EPA-600/3-77-126a
November 1977

GREAT LAKES ENVIRONMENTAL PLANNING USING LIMNOLOGICAL SYSTEMS ANALYSIS: SUMMARY

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DISCLAIMER

FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise, and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment requires a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The Office of Research and Development contributes to this multidisciplinary focus through programs engaged in

> studies on the effects of environmental contaminants on the biosphere, and
>
> a search for ways to prevent contamination and to recycle valuable resources.

This report assesses the technical feasibility and economic practicality of developing mathematical models to assist in defining and making selections among alternative management strategies and structural solutions proposed for solving water resource problems of the Great Lakes. The deliberate decision-making process reported is a milestone in preapplication analysis of modeling for natural resource management purposes.

ABSTRACT

The report documents the deliberate decision making process used by the Great Lakes Basin Commission in concluding that rational modeling methodologies could be used to evaluate the effect of different planning alternatives on the Great Lakes and that planning for specific problems affecting the Great Lakes system can be technically and economically supported through mathematical modeling and systems analysis. It assesses the technical and economical feasibility of developing mathematical models to assist in making selections from among alternative management strategies and structural solutions proposed for solving water resource problems of the Great Lakes. The study reviews, evaluates and categorized present and future water resources problems, presently available data, problem-oriented mathematical models and the state of models and model synthesis for large lakes. A demonstration modeling framework for planning is developed and applied to western Lake Erie and the Great Lakes system. The report evaluates four widely ranging alternatives for future modeling efforts in the Great Lakes and recommends the modeling level most feasible to answer planning questions on scales ranging from the Great Lakes to regional areas. Also discussed is a proposed Commission study which will apply limnological systems analysis to the planning process.

The report consists of three volumes:

a. Summary
b. Phase I - Preliminary Model Design
c. Model Specifications

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ACKNOWLEDGMENTS

The completion of this report would not have been possible without the continuing support of the eight Great Lakes states, Great Lakes Basin Commission, the twelve Federal agencies with membership on the Great Lakes Basin Commission, and the Plan and Program Formulation Committee of the Commission. The leadership and direction provided by Frederick O. Rouse, Chairman of the Commission, is sincerely appreciated. David C.N. Robb, Paul R. Vachon, and other staff members of the Basin Commission provided valuable support to the project.

Special thanks are extended to Hydroscience, Inc., particularly to John L. Mancini, Donald J. O'Connor, Dominick M. DiToro, and Robert V. Thomann for their valuable contribution to this modeling study as well as to modeling studies for the Great Lakes in general.

Also deserving of recognition for their support and invaluable guidance are the following individuals who comprise the Board of Technical Advisors: John M. Armstrong, University of Michigan; Leo R. Beard, U.S. Army Corps of Engineers; A. M. Beeton, University of Michigan (formerly of University of Wisconsin-Milwaukee); G. E. Birchfield, Northwestern University; Carl W. Chen, Tetra Tech, Inc.; Everett J. Fee, Freshwater Institute, Environment Canada; Theodore Green III, University of Wisconsin; Leo J. Hetling, New York Department of Environmental Conservation; Norbert Jaworski, Environmental Protection Agency; Edwin L. Johnson, Environmental Protection Agency; James Kramer, McMaster University, Canada; Ronald McLaughlin, Environment and Water Resources Systems; Arthur Pinsak, Great Lakes Environmental Research Laboratory, NOAA; Howard L. Potter, Upper Great Lakes Regional Commission; and Sam B. Upchurch, South Florida University.

Special thanks are extended to the representatives of the Canadian government at the provincial and federal levels for their cooperation in providing needed data and valuable comments.

The continuing commitments and contributions of Stephen Poloncsik, Project Officer, U.S. Environmental Protection Agency, Region V, is sincerely appreciated.

Much of this work was performed by Hydroscience, Inc., in fulfillment of Contract Number DACW-35-71-C0030 with the Great Lakes Basin Commission. The work was jointly sponsored by the U.S. Army Corps of Engineers, the Upper Great Lakes Regional Commission, the U.S. Environmental Protection Agency, and the Great Lakes Basin Commission.

