hydrologic reasonableness.

Recent theoretical work on groundwater flow systems near lakes indicates that studies of the interaction of lakes and groundwater should be scrutinized carefully because often the data cannot be used to analyze properly the interrelationship. The theoretical studies show that the interaction of lakes and groundwater is controlled by the position, extent, and hydraulic conductivity contrasts of the geologic units in the entire groundwater system, not just those units in contact with the lake. The interaction is also controlled by the height of the areal water-table divide (groundwater watershed) on all sides of the lake relative to lake level, and lake depth. The head relative to lake level and continuity of the divide separating the local from intermediate and regional groundwater systems is the key to understanding the interaction of lakes and groundwater.

To define the groundwater flow system near a lake, it is necessary to monitor lake level, the fluctuations of the water table along the groundwater divide around the lake, and the point of minimum head along the flow-system boundary separating local from larger magnitude groundwater flow systems beneath the lake.

Introduction. The interrelationship of lakes and groundwater has long been neglected or studied inadequately in limnological investigations. The recent increasing interest in nutrient budgets and lake level fluctuation patterns related to evaluating lake management

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practices has resulted in a corresponding need to determine water budgets for lakes. Most water-budget studies are crude because measurement of atmospheric, surface, and groundwater interchange with a lake is expensive. In addition, the principles underlying the interaction of lakes and groundwater have never been studied adequately; therefore, guidelines for defining the relationship have never been developed.

Water budgets for lakes are usually determined in the following manner. For atmospheric water interchange with the lake, a rain gage might be established on the lake - in the well-financed studies, it might be a recording gage; in those less well financed, it might be an observer-read plastic cup; and, in the poorly financed studies, a precipitation record from a nearby weather station is used and a correction factor applied to the data. Evaporation is rarely measured with instrumentation. In most studies an evaporation-pan value from a nearby weather station is modified by a correction factor and applied to the lake of interest.

Streamflow interchange with a lake might be measured with a recording gaging station. In studies that have less money, a flume might be established and rated with a few current-meter discharge measurements. In many studies, this aspect of the lake-water budget is determined simply from miscellaneous discharge measurements, or even by determining flow velocities by timing how long it takes a buoyant object to float down a given length of stream.

The change in storage in the lake is measured either by a recording gage or by a staff gage read periodically by an observer.

In the few studies that have tried to measure the groundwater interchange with a lake, either two few water-level observation wells are used, or more are installed than are really needed. In either case the wells are often not placed in the best locations. Examples of both approaches are Allred et al. (1971), Manson et al. (1968), Sloan (1972), and McBride (1969).

In most studies of lake water budgets, groundwater is calculated as the residual of the balance equation. This practice can be very misleading for two important reasons. The first is that overland runoff, the non-channelized surface flow into a lake, is often lumped into the residual with groundwater. Because it is a very difficult parameter to measure and evaluate, it is usually ignored, or even rarely thought of. The second is that the measurement errors for the parameters that are considered are rarely discussed. These errors can be very large in the more crude water-budget studies, and they can be considerable even in the well-instrumented studies. Thus, the estimates of groundwater interchange with lakes can be very misleading and in some cases totally unreasonable.

There is clearly a need for studies of the interaction of lakes and groundwater. Theoretical studies are needed to define the principles underlying this interaction. Field studies are needed to verify the theoretical models and to develop practical field measurement techniques.

In few studies of the interaction of lakes and groundwater has theoretical analysis preceded fieldwork to optimize placement and numbers of wells. McBride and Pfannkuch (1975) used a numerical model to evaluate the vertical component of groundwater flow into one side of a lake for a number of hypothetical settings. Winter (1976) used numerical simulations of vertical groundwater flow to examine the hydrogeologic factors that control the interaction of lakes and groundwater along the entire lake bottom for a wide variety of hypothetical settings.

The purpose of this paper is to identify and evaluate the parameters that affect the interaction of lakes and groundwater, and to suggest field methods that will help in determining whether a lake acts as an area of recharge to or discharge from the groundwater system, or both. This type of information is critical to understanding and evaluating hydrologic and nutrient budgets of lakes, lake-level fluctuation patterns, and movement of chemicals through lake beds.

The study by Winter (1976) showed that movement of groundwater to and from a lake depends on the continuity of the boundary separating the local groundwater flow system associated with the lake, from intermediate and regional flow systems passing at depth beneath the lake.

That study showed further that the key to determining the continuity of the flow-system boundary is the presence of a stagnation point, the point of minimum hydraulic head along that boundary. The definition, location,and importance of the stagnation point is elaborated on in the next section of this paper. Following that discussion, field methods are suggested for determining the interrelationship of lakes and groundwater (including location of the stagnation point), and finally, implications of groundwater flow for chemical transport to and from lakes are discussed.

Hydrogeologic Factors that Control the Interaction of Lakes and Groundwater. To evaluate the hydrogeologic factors that control the interaction of lakes and groundwater, a two-dimensional digital model of groundwater flow, developed by the U.S. Geological Survey (Trescott, Pinder, and Larson, 1976), was used to calculate the distribution of hydraulic head within the groundwater system. A cross-section approach of steady-state conditions was used so the patterns of groundwater flow beneath lakes could be examined. In addition to the steady-state water table, it is further assumed that there is no lateral flow across the vertical boundaries and no vertical flow across the base of the section. Because it is a two-dimensional model, the y-dimension (perpendicular to the section) is large. The hydraulic conductivity (K) of the various units, such as lakes, sediments, and geologic rock units, as well as the ratio of horizontal to vertical hydraulic conductivity (K_h/K_v) of the entire groundwater system, must also be given.

It must be kept in mind that the specific results (height of water table, depth of lake, etc.) of the diagrams discussed in this study apply to groundwater systems that approximate the given boundary conditions. The illustrations should be considered only as examples. If the boundaries of the system, including the complexities of the geologic setting, are greatly changed relative to each other, the problem is then changed. However, if the new problem were analyzed as in this study, the general conclusions would be similar to those of this study.

To appreciate the following discussion, the reader must be aware of the essential nature of vertical groundwater flow diagrams. Such a diagram shows the distribution of hydraulic head in the groundwater system and the groundwater flow lines controlled by that head. After the computer calculates the head for each node, the head values are contoured and flow lines are drawn such that water flows down gradient. A flow net, uncorrected for vertical exaggeration and anisotropy (see Winter, 1976, for discussion of flow-net construction), is shown in Figure 1 to define salient features of flow nets and groundwater flow systems.

A flow net shows the distribution of hydraulic head within the groundwater reservoir - the isopotential lines connect points of equal head - and the directions of groundwater flow controlled by the distribution of head. Hydraulic head is easily visualized because it is equivalent to the altitude to which water will rise in a well open only at a single point in the groundwater reservoir. Thus, if a series of wells were completed along an isopotential line, all wells would record the same water-level altitude regardless of their depth. On the other hand, if a group of wells, each completed at a different depth, were located at a single site, they would all have different water levels. If each successively deeper well has a lower water level, the group of wells is in a groundwater recharge area (e.g., the right edge of Figure 1). If each successively deeper well has a higher water level, the wells are in a groundwater discharge area (e.g., left side of Figure 1).

The groundwater system illustrated in Figure 1 consists of several flow systems of different magnitude. The upper part of the groundwater system consists largely of four local flow systems where water moves from high points on the water table (water-table mounds) to adjacent lowlands occupied by the three lakes and the stream at the left edge of the diagram. Regional groundwater flow passes beneath the local systems at depth in the groundwater reservoir. Recharge to the regional flow system occurs at the highest drainage divide at the right side of the diagram, and discharge from this system is to the stream at the left edge of the diagram. A zone of intermediate flow is recharged at the water-table mound between lakes 2 and 3 and is discharged into lake 1. It should be noted that much more groundwater moves through local flow systems than the deep regional system, as shown by the closer spacing of the flow lines in the former. (Quantitative aspects of lakes and groundwater are discussed by Winter, 1976.) A thorough discussion of similar type groundwater-flow diagrams is given by Toth (1963), Meyboom (1966, 1967), and Freeze (1969).

Of special interest to this study are the lines, hereafter referred to as boundaries, separating the flow systems. In following the boundary line separating the zone of local flow from zones of larger magnitude flow (by lake 3, Figure 1, for example), there is a point on the boundary at which the head is a minimum compared to every other point along the boundary. More specifically, as one traces the boundary into the groundwater reservoir from the highest water-table mound on the right side of the diagram, one sees that it crosses successively the 345, 340, 335, 330, 325, and 323 isopotential lines before reaching the point labeled 2.2. Continuing along the boundary upward twoard the water-table mound between lakes 2 and 3, the line crosses isopotential lines of increasingly higher head, 323, 325, 330, and 335. The point of minimum head is labeled such because the head at this point along the boundary is 322.2, which is 2.2 feet (0.7m) higher than the water-level altitude of lake 3. To visualize this, if a well were drilled such that it would be open only at the stagnation point, the water level in the well would rise to a level 2.2 feet higher than lake level. Because the hydraulic head everywhere else along the boundary is even greater than 2.2 feet (0.7m) above the lake-level altitude, it is impossible for water to move from the lake to the groundwater system because the hydraulic gradient is toward the lake bottom.

This point of minimum head is the stagnation point commonly referred to in flow-field literature. It is a point in the flow field at which vectors of flow are equal in opposite directions and therefore cancel. As shown above, a value of head exists at the stagnation point; and it is this value of head relative to the head represented by lake level that is the key to understanding the interaction of lakes and groundwater. If a stagnation point exists, it has a head greater than that of lake level, and a continuous groundwater boundary exists beneath the lake making it impossible for water to move against the hydraulic gradient from the lake to the groundwater system. It should be noticed that a stagnation point exists by each of the three lakes in Figure 1, thus none can lose water to the groundwater system.

Note that on Figure 1 the stagnation point is a point of diversion of groundwater flow paths. Water moving downward from the water-table mound on the downslope side of the lake is diverted upward toward the lake. A small amount of water that moves beneath the lake from the upslope side is diverted upward toward the lake on the downslope side. Water moving in the local or intermediate flow systems of the lakes downslope is diverted downslope and water moving in the regional flow system is diverted deeper into the groundwater reservoir.

The following discussion is a comparison of only a few of many simulations analyzed during the course of this project. They illustrate the relative effect of various hydrogeologic controls on the interaction of lakes and groundwater. As discussed above, the basic relationship can be determined simply by establishing the presence and head value, or the absence of the stagnation point - it is not necessary to construct flow nets unless quantities of water are to be calculated. The diagrams are dimensionless, but for ease of discussion, realistic values in terms of English (and metric equivalent) units are used in this paper.

Parameters that were varied in the modeling study were: the height of the water table relative to lake level on both sides of the lake; position and hydraulic conductivity of highly permeable zones (aquifers) in the groundwater system; ratio of horizontal to vertical hydraulic conductivity (K_h/K_v); lake depth; presence and absence of lake sediment; regional slope of the water table; and groundwater-system thickness.

The distribution of hydraulic head in the vicinity of a lake that has a water-table mound 70 feet (21m) higher than lake level on the upslope side and 20 feet (6m) higher on the downslope side, is 10 feet (3m) deep, contains lake sediment, has no aquifers in the groundwater system, and K_h/K_v is 1,000, is shown in Figure 2. The head at the stagnation point is 4.2 feet (1.3m) higher than lake level; therefore, a continuous groundwater boundary exists beneath the lake and it cannot lose water to the groundwater system.

If all parameters are the same as in the previous example (Figure 2), but the water table on the downslope side of the lake is only 10 feet (3m) higher than lake level (Figure 3), the head at the stagnation point is 1.4 feet (0.4m) above lake level. The strength of the continuous groundwater boundary is thus weakened, but it still exists and the lake still cannot leak. Other simulations show that lowering the water table on the upslope side of the lake has a considerably lesser effect on the head at the stagnation point than lowering it on the downslope side.

In a three-lake setting that has shallow lakes (about 10 ft; 3m deep), high water-table mounds between each lake, aquifers of limited extent at the base of the groundwater system 1,000 times more permeable than the surrounding geologic materials, and K_h/K_v of 1,000, a stagnation point exists near each lake; therefore, none of the lakes lose water to the groundwater system (Figure 4).

If all parameters are the same as in the previous example (Figure 4), but the lakes are deepened from 10 to 50 feet (3 to 15m), lakes 1 and 3 lose water through the downslope half of their bed and the head at the stagnation point near lake 2 is decreased (Figure 5).

As a final example, Figure 6 can be compared to Figure 4. In both figures, all parameters by lakes 1 and 2, except the vertical position of the aquifers, are the same. The higher position of the aquifers in Figure 6, compared to Figure 4, lowers the head at the stagnation point by each of these two lakes. By lake 3, in addition to raising the aquifer closer to the lake bed, the water table is lowered on each side of the lake, compared to lake 3 of Figure 4. This combination causes the lake to lose water to the groundwater system through much of the downslope half of its bed. Notice that there would be groundwater flow into the littoral zone of lake 3 on its downslope side, in addition to groundwater flow into the upslope half of the lake.

General conclusions concerning movement of water between lakes and the groundwater system are:

1. The interaction of lakes and groundwater is affected by the entire geologic environment (to bedrock) - therefore, definition of surficial geology is not enough. (See Figures 4, 5, and 6 and conclusions 2e, 3, and 4 below.)
2. In the simulation approach used for this study, the following changes in parameters tend to lessen the difference in head between the lake and the stagnation point beneath a lake or tend cause a lake to lose water: (a) lowering the water table on either side of a lake (lowering it on the downslope side has a greater effect than lowering it on the upslope side); (b) increasing K_h/K_v; (c) increasing the hydraulic conductivity of aquifers; (d) increasing the depth of lake; and (e) raising aquifers from the base to an intermediate level in the groundwater system.
3. Aquifers that extend the full length of the groundwater basin have a greater effect on the interaction of lakes and groundwater than aquifers of small extent. If no aquifer is present, a lake generally will not lose water even if K_h/K_v is 1,000.
4. Aquifers of small extent upslope and beneath a lake have little effect on the flow-system boundary beneath a lake. Under the conditions simulated in this study, aquifers in these positions will not cause the boundary to weaken regardless of the hydraulic conductivity of the medium. Aquifers of limited extent downslope from a lake, whether at the base or at an intermediate vertical position in the groundwater system, have a significant effect on the interaction of lakes and groundwater because under many conditions of high K_h/K_v and K_{aq}/K_t and low water-table configurations,

a lake in this setting will have a weak groundwater boundary or will lose water.

5. In every simulation run for this study, the stagnation point associated with the groundwater boundary is always under the downslope littoral or shoreline zone of a lake. This has particular significance when designing an observation-well program for studying the interaction of lakes and groundwater because determining the position and head, or absence, of the stagnation point is the key to the relationship.
6. Changing the height of a water-table mound or the position of aquifers by one lake and not by the other, when there are a series of lakes along a valley side, has a considerable effect on that one lake, but little effect on adjacent lakes. Thus, the lakes act essentially independently. If there is leakage, it is usually to the deeper parts of the groundwater system, not to the next lake downslope.
7. Most groundwater flow into a lake takes place in the littoral zone (McBride and Pfannkuch, 1975) regardless of whether sediments are present or not. If lakes do lose water to the groundwater system, in most cases the loss occurs in the deeper parts of the lake and the water must move through the sediments, thereby reducing the quantity considerably compared to that entering in the littoral zone.

A word of caution is in order at this point. Studies of the interaction of lakes and groundwater by the U.S. Geological Survey are only beginning, and the work discussed here is a first step. Much work remains to be done in verification and field testing of the ideas presented above in addition to obtaining specific ranges of field values of certain parameters, such as the ratio of horizontal to vertical hydraulic conductivity (K_h/K_v).

Implications for Field Studies. Based on the above discussion, it is now possible to evaluate field methods that have been used to this time, and to suggest new approaches to the study of the interaction of lakes and groundwater.

Critique of commonly-used approaches. In examining any hydrologic section that has more than one lake (Figure 1, for example), it can be seen that placement of one well between adjacent lakes can result in conflicting interpretations of the relation of groundwater to lakes. If the well is placed closer to lake 3 than lake 2, for example, the water level in the well will be higher than lake level. However, if the well is not located at the highest point on the water-table mound, but records a lesser water level, a different picture of the strength of the flow-system boundary beneath a lake will be suggested. The importance of knowing the altitude of the highest point on the water-table mound on the downslope side of a lake was pointed out in the previous discussion. (Compare Figures 2 and 3.)

If the well is placed closer to lake 2 than lake 3 (Figure 1) the water level will be at an intermediate altitude between the two lakes, and one would mistakenly interpret the situation as water moving out of lake 3 through the groundwater system to lake 2, when, in fact, there is no water moving from lake 3 at all.

It is important to remember that the upper line on the diagrams is the water table, not land surface. The land surface could be any configuration between the lakes shown. And because water-table mounds do not always directly underlie land surface highs, locating the highest point on the water-table mound in the field can be a difficult chore.

Another important consideration in placement of wells in groundwater studies is the precise position of the well opening in the groundwater system. The hydrologic sections show the distribution of hydraulic head within the groundwater reservoir. As pointed out earlier, if wells are placed at different locations along the land surface such that they are open only along one particular isopotential line, the water levels in them will all be at the same altitude. If wells of a closely-spaced group of wells are all completed at different depths at one location along the hydrologic section, they will all have different water levels. If the water levels are lower in each successively deeper well, it is a groundwater recharge area (groundwater moves away from the water table), and if they are higher in each successively deeper well, it is a groundwater discharge area (groundwater moves toward the water table). (See Figure 1.) Thus, any well not completed at the water table does not record the altitude of the water table, but rather some hydraulic head either higher or lower than the water table. (The heads may be the same in all of a closely grouped nest of wells if the wells are located in a zone of lateral groundwater flow.)

From the above discussion, it is clear that studies in which one or two wells are placed between adjacent lakes should be closely scrutinized because the data and interpretations can be very misleading.

Studies in which many wells are placed within a lake's drainage basin can also be misleading. The water level data are usually used to construct areal flow nets, which do not show the vertical components of groundwater flow. As seen in the hydrologic sections of this report, vertical flow can be the dominant direction of flow in certain parts of groundwater flow systems. Further, the hydrologic sections show that water can be moving out of a lake through deeper parts of its bed while groundwater is moving into the lake in its littoral zone. (See lakes 1 and 3, Figure 5, and lake 3, Figure 6.) An areal flow net of these sites, which would show movement of groundwater toward the lakes on all sides, would not show this leakage of water from the lakes through the sediments.

The problem of where the wells are open in the groundwater flow system is as applicable when setting many wells as it is when setting a few wells, as discussed above. That is, are the wells recording the true water table or are they recording hydraulic heads at various other points in the groundwater flow system?

Interest in the use of seepage meters, such as that described by Lee (1977), is growing among limnologists. Seepage meters are potentially a valuable tool in lake water and nutrient-balance studies, especially for reconnaissance work. They also are the only device available for directly collecting groundwater samples for chemical analysis, without having to drive a well through the lake bed. Because they are a point measurement, both in space and in time, however, they should be used for quantitative purposes with a clear understanding of statistical sampling procedures. Further, they obviously cannot be used for continuous monitoring. Seepage meters could be used most efficiently where one has an understanding of the groundwater flow systems associated with the lake of interest.

Suggested field methods. Knowledge of the possible variations of groundwater flow systems near lakes, as demonstrated in the simulations of this study, suggest placement of wells (piezometers) that would optimize information on the interaction of lakes and groundwater using a minimum number of observation points.

Rather than place piezometers within the drainage basin of a lake, most effort should be on finding the maximum altitude of the water table along the areal groundwater divide around a lake. It is necessary to find this maximum point on the water table and to place a piezometer on it for each segment of the lake's drainage basin where different groundwater flow patterns are suspected. (See Winter (1976) for discussion of areal and temporal variations of groundwater flow near lakes.) As seen from the simulations, one of the most important locations is on the lowest point on the areal divide on the downslope side of the lake.

In addition to locating key points along the water-table divide around a lake, it is important to know the location and head relative to lake level of the stagnation point on the boundary separating flow systems beneath the lake, if a continuous boundary exists. This is best accomplished by placing a nest (group) of closely spaced wells, each completed at a different depth, in the most appropriate location. As suggested by the simulations of this study, the most appropriate location to look for the stagnation point is beneath the shore line on the downslope side of the lake.

The stagnation point can be recognized from the water-level data obtained from the nest of wells in the following way. The hydraulic head should increase in successively deeper wells to the stagnation point, then decrease in the successively deeper wells below the stagnation point. In other words, the water level in the well that is open at the stagnation point should be higher than in all the other wells open at points in the groundwater system above and below it. In a few situations simulated by Winter (1976), there is only a very slight decrease in head below the stagnation point before the heads begin to increase again with depth. In such situations, it might be very difficult to identify the stagnation point. Whether the point is identified in these cases or not is somewhat immaterial, however, because in such situations the fact that the heads increase with depth indicates that the gradient is toward the lakes and the lakes cannot lose water through their bed.

If no stagnation point is present, that is, the lake is losing water to the groundwater system, the water-table well should have the greatest head and successively deeper wells should have successively lower water levels.

In some situations in which lakes lose water through their bed, there could be a problem in misidentifying a head maximum that is really not a stagnation point. An example is near lake 3, Figure 5. If a nest of wells were installed at the shoreline on the downslope side of that lake, there would be a slight increase in head with depth immediately below the water table, then a decrease in successively deeper wells. The only clue to recognizing this situation, that the writer is aware of at this time, is that in very few situations is the stagnation point that close to the water table. And if it is, the water level in the well at the stagnation point would be very close to lake level, signifying that the boundary between flow systems beneath the lake is very weak and is close to a leaking-lake situation anyway. If a lake is suspected of losing water to the groundwater system, and if the nest of wells could be installed within the lake on its downslope side, this problem could be avoided in most cases.

Data on the other factors that control groundwater flow (hydraulic conductivity of the various geologic units, defining hydrogeologic boundaries, location of aquifers) are not easily obtained, but there are accepted drilling and geophysical methods for doing so.

Field determination of the critical K_h/K_v ratio, on the other hand, is a serious problem. Although it has not been field tested, the method of determining K_h/K_v from measured head values proposed by Gillham and Farvolden (1974) may prove useful.

It should be noted that the entire discussion to this point concerns lakes that have a water-table mound on their downslope side. If one assumes that a straight-line, water-table profile connects lakes at different altitudes, then water would flow out the downslope side of the higher lake, through the groundwater system, into the upslope side of the lower lake. This is obvious, and modeling of such a situation was deemed unnecessary. Also, this is the only situation that would warrant placing observation wells immediately adjacent to a lake. Even this practice can be misleading. Meyboom (1966) showed that the water table immediately adjacent to a prairie pothole was lower than lake level, not because lake water was moving to the groundwater system, but because phreatophytes near the lake shore were creating a cone of depression - both groundwater and lake water were being discharged by the plants.

Another major type of lake setting not considered in this paper is that of lakes situated in a major valley bottom (usually reservoirs). In such situations, the study approach used by Van Everdingen (1972) and Downey and Paulson (1974) should be considered. They placed nests of piezometers along a section across a valley, from the upland on one side to the upland on the other. They then observed the changes in direction of groundwater flow at various depths as a result of reservoir filling.

Implications for Chemical Transport to and from Lakes. Groundwater chemistry is controlled partly by the length of time a particle of water is in contact with minerals in the geologic framework through which the water flows. Thus, the longer the flow path, or the lower the hydraulic conductivity, the longer the residence time, the greater will be the opportunity for chemical interchange between rocks and water. For lakes situated on geologic materials of similar hydraulic conductivity, those that receive groundwater from intermediate or large local groundwater flow systems are more likely to contain more, and a wider variety of, dissolved minerals than lakes that receive groundwater from small local flow systems.

It can be seen in Figure 1, for example, that lake 1 receives groundwater from an intermediate flow system that is recharged at the water-table mound between lakes 2 and 3. The longer flow path, greater residence time, and possibility of encountering deeper rock units not encountered by groundwater flowing in the overlying local systems could easily account for different chemicals being carried into lake 1 than into lakes 2 and 3. Lakes receiving discharge from regional groundwater flow systems conceivably could receive even more and a greater variety of dissolved minerals because flow paths, residence times, and depth of geologic units encountered would be even greater than in the intermediate systems.

Differences in lake-water chemistry can also be explained by variations in local groundwater flow systems. Because hydrogeologic factors that control the interaction of lakes and groundwater can vary greatly near individual lakes, depth of penetration of local groundwater flow systems associated with adjacent lakes also varies greatly. Thus, it is conceivable that water chemistry in adjacent lakes could be different because one lake might be receiving water that traveled along longer flow paths in the local system, causing greater residence time than the other lake. Therefore, the large variation in lake-water chemistry that is observed so frequently in lakes in close proximity in many lake regions is not at all surprising. On the contrary, after becoming aware of the factors that control the interaction of lakes and groundwater discussed in this report, and realizing that virtually every lake has its unique relation to the groundwater system, a wide variety in the chemistry of lakes should be expected.

It was noted earlier that if a water-table mound exists on the downslope side of a lake, water loss from the lake to the groundwater system takes place in the deeper part of the lake. Movement within the groundwater system, then, is to the deeper part of the system, not to adjacent lakes. Thus, a contaminant in a losing lake conceivably could affect a large part of the groundwater reservoir.

An important difference between groundwater entering a lake and lake water entering the groundwater system is that in the former most water enters in the littoral zone and does not have to move through sediments (although some does), and in the latter it must nearly always move out through the sediments. Therefore, the sediments acting as an ion-exchange column could have considerable effect on water moving from a losing lake, but a relatively lesser effect on water moving into a gaining lake.

Conclusions. Studies in which one or many wells are placed near a lake to determine the interaction of lakes and groundwater must be scrutinized carefully, because placement and construction of the wells are critical to a proper understanding of the interrelationship of lakes and groundwater.

Based on a recent study by Winter (1976), the interaction of lakes and groundwater is controlled by: (1) the position, extent, and hydraulic conductivity contrasts of the geologic units in the entire groundwater system, not just those in contact with the lake; (2) the height of the water-table divide on all sides of the lake relative to lake level; and (3) lake depth. The position and head, relative to lake level, of the stagnation point along the flow-system boundary between local and larger groundwater flow systems is the key to understanding the interaction of lake and groundwater.