SECTION I

INTRODUCTION

It has been apparent for some time that conventional planning techniques will not provide the tools necessary to analyze the responses of the Laurentian Great Lakes to alternative water resources management strategies. Because of the magnitude of the Great Lakes, perhaps more properly termed "inland seas," many conventional planning strategies utilized for much smaller watersheds are inappropriate when applied to the Great Lakes. For example, the long flushing time and small watershed-to-lake-surface-area ratio for the Great Lakes are situations not commonly found for most inland lakes. Also, the Great Lakes are interconnected, so management strategies for the upper Great Lakes may affect the lower lakes.

One of the major goals of regional planners in the Great Lakes Basin is the development and maintenance of a comprehensive coordinated joint plan for the Basin. This requires projections of population, economy, resource needs, and pollutant loadings for the near, medium, and long-range future. Although a number of attempts have been made with more or less success at modeling individual aspects of these factors, an integrated approach is necessary. An important step in developing a comprehensive coordinated joint plan would be a limnological systems analysis of the Great Lakes that is responsive to exogenous socio-economic variables.

Although scientists have generally concluded that systems analysis could assist in establishing the programs necessary to resolve many Great Lakes problems, concern was expressed by some several years ago that an incomplete and inconsistent data base, an insufficient knowledge of basic water circulation and hydrodynamic characteristics, an inadequate knowledge of interactions among the chemical, physical, and biological aspects of the lakes, and other factors that would prevent the usefulness of a systems analysis approach to planning problems. Consequently, the Great Lakes Basin Commission, which is responsible under the Water Resources Planning Act (Public Law 89-80) for overall planning activities in the Great Lakes Basin, sponsored a feasibility study of (1) planning problems which were amenable to resolution by systems analysis, (2) the availability of adequate data associated with these problems, (3) the state-of-the-art of available models, (4) the synthesis of models in relationship to a particular planning problem, and (5) the relationship of the synthesized models to current computer capability. This study also included demonstrations of the application of systems analysis to existing or hypothetical situations within large lakes.

As a result of this feasibility study, a comprehensive report known as "A Limnological Systems Analysis of the Great Lakes, Phase I" (LSA Phase I report) (see Appendix A) by Hydroscience, Inc. was produced in 1973. A follow-up report entitled "Limnological Systems Analysis of the Great Lakes: Model Specifications" (Specification report) (see Appendix B) was produced by Hydroscience, Inc. in 1975.

The substance of these reports is considered below in presenting the Basin Commission staff's conclusions on the technical feasibility and economic practicality of utilizing limnological systems analysis in water resource planning programs for the Great Lakes Basin. These conclusions are based not only on the Hydroscience, Inc. reports, but also on the new developments in Great Lakes modeling that have occurred recently. Also discussed in this paper is the proposed second phase of the Great Lakes Basin Commission's modeling study, which will incorporate model development, verification, and use associated with Great Lakes environmental planning.

SECTION II

CONCLUSIONS

(1) Planning for specified problems affecting the Great Lakes system can be technically and economically supported through mathematical modeling and systems analysis.

(2) Limnological systems analysis would be an effective method of integrating and evaluating the effects to the Great Lakes system of plans and programs conducted by the many levels of government and the private sector in the international Great Lakes system.

(3) Rational modeling methodologies currently exist which could be used to evaluate the effect on the Great Lakes of different planning alternatives. Available models need to be molded into workable programs relevant to planning needs.

(4) The LSA Phase I report and the Specifications report provide a reasonable framework to initiate a Great Lakes Environmental Planning Study.

SECTION III

RECOMMENDATIONS

The Great Lakes Basin Commission staff recommends that:

(1) A Great Lakes Environmental Planning Study should be undertaken which utilizes limnological systems analysis (mathematical modeling) as a planning tool to analyze the probable spatial and temporal effects on the Great Lakes of different plans or management strategies being developed in the Basin.

(2) Primary consideration should be given to integrating currently available analytical methodologies into a workable program for planning needs.

(3) The following specific problem areas should be initially addressed in a comprehensive Great Lakes Environmental Planning Study.

(a) Water Quality
--Dissolved oxygen
--Chemical interactions

(b) Public Health (regional and lakewide)

(c) Eutrophication--Biomass

(d) Food Chain--Toxic or Harmful Substances

(4) Modeling frameworks and planning objectives should be directed toward three spatial scales:

(a) Great Lakes

(b) Lakewide

(c) Regional

(5) The planning process utilized to conduct these programs should provide maximum input from and involvement of the Great Lakes states, federal agencies, citizens, and other interests to assure its utility in developing a comprehensive coordinated joint plan (CCJP) for the Great Lakes.

SECTION IV

PROJECT HISTORY

AUTHORITY AND PURPOSE

The Great Lakes Basin Commission was established by Executive Order 11345 on April 20, 1967, under the authority of Title II of the Water Resources Planning Act of 1965, Public Law 89-80. In accordance with Section 204(3) of P.L. 89-80, the Great Lakes Basin Commission shall

> ". . .submit to the [U.S. Water Resources] Council for transmission to the President and by him to the Congress, and the Governors and the legislatures of the participating states, a comprehensive, coordinated, joint plan, or any major portion thereof or necessary revisions thereof, for water and related land resources development in the area, river basin, or group of river basins for which such commission was established."

Public Law 89-80 also provides that a river basin commission shall

> "[1] serve as the principal agency for the coordination of Federal, State, interstate, local and nongovernmental plans for the development of water and related land resources in its area. . .
>
> [2] prepare and keep up to date. . .a comprehensive, coordinated joint plan for. . .development of water and related land resources. . .the plan shall include an evaluation of all reasonable alternative means. . .and it may be prepared in stages. . .
>
> [3] recommend long-range schedules of priorities for [individual] projects. . .
>
> [4] engage in such activities and make such studies and investigations as are necessary and desirable in carrying out the policy set forth in section 2 of this Act. . ."

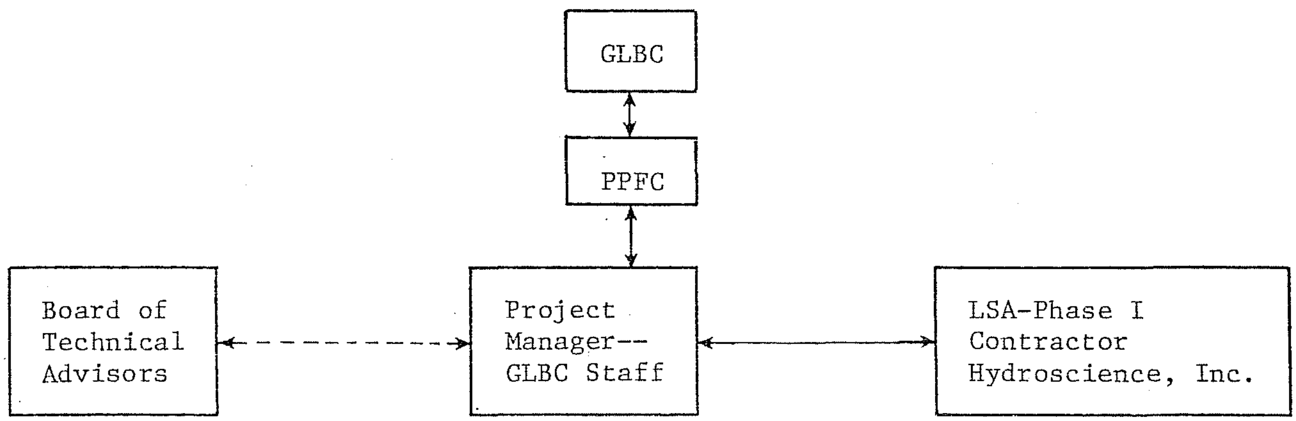
As early as March, 1969, it was apparent to the Commission that special planning tools were necessary for analyzing the responses of the Great Lakes to alternative resource management strategies employed in upland areas as well as in the lakes themselves. There was no evidence that correction of upland water and related land resource problems would necessarily achieve the desired goals of providing Great Lakes Basin residents with an acceptable measure of environmental quality and economic growth. The special study entitled "Limnological Systems Analysis of the Great Lakes, Phase I"

(LSA Phase I) was undertaken as a measured, deliberate step towards planning for the Great Lakes. The Phase I project recommendations, as well as recent developments in Great Lakes modeling, are the basis for final conclusions and recommendations on future Great Lakes environmental planning using systems analysis.

PROJECT COORDINATION

The Commission directed and coordinated the LSA Phase I project under an organizational structure simply illustrated in Figure 1. The nature of the Phase I effort is described in detail in Appendices A and B.

The responsibility for reviewing technical performance under conditions of the Phase I contract rested with a Board of Technical Advisors. The Board's members and several observers came from universities, government, private consulting firms, and the Great Lakes states. Their guidance to the Commission and the contractor insured that Phase I recommendations were the product of a varied expert technical input.