To define the groundwater flow system near a lake, it is important to place observation wells along the areal groundwater divide around the lake, and to locate and measure the head value of the stagnation point. This is best accomplished by constructing a nest of observation wells at the shoreline on the side of the lake at which the lowest altitude along the areal divide occurs, usually the regional downslope side.

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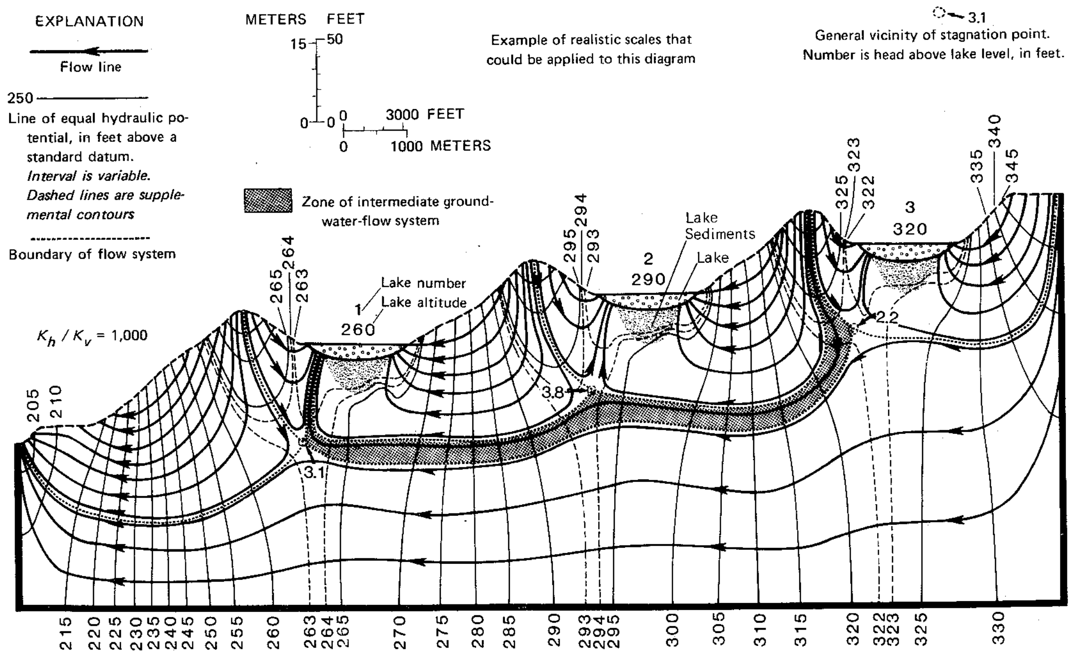

Fig.1 A quasi-quantitative flow net of groundwater lakes in a multiple-lakes system taht does not contain aquifers.

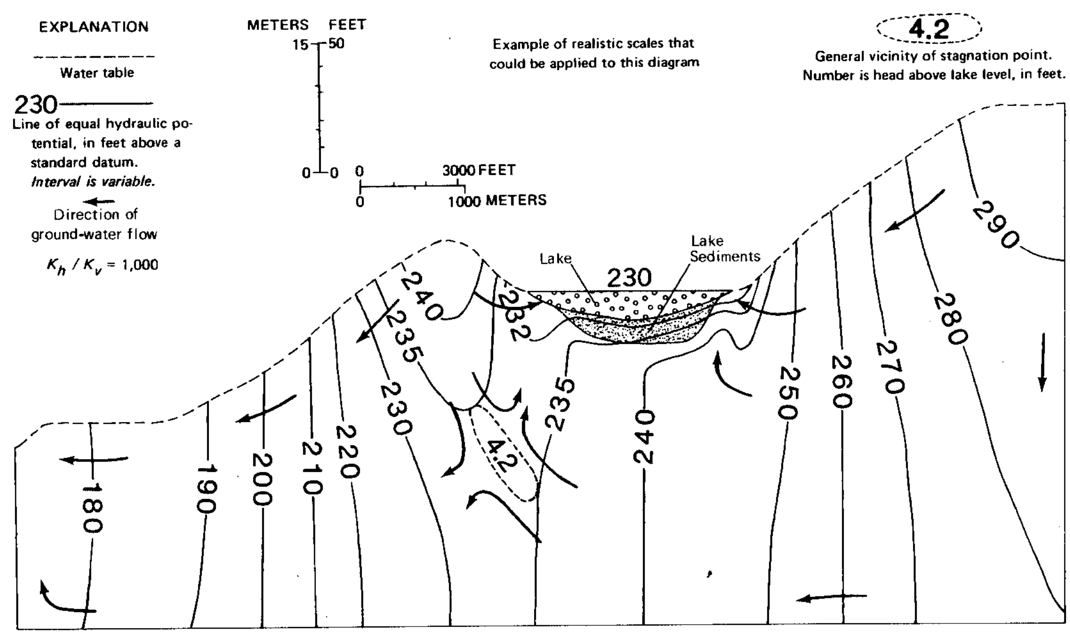

Fig. 2 Distribution of hydraulic head in the groundwater reservoir of a one-lake system that contains lake sediments but does not contain aquifers.

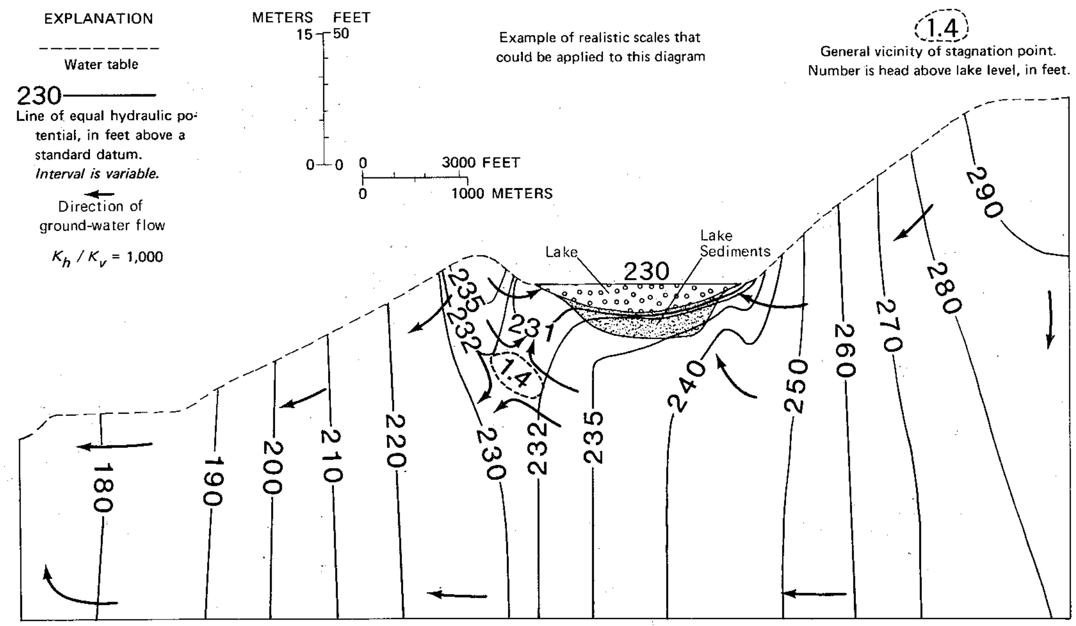

Fig. 3 Distribution of hydraulic head in the groundwater reservoir of a one-lake system that has a low water-table mound on the downslope side of the lake and does not contain aquifers.

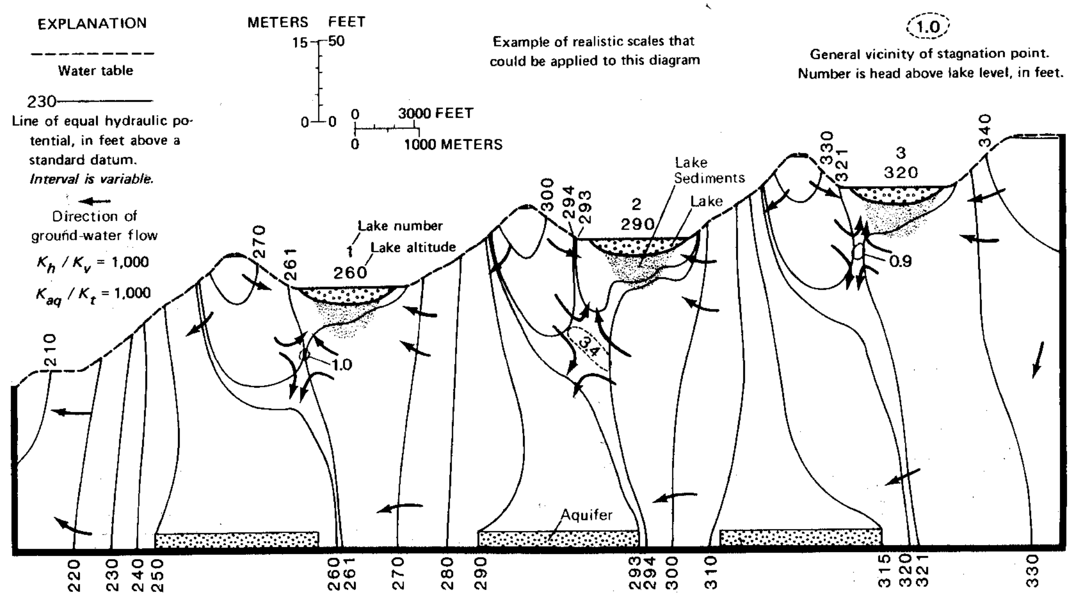

Fig. 4 Distribution of hydraulic head in the groundwater reservoir of a multiple-lakes system that has high water-table mounds and aquifers of limited extent at the base of the system.

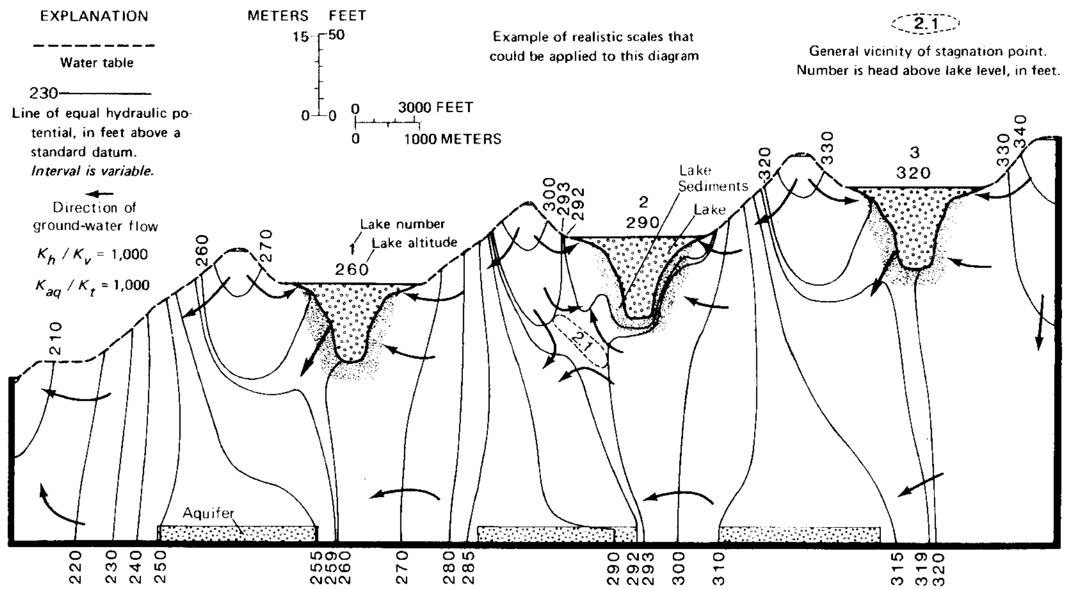

Fig. 5 Distribution of hydraulic head in the groundwater reservoir of a multiple-lakes system that has deep lakes, high water-table mounds and aquifers of limited extent at the base of the system.

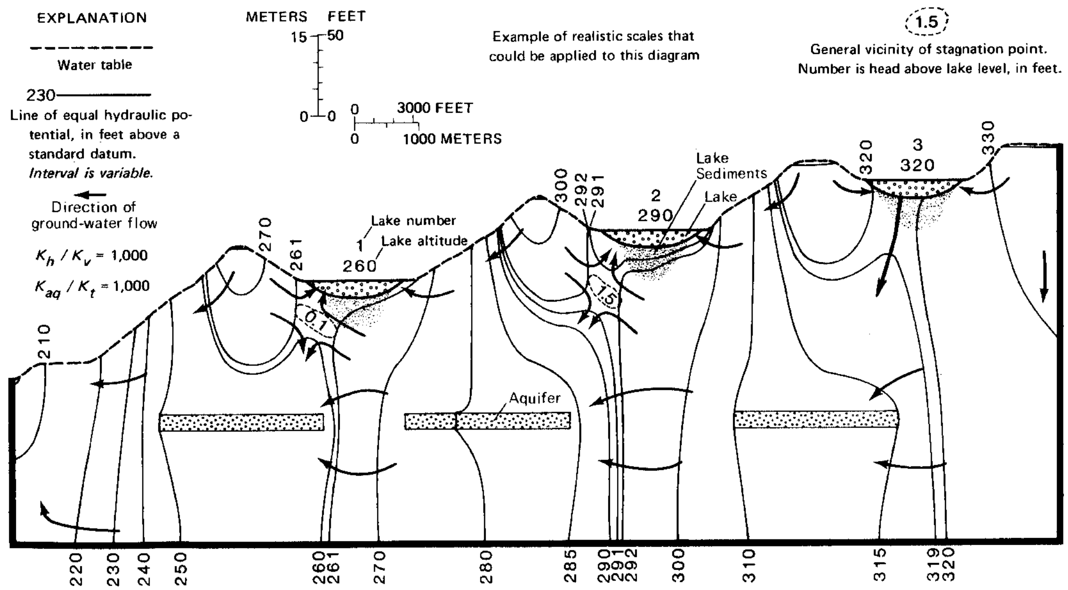

Fig. 6 Distribution of hydraulic head in the groundwater reservoir of a multiple-lakes system that has various height water-table mounds and aquifers of limited extent in the middle of the system.

A CONNECTICUT LAKES MANAGEMENT PROGRAM EFFORT

by

Robert B. Taylor*

Appropriately as a public agency, our efforts are prioritized by public demand, which on occasion is expressed in the form of special interest legislation. The public and their political representatives, however, also does and should demand our advice on how their money should best be used to achieve desired ends.

In our effort to meet our obligations to the public, we have been working to confirm an analysis technique which I hope may be generally useful to those actively working on the study and control of eutrophication problems. By presenting the results of our work effort to date at this conference, I hope to interest the participants in assisting us to further our efforts by suggestion, criticism and data.

The basis for the analysis technique is not original and it is framed largely from the more detailed individual efforts of some of you in this room today and your colleagues working in the field. I feel the technique may be quite useful in a particular function of my office, that of presenting data in a manner which can be understood by the general public.

Although the formal effort to develop this analysis technique was initiated during the past winter when I asked Charlie Fredette and Jim Murphy of the Water Compliance Unit staff to develop and test the concept against available data, the initial seeds of the concept were planted

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during 1967 by Charlie Frink's paper (1) on the nutrient budget of Bantam Lake as a predominately natural phenomenon rather than culturally caused. His subsequent paper on Candlewood Lake in 1971 (2) was even more thought provoking due to the data presented on the annual nutrient loadings per unit area of Candlewood Lake compared to Bantam Lake, Lake Lillinonah and Lake Zoar.

Dick Benoit provided a further rationale to the concept, in his testimony (3) before the department during its hearings on the effects of detergent phosphates, by his discussion of the chemical equilibrium reactions of phosphorus with iron, calcium and aluminum in soils. On the basis of these data and the wealth of other data accumulated in the department investigation on detergent phosphates, an initial analysis effort was made in our report to the legislature correlating the eutrophic state of a lake with the ratio of watershed area to lake surface area.

The analysis concept finally jelled into the form in which I will present it today as a result of a somewhat legally stilted debate on Vollenweider's recent works (4) between myself and Dick Benoit and Dr. Brezonik (5,6) of Florida during the formal hearings on the permit applications filed with the department in conjunction with the proposed Connecticut Park Race Track in Wolcott, Connecticut.

Vollenweider's published papers (4,10) present a mathematical model for the mass balance of nutrient loadings on lakes which express the concentration of a nutrient in a lake as an exponential function of the loading of the nutrient per unit surface area, mean depth and flushing of sedimentation rate. Vollenweider (4) used this conceptual model as a basis for plotting annual nutrient loading per unit area of lake surface versus the quotient of mean depth divided by hydraulic retention time. From this plot he empirically determined "permissible" and "critical" loading rages which created zones generally corresponding to the three classically defined trophic conditions; oligotrophy, mesotrophy and eutrophy. The EPA National Eutrophication Survey report (Working Paper No. 23) (7) included plotted data for phosphorus limited lakes and found that Vollenweider's loading concepts generally held true; oligotrophic lakes generally were below Vollenweider's "permissible" loading line, and eutrophic lakes were generally above Vollenweider's "critical" loading line.

Thus, with sufficient phosphorus loading information, Vollenweider's concept can be used to estimate the trophic condition of a lake and to evaluate potential changes in the trophic condition which might be induced due to changes in phosphorus loading. An obvious drawback of this approach is that an extensive monitoring program must be conducted to develop adequate loading information.

It was determined, based on conceptual analysis of data on Connecticut lakes, that an alternative might be to consider watershed area as an approximation for nutrient loading data. This substitution assumes watershed characteristics such as slope, type of soil and even the type, extent and intensity of land use have relatively minor significance or could be separately accounted for by exception. My purpose today is to present the results of our examiniation of the validity and utility of this modification of Vollenweider's concept using available data on Connecticut Lakes.

Our data source for watershed area was the "Gazetteer of Natural Drainage Areas of Streams and Water Bodies within the State of Connecticut" (8) by Mendall Thomas. Lake surface area was subtracted from the watershed area to obtain a relative measure of upland influence.

Data for lake surface area were taken from "A Fishery Survey of the Lakes and Ponds of Connecticut" (9) published by the State Board of Fisheries and Game in 1959 or from the State Health Department water supply inventory information.

Mean depth data were taken from the 1959 Fishery Survey (9) or calculated for some reservoirs by dividing volume by surface area where such data were available in the State Health Department inventory.

The trophic status data used in the analysis were selected from information available in the National Eutrophication Survey (7), the 1975 publication "Water Chemistry and Fertility of Twenty-three Connecticut Lakes" (10) by Norvell and Frink, and from data in the 1959 Fishery Survey (9). In the absence of definitive scientific information, trophic status was judged from available data concerning thermal stratification, hypolimnetic oxygen content, the extent and density of weed beds and the frequency and severity of algal blooms. For the purpose of the analysis, two additional trophic categories, meso-eutrophic and meso-oligotrophic, were chosen to segregate the classic mesotrophic range into three categories, retaining the term mesotrophic to represent lakes in the range which did not exhibit a tendency towards either eutrophy or oligotrophy.

Lakes and ponds formed due to natural geological processes were separately identified. This was done to ascertain the morphology of natural lakes and their relationship to watershed size to see if any pattern was apparent and to determine what trophic conditions had been naturally produced. This attempt to reduce variability served at least to identify base conditions against which artificially impounded lakes and ponds could be compared.

We included within the category of natural lakes those having a low dam which raised the water surface elevation three feet or less. These lakes are shown in Figure 1 and subsequent figures as hexagons. This category includes natural lakes without a dam and together accounted for 40 of the 102 lakes we analyzed.

We also established a category of natural lakes which had been altered more drastically by dams which raised the water surface elevation by more than three feet. This category included 20 of the lakes analyzed and are shown as circles.

Totally artificial lakes, including lakes impounded over wetlands are represented by triangles. 42 of the 102 lakes analyzed were determined to be in this category.

The code on the figure represents the trophic status selected for the lakes. The ordinate represents the number of lakes in each category and selected trophic status. Some trend toward oligotrophic conditions appears to exist for natural lakes, including those which have been drastically altered by dams. Quite obviously the reverse appears to be true for artificial impoundments which tends toward eutrophic conditions.

Figure 2A is another attempt to plot the same basic data. The top line starting from the left represents natural lakes, the middle line altered natural lakes and the bottom line artificial lakes. The position of the line on the ordinate quantifies lakes by origin and trophic status and the amplitude of the bar for each selected trophic status, the total number of lakes in that class.

Figure 2B is presented to dampen out the effect of our choosing to subdivide the mesotrophic range. It depicts the precipitious trends toward eutrophic conditions encountered in artificially impounded lakes.

Figure 3 is a plot which generally follows the methodology of Vollenweider (10). We have substituted the ratio of watershed area to lake surface area for grams of phosphorus per unit lake surface area on the ordinate. On the abscissa, we have substituted mean depth for the quotient of mean depth divided by detention time. In Vollenweider's initial paper (4), he had not considered detention time. I remain unconvinced the increased importance of nutrient retention in culturally eutrophic lakes is accurately accommodated by adding hydraulic detention time to the plot.

Zone lines have been plotted on Figure 3, on the basis of data available for natural lakes, to segregate groups of lakes which have or should have, in the absence of overriding natural or cultural influences, similar trophic conditions. These zone lines should not be considered definitive. They have been placed to represent a "best-fit" analysis of available data. These lines might be shifted substantially upon the receipt of new or additional data on Connecticut lakes. None-the-less, they do serve to visually illustrate relationships which apparently do exist between the morphology of a lake and its watershed and the trophic condition of that lake. The lines establish three zones and appear to approximate a lower limit for the zone in the upper left where lakes which exhibit a strong tendency towards eutrophy are clustered in the plot, and an upper limit for the zone in the lower right where lakes which exhibit a strong tendency toward oligotrophy fall. Lakes which have been selected to represent mesotrophic conditions quite obviously appear to be scattered in the plot. This pattern is generally consistent with plots of data using Vollenweider's technique (4). The pattern which appear to be associated with the origin of the lakes, which were discussed in conjunction with Figures 1, 2A and 2B, are again discernable.

Figure 4 is a plot of more than 80 Connecticut water supply reservoirs. Since definitive data to allow the selction of trophic status were not available from the source documents used to plot the majority of the reservoirs, no effort was made to generate zone limit lines based solely on reservoir data. The zone lines plotted were carried over from Figure 3. Where data did exist to allow the selection of trophic status, it is depicted. The most striking feature of the plot is the small number of data points which fell into the zone where oligotrophic conditions would be expected based on the data depicted in Figure 3 and by contrast, the large number of data points in the zone where eutrophic conditions are indicated. It would appear the large majority of Connecticut water supply reservoirs are at risk of becoming eutrophic due to natural upland influences and suggests extreme care should be taken to avoid those cultural influences which could enhance eutrophication.

In order to test the validity of the analysis technique which is being proposed, an attempt was made to ascertain whether or not there were obvious reasons that the selected trophic status of some lakes did not fall within the appropriate zone. On Figure 4, the data point most obviously at variance is the lowest dotted triangle which represents Marjorie Reservoir (#21) in the Danbury water supply system. It was found that the reservoir had been constructed over a swampy area which was not excavated during construction and that the effective watershed area is much larger than is represented by the plot due to the intentional diversion of runoff waters from outside the watershed into the reservoir. Although precise data have not yet been acquired, by map observation it would appear that adjusting the data to represent actual conditions will cause the reservoir to fall within the eutrophic zone.

On Figure 3, additional data points which appear to represent exceptions were checked. The meso-oligotrophic lake just to the left of the top of the line depicting the lower limit of the eutrophic zone represents West Side Pond (#98) in Goshen. The pond elevation was, at one time, three to four feet higher than the present elevation and has lowered due to the failure of a dam. The natural pond occupies what is apparently a kettle hole and is characterized by a narrow littoral shelf. There is a substantial upstream wetland on the tributary feeder stream which probably acts as a nutrient sink.

Immediately below and to the left of West Side Pond is a data point which represents Bigelow Pond (#17). Bigelow Pond, which is formed behind an eight foot dam, lies immediately downstream of a relatively large mesotrophic lake, Lake Mashapaug, which obviously acts as a sink protecting

Bigelow Pond from becoming eutrophic.

Just below the line representing the apparent upper limit of the oligotrophic zone on the four foot mean depth line is a eutrophic artificial impoundment representing Winchester Lake (#99) which was created by flooding a low lying forest which is thought to have been a swamp and consequently, the shallow bottom is abundant in decaying organic matter.

The final exception which I will discuss is the lowest eutrophic impoundment depicted in the oligotrophic zone on the plot, Hitchcock Lake (#47) in Wolcott. This lake has a densely developed watershed in which sewers have been constructed to eliminate sewage discharges to the lake from residences. There is at least some reason to expect that conditions in Hitchcock Lake should improve as a result. We have very little data to establish a basis for the zone lines for shallow lakes with relatively small watersheds. Indeed, there are many factors which would cause one to expect a discontinuity in the zone lines as they are extended into the portion of the plot where unstratified (shallow) lakes would be plotted.

Very few of the total number of lakes which are plotted as mesotrophic are lakes for which definitive data on trophic status are available. We expect that the apparent scatter of data points which represent lakes selected as mesotrophic reflects the lack of precision in definition and/or probably cultural influences which may or may not be reversible through control program efforts. The probability of successful control would appear to be greatest for those lakes for which a mesotrophic status has been selected and which lie in the oligotrophic zone. At the opposite extreme, means of achieving success may be demonstrated by detailed study of the oligotrophic and mesotrophic lakes which lie in the eutrophic zone.

Figure 5 appears to show that as mean depth increases, eutrophic conditions are less probable. An apparent boundary depth of four meters appears to be indicated. However, it would be presumptious to attempt to draw conclusions due to the lack of data (which was mentioned previously) for shallow lakes with relatively small watersheds. If extension of the zone lines into the portion of the plot where shallow lakes with small watersheds would lie is valid, it is this type of lake that would be expected to exhibit oligotrophic characteristics.

We feel that by concentrating our efforts on the exceptions to the rules that are implied by this analysis technique and by attempting to influence others working in the field to do likewise, maximum gains will be achieved at least cost and we may be able to avoid squandering our limited resources where the probability of implementing successful controls appears remote.