GLBC - Great Lakes Basin Commission
PPFC - Plan and Program Formulation Committee
------ Advised as needed

Figure 1. LSA Phase I Organizational Structure

At its final meeting on June 27, 1973, the LSA Board of Technical Advisors reviewed the findings of Hydroscience, Inc. and recommended that:

(1) The Great Lakes Basin Commission approve the mathematical modeling development, verification, and testing program on the Great Lakes at the two million dollar level to be used as a tool for planning.

(2) The LSA Phase II program allow sufficient flexibility in its development, initial application, and continuing maintenance to achieve most effectively desired planning objectives.

The Board also determined that the minimum criteria for successful conduct of a systems analysis Phase II program were:

(1) Close management control with adequate funds, contract administration, and qualified personnel.

(2) Employment of a technical management contractor to support and assist the study manager in the following ways:

(a) Oversee and coordinate technical compliance of numerous subcontracts required in Phase II.

(b) Integrate planning requirements established through the study management structure with model design, development, and application.

(c) Train individuals in state and federal agencies in model use to enhance improved planning applications after study completion.

(3) Use of a Board of Advisors to advise study management by monitoring and evaluating the progress of all projects included in LSA Phase II, rather than by providing technical expertise.

(4) Development among Commission member agencies of users educated in the application of LSA models to planning objectives, preferably during model development. Users should commit significant time to the model development effort to be sufficiently informed to apply the improved planning tools to future planning problems and to answer planning questions after the study is completed.

SECTION V

LIMNOLOGICAL SYSTEMS ANALYSIS AND THE PLANNING PROCESS

PLANNER USE OF MODELS

For many years, water resources planners have advocated the use of the systems approach as a tool for managing our lakes and streams. In the past several years, there have been many attempts at chemical and biological lake effects modeling, physical-dynamical modeling, optimization modeling of dissolved oxygen concentration in streams and estuaries, and modeling of processes in wastewater treatment. Increased efforts in the last few years have also been applied to socio-economic models, which must be part of any complete systems analysis of a water resources problem.

These subjects represent only a few of the many areas of the aquatic environment to which modelers are directing their attention. Indeed, rational modeling methodologies are currently being developed for application to a variety of water resources problems. However, a job that is becoming more important is the integration of available models into a workable systems program useful for evaluating planning and program needs. For example, a set of linked models, where the output of certain models serves as an input for another or where two models are run in tandem, are often necessary to solve water resources planning problems. This coordination of physical, chemical, biological, social, and economic modeling efforts will enable planners and managers to effectively use them in dealing with our water resources problems.

Increased emphasis in the future needs to be given to applied modeling, using existing methodologies which could potentially yield information of practical importance to managers and planners. An assessment of the usefulness and limitations of the modeling program in comparison to other planning techniques should also be made. The development of new models, the refinement of old models, or the verification or negation of existing models will serve to update the total effort. Where applicable, the results of several different methodologies which model the same parameter or problem should be used to set the probable output ranges in planning scenarios.

An important aspect of successful application of a systems analysis approach to water resources planning is the degree of coordination between the planners and the modelers. It is essential that the planners have a major input in the beginning of the model development and that they be involved throughout the process. Planners must be aware of the limitations of the model, including the specific assumptions that were made, if the finished model is to be an effective planning tool.

ESTABLISHING OBJECTIVES

Because of the multiple objectives that must be considered when planning for and managing Great Lakes water and related land resources, the objectives in a limnological systems analysis approach must be clearly defined. Planners have the responsibility of clearly defining these objectives. The objectives must be detailed with respect to the scope of the problem, as well as to the spatial and temporal scale involved. Unfortunately, the setting of objectives in multi-faceted water resources issues is not necessarily straightforward. One of the advantages of a systems analysis approach is that it forces objectives to be refined to a greater degree than they might normally be.

The best modeling strategy is that which meets the given objective. For example, there is no advantage in developing a quantitative predictive model for planning purposes with an accuracy of ± 1 percent if an accuracy of only ± 25 percent is sufficient to make a rational judgment on planning alternatives. The more detailed model is often more susceptible to being unduly sensitive to slight changes in inputs. This can be a difficult problem when dealing with natural systems, and the relationships of components may compound the problem.