We expect application of this analysis technique to define our priority needs for detailed data should result in a continuous improvement in our ability to identify and propose controls to improve the trophic status of Connecticut lakes which are adversely affected by natural or cultural influences. We also expect to improve our ability to predict whether or not a proposed new impoundment should be expected to become eutrophic and avoid its construction or insure mitigating controls are an integral part of the planning and design process.

In closing, I should acknowledge that any particular graphic or mathematical model based on the analysis technique described will probably be accurate only for the geographical area from which the base data are acquired due to the influence of local geology and weather patterns. It may even be that more than one model should be established to accommodate the variability of such influences within Connecticut.

We do not expect to conclude this phase of our analysis technique in written form in the near future. I again solicit your suggestions, criticisms and especially your data to assist our effort.

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CONNECTICUT LAKES MANAGEMENT PROGRAM EFFORTS

FIGURES 1-5

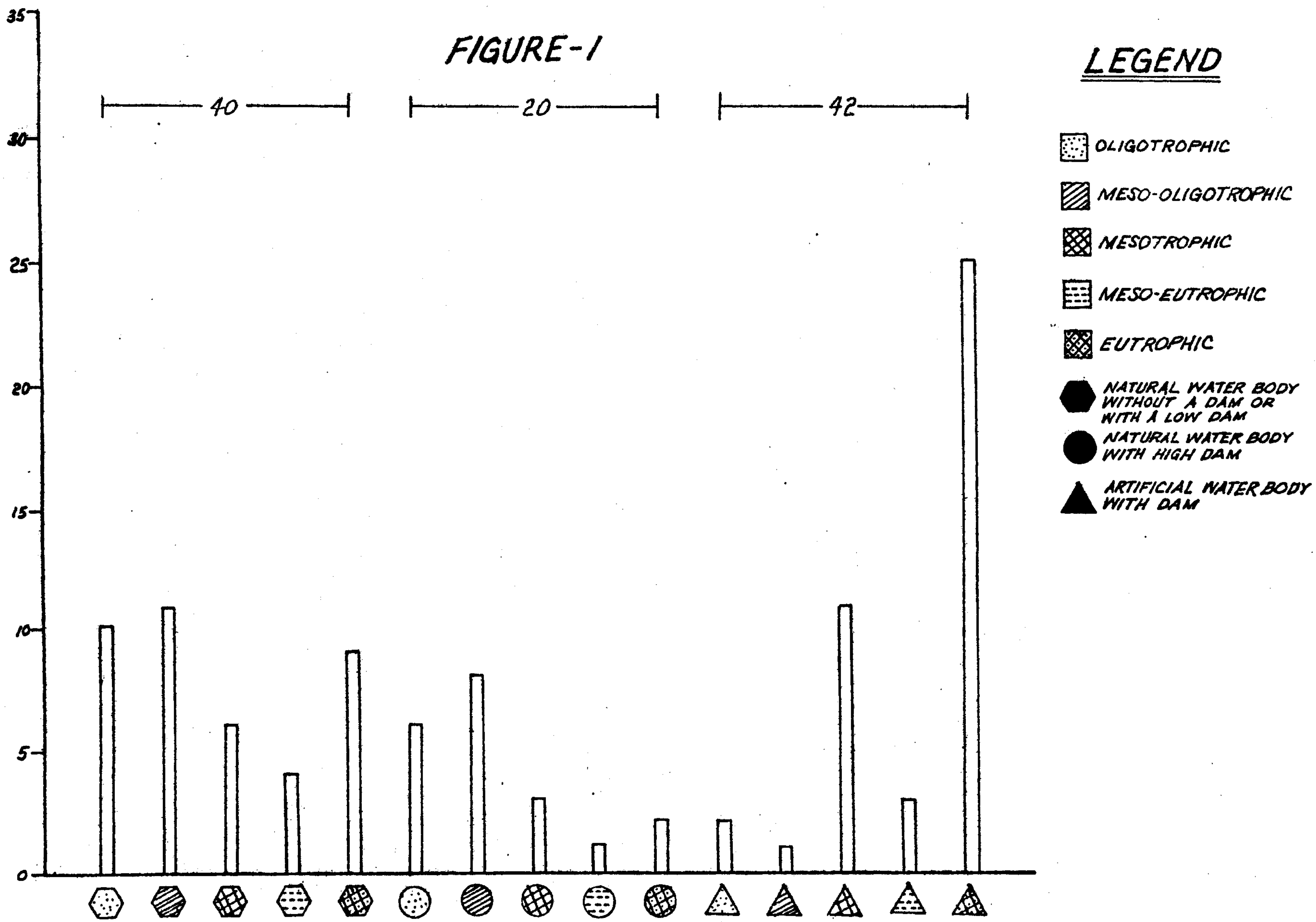
FIGURE-1
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MESOTROPHIC
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EUTROPHIC
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NATURAL WATER BODY WITH HIGH DAM
ARTIFICIAL WATER BODY WITH DAM

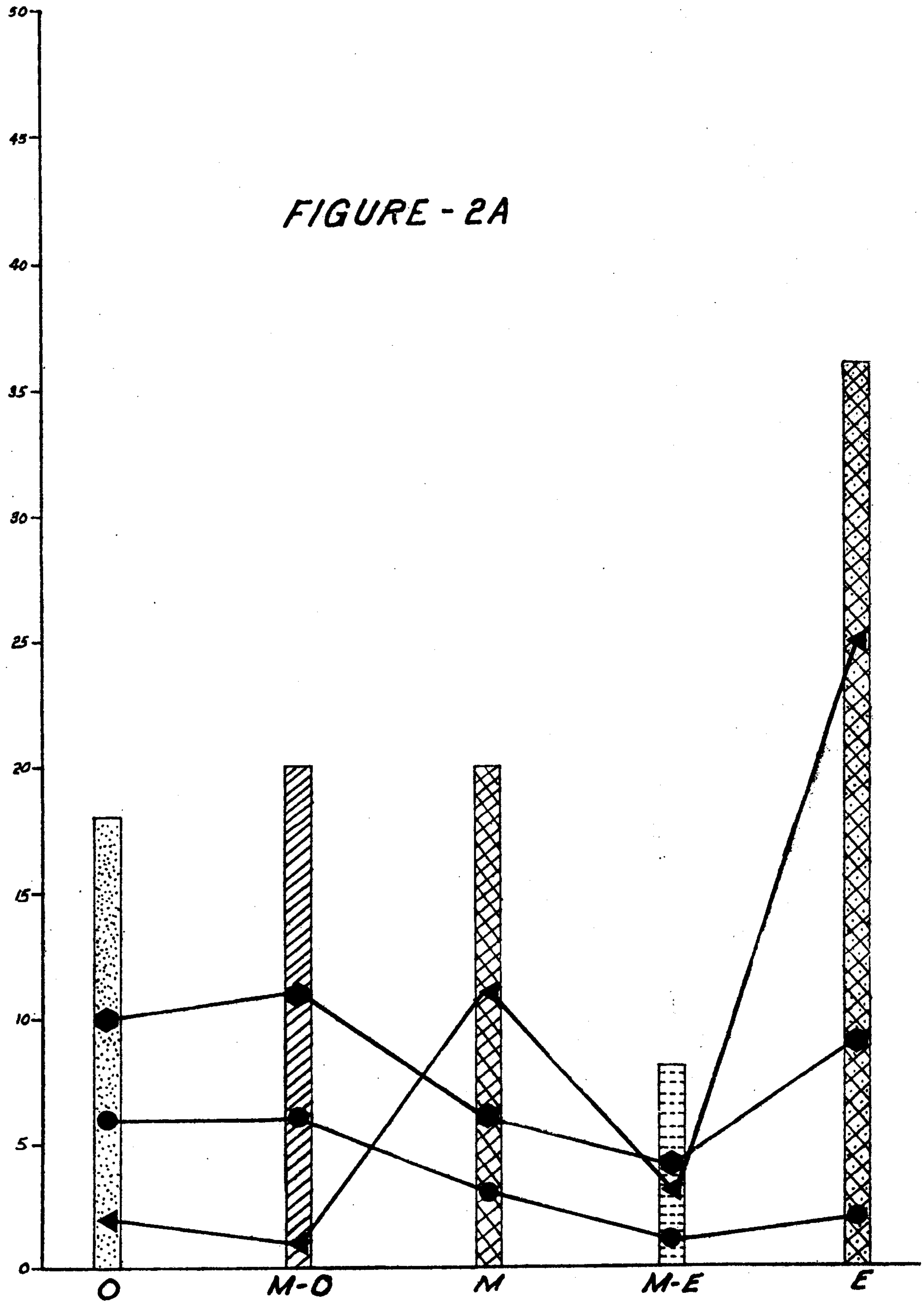

FIGURE - 2A

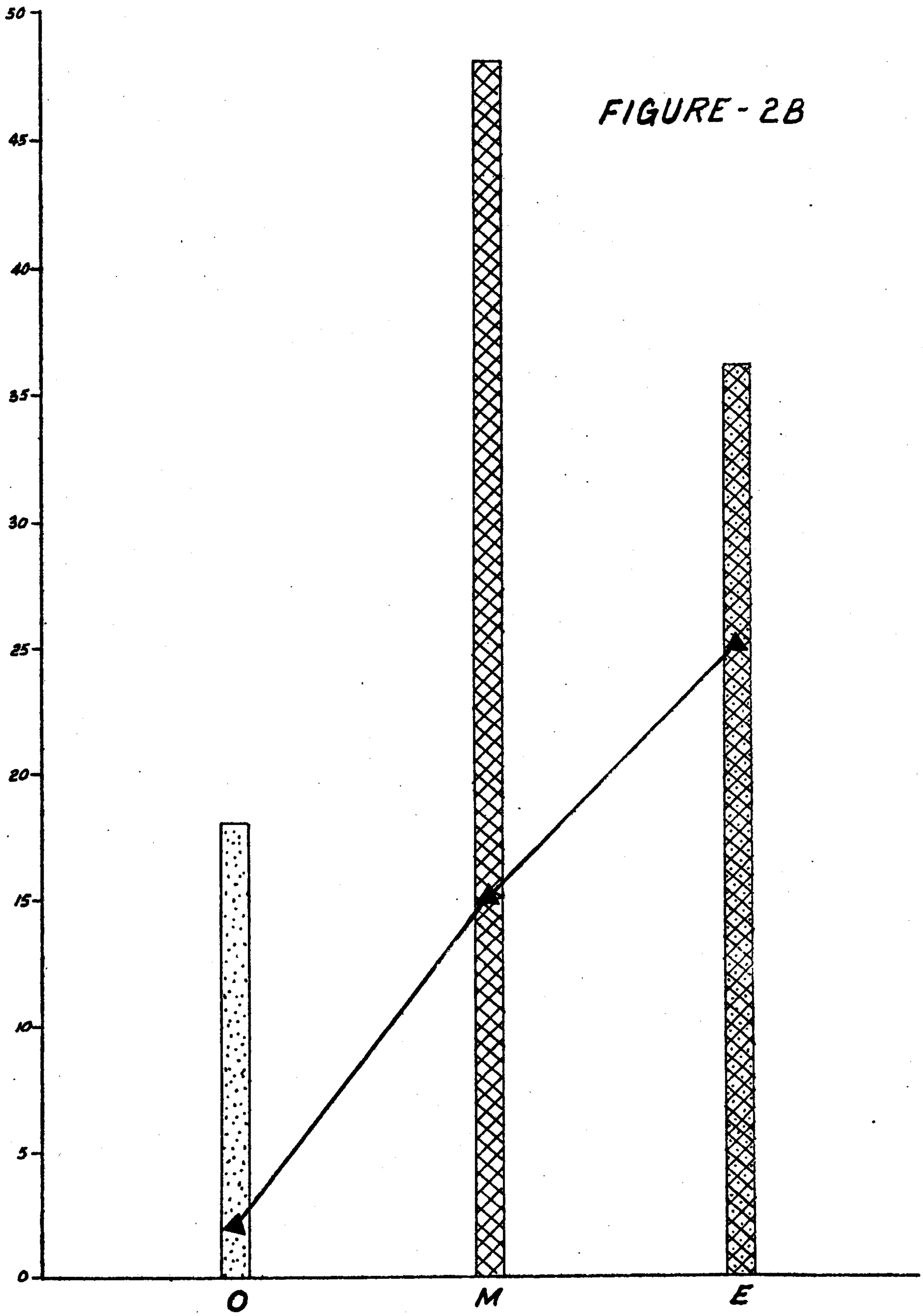
FIGURE - 2B
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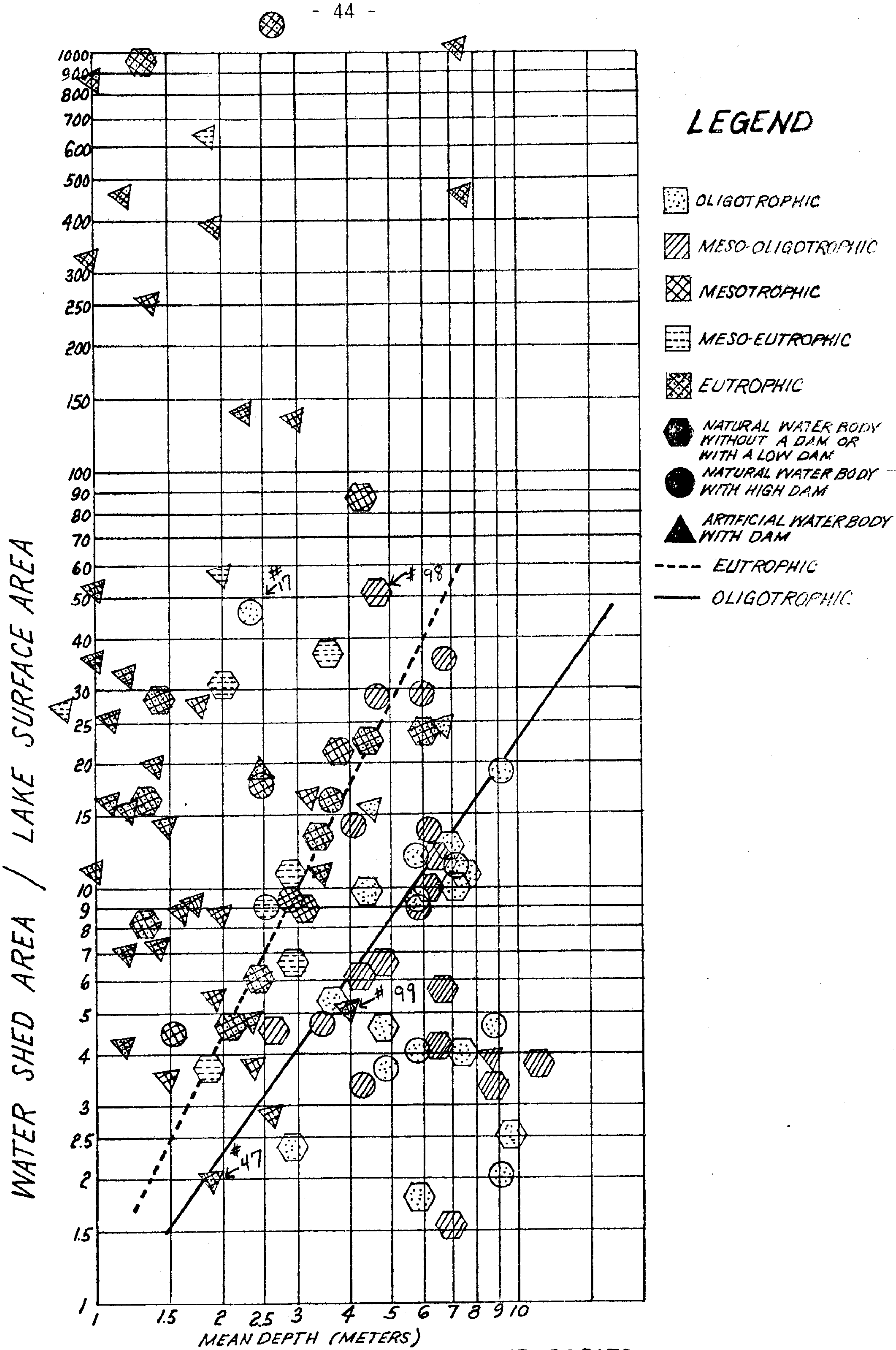
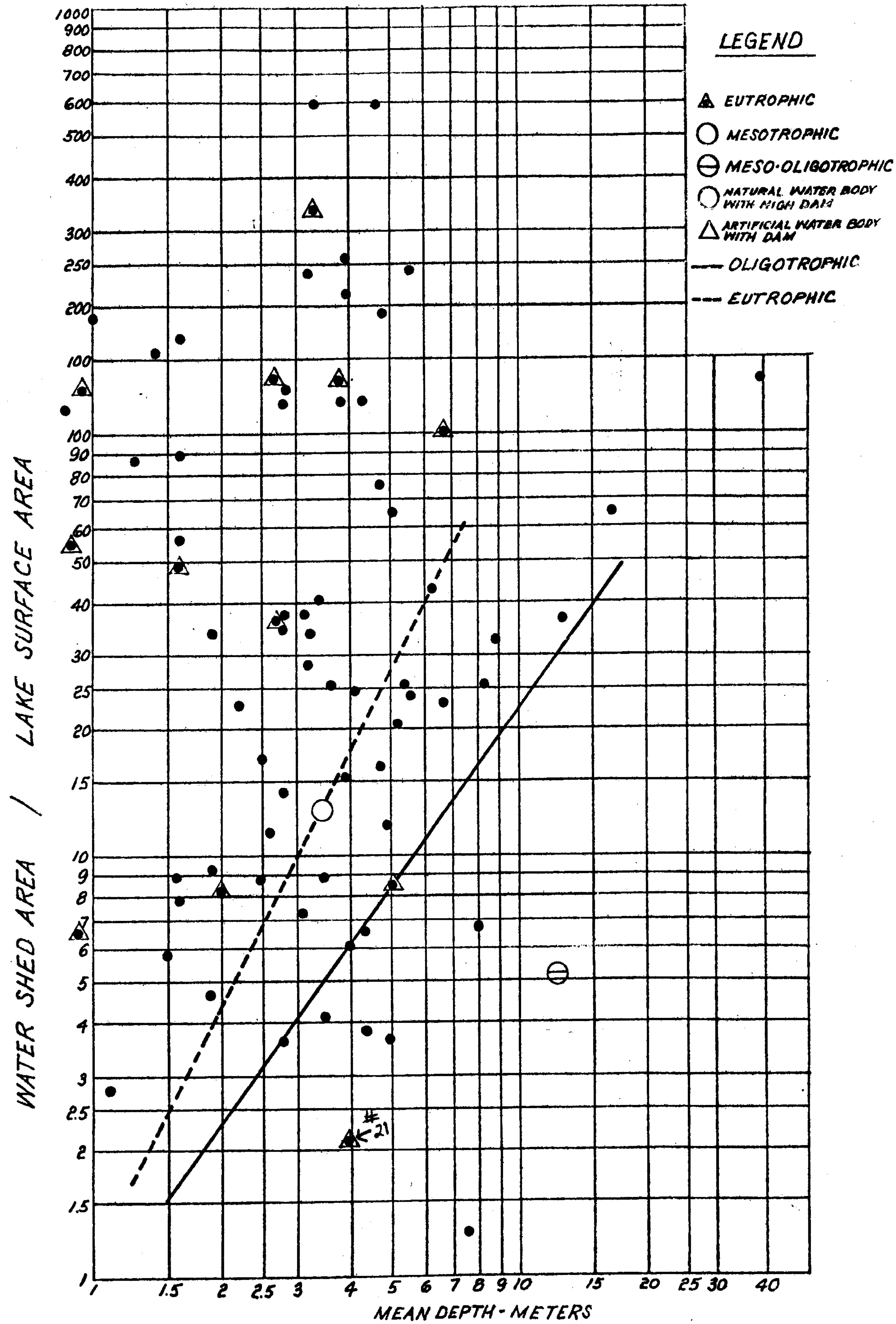
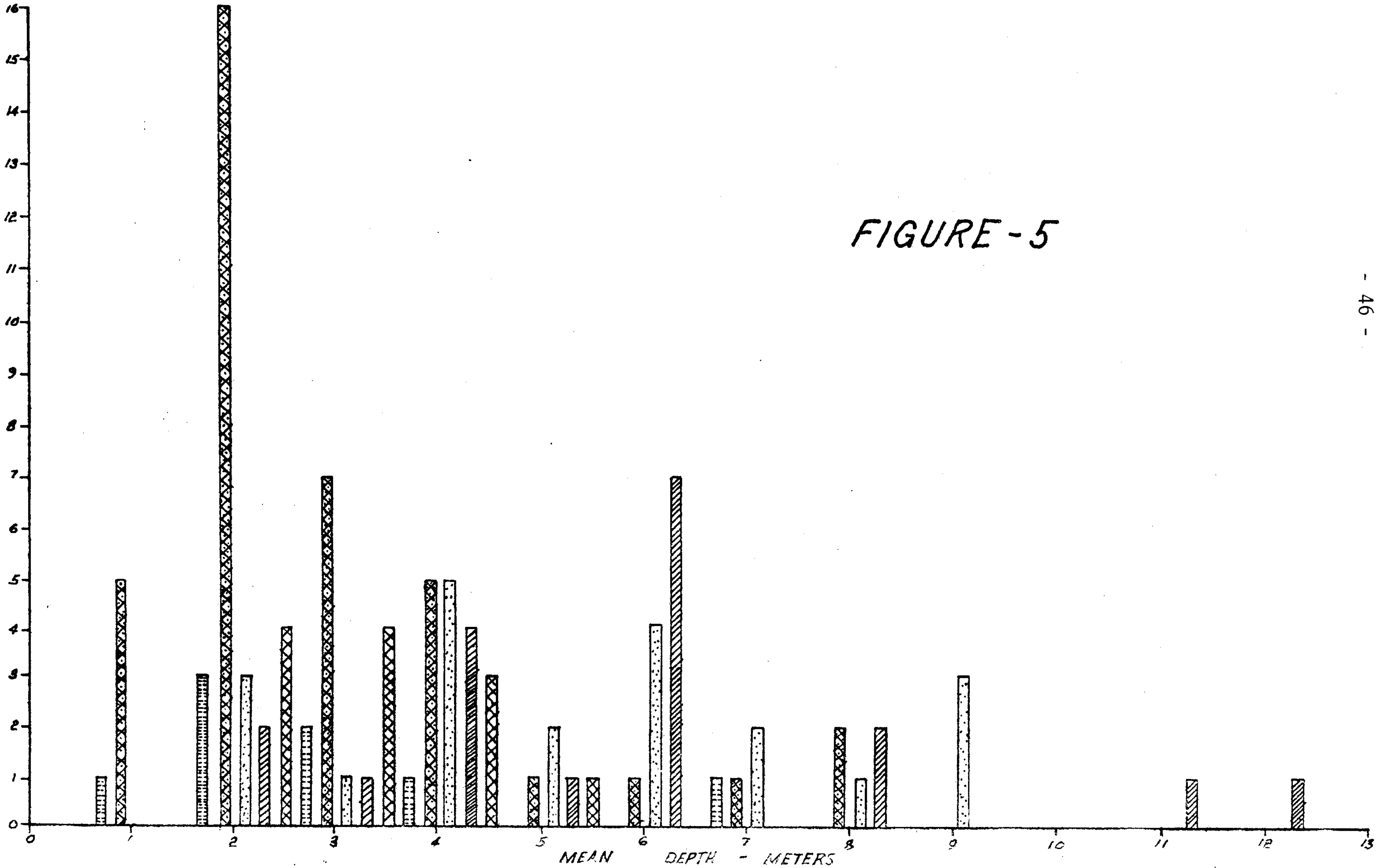


IMPOUNDMENTS & NATURAL WATER BODIES FIGURE-3



RESERVOIRS FIGURE-4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MEAN DEPTH - METERS

FIGURE - 5

WATER COMPLIANCE UNIT LAKES MANAGEMENT STRATEGY

by

Charles G. Fredette*

What I'd like to do, before Bob gives his presentation on the analysis that we've been working on for quite a few days now, is give you a brief summary of what Water Compliance's lake management program entails. We have had a lakes management program since the Water Resource Commission was established in 1967, and we have had a number of water pollution control programs since that time which have been impacting favorably on lakes and lake water quality. We have had, and we will continue to have, a lakes management program because we recognize that natural and man-made eutrophication is actually the major threat to lake water quality in Connecticut.

We also recognize that there is a good deal of research which has been done on limiting nutrients in Connecticut lakes. For most cases, phosphorus is the limiting nutrient in Connecticut lakes, so we have emphasized our efforts on the control and analysis of phosphorus in Connecticut lakes. This emphasis is reflected in our water quality standards which express our policy that point source discharges to lakes in Connecticut, natural lakes, and ponds and many impoundments which are considered to be natural lakes and ponds, will receive treatment so that they do not raise the concentrations of the lakes and ponds and their tributary waters to a level about .03 mg/l total P, which is essentially a background condition. So we don't have, except for run of the river impoundments, lakes in Connecticut that are being impacted by point source discharges of phosphorus. Consequently, most of our problems are related to non-point source phosphorus inflow. I think most of you probably know the difference between point source and non-point source discharges. Basically, point source refers to a discharge from a pipe, which you can see and measure; non-point source refers to a more diffuse, undefined source, such as runoff from agricultural land, or runoff from lawns and gardens.

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Recently we were given the opportunity through our 208 Areawide Waste Treatment Management Program to fund two special projects which will begin a detailed analysis of non-point source phosphorus loadings to lakes. The first study is the Lake Waramaug Study, which is being conducted by the Northwestern Regional Planning Agency, with the assistance of the U.S. Geological Survey, the Lake Waramaug Task Force and the Litchfield County Soil and Water Conservation District. The other is being conducted by the Windham Regional Planning Agency on Lakes Coventry and Columbia. The basic concept for both of these studies is to evaluate non-point sources of phosphorus in the watersheds of the lakes, to develop strategies of controlling the non-point sources of phosphorus, and also to examine the legal and institutional framework which is necessary to implement any control strategies which are developed.

Their approaches are somewhat different. Lake Waramaug started a "hands on" type of study, with a great deal of emphasis on fieldwork, on monitoring, and actually reviewing inputs from various parcels of land to determine whether they were having any problems with non-point sources.

In contrast, the Windham Regional Planning Agency study is a little more abstract. They're reviewing the available mathematical modeling techniques in order to develop a mathematical model which they will be able to use with land use information to determine various inputs for various categories of land use. They're also attempting to determine what the permissible and critical phosphorus levels in the lake are so that they can evaluate various future changes in land use through the application of the models and determine which changes would be protecting the lake and which ones would not. They will be doing some limited sampling to refine and further verify the coefficients that they will be using.

We expect to learn a great deal from the 208 program and the 208 studies on these lakes. A great deal of the information that will be developed during these projects will be used as a valuable guide to lake studies in general, lake management studies,and non-point source inventory and control programs for other Connecticut lakes.

I'd like to briefly run down the other elements we have in our program which impact on lakes. Probably some of you are familiar with these because you've utilized them already. For example, Section 25-3c of the Connecticut General Statutes provides reimbursements to towns, and now to lake authorities, but not lake associations, for algae and weed control projects for lakes which are open to the general public for recreational opportunities. Under Section 25-54r of the Connecticut General Statutes, we provide for one hundred percent funding for the construction of any wastewater treatment facility that may be needed to control nutrients which are causing eutrophication. Under Section 25-54oo of the Connecticut General Statutes, the Commissioner of the Department of Environmental Protection has the authority to impose a ban on phosphate detergents on specific watersheds where it can be demonstrated that the ban will be effective in reducing eutrophication. I think, as time goes on, this particular statute has less and less utility because the phosphate content of detergents is coming down, mainly because of better technology in building detergents.

We have applied our construction grants program in a way which has been beneficial to lakes where we have older lakeside communities with high density development and inadequate subsurface disposal conditions. These grants have been used to install sewers. Some of these you may be familiar with: Lake Pocotopaug in East Hampton; Lake Plymouth in Plymouth; Lake Garda in Farmington.

We are interested in participating, of course, in the 314 program. As it was established, it has been up to this point of limited utility in Connecticut, because it does not provide funds for diagnostic surveys of lakes, and we do have a definite need for that. It's also a fifty-fifty matching program. We have heard some encouraging news from Washington. The EPA will be giving this program higher priority and they are reviewing the funding arrangement and are considering more favorable cost-sharing arrangements. Also, they are taking a very close look at whether they may begin to fund diagnostic studies of lakes.

Our staff does some diagnostic work with varying intensity depending on the particular problem we're looking at. Smaller lakes and ponds and smaller problems are handled on a complaint basis. We have enough complaints on the list right now to keep us busy for the rest of the year. Very often, these studies will involve nutrient sampling, temperature, dissolved oxygen profiles, and the identification of aquatic organisms, particularly phytoplankton and aquatic plants. We have been involved with one fairly extensive lake investigation, the investigation of Lake Wononscopomuc. We are continuing the two-year study there; we're evaluating the lake eutrophication problem, supplementing and complementing information that has been developed by Union Carbide (through a contract with the Town of Salisbury) and the Connecticut Agricultural Experiment Station.

For the larger lakes, we have identified priority lakes, and we're expending our research resources on those priority lakes, which are generally the larger lakes which provide the greatest opportunity for public recreation. These are Bantam Lake, the Housatonic Lakes, Candlewood Lake, and Lake Waramaug, which is fortunate to have 208 funding. Very often on these larger lakes, it's more a matter of our gathering available information than it is actually going out and doing our own data collection because many of these lakes have been studied and are continuing to be studied by other people in the state, particularly the Connecticut Agricultural Experiment Station.

I think I'll just give you one brief example of how we're using our construction grants program to evaluate some priority lakes. The Housatonic Lakes, Lake Lillinonah, Lake Zoar and Lake Housatonic, are priority lakes. We have in our 303e basin plan done a phosphorus analysis of these lakes based on work done by Dr. Frink at the Connecticut Agriculture Experiment Station and also based on some work by the EPA National Eutrophication Survey. We looked at both budgets and we quantified point sources from information that we had in our own files and from New York and Massachusetts, and we began to separate non-point source loadings. We got to the point where it looks like, depending on whose budget you see, between 22 and 29 percent of the phosphorus load on the lakes is due to the Danbury Wastewater Treatment Plant effluent, a discharge to the Still River about seven miles from the lake. We don't know whether if we go to phosphorus removal at that plant, we will see a significant improvement in the lake. So we have, with the cooperation of FMC Corporation and DuPont Chemical Company, this morning started up a temporary phosphorus removal facility, that will be running for approximately one hundred days. FMC Corporation has done extensive monitoring of this system in the Still River and the lakes last year; they're repeating that again this year. So we will be able to see in this effort the benefits due to the point source phosphorus removal for these lakes.

So that's briefly what we're doing. I could talk about a number of other lakes, but that's just an example of how we're involved. So I will turn the program over to Bob, and he can tell you about the analysis of the watershed areas and other items.

APPLICATION OF COST EFFECTIVE METHODOLOGY TO LAKE EUTROPHICATION CONTROL

by

William V. McGuinness, Jr.*

This paper summarizes CEM's planning for the control of eutrophication (overnourishment) in 12 lakes in western and central Massachusetts. The planning was accomplished under two separate areawide wastewater management studies, authorized under Section 208 of P.L. 92-500, funded by the U.S. Environmental Protection Agency, and administered by the Berkshire County and Central Massachusetts Regional Planning Commissions. For each lake, the key problem was cultural eutrophication (man-accelerated overnourishment).

As listed in Figure 1, this paper will explain: (1) the concept of watershed; (2) why the control of phosphorus appears to be the key to controlling lake eutrophication; (3) how the phosphorus tolerance of each lake was estimated; (4) the annual estimated input (supply) of phosphorus to each lake from each part of its watershed; from many different sources; under pristine, current, and future conditions; (5) how these supply estimates were validated; (6) the evaluation of measures to control the supply; (7) a cost effective watershed control program; (8) supplementary in-lake control measures; and (9) public feedback.

Concept of the Watershed. Vollenweider, Dillon, Rigler, Uttormark, Schindler, the National Eutrophication Survey, and essentially all limnologists and water resources researchers and planners now seem to agree that the causes and therefore the solution for lake eutrophication problems lie not just in the lake itself but in its entire drainage basin. As the Massachusetts Division of Water Pollution Control points out in summarizing the general state of the art in

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a recent lakes water quality report for the study area, "In order to understand lake conditions, one must realize that the entire watershed and not just the lake, or the lake and its shoreline, is the basic ecosystem. A very important factor, and one on which the life of the lake depends, is the gravitational movement of minerals from the watershed to the lake. Admittedly [the Division report on baseline water quality studies of selected lakes and ponds] concentrates mainly on the lake itself. Yet the foremost problem affecting the lakes and ponds today is accelerated cultural eutrophication, which originates in the watershed and is translated into various and sundry nonpoint sources of pollution. A great deal of lake restoration projects will have to focus on shoreland and lake watershed management."

Reasons for Keying on Phosphorus. Rather than trying to control all or many of a large number of nutrients, it is more efficient to concentrate on one, usually, but not always, the "limiting nutrient" - the nutrient least available relative to the growth requirements of unwanted algae and weeds. That way, growth is limited by the availability of that particular nutrient. Although many nutrients are necessary to support life, those not likely to be limiting can be quickly narrowed down to phosphorus and nitrogen (and in rare, mostly theoretical instances, carbon).

In theory, one should be able to judge which nutrient is limiting by comparing the ratio of "available" or total nitrogen and phosphorus in the lake water itself. Based upon surveys taken by others, mostly in July and August, most of the ten Berkshire lakes appeared to be nitrogen-limited, but the ratios were very erratic, varying in instances from zero to infinity at the same place in the same lake less than one month apart.

Partially because of this often erratic and limited seasonal nature of the sampling program, and the absence of any spike tests, but mostly because of the following five reasons listed in Figure 2, we chose to emphasize the control of phosphorus, not nitrogen.

(1) *Even if initially nitrogen-limited, a lake is likely to become phosphorus-limited during the course of restoration to mesotrophic or oligotrophic conditions.* EPA's National Eutrophication Survey (NES) surveyed 191 lakes in the northeastern and north central United States. Of these, 71 were considered nitrogen-limited - but not a single one of these 71 lakes were mesotrophic or oligotrophic.

(2) *According to the impressive whole-lake experiments of Schindler, equilibrium conditions tend to be phosphorus-limited.* Thus, whenever he artificially made nitrogen limiting, blue-green algae increased rapidly to pump in more nitrogen from the atmosphere.

(3) *The degree of eutrophication correlates much more closely with phosphorus than with nitrogen.* Regardless of the limiting nutrient determination, NES found that the degree of eutrophication correlates more closely with inputs of total phosphorus than with any other single determinant.

(4) *Phosphorus is much easier to control than nitrogen.* Some 10 to 15 times more nitrogen would have to be kept out of the lake to have the same control value, yet the quantification and localization of nitrogen sources is very uncertain and significant nitrogen control measures are simply not known.

(5) *EPA concludes that phosphorus control is the most feasible approach.* EPA's overall conclusion is summarized in the following overview passage which has appeared with some frequency in NES lake eutrophication reports:

> "In general, few lakes are nitrogen-limited as a result of low nitrogen. Rather, excessive phosphorus levels shift limitations to nitrogen or other factors. Regardless of the primary nutrient limitation suggested by either algal assay or nutrient ratios, the most feasible approach, if desirable, is through available phosphorus control technology and subsequent establishment of phosphorus limitations within the water body."

Lake Phosphorus Tolerances. Vollenweider, Dillon, Rigler, Schindler, Chapra, Tarapchak, Snodgrass, Shannon, Brezonik, the EPA National Eutrophication Survey, the U.S. National Academy of Science, the General Assemblies of both the International Limnological Congress and the International Ecology Congress, and many others have recognized a strong empirical and theoretical correlation among (1) the total annual phosphorus supply to the lake from external sources (the watershed and atmosphere); (2) the in-lake concentration of total phosphorus; and (3) the eutrophic level of the lake. Sometimes referred to as a "black box" approach, use of this concept is analogous to getting a patient to reduce by feeding him less without denying the importance of, or trying consciously to manipulate, the patient's internal metabolism which may or may not be really understood anyway. Thus, the "black box" approach does not deny that there are important in-lake changes as various forms of phosphorus constantly migrate to and from the sediments, flora, and fauna in partially understood seasonal patterns. Recirculation certainly occurs, for example, for thermal reasons during the spring and fall turnovers, for chemical reasons whenever waters turn anaerobic, for biological reasons through the feeding and dying of aquatic plants and animals, and for physical reasons through the action of winds and motor boats in shallow waters. These interrelationships are complex, yet: (1) the net long-range flux of phosphorus is clearly and strongly from the water column to the sediments or lake outlet; and (2) for as yet incompletely understood reasons, the trophic condition of lakes seems to be primarily related to the supply from out-of-lake sources during the current year or few previous years - not to the substantial age-long accumulation of phosphorus in the bottom sediments or to their recirculation within the lake. This is the major, now widely accepted, conclusion of the Vollenweider-Dillon school. Therefore, as indicated earlier, this paper focuses on the consequential sources - those from the watershed as a whole.

Vollenweider has graphed the overall relationship between total annual phosphorus input (loading) and in-lake phosphorus concentrations (his "dangerous" and "critical" conditions). Dillon and Rigler have described the relationship in terms of Equation (1) in Figure 3. Equations (2), (3), and (4) are alternative forms of the equation, more useful for our purposes. The mean concentration at the outlet is by definition equal to the annual phosphorus load passing through the outlet, P(1-R), divided by the annual flow through the outlet, Q. Thus,

$$[P]_{outlet} = \frac{P(1-R)}{Q}$$

If we can assume that outlet concentrations approximate in-lake concentrations, we will prove one form of the Dillon-Rigler Model (Equation 4, Figure 3). At least in this study area, the larger the number of samples to be averaged, the more the above assumption appears to be valid. Thus, considerable variation was observed between in-lake and outlet concentrations for individual sampling periods. When the samples were averaged for individual lakes, however, the spread was less. For the most sampled lake and the only one sampled regularly throughout a year (Pontoosuc with 45 samples), the spread was zero - μg/ℓ for mean concentrations of total phosphorus both in the lake and at its outlet. For the *total* for all ten lakes, the corresponding figures were 25 and 23. The closeness of this fit is given further stature when it is recognized that the individual samples were recorded only to the nearest 10 μg/ℓ. The units digit was thus determinable only by averaging a large number of samples.

It thus appears that the Dillon-Rigler Model does indeed represent overall conditions in the study area surprisingly well. One cannot expect it to be so precise, however, for each individual lake, especially for lakes samples only seasonally or principally during one season, even though this model is the best we know.

The very close correlation between the in-lake concentration of total phosphorus [P] and the in-lake concentration of chlorophyll a (the most widely accepted index of eutrophication) has been observed by Sakamoto, Dillon, Rigler and many others. More directly, many investigators and authorities have suggested the correlation between [P] and the eutrophic level of a lake. For example, the U.S. National Academy of Science defines the lower and upper limits of the mesotrophic range as 15 and 30 μg/ℓ, respectively. Substituting these values in Equation (3) along with the values of Q and of R (estimated according to methods suggested by Dillon), P can be estimated for certain critical index conditions.

This was done and the results were characterized as "Conditions 1, 2, 3 and 4," or decimal fractions thereof. Conditions 2 and 3 are the lower and upper limits of the mesotrophic range as computed above.

Condition 1 is merely half of Condition 2 and represents an ultra-oligotrophic lake. Condition 4 is twice Condition 3 and represents a hyper-eutrophic lake.

Quantification of Annual Phosphorus Supply. Now that a range of phosphorus tolerances has been estimated, the next step is to estimate the phosphorus supply by subbasin, time frame and type of source (Figure 4). An explanation of the quantification methods used is beyond the scope of this paper, except to say: (1) that the erosion estimates made prominent use of a modified Universal Soil Loss Equation; and (2) the septic system losses employed a fundamental five-step methodology developed by CEM to trace the generation, flow,and retention of phosphorus on its path from major household appliances, through the septic tank leaching field and soil prism, and into the lake.

Table 1 summarizes the proportional significance of the major sources. Note the dominant effect of erosion, which in turn is prominently affected by land use. By the year 2000, the contribution from septic systems should increase from its present 14 percent to about 26 percent. The principal reasons for this increase are: (1) each existing system will be 24 years older with much less phosphorus retention capacity; and (2) many cottages are converting to year-round use.

Table 2 breaks down the erosion estimates according to land use. Note the dominant effect of urbanization. The emission rate for forests would have been even lower if it were not for the fact that forests are located on much steeper slopes than any of the other uses.

Table 3 provides more detail by focusing on one of the lakes, Lake Pontoosuc. Note how the total phosphorus supply increased from 402 kg P/year under pristine conditions, to 1,674 kg P/year by 1976, to 2,159 kg P/year by the year 2000. The corresponding "lake conditions" increase from 0.8-Oligotrophic to 2.8-Mesotrophic to 3.2-Eutrophic. Also note the large increase from septic systems expected in the future for reasons explained earlier.

Validation of Supply Estimates. How valid are these estimates? We tested them in six different ways (Figure 5):

(1) The in-lake concentrations corresponding to our estimated total current annual phosphorus supplies were calculated by using Equation (4) of Figure 3. The mean for all lakes was 26 μg/ℓ. This compared closely with the mean of 25 μg/ℓ measured in the lakes.

(2) The calculated trophic conditions for each lake seemed about right for both current and reconstructed pristine conditions.

(3) Whenever tributary concentration samples were available, we compared them with concentrations calculated by dividing our total annual load for that watershed by the estimated total annual stream flow. Although there was a large variation due to varying weather conditions, the mean of the calculated values (32 μg/ℓ) compared closely with the mean of the sampled values (33 μg/ℓ).

(4) As Figure 5 indicates, our calculated emission rates (kg P/μm^2/yr) fall reasonably within the range of literature values summarized by Uttormark.

(5) As also shown in Figure 5, our sediment estimates (an intermediate estimate in determining phosphorus erosion) compare reasonably well with a number of SCS annualized sediment surveys in streams in Berkshire County.

(6) For the septic loads, it was noted that the current estimated annual supply from this source is 38 percent of the load discharged to the septic tank. This proportion seemed "about right."

Phosphorus Control Measures. Figure 6 lists the principal measures for controlling the phosphorus supply and shows their interrelationships. An explanation of each measure is beyond the scope of this paper. Many of the measures are interrelated. For example, the supply of phosphorus from septic systems can be controlled at the contributor level by using non-phosphorus detergents, and/or at the source level by a 7-step program of managing septic systems, or by sewering. If non-phosphorus detergents are used, the effectiveness (μg P/yr removed) of septic system management will be somewhat reduced because some of the phosphorus will have already been removed.

Cost Effective Watershed Control Programs. Table 4 summarizes the watershed control program for Pontoosuc Lake. Note that the measures are listed in cost-effectiveness order ($/kg P reduced/year). Also note how, as successive measures are applied, the annual phosphorus supply diminishes and the lake condition improves. Presenting the program this way gives the local community many options. The entire recommended program costs about $251,000 a year, but most of this cost is for sewers. Sewers were included here (but left out in most lake programs) because they are fully justified for density and health reasons even if they were not lakeside, because they are part of a larger nearby sewering program; and because a large proportion of their costs will be borne by Federal and Commonwealth Governments. If sewers are not provided, however, an alternative program producing almost as good results is also shown in Table 4, for $144,300 a year. A lesser program (Measures 1 through 7) would produce almost the same results for less than half that cost - $65,000/year. Furthermore, if midmesotrophic conditions were judged acceptable, the program could be cut off at the end of Measure 4 at an annual cost of only $26,500.

Table 5 summarizes the recommended control measures for all ten lakes, and Table 6 summarizes the effects upon each of the ten lakes.

Supplementary In-Lake Measures. It is emphasized that this paper concentrates exclusively upon measures to limit the annual phosphorus supply coming from the watershed. *In-lake* measures should also be considered. These include dredging, weed harvesting, outlet modifications, chemical treatment, drawdown and freezing, and aeration.

Public Feedback. The results of this study were presented in preliminary form, along with other water quality programs, at a series of ten public meetings in Berkshire County in late 1976 and early 1977. The study was well received, and comments from the meetings and from Commonwealth and EPA reviews were incorporated into the final report, which should be published in the fall of 1977.

Summary. Figure 7 summarizes the preceding nine steps.

CEJM

S C O P E

1. CONCEPT OF THE WATERSHED.
2. REASONS FOR KEYING ON PHOSPHORUS.
3. LAKE PHOSPHORUS TOLERANCES.
4. QUANTIFICATION OF ANNUAL PHOSPHORUS SUPPLY.
5. VALIDATION OF SUPPLY ESTIMATES.
6. PHOSPHORUS CONTROL MEASURES.
7. COST EFFECTIVE WATERSHED CONTROL PROGRAMS.
8. SUPPLEMENTARY IN-LAKE MEASURES.
9. PUBLIC FEEDBACK.

Figure 1.

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REASONS FOR KEYING ON PHOSPHORUS

1. Even if initially nitrogen-limited, a lake is likely to become phosphorus-limited during the course of restoration to mesotrophic or oligotrophic conditons.
2. According to Schindler's work, equilibrium conditions tend to be phosphorus-limited.
3. The degree of eutrophication generally correlates much more closely with phosphorus concentrations than with nitrogen concentrations.
4. Phosphorus is <u>much</u> easier to control than nitrogen.
5. NES concludes that phosphorus control is the most feasible approach.

Figure 2.

CEM

DILLON-RIGLER MODEL

(1) $L = \frac{[P] \cdot \bar{z} \cdot \rho}{(1 - R)}$

(2) $P = \frac{[P] \cdot A_o \cdot \bar{z} \cdot \rho}{(1 - R)}$

(3) $P = \frac{[P] \cdot Q}{(1 - R)}$

(4) $[P] = \frac{P(1 - R)}{Q}$

--in which--

L = the annual total phosphorus input from <u>all</u> exterior sources in grams per square meter of lake surface area.

[P] = the mean in-lake concentration of total phosphorus in mg/ℓ. It is usually best determined by taking samples at the time of the spring turnover.

$\bar{z}$ = the mean depth of the lake in meters.

ρ = the flushing rate in times per year.

R = the retention coefficient, the proportion of the phosphorus input that does not pass through the overflow.

P = the annual input of total phosphorus in grams per year.

A_o = the lake surface area in square meters.

Q = the volume of water passing through the lake in cubic meters per year.

Figure 3.

QUANTIFICATION OF ANNUAL PHOSPHORUS SUPPLY

BY SUBBASIN

BY TIME FRAME
- Pristine
- Current
- Future

BY TYPE OF SOURCE
- Erosion
- Atmosphere
- Septic Systems
- Livestock
- Motor Vehicles
- Point Sources
- Landfills

Figure 4.

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ANNUAL PHOSPHORUS SUPPLY BY SOURCE

--10 Western Massachusetts Lakes in 1976--

Erosion	68%
Septic Systems	14%
Atmosphere	12%
Livestock	4%
Motor Vehicles	1%
Landfills	1%
	100%

Table 1.

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QUANTIFICATION OF EROSION-RELATED PHOSPHORUS

--10 Western Massachusetts Lakes in 1976--

Watershed Land Use	% Area	% P	Rate (kg/km^2)
Urban	8	51	184
Forest	70	30	13
Cropland	7	11	42
Pasture	11	4	11
Other	4	4	28
	100	100	28

Table 2.

ANNUAL PHOSPHORUS SUPPLY TO PONTOOSUC LAKE

(kg P in 1976)

Lake and Subbasin	Pristine			1976							2000				
	Eros.	Atmos.	Total	Eros.	Atmos.	Septic Sys.	Live-stock	Motor Veh.	Other*	Total	Eros.##	Atmos.	Septic Sys.	Other**	Total
Pontoosuc L.															
T	136		136	357		0	93	30	0	480	395		0	123	518
H	43		43	45		0	0	0	0	45	45		0	0	45
S	53		53	86		0	0	2	58	146	88		0	60	148
M	14		14	51		88	0	2	0	141	54		161	2	217
O	17		17	57		0	0	2	0	59	60		0	2	62
L	12		12	172		161	0	2	0	335	185		315	2	502
P	30		30	185		135	0	2	0	322	196		323	2	521
Lake		97	97		146					146		146			146
Total	305	97	402	953	146	384	93	40	58	1,674	1,023	146	799	191	2,159
Lake Conditions#			0.8-Olig.							2.8-Mes					3.2-Eut

*Includes phosphorus supplied from point sources and solid waste landfills.

**Includes phosphorus supplied from point sources, solid waste landfills, livestock and motor vehicles.

#Lake Conditions: 1.0-1.9 = oligotrophic, 2.0-2.9 = mesotrophic, 3.0 and higher = eutrophic.

##Urban component of 1976 erosion increased by 15 percent to approximate consequences of future growth.

Table 3.

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VALIDATION OF PHOSPHORUS SUPPLY ESTIMATES

1. Comparison with phosphorus concentrations in lake.
   (26 μg/ℓ vs. 25 μg/ℓ)

2. Comparison with most probable pristine conditions.
   (all oligotrophic)

3. Comparison with phosphorus concentrations in tributaries.
   (32 μg/ℓ vs. 33 μg/ℓ)

4. Comparison with literature (Uttormark) values.
   (in kg P/km^2/yr)

	10 Lakes	Uttormark
Forest	12	5-80, mean 20
Agriculture	33	10-100, mean 30
Urban	263	100-500, mean 150

5. Comparison with SCS sediment measurements in nearby streams.
   CEM 13-39 metric tons/km^2/yr, mean = 25
   SCS 5-50 metric tons/km^2/yr, mean = 31

6. Comparison with maximum possible septic system loads.
   38 percent of maximum seems "about right"

Figure 5.

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INTERRELATIONSHIPS OF PHOSPHORUS CONTROL MEASURES

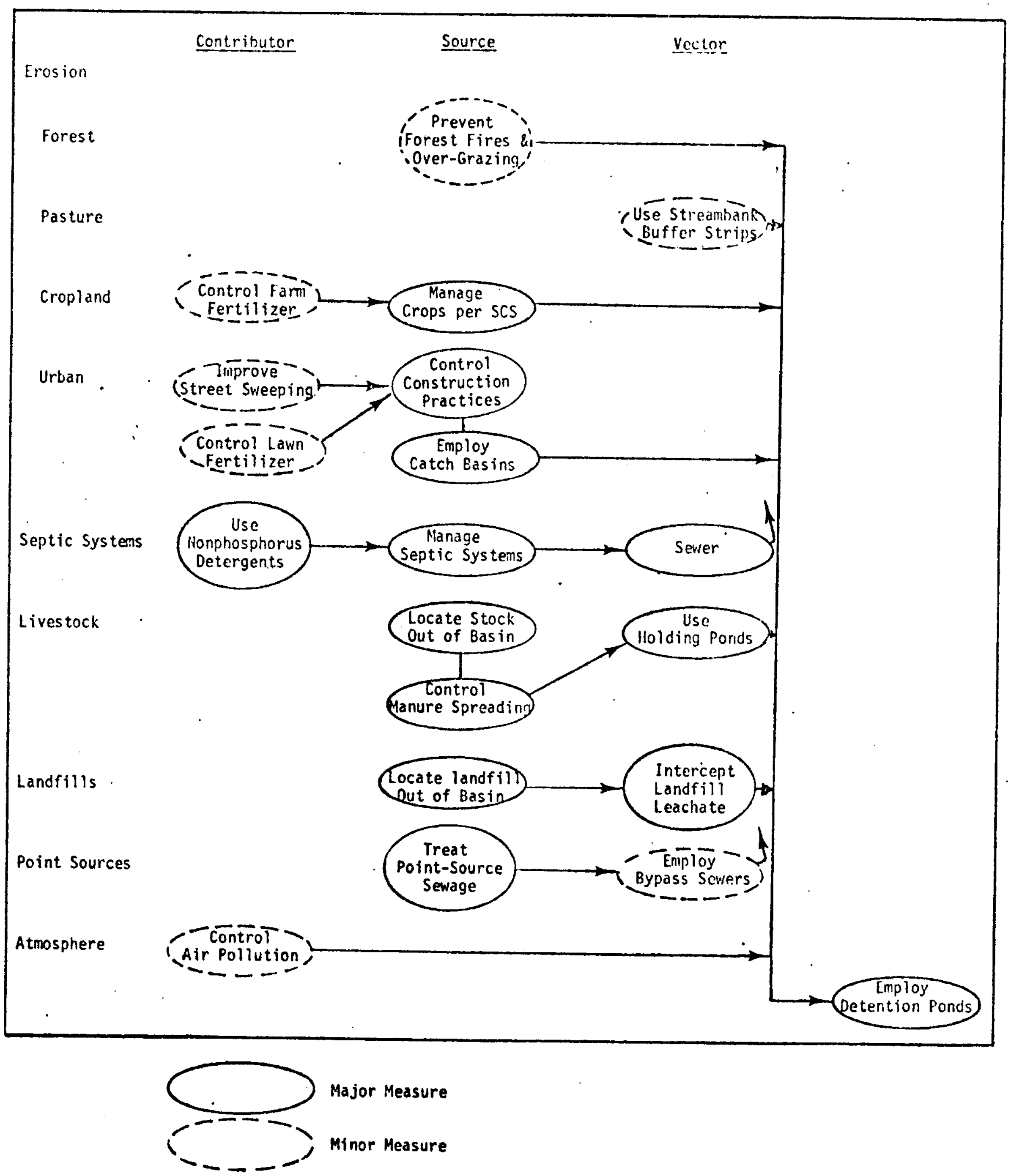

Figure 6.

CEM

PONTOOSUC LAKE WATERSHED CONTROL PROGRAM

Lake	Control Measure	Effectiveness (kg P/yr)	Cost ($1,000)	C/E ($/kg P/yr)	Remaining P (kg P/yr)	Lake Condition
Pontoosuc	Recommended Program					
	1. Do nothing	--	--	--	2,159	3.2
	2. Manage manure	70	1.8	25	2,089	3.2
	3. Maintain catch basins	385	12.7	33	1,704	2.9
	4. Intercept landfill leachate	58	9.9	170	1,646	2.8
	5. Manage crops per SCS	33	8.0	242	1,613	2.8
	6. Sewer	604	140.0	230	1,009	2.1
	7. Build detention pond at mouth of Subbasin T	76	30.0	390	933	2.0
	8. Control construction practices	38	23.9	630	895	1.9
	9. Build detention pond above mouth of Subbasin S	25	25.0	1,000	870	1.9
	Recommended Program	1,289	251.3	190	870	1.9
	Alternative Pontoosuc Program (without sewers):					
	1. Do nothing	--	--	--	2,159	3.2
	2. Use nonphosphorus detergents	304	3.0	10	1,855	3.0
	3. Manage manure	70	1.8	25	1,785	2.9
	4. Maintain catch basins	385	12.7	33	1,400	2.6
	5. Manage septic systems	295	30.0	100	1,251	2.4
	6. Intercept landfill leachate	58	9.9	170	1,193	2.3
	7. Manage crops per SCS	33	8.0	242	1,160	2.3
	8. Build detention pond at mouth of Subbasin T	76	30.0	390	1,084	2.2
	9. Control construction practices	38	23.9	630	1,046	2.2
	10. Build detention pond above mouth of Subbasin S	25	25.0	1,000	1,021	2.1
	Alternative Program	1,138	144.3	110	1,021	2.1
	*11. Sewer	151	140.0	930		

*Not suggested because of poor cost effectiveness or insignificant effectiveness.

Notes:
1. Effectiveness is measured in kg P kept from entering the lake/yr.
2. Cost is shown in $1,000's as annual cost, January 1976 dollars (ENR=2305), 7% discount rate.
3. Cost effectiveness (C/E) is shown as $/kg P kept out of the lake/yr.
4. Lake conditions: 1.0-1.9 = oligotrophic, 2.0-2.9 = mesotrophic, 3.0 and higher = eutrophic.
5. Each control measure is evaluated as if the measures above it were operating. For example, the effectiveness of sewering in the alternative program is greatly reduced because much of the phosphorus in that program will have been removed by the use of nonphosphorus detergents and the management of septic systems.

Table 4.

SUMMARY OF PHOSPHORUS-SOURCE-CONTROL PROGRAM

Control Measure	C/E ($/kg P Removed)	Effect (kg P Removed/Yr)	Costs: Annualized ($1,000's)	Costs: Equiv. Capital ($1,000,000) (7% & 40 Years)	Incidence of Costs
1. Use nonphosphorus detergents	10	417	4.2	0.06	Inconvenience costs at dwellings within 300 feet of lakes and equipped with clothes washers and dish-washers.
2. Manage manure	25	236	6.0	0.08	Increased operational costs to livestock owners in lake basins.
3. Employ catch basins	53	572	30.2	0.41	Increased operational costs to several municipalities for frequent cleaning in lake basins, plus some new construction.
4. Manage septic systems	100	262	25.9	0.35	Increased capital or opera-tional costs at dwellings within 300 feet of lakes, especially for year-round dwellings.
5. Manage crops per SCS	120	157	18.9	0.25	Increased operational costs to cropland owners in lake basins.
6. Intercept landfill leachate	170	58	9.9	0.13	Increased capital and opera-tional costs at Lanesborough landfill.
7. Build detention ponds	380	713	272.0	3.63	Primarily capital costs to municipalities, unless cost sharing can be obtained.
8. Control construction practices	630	291	183.4	2.45	Primarily capital costs to builders in lake basins.
Total*	203	2,706	550.5	7.36	

*Excludes sewering at Ashmere, Plunkett, Pontoosuc and Onota to avoid double costing with sewering program.

Table 5.

CEM

SUMMARY OF RESULTS ACHIEVABLE BY RECOMMENDED PHOSPHORUS-CONTROL PROGRAM

Lake	Trophic Condition			
	Pristine Conditions	Current Conditions	Year 2000 Conditions	
			Uncontrolled	Controlled
Ashmere	Low Olig.	Mid Meso.	Mid Eut.	High Meso.
Buel	Mid Olig.	Low Eut.	Mid Eut.	High Meso.
Garfield	Low Olig.	Mid Meso.	Low Eut.	High Meso.
Goose	Low Olig.	High Olig.	Low Meso.	Mid Olig.
Laurel	Low Olig.	Low Eut.	Mid Eut.	Mid Meso.
Onota	Low Olig.	Mid Meso.	High Meso.	Low Meso.
Plunkett	High Olig.	Mid Meso.	Low Eut.	Low Meso.
Pontoosuc	Low Olig.	High Meso.	Low Eut.	High Olig.
Richmond	Low Olig.	Low Eut.	Mid Eut.	Low Meso.
Stockbridge	High Olig.	Mid Eut.	High Eut.	High Meso.

Table 6.

CEM

SUMMARY OF PROCEDURE

1. EMPHASIZE THE WATERSHED CONCEPT.
2. KEY ON PHOSPHORUS.
3. ESTIMATE LAKE TOLERANCE.
4. QUANTIFY THE ANNUAL PHOSPHORUS SUPPLY.
5. VALIDATE THE SUPPLY ESTIMATES.
6. DEVELOP PHOSPHORUS CONTROL MEASURES.
7. DEVELOP COST EFFECTIVE WATERSHED CONTROL PROGRAM.
8. SUPPLEMENT WITH IN-LAKE MEASURES.
9. READJUST BASED ON PUBLIC FEEDBACK.

Figure 7.

UNCERTAINTIES IN APPLYING LAKE MANAGEMENT STRATEGIES

by

John F. Dowd* and Arthur P. O'Hayre**

Introduction. Accelerated lake eutrophication has become a serious national problem. The Sixth Annual Report of the President's Council on Environmental Quality recently stated that most lakes studied in the eastern states are suffering some degree of accelerated eutrophication. The report suggested that stemming accelerated eutrophication for most of the problem lakes would appear to require control of non-point sources as well as point sources of nutrients. However, the effects of changing nutrient inputs through regional land use management, waste water treatment, or effluent diversion are not clear; and managers are quickly discovering that decisions which are effective in controlling eutrophication for one lake are often unsuccessful when applied to another (Emery et al., 1973).

Despite the complexity of the eutrophication process, simple empirical relationships are often used to predict the impact of management decisions. Errors in estimation could result in substantial costs associated with overdesign or underdesign. However, costs associated with estimation errors are rarely considered in lake eutrophication management. Appropriate safety factors could be employed to help balance the expected costs due to overdesign or underdesign when the cost of one is substantially larger than the other. Expected costs may be further reduced by providing more precise predictions through improved models or additional data.

Lake Restoration Techniques. Eutrophication is the natural process of enrichment or aging of a water body. It is characterized by a high primary productivity because of a large supply of available nutrients and can be accelerated by man. This has happened to many of the lakes in the State.

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Bartsch (1972) concludes that the limiting of phosphorus availability in lakes is the single most important step to be taken in the control of eutrophication. While this is not universally true, and some lakes are limited by nitrogen, carbon, or a trace element, these lakes are far less common. Even so, the first step in the rehabilitation process is to examine the relative concentrations of the various nutrients, and trace elements, if one of the nutrients does not appear to be limiting.

Restoration techniques can be divided into two categories: (1) watershed techniques, and (2) in-lake techniques. The reason for this division will become clear in the discussion of nutrient loading models. Watershed techniques are those strategies designed to limit the production and transport of a nutrient (for this paper, phosphorus) to the lake. This production and transport can be expressed as loading: the amount of nutrient added per unit of lake area per unit of time, and normally expressed as grams per meters squared per year.

Phosphorus loading can come from either point sources or non-point sources, and control strategies must be designed in light of the relative importance of each source. For point sources such as waste treatment plants, tertiary treatment, or effluent diversion may significantly reduce phosphorus loadings. Where non-point sources are important, techniques such as erosion control, strict enforcement of health regulations of on-site sewage disposal, control of agricultural wastes, restriction of lake shore development, or low density zoning in the watershed may be necessary.

The in-lake restoration techniques attempt to reduce the availability of phosphorus which has already reached this lake. These techniques include: water replacement by displacement; drawdown and refill; withdrawal to external treatment facility and return; nutrient inactivation by addition of multivalent metal salts, fly ash,or clay; nutrient removal by controlled aquatic plants; oxygenation by destratification using water pump or diffused air or oxygen systems; covering of bottom sediments with sand, particulate material, or plastic liners; dredging; chemical, mechanical, biological, and physical control of aquatic plants (Boyter and Wanielista, 1973).

While the importance of identifying the causes of eutrophication in a lake before selecting a management strategy or management strategies cannot be overstressed, this is an extremely difficult task. Uncertainties in nutrient loadings, especially from non-point sources, and in-lake processes which affect nutrient availability provide a tenuous base for decisions of large social and financial magnitude.

Restoration Examples. One example of successful control of eutrophication by limiting nutrient loading is that of Lake Washington, in the State of Washington. By 1952, ten sewage treatment plants discharged directly into the lake and conditions in the lake such as chlorophyll a concentration, Secchi disc transparency, hypolimnetic oxygen deficit, and phosphorus concentration gradually worsened until 1963, the year following initiation of sewage diversion. By 1969, diversion of all sewage treatment wastes was complete, reducing phosphorus loading by 55% (Dillion, 1974a). Lake conditions have improved, and the lake is no longer considered eutrophic.

Because of the success with Lake Washington, similar diversions were undertaken and completed in 1968 for Lake Sammamish, a lake near Lake Washington. However, the lake did not respond as expected. Dillon (1974a) has suggested several reasons for this:

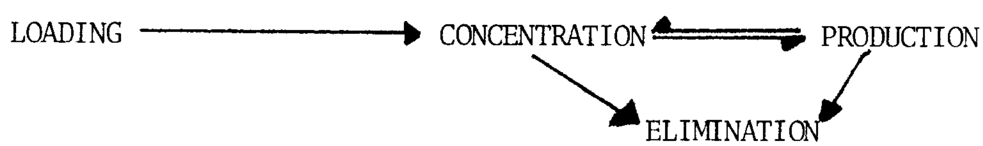
a) the reduction of phosphorus only amounted to 39% of the total load, with a resultant load well above Vollenweider's "permissible" level;
b) the mean depth of Lake Sammamish is considerably less than Lake Washington; and
c) the water renewal time is considerably longer than Lake Washington.

The experience with these two lakes illustrates the hazard of employing a control strategy merely because it worked on another lake. Clearly, the residual loading resulting from a management strategy needs to be evaluated with regard to the physical characteristics of the lake.

Another example of a strategy that was less effective than expected was the aeration of the hypolimnion of Lake Waccabuc, New York (Garrell et al., 1977). The lake was aerated for two summers (1973 and 1974) and although hypolimnetic phosphorus concentrations were reduced in the first summer, this reduction failed to appear in the second summer. It was concluded that the lake was subject to substantial external loadings that masked the effect of aeration on the internal nutrient cycles.

Lake Models. Because the cost (social or financial) of an inappropriate or ineffective management strategy can be very large, it would be useful to predict the effect of a strategy or strategies before implementation. And if the results of a strategy can be predicted, the most cost effective strategy or combination of strategies can be chosen.

One analytical tool for evaluating the effectiveness of a strategy, or evaluating the sensitivity of a lake to becoming eutrophic, is a lake model. The two types of lake models that will be examined are nutrient loading models, and nutrient balance models expressed as the average annual concentration of phosphorus. The following relationship (Dillon, 1974a) is the rationale for using these models for predicting eutrophication, and shows the relationship between loading, concentration, and production.



While it is recognized that nutrient concentration, rather than supply, will control the standing crop of phytoplankton and macrophytes in a lake, loading is a simpler parameter to handle. The concentration of phosphorus can be related to physical expressions of lake water quality, or measures of eutrophication, through regression; for example, the relationship of phosphorus concentration to chlorophyll a. It is possible to similarly relate phosphorus concentration to Secchi disc transparency.

Some of the lake models will now be examined to identify some of the uncertainties in evaluating their parameters or in the way they handle complex interactions. First, nutrient loading models. The simplest nutrient loading model is loading versus mean depth, where mean depth is defined as the volume of the lake divided by the surface area. This is represented graphically in Figure 1. By plotting a number of lakes, it was discovered that most oligotrophic lakes fell below the bands, eutrophic lakes above the bands, and mesotrophic lakes between the bands. Of course, there is great uncertainty concerning the plotting positions of most lakes, thus, uncertainty as to where these divisions should be plotted on the graph. While the mean depth is relatively easy to estimate, the loading is not. This uncertainty is especially great with respect to non-point sources of phosphorus. Figure 2 illustrates the wide variation in total phosphorus loading versus land use, here percent agricultural plus urban land. Because the variation is poorly accounted for, uncertainty is associated with any loading value derived from the land use classification. Other sources of loading uncertainties are groundwater and direct precipitation on the lake. Also, there is the problem of accounting for phosphorus loading from animals such as waterfowl.

One problem with this loading versus mean depth relationship is that for some lakes, it is a poor representation of the complex processes at work. Vollenweider (1973) revised this loading model by multiplying the mean depth by the flushing rate (expressed as the residence time of water). The model is loading versus mean depth divided by residence time, and is graphically represented in Figure 3.

An example of how this may better represent a lake is illustrated by Lake Tahoe (T). On the loading versus mean depth graph (Figure 1), Lake Tahoe plots in the lower right-hand corner, well below the permissible level of loading. On the loading versus mean depth over residence time graph (Figure 3), Lake Tahoe plots on the left, much nearer to the permissible loading line. This is because Lake Tahoe is a very deep lake, but it has an extremely long residence time. Limnological investigations indicate that Lake Tahoe, while oligotrophic, is relatively close to its level of permissible loading. The addition of this parameter, residence time, does not always result in a significant shift in plotting position. Lake Vanern (V) is oligo-mesotrophic with either model.

This model has not resolved any of the problems associated with determining nutrient loadings, but it has improved the loading versus lake characteristics relationship. Dillon (1974a) called this model "the best method available for obtaining an estimate of the degree of eutrophy of a given lake."

The first two models assume that the outflow concentration is the same as the lake concentration. This will not be true in stratified lakes. Dillon (1974b) proposed a third nutrient loading model which attempts to account for this difference:

$$L\ (1-R)/\rho \text{ versus } \bar{z}$$

where L is the loading, (1-R) is the fraction of loading that is not retained in the lake but is lost by outflow (R is the retention coefficient), ρ is the flushing rate, and $\bar{z}$ is the mean depth. There is, of course, uncertainty concerning the value of R, the retention coefficient.

One example of a simple nutrient concentration model, here expressed as steady state, is:

$$[P] = \frac{L}{\bar{z}\ (\sigma+\rho)}$$

where [P] is the total phosphorus concentration and σ is the sedimentation rate coefficient. As stated earlier, phosphorus concentration can be related to chlorophyll a concentration or Secchi disc depth. These in turn can be defined in terms of a Trophic State Index, to describe whether a lake is eutrophic, mesotrophic, or oligotrophic. In theory, then, one need only solve this equation for the phosphorus concentration and thus adequately describe the condition of the lake. This representation will be correct if two conditions are met: the model's parameters are correctly enumerated; and the model accurately represents the physical processes of the lake.

Only the parameter "sedimentation rate coefficient (σ)" is new in this model. Uncertainties remain with estimating the other parameters and a new parameter has been added for which uncertainty exists.

In fact, because of the difficulty in estimating σ (the sedimentation rate coefficient), Vollenweider related it to retention and obtained it indirectly when validating this model.

The utility of this approach can be evaluated by examining four important assumptions inherent in this model (Dillon, 1974b):

1) The loading, flushing, and sedimentation rates are assumed constant through time;
2) The sedimentation process is treated as a first order chemical process dependent only upon the concentration in the lake;
3) Stratification is ignored, resulting in an unrealistic flushing rate; and
4) The phosphorus concentration in the outflow is equated to the mean phosphorus concentration of the lake.

Assumptions one and two, while obviously not realistic from a lake process point of view, are probably adequate assumptions for most lakes. The assumption of no stratification is invalid for a number of lakes, and for some may lead to significant error. Vollenweider attempted to account for stratification by introducing the parameter ρ_{eff} (the effective washout coefficient) into his lake model. This parameter is expressed as:

$$\rho_{eff} = \frac{\rho}{1 + (V/V_E - 1)\rho}$$

where V is the lake volume and V_E is the "mean exchange epilimnion," the fraction of the lake taking part in the washout process. The "mean exchange epilimnion" is less than the volume, and the effective washout coefficient approaches the flushing rate as the "mean exchange epilimnion" approaches the volume. While this more closely approximates the physical process, a new parameter has been introduced that must be evaluated - the "mean exchange epilimnion (V_E)."

The last assumption, that the outflow concentration of phosphorus is equal to the mean lake concentration, is not correct for stratified lakes. While this difference is partially accounted for by the effective washout coefficient, Dillon (1974b) suggests that the simple representation of the outflow being a constant fraction of the average lake concentration would be a suitable representation for the present time.

Uncertainty Analysis Framework. Given the uncertainties in parameter values and model selection, an analysis framework has been devised which enables these uncertainties to be stated explicitly (O'Hayre and Dowd, 1976). This is illustrated in Figure 4. To shorten the discussion, it is assumed that Vollenweider's loading versus mean depth water fill-in time model is an accurate representation of a lake. Examining the model, it is obvious that the key parameter with respect to uncertainty is loading. To express this uncertainty, a probability mass function of loading can be constructed by fitting a theoretical distribution to measured values obtained, for instance, from the literature (Figure 5). This example is for agricultural land.

If there are insufficient data to fit a distribution directly, a probability density function may be fitted. Figure 6 represents two land use classifications fitted to a Weibull distribution using a 5 parameter assignment technique of Mercer and Morgan (1975). Two important points are illustrated by this figure. First, different loading values. (The mode for open land is approximately 0.4 Kg/ha-yr, while the mode for urban land is approximately 1.5 Kg/ha-yr.) Second, the variation of values in the literature is represented by the shape of the PDF. If the uncertainty represented by this curve, for example the urban land curve, is considered too large, this estimate may be improved by obtaining additional data, such as by sampling.

One way to relate probability density functions for loading to the probability of the lake becoming eutrophic is by using Monte Carlo simulation. This is accomplished by randomly selecting loading values from the probability density function, evaluating the values using the lake model, and calculating the probability of exceedance.

Two other families of uncertainties are those associated with the cost of various strategies and those associated with the applicability of the model. The cost uncertainties could be handled similarly to the loading uncertainties. Model uncertainties are far more difficult to handle.

The decision step in Figure 4, "Are criteria satisfactory?", indicates that lake managers have to become used to some measure of risk associated with eutrophication potential for a management strategy. Obviously, there has always been risk associated with a management choice. Here we are trying to explicitly define this risk.

The way that additional information is incorporated into the analysis is by using Bayes Theorem. This would be used if, for instance, the worth of gathering additional information on urban loadings justifies the cost of gathering these data.

Summary. In conclusion, while there are a number of lake management strategies for controlling eutrophication, no one strategy or combination of strategies can be expected to be effective (or the most cost effective) for all lakes in a region. The choice of rehabilitation technique has to be made in light of the causes and processes at work for a given lake. Because of the uncertainties involved in both the appropriateness of lake models and the values of lake model parameters, strategies may best be handled in an uncertainty framework.

The critical parameter for the useful loading versus mean depth over residence time model is loading. One way of evaluating land use changes is to fit a Weibull distribution to the available land use - loading data and evaluate the exceedance probability by Monte Carlo simulation.

If the goal is to characterize the present condition of a lake, the best approach is to sample the lake. If the goal is to predict future conditions, one needs to employ some form of a model, recognizing the many uncertainties involved.

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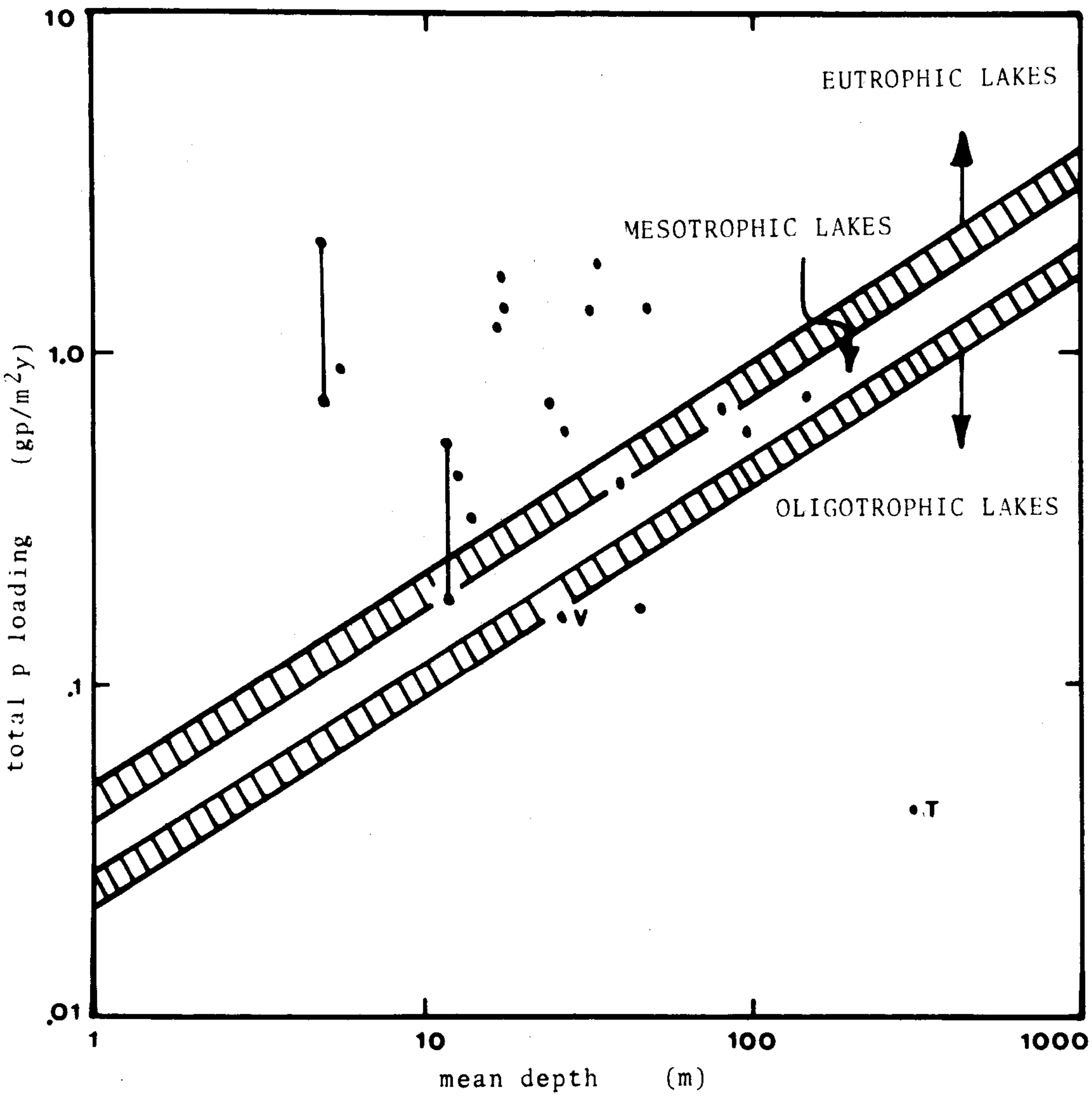

Figure 1. Loading versus mean depth (Dillon, 1974a). T is Lake Tahoe and V is Lake Vanern.

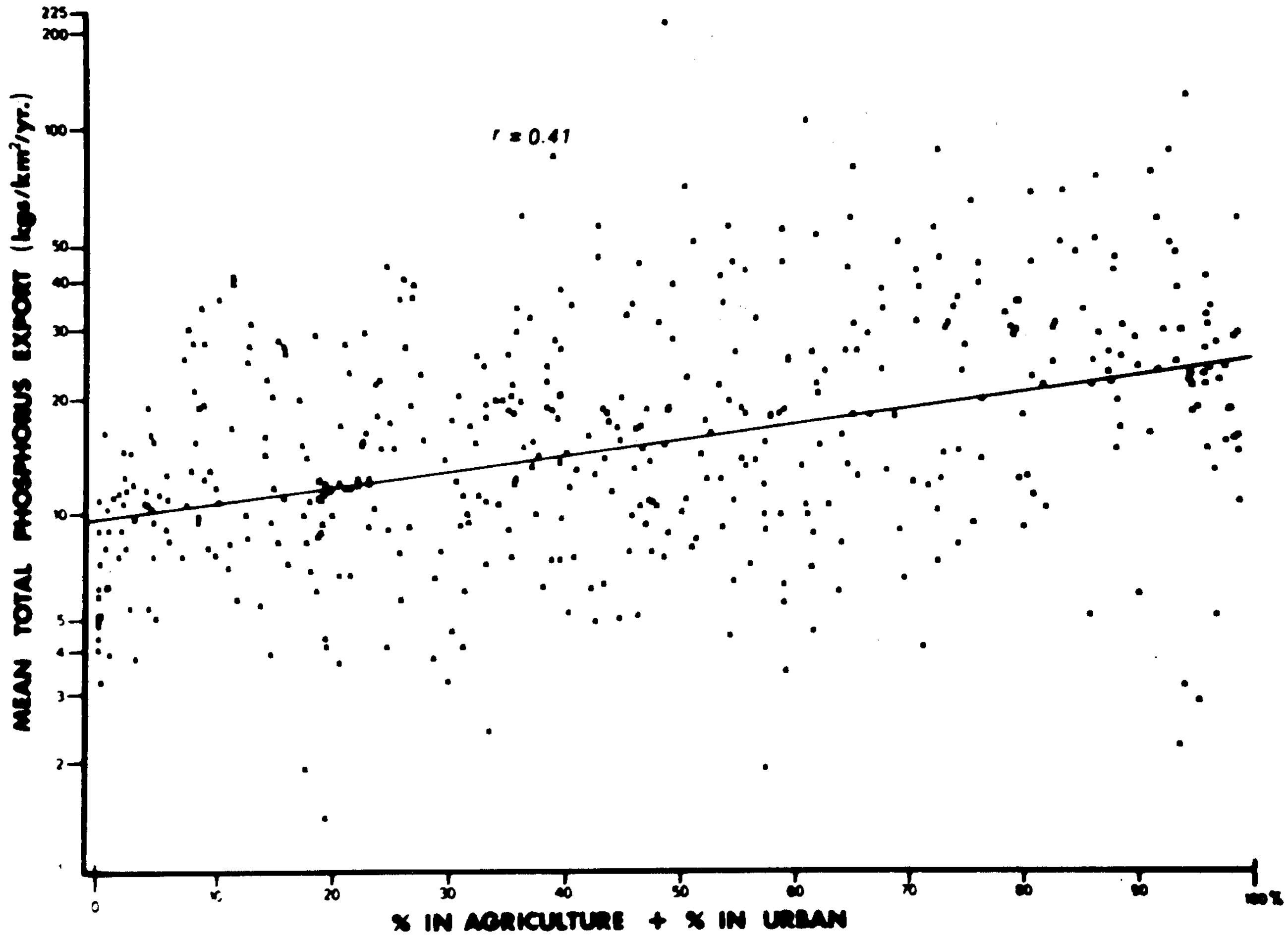

Figure 2. Scattergram of mean total phosphorus export versus percent of agriculture and urban land (Omernik, 1976).

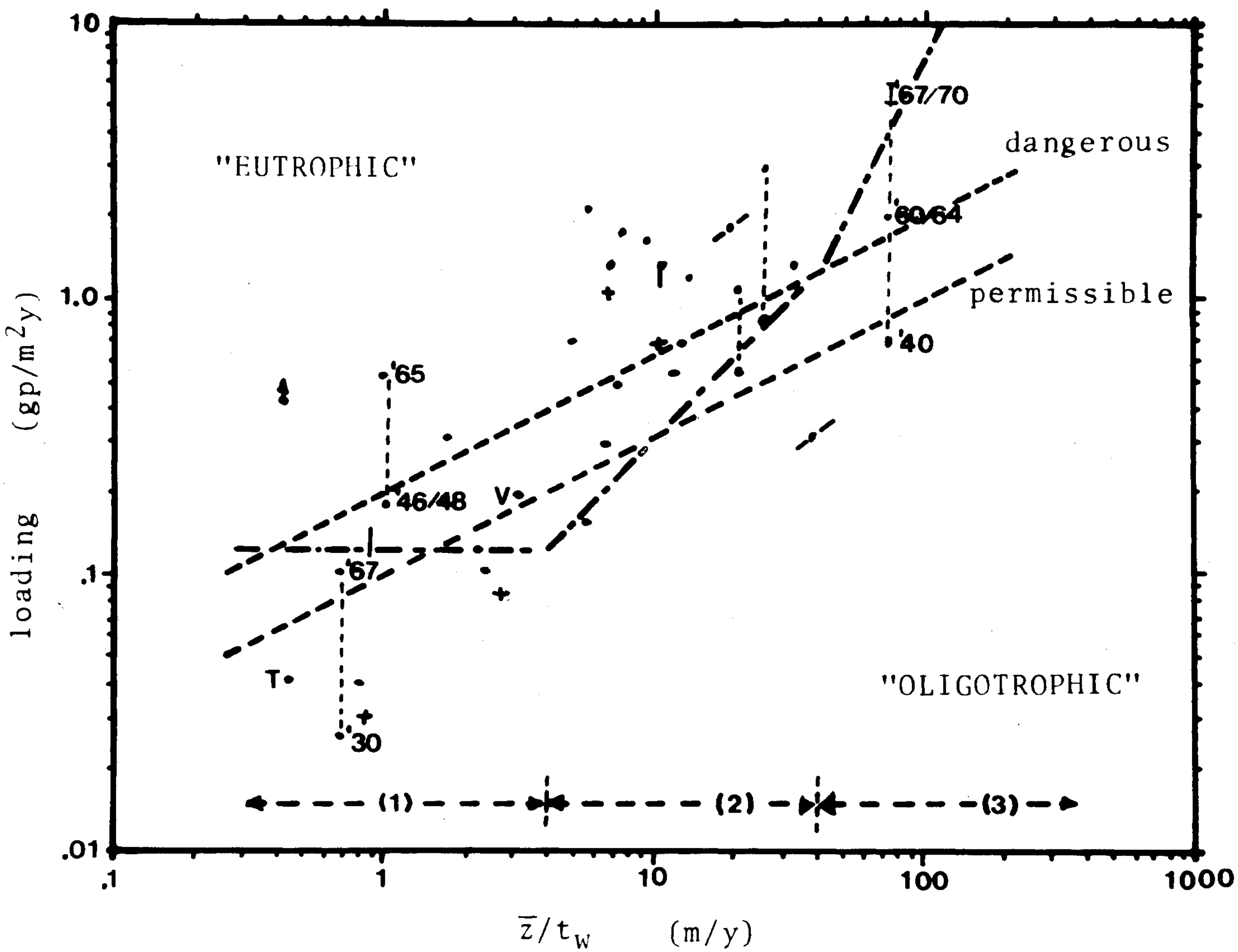

Figure 3. Loading versus mean depth/residence time (Vollenweider, 1973).

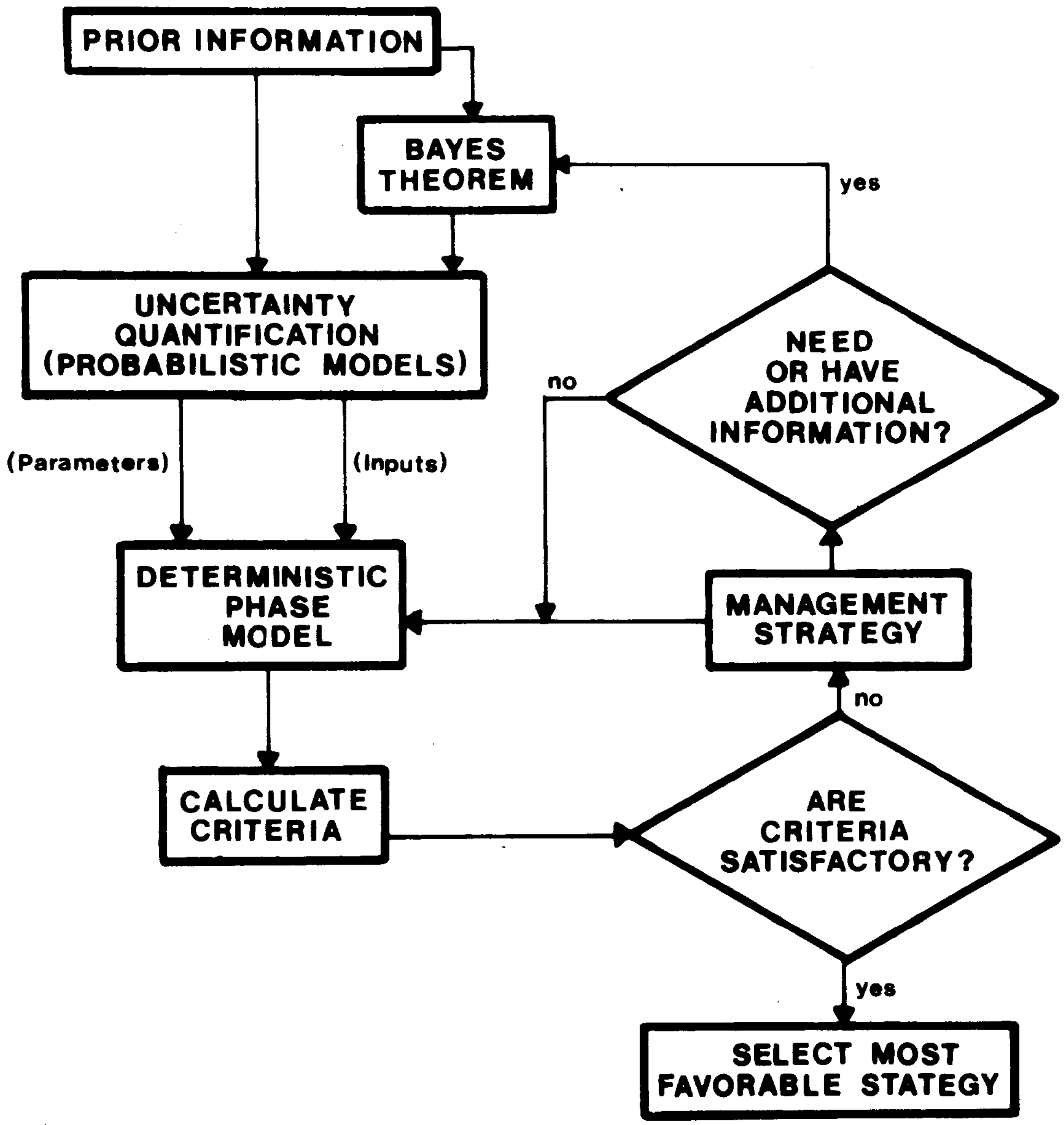

Figure 4. Planning methodology for managing lake eutrophication (O'Hayre and Dowd, 1976).

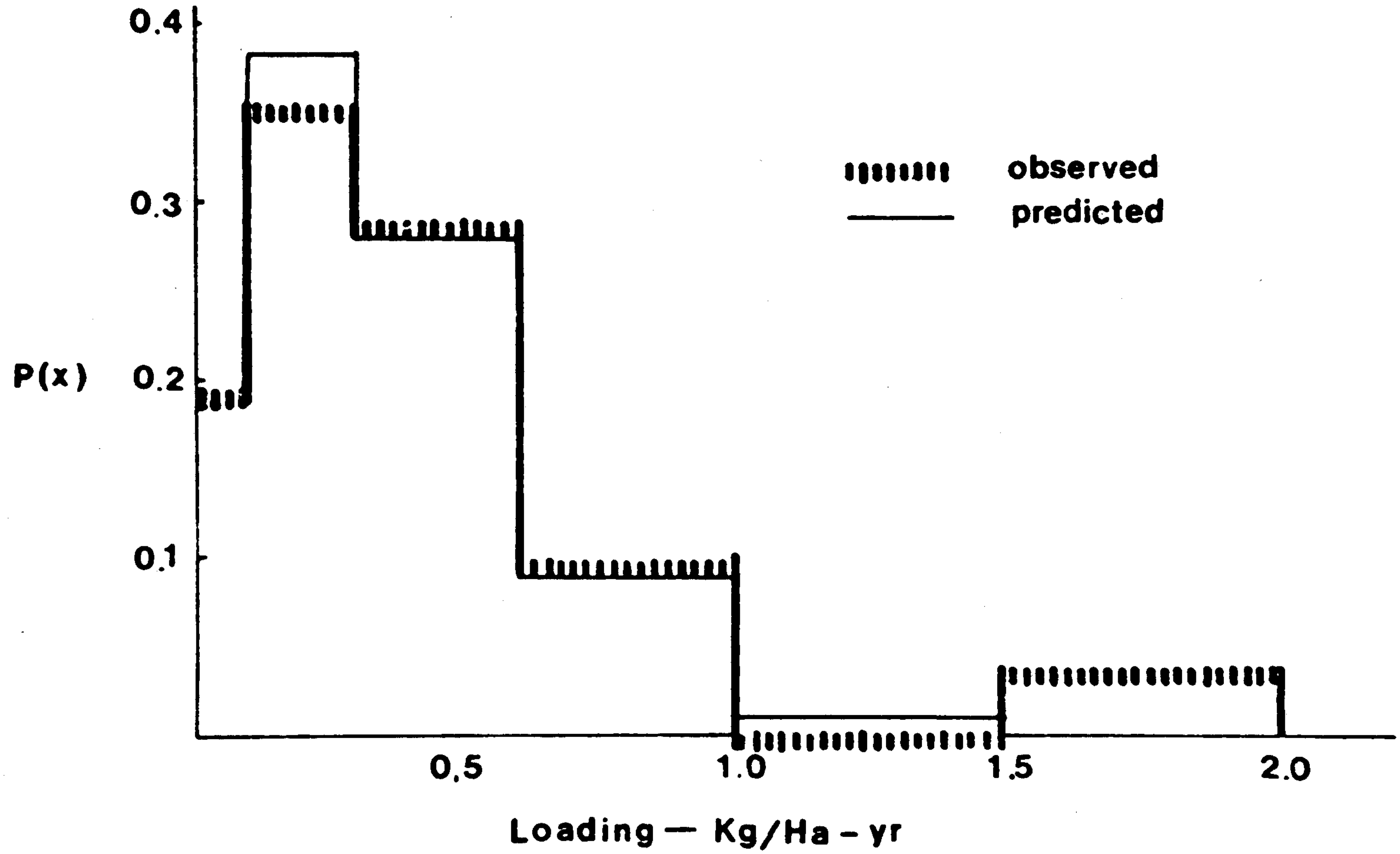

Figure 5. Weibull distribution fitted to data on phosphorus loss from agricultural land (O'Hayre and Dowd, 1976).

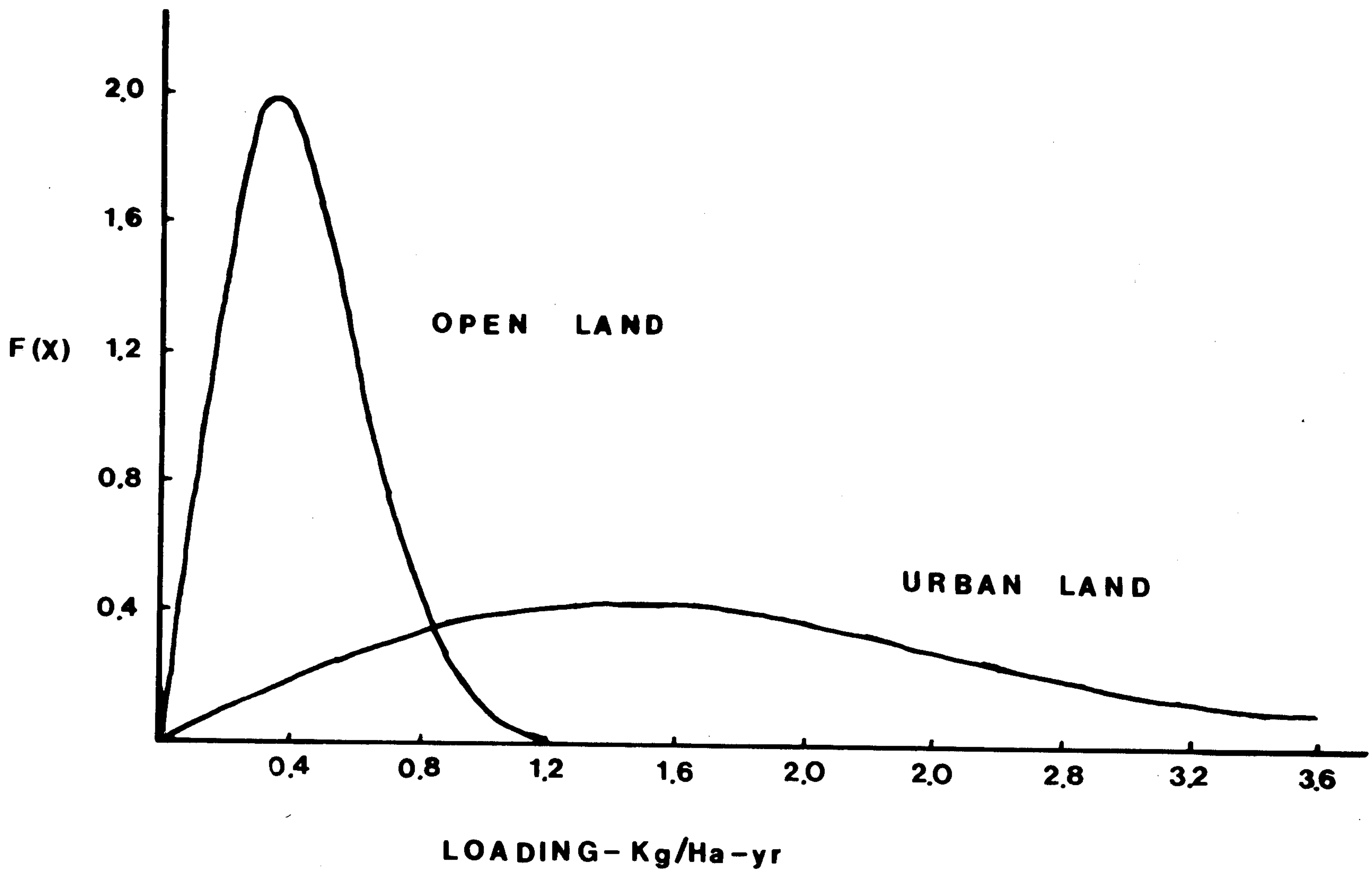

Figure 6. Phosphorus loading distribution for open land and urban land (adapted from O'Hayre and Dowd, 1976).

RELATIONSHIP OF LAND USE TO WATER QUALITY

by

Henry I. Snider*

An Office of Water Research and Technology (OWRT) allotment research grant was awarded in July 1975 to myself, Dr. Michael Gable, Biological Sciences Department, and Mr. R. Max Ferguson, Earth and Physical Sciences Department, Eastern Connecticut State College. The primary project objectives fall into two categories: research and educational (see Research Completion Report, A-068-CONN).

Specifically, the research objectives were as follows:

1. To examine the relationship of selected environmental factors to current land use and zoning in drainage basins containing standing bodies of water.

2. To examine current land use and zoning with respect to proposed future planning models.

3. To define the most important environmental factors and land use criteria for examination of existing and forecast of potential eutrophication and pollution problems.

4. To study the chemistry of eastern Connecticut lakes and ponds on a reconnaissance basis with intense study of five or more specific lakes.

During early work, it became apparent that the study of zoning was impractical for several reasons; therefore, the zoning aspects were not pursued. It also became obvious that there were limited recent chemical data for the lakes and ponds of eastern Connecticut: data essential for analysis of degree and rate of eutrophication of water bodies. Research objective 4 was therefore added. Specific achievements for each objective are as follow:

Research Objective 1: Methodologies and techniques for land use versus environmental factors were developed. Relationship of land use to Natural Soils Groups was emphasized and has been examined in 12 lake drainage basins (watersheds.) Lake morphometric parameters, drainage basin morphometric parameters, lake water specific conducti-

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vities and lake water chemistries have been gathered for examination and several interrelationships analyzed.

Research Objective 2: Future planning models in Connecticut consist of two categories: (1) Comprehensive Plans of Development at town, river basin, regional and state levels; and (2) Individual plans based on eutrophication or pollution studies. Comprehensive plans are stated in general terms and include but do not discriminate watershed areas with lakes or ponds versus those without. Individual watershed plans are usually after-the-fact studies based on problems brought on by eutrophication, pollution or nuisance types of algal blooms and usually are unrelated to other watersheds except for procedures or methodologies developed for the individual problem area.

Current land use has been qualitatively analyzed with respect to the above and recommendations made for future zoning concepts.

Research Objective 3: Important environmental factors to be related to land use for analysis and lake management must be practicable, attainable, rapid and inexpensive. Unfortunately, there is no single factor that can be used to examine and forecast the degree and rate of eutrophication or pollution. The relationship of land use to soils based on standard land use (SLUCONN) and Natural Soils Groups is a powerful, inexpensive and practicable methodology. Lake and drainage basin parameters and parameter ratios, lake water chemistry and physical measurements of specific conductivity and Secchi Disc transparency are necessary adjuncts for complete analysis.

Interrelationships of several of the above factors have been analyzed.

Research Objective 4: Specific conductivity measurements were taken on 578 water samples from 108 lakes or ponds (74 lakes by June 1977- Figure 1), 89 of which were in eastern Connecticut. Chemical analyses were made on 429 water samples from 95 lakes or ponds, 76 of which were in eastern Connecticut. The 19 lakes or ponds in central and western Connecticut were sampled for cross-correlation with other recent studies or were of interest to specific students. Intensive study on six lakes has been carried out for more than two years, and lakes in proximity to major highways have been sampled at shore or spillway points during the last year. The relationship of specific conductivity to major chemical constituents has been verified, and anion and cation dominance of lake waters has been analyzed. A potential method for calculating "original" water chemistry has been derived using current water chemistry and historical chloride and bicarbonate analyses.

Research Procedures Used.

Research Period: Collection and collation of land use, zoning and drainage basin outline maps commenced during the summer of 1975. Soil maps were collected at the same time but were pantographed to an appropriate scale during the summer of 1976. Chemical and physical measurements on Crystal Lake and Crystal Pond started in November 1975, with Alexander Lake added on the second sampling date in April 1976. During the summer of 1976, 17 lake or pond waters were sampled with specific conductivities measured for 35 lakes or ponds. In November 1976, a wide reconnaissance net for specific conductivities was undertaken for 47 lakes, most of which had previously been measured. This work was done to verify previous measurements and to widen out baseline. During the summer of 1977, specific conductance with concurrent chemical analyses will be made on 77 lakes. During the fall semester of 1977, an additional 14 lakes will be analyzed.

Map overlay work and parameter measurements were continuously carried out from 1975 throughout the grant period and continued on in current course work.

Methods Used.

Map Overlay Technique : Land use, soils and drainage basin maps were collected from state and federal sources. Land use and drainage basin outline maps were at a common scale of 1" = 2000'. Detailed soils maps or general soils maps on a 1" = 1320' scale were pantographed at a 1 1/2 reduction to 1" = 1980', compatible with the land use and drainage basin maps and having an approximate areal error of two percent.

Lake and drainage basin outlines were traced onto several sheets of transparent paper. Individual tracings were then made for land use for each watershed and for combined soil series based on Natural Soils Groups (Table 1) for each watershed. Areal computations were made for each drainage basin for land use and soils by overlaying transparent 10 x 10 to 1 inch cross section paper on the individual maps and counting the squares; each square is equal to 0.918 acres. These areas were also measured with a compensated optical planimeter having one variable arm adjusted to read acres directly. In many cases graph and planimeter measurements were done by several students; these were then averaged.

Land use maps were then overlain onto soils maps for measurement of housing on soils, agriculture on soils, etc. Again, multiple measurements were averaged.

Averaged measurements were then tabulated and percentages computed.

Lake and Drainage Basin Parameter Measures : Lake surface areas and drainage basin areas were measured by graph and planimeter techniques described above. Linear measurements were made with a map measurer (rotometer). Elevations were taken from standard U.S. Geological Survey 7 1/2 minute topographic quadrangle maps for computation of basin relief. Lake and drainage basin morphometric parameters and computations follow standard limnological texts and manuals and modifications by Dr. J.J. Kerekes, Department of Environment, Canadian Wildlife Service, c/o Biology Department, Dalhousie University, Halifax, N.S., Canada, in a series of papers from 1968 to the present.

Chemical and Physical Procedures : Variable sampling procedures have been used, starting with sampling from shore points convenient to roads or to boat launch areas. From 1977 on, however, samples were taken at or near spillways, when possible. On lakes, samples were taken from a small boat anchored at approximately the deepest point of the lake, verified by electronic depth recorders. Water samples for chemical analysis taken from surface waters were collected directly into polyethylene bottles held wrist deep below the surface (approx. 0.2 meters). Subsurface samples were taken from the bottom water (0.5 to 1.0 meters above the bottom) and from an intermediate depth (about one-half the maximum depth) with a 1.2 liter Kemmerer sampler (brass in 1975-76, non-metallic in 1977-78).

Chemical analyses for inorganic constituents such as Ca^{++}, Mg^{++}, HCO_3^-, $SO_4^=$ and Cl^- were taken to the Earth and Physical Science Department's laboratories at ECSC. Analyses were usually completed within 24 hours after sampling, many within 8 hours. Samples were raw water except for extremely turbid or algal-rich waters which were filtered through rapid-flow qualitative filter paper.

Chemical tests were run with a Hach DR-EL/2 Direct Teading Engineer's Laboratory. Alkalinity (HCO_3^-), Hardness (Ca^{++} & Mg^{++}) and (Cl^-) tests were titrations; all others were spectrophotometric. High range Silica (0-15 mg/1) was substituted for the standard low range (0-2mg/1), alleviating the need for sample dilutions in all but one lake. Distilled water has been used in the laboratory since the summer of 1976 when it became apparent that deionized water was reacting like silica-rich water;

i.e., sample dilutions for low range tests all measured much greater than 2 mg/1. To avoid any possibility of interference by resins in deionized water, all final washing, rinsing and sample dilutions use distilled water.

Dissolved oxygen, temperature, conductance, Secchi Disc transparency and transmissivity (of light) were measured in situ. Dissolved oxygen and temperature measurements were taken at least at 1 meter intervals with a YSI=54ARC D.O.-Temperature meter. Some measurements were taken at 1/2 or 1/4 meter intervals, especially when values changed rapidly. Conductance and temperature were measured in situ with a YSI-33 Conductivity-Temperature meter as well as water samples being measured with a Lab-Line (Electronic Switchgear) Mark IV temperature compensating Conductivity Meter with a Sproule cell, K=o.1. The Secchi Disc was an 8-inch (20 cm) disc with balck and white quadrants. A Beckman Environeye Transmissivity Meter, EV3, was used in 1976; unfortunately, since then, it has been out of commission.

Results and Conclusions.

Research Objective 1: Selected Environmental Factors and Land Use. Table 2 lists the lake and drainage basin morphometric parameters for 12 lakes studied in eastern Connecticut. Land use, lake water chemistry, soils and regional geological data were all essential for analysis of lake water- drainage basin relationships. Natural Soils Groups clustering from detailed soil series maps simplifies areal computations and data analysis is rapid and is more useful than individual or combined soil series since the NSG system inherently combines soil characteristics, limitations and suitabilities common to a variety of member soils.

In the lake basins studied, past land use practices in residential and agricultural siting have not been the prevalent cause of lake eutrophication in most of eastern Connecticut. The most adaptable land has been the most used in the past. This suggests, however, that further residential intensification will become a major contributing factor to accelerated eutrophication since the less adaptable "hardpan" and close to bedrock soils are left for development.

Recommendations for lake watersheds are:

1. Local or state purchase of land with limiting factors of severe

or very severe for septic system or leach field design;

2. Variable high acreage (low density) zoning on limited capability soils;
3. Mandated engineering specifications for limited capability soils; and;
4. Strict enforcement of the Inland Wetlands Act.

Research Objective 2: Future Planning Models . Connecticut planning processes show no specific concern for lake or pond watersheds. Town, regional and state plans formulated to date are general in nature and show concern for Inland Wetlands and "point source discharge to natural lakes" only. Strategies are based on phosphorus control measures.

It would be presumptuous to recommend panaceas in this area other than to suggest discontinuance of the use of road salt or other chemical additives during winter sanding and to emphasize air quality improvement for the State of Connecticut, since wet and dry fallout are major contributors of specific chemical constituents and plant nutrients to lake waters.

Individual lake and lake watershed studies are currently being carried out under 208 funding by various regional agencies in Connecticut. Lake management methodology developed from these studies emphasizes phosphorus control measures. Analytical techniques appear to be sound and could be expanded for analysis of nutrients other than phosphorus. Strategies are based on cost-effectiveness and should also be of value in analysis of nutrient and pollution sources other than phosphorus. These studies, although valuable, are overly simplistic, restricted to the study of nitrogen and phosphorus, and limited in their views as to the need for baseline data acquisition and the need for monitoring.

Efforts made in both areas of planning, the broad area and the specific lake area are respected; however, cookbook methodology to solve the problems of lakes with different chemistry, bottom sediments, nutrient content, etc., are viewed pessimistically.

Research Objective 3: Environmental Factors and Land Use Criteria. Unfortunately, neither single nor paired factors can be used to examine and forecast eutrophication or pollution potential or rate. Direct measurement and modeling techniques have both been used to develop concepts and techniques for eutrophication plans. Natural Soils Groups surrounding land use, major chemical content and specific conductivity of lake water are minimal parameters necessary for analysis of lake water quality in relationship to the lake watershed (Table 4).

In retrospect to the study done, it has been found that the relationship of Natural Soils Groups versus land use is a good guide for initial management judgement. Indepth studies for particular situations should not stop with this simplistic reference, nor should studies be restricted to one or two intensely studied parameters. The crux in solving any problem is first in defining the problem. In the case of lake watersheds, it is too often stated that the "problem" consists of point and non-point sources of nutrients in the eutrophication process. The "problem," as seen here, is the potential malpractice of using soils that are not suitable for the use proposed. Natural Soils Groups are suited for rapid computation, are easily obtained from either detailed or general soils maps, and can be readily analyzed for land use capability. The relationship of this parameter to current land use, therefore, is practicable, attainable, and most importantly, correlatable with areas not necessarily having the same soil series, but having similar capabilities.

Currently there are many working tools for obtaining a multitude of parameters that are useful in lake and lake watershed analysis. There are topographic and soils maps for slope measurement; topographic maps for elevations, relief and lake surface parameters; soils maps and land use maps for all of Connecticut; drainage basin maps and published data on drainage basin areas; bathymetric maps and depth data for more than 160 lakes and ponds; historical chemical data on many lakes and ponds; and a multitude of equations and models interrelating parameters that are measurable from the above.

The need is for: current chemical analyses of lake waters, not only for nutrients, but also for trace metals and organic material that may be hazardous to health; extension of lake mapping for depth data and bathymetric maps; and commitment to a long-term water quality monitoring program.

In detailed studies familiar to the author, phosphorus impact on two lakes in eastern Connecticut was analyzed by a set of models using measured and estimated values and data from literature searches. The analysis was based on: (1) Erosion-related sources; (2) Contribution from septic systems; (3) Atmospheric contribution; (4) Livestock contribution;

(5) Motor vehicle contribution; and (6) the Dillon-Rigler Phosphorus Analysis equation. The two studies - Connecticut 208 Special Lake Study on Columbia Lake, and Wangumbaug (Coventry) Lake - will be available from the Windham Regional Planning Agency, 21 Church Street, Willimantic, Connecticut 06226. The comprehensive methodology developed in these studies, although restricted to phosphorus analysis, could be modified for a number of other elements, either nutrient sources leading to eutrophication or metals and organics detrimental to health.

Alternative methodologies to the above should be developed to check the validity of estimates made. Kerekes (1974) suggested the ratio of shore length to lake volume as a meaningful morphometric index, while Rawson (1960) noted that lakes with high total solids have relatively heavy biological crops. These references are illustrative of the view that morphometric parameters, lake water chemistry, and soils and land use information are all necessary for intelligent analysis.

One point that must be emphasized, however, is that the factors of time and timing are the weakest link in our understanding of lake processes. The rate of removal of nutrients may limit organic production as well as the lack of nutrients. Inversely, the rate of input at optimum growth periods would enhance production even though yearly averages show submoderate amounts of nutrients available in a lake. There is an apprehension, therefore, of the subordinate role of seasonal dwellings in proximity to lake shores in the analysis of phosphorus control. The concerns are: first, that seasonal occupation of these dwelling contributes septic system leachate near or at peak times for algal growth; and second, that the seasonal dwellings of today will become year-round dwellings in the near future, thereby contributing leachate on a continual basis.

Research Objective 4: Lake Water Chemistry: Lake waters of eastern Connecticut vary from extremely soft to medium hard. The breakdown is as follows:

Extremely soft (HCO_3^- <10 ppm)	41	
Soft (HCO_3^- 10-28 ppm)	33	
Medium Hard (HCO_3^- 28-84 ppm)	1	(man-made farm pond)

Versailles Pond, a paper mill pond formed by damming a river, varied from medium hard to extremely soft water, prior to and after artificial agitation, respectively. This could be anticipated since eastern Connecticut is primarily underlain by granitic and gneissic bedrock and probably the major components of the glacial deposits within which the lakes and ponds lie. The total dissolved material and the specific conductance of the waters do not conform to this simplistic categorization, however.

A total of 108 lakes were measured for specific conductivity, 90 of these from eastern Connecticut. Table 5 summarizes these data. Freshwater inland lakes would have expected dominance of Ca> Mg> Na> K and $HCO_3 > SO_4 > Cl$ (Rawson, 1960). Na and Cl could be predominant ions in lakes nearest ocean areas (Kerekes, 1973) and presumably may have Mg and SO_4 also contributed by sea water spray and precipitation from ocean sources. Na and Cl alone could be added constituents from road salt. Several precipitation samples analyzed from 1976 through 1978 show high H^+, Cl and SO_4 with negligible Ca and Mg content. The variety of lake waters found implies that original Ca and HCO_3 dominant waters have been heavily influenced by precipitation and humanly induced chemical input (road salt, water conditioning effluent, automobile emissions, etc.).

Ca and Mg analyses using 10 ml aliquots for titration of this study were checked versus Atomic Absorption work of Norvell and Frink (1975) on 14 lakes. Of the 28 analyses checked (14 for each Ca and Mg), 79 percent were within one ppm and all were within two ppm. HCO_3 analysis from 10 ml aliquot titrations were compared with Total Inorganic Carbon analyses from the University of Connecticut's Biology Department, 9 or 11 being within 2 ppm. Equipment and chemicals for titrametric analysis are inexpensive and portable, and careful titrations result in data comparable with major analytical instrumentation.

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Abstract

Land use, soils and lake water chemistry were studied in 12 lake drainage basins in eastern Connecticut. Housing and agriculture are the most prevalent uses of land in the lake watersheds; however, the percentage of use varies substantially. Soil studies were based on Natural Soils Groups which also varied from basin to basin. In general, the most adaptable land for urban development has been the first used for residential subdivision. Further residential intensification, especially on hardpan soils, could become a major factor in eutrophication acceleration and water pollution. The relationship of land use and soils to water chemistry is complex and must consider regional differences in waters prior to examination for change.

Connecticut planning processes do not specifically differentiate lake watersheds from other land areas. Strategies are based on phosphorus control only. Baseline data acquisition and a monitoring system are recommended additions for future planning models.

Environmental factors of land use, soils and water chemistry can be augmented with lake and drainage basin morphometric parameters for analysis of sources and rates of eutrophication and pollution. These indices may be useful for moderate to long-range estimation, but must

be modified to cover seasonal changes.

Eastern Connecticut lakes are mostly soft and extremely soft with respect to bicarbonate content. Specific conductivities of lake water range from 34 to 154.4, with a mean of 68 and median of 62 micromhos/cm. for 76 lakes sampled. An approximation of total dissolved solids in ppm or mg/l can be made by multiplying specific conductance by 0.63. Major cation and anion dominance vary. "Original" water dominated by calcium and bicarbonate ions has been changed mainly by addition of sodium and chloride ions.

Figure 1. Location Map of Lakes Studied.

MAP SYMBOL	LAKE/POND	STUDY*
A1	ALEXANDER	1
A2	ALVIA CHASE	4
A3	AMOS	1
A4	AMSTON	3,4
A5	ANDERSONS	6
A6	ANDOVER	1
A7	ARMITAGE	4
A8	ASHLAND	6
A9	AVERY	4
B1	BABCOCK	4
B2	BASHAN	4
B3	BEACH	4
B4	BEACHDALE	6
B5	BIGELOW-Hampton	4
B6	BIGELOW-Union	4
B7	BILLINGS	4
B8	BLACK	4
B9	BOG MEADOW-Killingly	4
B10	BOG MEADOW-Norwich	4
B11	BOGUE BROOK	4
B12	BREWSTER	4
B13	BUNGEE	4
C1	CHAFFEE	4
C2	COLUMBIA	1
C3	COVENTRY (WANGUMBAUG)	1
C4	CRYSTAL LAKE	1
C5	CRYSTAL POND	1
D1	DARROWS	4
D2	DECKMORE	4
D3	DEEP RIVER	5
F1	FAIRY LAKE	6
F2	FITCHVILLE	3
F3	FROG	4
G1	GARDNER	1
G2	GLASGO	6
H1	HALLS	4
H2	HANOVER	4
H3	HAYWARD (SHAW)	4
H4	HODGE	4
H5	HOLBROOK	4
H6	HOPEVILLE	6
H7	HORSE	4
K1	KNOWLTON	4
K2	KONOMOC	6
L1	LAKE MARIE	6
L2	LAKE OF ISLES	4
L3	LONG POND	1
M1	MASHAPAUG	4
M2	MONO	2
M3	MOODUS	4
M4	MOOSUP	1
M5	MOREY	4
N	NORWICH POND	4
O	OXOBOXO	4
P1	PACHAUG	6
P2	PATAGANSET	4
P3	PICKEREL	4
P4	PINE ACRES	4
P5	POCOTOPAUG	4
P6	POWERS	4
Q	QUADDICK	4
R1	RED CEDAR	2
R2	ROGERS	4
R3	ROSELAND	3
R4	ROSS	4
S1	SHENIPSIT	4
S2	STAFFORD	4
S3	STATE LINE	4
T	TERRAMUGGUS	1
U	UNCAS	4
V	VERSAILLES	4
W1	WAPPAQUASSETT	2
W2	WHEELER	4
W3	WILLIAMS	4

*STUDY

1-Lake chemistry and drainage basin study.
2-Shore or spillway sample and drainage basin study.
3-Lake chemistry.
4-Shore or spillway sample chemistry.
5-28 Foot depth sample chemistry only.
6-Specific conductivity only.

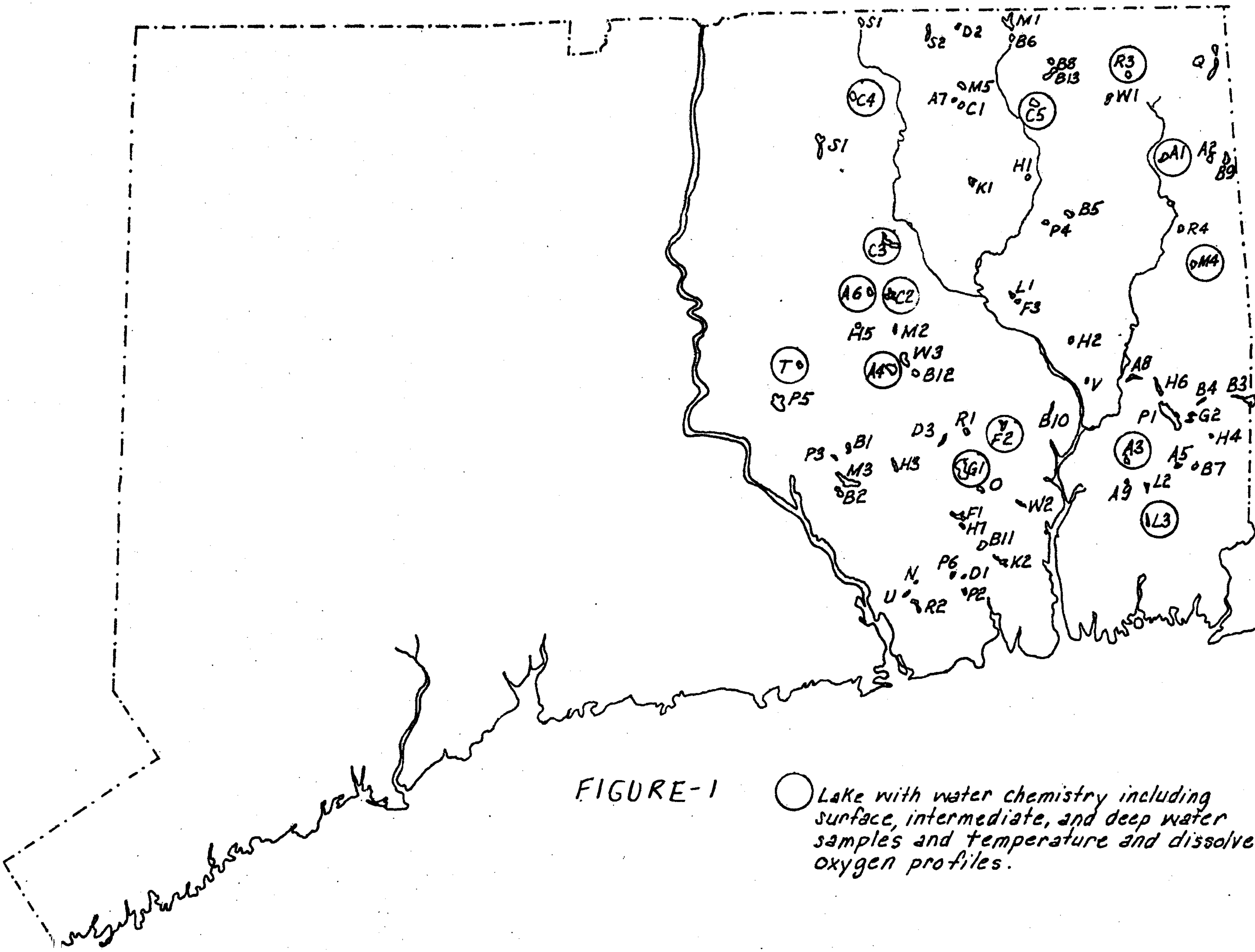

FIGURE-1

◯ Lake with water chemistry including surface, intermediate, and deep water samples and temperature and dissolved oxygen profiles.

Table 1. Natural Soils Groups[1] and General Urban Suitability.

NATURAL SOILS GROUPS[2]	URBAN SUITABILITY[3]
A. TERRACE SOILS - over sand and gravel	generally good, stoniness and high slopes are problems
B. UPLAND SOILS - over friable to firm glacial till	generally good, stoniness and high slopes are problems
C. UPLAND SOILS - over compact glacial till (Hardpan)	generally poor, seasonally high water table affects leach field capability
D. UPLAND SOILS - rocky and shallow to bedrock	moderate to poor, shallow to bedrock affects leach field potential to pollute water table
E. FLOOD PLAIN SOILS	poor - Inland Wetlands
F. MARSH AND SWAMP SOILS	poor - Inland Wetlands
G. LAKE TERRACE SOILS - over strata high in silt and clay	n/a in eastern Connecticut.
U. OTHER LAND	

1. For more complete details see Know Your Land, 1971, U Conn, Coop. Ext. Svc. Publ. 71-56.
2. Each Group is subdivided into smaller units such as A1a, A1b, A1c, A2a,etc.
3. All A3,B3 and C3 soils are poorly and very poorly drained and are Inland Wetlands.

Table 2. List of lakes studied and selected lake drainage basin morphometric parameters.

Lake	Location Town	County	Origin	Lake Surface Area ha.	Drainage Basin Area ha.	Mean Depth m.	Maximum Depth m.	Lake Perimeter Km.	Lake Volume $10^6 m^3$
Alexander	Killingly	Windham	Nat.	77	235	7.4	16.2	5.7	5.7
Amos	Preston	New London	Nat.	43	218	5.8	14.6	3.7	2.5
Columbia	Columbia	Tolland	Art.	114	788	5.1	7.8	6.0	5.8
Coventry (Wangumbaug)	Coventry	Tolland	Nat.	153	860	8.8	12.2	7.9	13.5
Crystal Lake	Ellington-Stafford Springs	Tolland	Nat.	81	720	6.0	15.2	4.2	4.9
Crystal Pond	Eastford-Woodstock	Windham	Nat.	61	215	4.4	13.4	4.4	2.7
Long Pond	Ledyard-No. Stonington	New London	Nat.	40	1181	4.6	21.9	6.2	1.8
Mono Pond	Columbia	Tolland	Art.	46	339	n/a	n/a	4.5	n/a
Moosup Pond	Plainfield	Windham	Nat.	39	300	2.8	7.9	2.5	1.1
Red Cedar	Lebanon	New London	Art.	52	161	n/a	n/a	4.0	n/a
Terramuggus	Marlborough	Hartford	Nat.	34	140	6.5	13.1	2.9	2.2
Wappaquassett	Woodstock	Windham	Art.	41	259	1.8	3.4	4.1	0.7

1 ha.= 2.47 acres; 1 m. = 3.28 feet; 1 cubic meter = 35.3 cubic feet = 264.2 gallons (U.S. Liquid).

Table 3. Eastern Connecticut Lakes: Percent Land Use and Specific Conductance. (1970 Land use (CT DOT); Specific Conductance 1976-77, this study.)

LAKE	PERCENT OF LAND: HOUSING & CAMPS	PERCENT OF LAND: AGRICULTURE	PERCENT OF LAND: OPEN	DRAINAGE BASIN, Acres	SPECIFIC CONDUCTANCE
ALEXANDER LAKE	20.8	19.5	48.	580	48.4
AMOS LAKE	9.2	12.	80.5	525	107
COLUMBIA LAKE	15.2	9.9	73.3	1955	60.5
COVENTRY (WANGUMBAUG) LAKE	32.8	----	65.5	1980	110
CRYSTAL LAKE	11.1	0.6	86.4	1730	66
CRYSTAL POND	14.6	16.5	68.6	520	52.4
LONG POND	2.8	2.8	85.4	2930	69.5
MONO POND	0.8	3.6	95.5	835	35
MOOSUP POND	8.5	----	92.9	720	64.4
RED CEDAR LAKE	22.3	----	77.6	345	35
TERRAMUGGUS LAKE	42.7	----	44.2	340	131
THAMES RIVER BASIN	5.1	10.3	82.4	809,971	63

Table 4. Crystal Pond Soils Groups and Land Use.

NATURAL SOILS GROUPS[1]	B-1a	B-2	C-1a	C-2	D	WETLANDS
Total Group Acreage	34.5	17	120	85	135.5	32.5
LAND USE (1970)	ACRES	ACRES	ACRES	ACRES	ACRES	ACRES
Ag[2]	6	0	37	11.5	9.5	1.5
H3	3.5	0	13	3	4	0
H4	4	0	0	0	15	0
RC	16	0	4	0	0	0
TOTAL	29.5	0	54	14.5	28.5	1.5
Use-Percent of Group	85.5%	0	45%	17%	21%	4.6%

1. For this study Natural Soils Groups were consolidated as follows:

This Study	Natural Soils Groups (for more detail see UConn Coop. Ext. Svc. Publ. 71-54)
B-1a	B1a, B1b, B1c
B-2	B2a, B2b
C-1a	C1a, C1b, C1c
C-2	C2a, C2b
D	D1, D2
Wetlands	A3, B3, C3, E, and F

2. Ag=Agriculture
H3=Suburban housing, high density (1-2 fam/acre, ie ½-1 acre spacing)
H4=Suburban housing, low density (1 fam/acre, greater than 1 acre spacing)
RC=Recreational Camp (for more detail see CT Dept. of Transportation's SLUCONN)

Table 5. Specific Conductivity

		SPECIFIC CONDUCTIVITY - micromhos/cm		
	No. of Lakes	Arithmetic Mean	Median	Range
Eastern CT. (not obviously altered)	85	68	62	34-154.5
Eastern CT.-Total	89	73	64	34-252
Central & Western CT.-non-limestone	16	134	94	40.5-361
Central & Western CT.-Total	19	152	97	40.5-361
Western CT.-Limestone Lakes	3	251	--	227-292
All Lakes & Ponds	108	86	67	34-361

Specific conductivity measurements reflect the amount of total dissolved solids in the lake waters. The measured values of Ca^{++}, Mg^{++}, HCO_3^- $SO_4^=$ and Cl- and calculated Na+ and K+ were summed and divided by the specific conductance (25°C); A common method of analysis with typically expected values of 0.6 to 0.7 in fresh waters. Results were as follows:

Table 6. Sum of Major Ions

		SUM OF MAJOR IONS (ppm) / Specific Cond. (@25°C)		
	No. of Lakes	Arithmetic Mean	Median	Range
Eastern CT.	76	.63	.63	.42-.83
Central & Western CT.	19	.69	.74	.43-.85
Total CT.	95	.64	.64	.42-.85

Considering that there is seasonal variability in bicarbonate and sulfate, an effect from high equivalent conductance of H+, Cl- and dissolved metals (especially iron and manganese not considered in this summation) and another effect from the low equivalent conductance of HCO_3^-, it is observed, with pleasure, that these results are comparable to commonly expected values.

Table 7. Major Cation Dominance (based on equivalent percentage)

	EASTERN CONNECTICUT		ALL LAKES	
	Number	Percent	Number	Percent
Na> Ca≥ Mg> K	39	51.3	47	49.5
Ca> Na≥ Mg> K	19	25.0	26	27.4
Ca≥ Mg> Na> K	14	18.4	18	18.9
Mg> Ca> Na> K	2	2.6	2	2.1
Na> Mg> Ca> K	2	2.6	2	2.1
TOTAL	76	99.9	95	100.0

These relationships should be considered preliminary since Na and K were calculated from millequivalent balancing of cations with anions. Values of potassium (K) ranged from 0.08 to 2.3 ppm (mean 1.24, median 1.2) in 31 analyses of Norvell and Frink (1975) and E. Jokinen (Univ. of Conn. Biology Dept. files, 1978). Cation millequivalence for K was assumed to be 0.03 with K being the last dominant of the four major cations.

Table 8. Anion Dominance

	EASTERN CONNECTICUT		ALL LAKES	
	Number	Percent	Number	Percent
$HCO_3 > SO_4 > Cl$	0	0	1	1
$HCO_3 > Cl > SO_4$	8	10	13	14
$HCO_3 \simeq Cl > SO_4$	7	9	10	11
$HCO_3 \simeq Cl \simeq SO_4$	2	3	4	4
$Cl > HCO_3 > SO_4$	21	28	25	26
$Cl > HCO_3 \simeq SO_4$	9	12	11	12
$Cl > SO_4 > HCO_3$	23	30	24	25
$Cl \simeq SO_4 > HCO_3$	5	7	6	6
$SO_4 > Cl > HCO_3$	1	1	1	1
TOTAL	76	100	95	100

Anion dominance based on equivalent percentage was also cauculated from the measured values of HCO_3^-, $SO_4^=$ and Cl^-, the major constituents in these waters. Anion values with a difference of less than 0.02 meq. were considered approximately equal.

EUTROPHICATION, PHOSPHORUS, AND ALGAE IN TWENTY-THREE CONNECTICUT LAKES

by

W. A. Norvell and C. R. Frink*

In the fall of 1973, we undertook a year-long study of the water chemistry and fertility of 23 lakes. Our main objectives were to find the extent and causes of eutrophication in a representative range of Connecticut lakes and to compare present conditions with conditions reported for the same lakes in 1937-1939 by the State Department of Fish and Game. The most important conclusions of our study are summarized herein; detailed results are reported in Station Bulletin 759 (Norvell and Frink, 1975).

The 23 lakes ranged from clear, infertile, near-oligotrophic waters to turbid, highly fertile, eutrophic waters that are subject to excessive growth of algae and other aquatic weeds. The main criteria used to identify the degree of eutrophy were the concentrations of total phosphorus and nitrogen measured during the spring, the summer concentration of chlorophyll-a (a measure of algae) and, in deep lakes, the rate of oxygen consumption in deep water (Table 1). Only two of the lakes were sufficiently low in fertility to be classified as oligotrophic: Alexander and West Hill. Ten lakes were intermediate in fertility and would be considered mesotrophic: Long; Gardner; Candlewood; Shenipsit; Pataganset; Quassapaug; East Twin; Terramuggus; Hayward; and Pocotopaug. Seven lakes were abundantly supplied with nutrients and would be considered eutrophic: Mudge; Taunton; Waramaug; Wononscopomuc; Beseck; Bantam; and Roseland. Four lakes were highly eutrophic and subject to heavy algae blooms: Cedar; Linsley; Lillinonah; and Zoar.

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*The Connecticut Agricultural Experiment Station, New Haven, Connecticut.

TABLE 1. Typical ranges of four lake characteristics for oligotrophic, mesotrophic, eutrophic, and highly eutrophic lakes.

Lake	Spring Overturn Total P	Spring Overturn Total N	Summer Chlorophyll-a	Summer Net Hypolimnetic O_2 Consumption
	ppb	ppb	ppb	$\mu g/cm^2/day$
oligotrophic	0-15	0-300	0-4	0-25
mesotrophic	10-30	200-600	2-15	15-55
eutrophic	20-50	400-1100	10-40	45-75
highly eutrophic	>40	>800	>30	>55

Oxygen consumption in the deep cooler water (hypolimnion) of thermally stratified lakes is related to the amount of organic debris that settles out from algae and weeds growing in surface waters. Oxygen consumption in the deep water of eutrophic lakes is frequently so high that oxygen supplies become completely depleted during the summer. This condition was well illustrated by Linsley Pond which became devoid of oxygen in its hypolimnion during the early summer and by Wononscopomuc, which, by late summer, became depleted in oxygen throughout most of its hypolimnion despite the relatively large volume of hypolimnetic water in this deep lake.

Although at least 13 inorganic plant nutrients are required for the growth of most algae, phosphorus is often found in shortest supply and hence, controls the amount of algae that can develop in a waterbody (Schindler, 1977; Dillon and Rigler, 1974). Evidence for the importance of phosphorus in Connecticut's lakes is threefold. First, the concentrations of phosphorus are low relative to those of the other major nutrients, nitrogen and potassium. For example, during the summer the nitrogen to phosphorus ratio exceeded 20/1 in most lakes, and in some lakes the ratio was in excess of 40/1. Concentration ratios above approximately 20/1 are usually associated with phosphorus deficiency in algae which depend on nutrients supplies in the water.

Second, direct analysis and extraction of filamentous algae (Fitzgerald, 1972; O'Shaughnessy and McDonnell, 1973) collected from most of the lakes showed that their phosphorus contents were so low that their growth would be limited. As expected, algae with low phosphorus contents were found most often when the nitrogen to phosphorus ratio of the lake water was greater than 20/1 and were found almost invariably when the nitrogen to phosphorus ratio was greater than 30/1.

Third, the correlation between phosphorus and the amount of algae in surface waters was good. Figure 1 shows the relationship between summer concentrations of chlorophyll-a and total phosphorus. More than 75% of the variation in chlorophyll-a could be predicted from differences in the concentrations of phosphorus. Clearly, as concentrations of phosphorus in the lakes increased, so did the amounts of algae. The above results suggest that reducing phosphorus inputs to lakes would be rewarded by lower numbers of algae.

Comparison of our results with those of the study by the State Department of Fish and Game shows that total phosphorus and algae have increased significantly in most of the lakes during the last three and one-half decades, while transparency and oxygen supplies in deep water have declined. Figure 2 compares the mean spring-summer phosphorus concentration in 1974 with the predominantly-summer phosphorus concentration in 1937, 1938, or 1939. Significant increases are shown for at least 13 of the 20 lakes which were included in both studies. Relatively large increases appear to have occurred in Shenipsit, Quassapaug, Waramaug, Wononscopomuc, Roseland, Linsley, and Zoar. Most of these same lakes also showed large increases in chlorophyll concentrations, indicating that more algae are now present as well.

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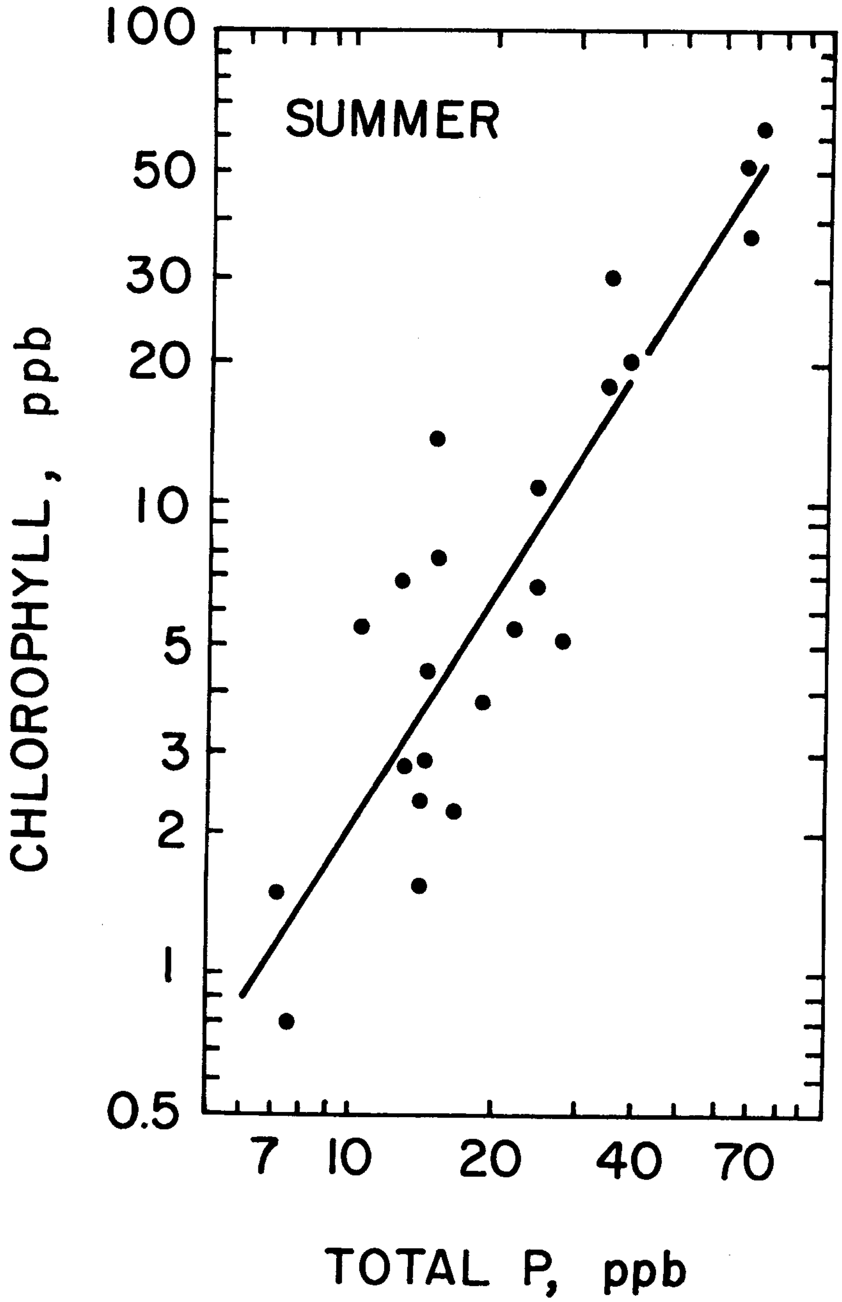

Figure 1. Relationship between concentrations of chlorophyll-a (as a measure of algae) and total phosphorus in 23 Connecticut lakes. Concentrations are expressed as parts per billion, ppb.

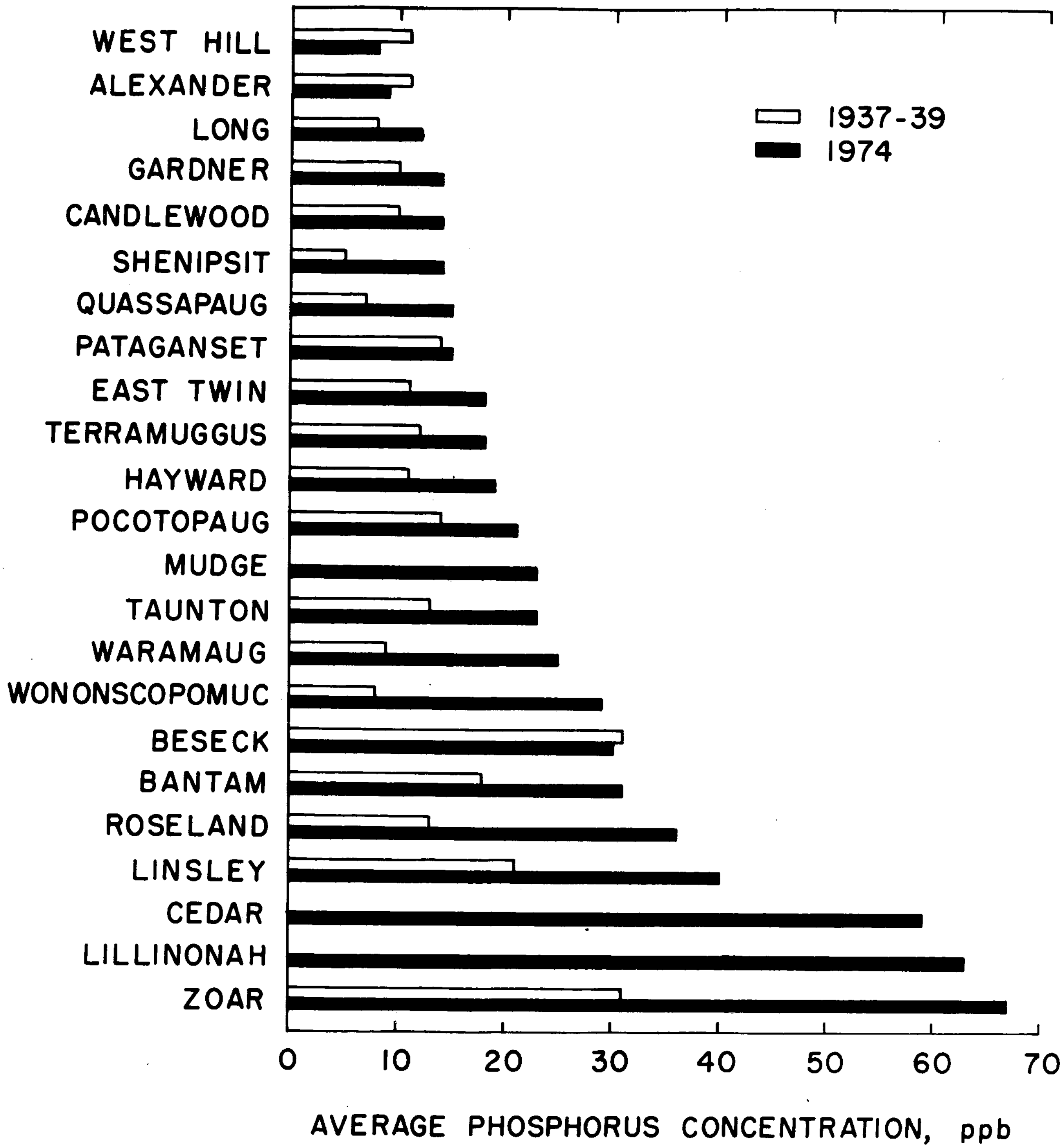

Figure 2. Comparison of phosphorus concentrations in Connecticut lakes in 1937-1939 and in 1974. The lakes are ranked by mean spring-summer phosphorus concentration for 1974.

A USEFUL NEW APPROACH TO LAKE MANAGEMENT

by

Peter H. Rich*

About ten years ago, a European limnologist named Vollenweider began to present evidence that certain key measurements could be used to determine the amount of phosphorus entering lakes. Bob Taylor and John Dowd have already talked about these results. Vollenweider later spent some time in Canada where other scientists began to use his approach, and in 1974, Peter Dillon and Frank Rigler published what is presently, I think, the best refinement of the work.

Table 1.

$$[P] = \frac{L\ (1-R)}{\bar{z}\ \rho}$$

[P] = concentration of P_{total} at spring overturn

L = $P_{in\ flow/lake\ area}$ (=P loading)

R = $1-(P_{outflow}/P_{inflow})$ (=retention coefficient)

$\bar{z}$ = mean depth (=volume/area)

ρ = rho = lake discharge/lake volume (=flushing rate)

The Dillon-Rigler model has been tested in a large number of lakes, in Switzerland by Vollenweider, in Ontario by Dillon and Rigler, and in Nova Scotia by Kerekes. The advantages of using the model of calculating phosphorus budgets has to do with the fact that you don't have to get <u>all</u> of the measurements generally required for a mineral budget. You can get some part of the measurements, the easier ones, and calculate the rest. As McGuiness described, you can run these models forward, backwards, and sideways.

I was involved in the project mentioned previously by Dr. Scottron, "The Impact of Urbanization of New England Lakes," sponsored by the New England Council of Water Center Directors.

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In Connecticut, Columbia Lake was selected for study.

Table 2. Morphometry and conductivity data for Columbia Lake.

Lake Area (A)	1.14 km^2
Watershed area (A_α)	7.43 km^2
Mean depth ($\bar{z}$)	5.1 m
Lake volume (V)	5.77 x 10^6 m^3
Conductivity	58 µmhos cm^{-3}

Columbia Lake is completely artificial. It's heavily developed, being completely surrounded by at least one tier of houses. The water level is adjusted each year (raised during the summer and lowered during the winter) by two to four meters. Columbia does not stratify very well in the summer, and has a very modest flushing rate of 1.2 times per year. A watershed map of the lake shows that much of the watershed is remote from the lake. We measured surface discharge of water from the watershed into the lake and from the lake over the dam. We took samples of water from the inflows each week, and determined the concentration of P_{tot}. Finally, we put it all together, and obtained estimates of the amounts of phosphorus entering and leaving the lake.

Table 3. Estimates of annual discharges of water and total phosphorus from the watershed and basin of Columbia Lake, from April 1975 to April 1976.

	Discharge ($m^3 \cdot yr^{-1}$) x 10^6	P_{tot} (kg $P.yr^{-1}$)
Inlet I	5.49	237
Inlet II	1.62	75
$Inlet_{tot}$	7.11	312
Outlet	6.66	235
Balance	.45 (6%)	77 (25%)

With these data, we were able to calculate each term of the Dillon-Rigler Model.

Table 4. Flushing rate (ρ), measured total phosphorus loading rate (L), measured total phosphorus retention coefficient (R), R estimated by the areal water load (R_p), and [P] predicted by $(L(1 - R)/\bar{z}$ for Columbia Lake.

ρ	$1.2\ m^3 \cdot yr^{-1} \cdot m^{-3}$
L	$275\ mg\ P \cdot m^{-2} \cdot yr^{-1}$
R	0.25
$R_p = 13.2/(13/2 + q_s)$	0.69
$L(1 - R)\bar{z}\rho$	$35\ mg\ P \cdot m^{-3}$
$L(1 - R_p)/\bar{z}\rho$	$15\ mg\ P \cdot m^{-3}$

The concentration of total phosphorus (P_{tot}) at spring overturn ([P]) was 4 mg P/m^3. The areal water load (L) was obtained from our weekly samples and amounted to 275 mg $P/m^3/yr$. The mean depth ($\bar{z}$) and the flushing rate (ρ) were obtained from the morphometric map and our discharge measurements, respectively. The mean depth was 5.1 m, and the flushing rate was 1$\cdot$ $\Sigma m^3/yr/m^3$. The retention coefficient (R) calculated directly from our estimates of phosphorus inflow and outflow was 0.25. The retention coefficient (R_p) estimated from the areal water level (Dillon and Kirchener, 1975) was 0.69. Using the directly calculated R in the formula and solving for [P] produces an estimate of 35 mgP/m^3 - lower than the observed [P]. Using the retention coefficient based on areal water load (R_p) and solving for [P] produces an estimate of 15 mgP/m^3 - <u>much</u> lower than the observed [P]. One must conclude from these calculations that either the real retention coefficient of Columbia Lake is higher than expected, i.e. too much P is leaving the lake, or that there is more P entering the lake than we measured.

The latter conclusion seems by far the most plausible; there are several non-point sources of P in Columbia Lake which we did not attempt to measure. The two most likely sources of P for which we have no estimates are atmosphere fallout and septic tank seepage. Using an estimate of atmospheric fallout of P obtained in New Hampshire (Likens and Bormann, 1974) of 100 $mgP/m^3/yr$ adds 230 kgP/yr to the P input of the lake. If one uses R_p and the actual [P] observed (42 mgP/m^3) and solves for L (P loading), an estimate of 580 mg $P/m^2/yr$ is obtained. This estimate converts to 660 kg P/yr in terms of actual lake inputs. Thus, more than a third of the P inputs predicted by the model could be supplied by atmospheric fallout. Presumably, the balance of extra inputs over and above watershed and atmospheric sources comes from septic tank seepage and other non-point sources.

Conclusions. Use of the Dillon-Rigler Model at Columbia Lake was distinctly worth the effort. Using relatively easy-to-obtain surface discharge samples and data, the model permitted us to turn a rather superficial study into a useful indictment of non-point sources of P. In particular, the potential role of atmospheric fallout of P was identified as worthy of more systematic study.

The implications of growing P fallout are startling. For instance, the degree to which the extra P entering Columbia Lake originates as fallout rather than septic tank effluent lifts responsibility from the citizens, the town, and, indeed, from the State of Connecticut. Further, increasing P fallout can be expected to change the behavior of lakes relative to eutrophication. Presently, the degree to which a lake is eutrophic is known to be directly correlated with its watershed/volume ratio, i.e. the greater the watershed size relative to lake size, the greater the amount of water and phosphorus entering the lake. If more P enters a lake as atmospheric fallout directly on the lake surface and as storm runoff from the immediate surroundings, eutrophication will begin to strike harder at those lakes with small watersheds which have less annual discharge to dilute the new P inputs. Ultimately lakes now naturally eutrophic might become far more desirable due to their stability in the face of atmospheric fallout when compared to presently pristine lakes about to be overwhelmed by increasing non-point source P input.

Note: Since this article was prepared, a P budget for Columbia Lake based upon land use in the watershed has been prepared for the Windham Regional Planning Agency by the Center for Environment and Man (CEM). The land use budget essentially confirms the work reported here. Three differences between the two studies are worth mentioning. First, the CEM study was based on 20 year mean precipitation and discharge data, while this study was based on the annual period April 1975 to April 1976, which had precipitation significantly above the mean. Second, CEM used a conservative estimate of atmospheric fallout (75 mg $P/m^2/yr$). Third, atmospheric fallout in the CEM approach appears in part as erosion from the watershed and in part as input directly to the surface of the lake, not as a combined estimate.

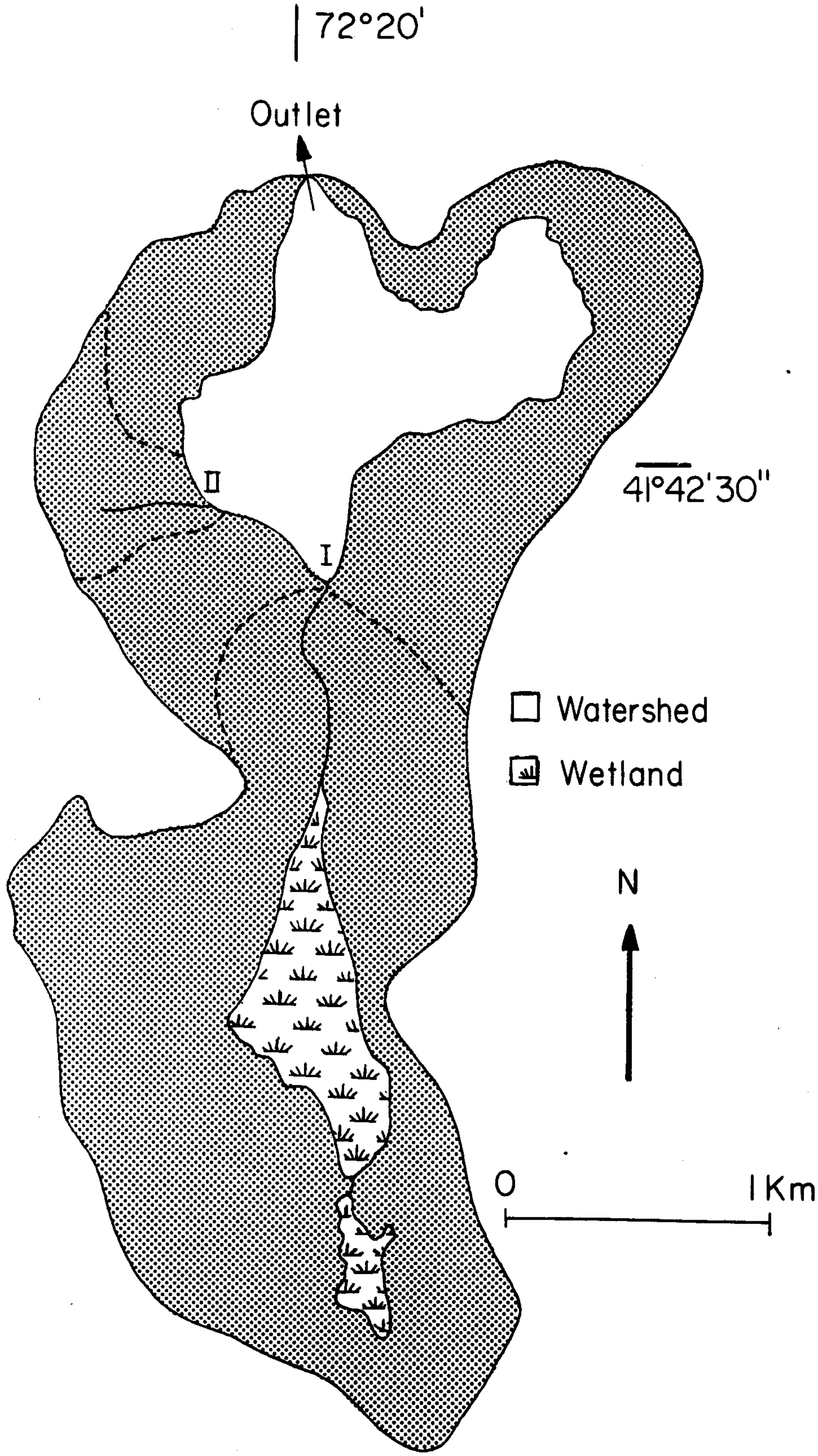

Fig. 1 Colubia Lake, with inlet sampling points (I and II) indicated.

INSTITUTE OF WATER RESOURCES

at the

UNIVERSITY OF CONNECTICUT STORRS, CONNECTICUT 06268

presents the

LAKE MANAGEMENT CONFERENCE

Thursday
9 June 1977
Pequot Room, Shippee Hall
Storrs Campus

PROGRAM

MORNING SESSION. Chairperson: Dr. Carroll N. Burke, Pathobiology Department, University of Connecticut

8:30 a.m. *REGISTRATION*

9:00 a.m. *WELCOMING REMARKS:* Dr. Victor E. Scottron, Department of Civil Engineering and Director, Institute of Water Resources, University of Connecticut.

9:10 a.m. *OPENING REMARKS:* Mr. Melvin J. Schneidermeyer, Deputy Commissioner and Director, Division of Environmental Protection, Hartford, Connecticut.

9:20 a.m. *ROLE OF GROUND WATER IN LAKE WATER AND NUTRIENT BUDGETS:* Dr. Thomas C. Winter, Hydrologist, Water Resources Division, U.S. Geological Survey, Denver, Colorado.

10:00 a.m. *CONNECTICUT LAKES MANAGEMENT PROGRAM EFFORTS:* Mr. Robert B. Taylor, Director, Water Compliance Unit, Connecticut Department of Environmental Protection, Hartford, Connecticut.

10:40 a.m. *COFFEE*

10:55 a.m. *APPLICATION OF COST EFFECTIVENESS METHODOLOGY TO LAKE EUTHROPHICATION CONTROL:* Mr. William V. McGuinness, Jr., Adjunct Senior Research Engineer, The Center for the Environment and Man, Inc., Hartford, Connecticut.

11:35 a.m. *UNCERTAINTIES IN LAKE EUTHROPHICATION MANAGEMENT STRATEGIES:* Mr. John F. Dowd, Hydrologist, McD Associates, Inc., Environmental Consultants, Hamden, Connecticut.

12:15 p.m. *LUNCH*

AFTERNOON SESSION. Chairperson: Dr. Antoni W.H. Damman, Ecology Section, Biological Sciences Group, University of Connecticut.

1:15 p.m. *THE RELATIONSHIP OF LAND USE TO LAKE WATER QUALITY:* Dr. Henry I. Snider, Earth and Physical Sciences Department, Eastern Connecticut State College, Willimantic, Connecticut.

1:45 p.m. *EUTROPHICATION OF 23 LAKES IN CONNECTICUT:* Dr. Wendell A. Norvell, Assistant Soil Chemist, The Connecticut Agricultural Experiment Station, New Haven, Connecticut.

A USEFUL NEW APPROACH FOR LAKE MANAGERS: Dr. Peter H. Rich, Ecology Section, Biological Sciences Group, University of Connecticut.

Drs. Norvell and Rich will present their findings as a panel.

2:45 p.m. *COFFEE*

3:00 p.m. *SUMMARY DISCUSSION:* All speakers.

4:00 p.m. *CLOSING REMARKS*

CONFERENCE COMMITTEE

Dr. Peter H. Rich, University of Connecticut
Dr. Hugo F. Thomas, Director, Natural Resources Center, Connecticut Department of Environmental Protection.
Professor Wilbur J. Widmer, Civil Engineering Department, University of Connecticut.
Dr. Victor E. Scottron, Director, Institute of Water Resources, University of Connecticut.

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