Simple modeling concepts can be valuable in answering certain questions. For example, a simple model of the residence times of certain parameters can be useful. The Great Lakes have extremely large volumes compared to inflows, and consequently have long natural flushing rates. Thus, the response time to a decreased rate of phosphorus loading (one of the key pollutants of the Great Lakes) might be expected to be quite long. In Lake Michigan, the second largest of the Great Lakes, the response time has been estimated by some to be approximately 100 years. However, this estimate is based on the assumption that plant nutrients such as phosphorus behave conservatively in the lakes and so their residence time in the lake is equal to that of the water. Such an assumption ignores the aqueous environmental chemistry of the element(s) that limit plant growth. This is a serious oversight because certain chemical and biological reactions play a major role in determining how long a nutrient will remain in lake water (i.e., nutrient residence time).

An important internal removal process is the trapping of biologically and chemically precipitated phosphorus in lake sediments. Although under certain conditions some release of phosphorus can occur (for example, release under anoxic conditions, such as occurs in the deep water of the central basin of Lake Erie), the net flux of phosphorus over an annual cycle is to the sediments, as shown by the accumulation of phosphorus in lake sediments. In Lake Erie and Lake Ontario, the two lower Great Lakes, it has been estimated that over three-fourths of the phosphorus entering the lakes is lost to the sediments. Thus, because of internal losses of phosphorus, the rate of response of lakes to the elimination of a point source of phosphorus will likely be more rapid than would be predicted from natural flushing.

Based on this internal loss mechanism, a model can be written accounting for internal phosphorus loss as a first order reaction. Such a model is similar to principles of a completely mixed reactor model familiar to sanitary engineers. Utilizing such a model for predicting long-term trends, Lake Michigan would be expected to adjust to a decreased fertilization rate within about 20 years rather than the 100 years predicted by some. Lake Superior and Lake Huron, roughly similar in size to Lake Michigan, would also equalize to a reduced loading more quickly than would be predicted if phosphorus were considered to behave conservatively. The smaller lakes, Erie and Ontario, could show a full response within a fewer number of years than previously expected.

The above predictions, although based on a relatively simplistic model, are of considerable consequence to planners. This model indicates that planners can expect results in a relatively short time period, rather than wait several generations for lake recovery.

While the above example shows how a simple model can be useful in answering certain planning questions, planning questions involving multiple objectives generally require more sophisticated systems models or combinations of simplistic models to be useful. Nevertheless, the objectives of a planning endeavor must always be kept in mind to avoid developing a model that is more detailed than necessary, and perhaps at a great loss of time and money.

SUPPLEMENTAL BENEFITS OF SYSTEM ANALYSIS TO PLANNERS

Another important use of systems analysis as a planning tool is to provide an orderly, systematic approach to the water and related land resources problems of the Great Lakes, which cannot be attained by local, state, and federal piecemeal efforts. It is essential to have an evaluative methodology which systematically relates all relevant information from these separate studies in order to gain a workable assessment of the impacts that alternative plans and programs would have on the Great Lakes. Unless a general systematic evaluative method is developed for understanding the total Great Lakes Basin system, management programs will continue to be duplicative and uncoordinated.

Literally hundreds of independent and essentially unrelated studies have been made on the Great Lakes, and a great deal of pertinent data have been acquired on a fragmented basis by many federal, state, regional, educational, and private organizations over a substantial period of time. Upon considering the current and projected expenditures for Great Lakes research and monitoring, waste treatment programs, definition and enforcement of quality standards, siting and design of power plants, shore protection works, maintenance and improvement of navigation works, and management of the sport and commercial fisheries, the need for systems study to aid the rational evaluation of the effects of these on the Great Lakes is obvious. In the development and maintenance of a comprehensive coordinated joint plan for the Great Lakes Basin, the organization and data coordination developed through a limnological systems analysis approach would be invaluable.

SECTION VI

RESPONSE TO THE LIMNOLOGICAL SYSTEMS ANALYSIS PHASE I REPORT

The LSA Phase I report was completed in March, 1973. Approximately 130 copies of the Phase I report were distributed to scientists, planners, politicians, university personnel, and interested citizens. Copies of the report were also available to the public in the state libraries of the eight Great Lakes states, and in over 40 libraries located at universities, institutions, and agency offices in the Great Lakes Basin, and at several locations in the United States and Canada.

GENERAL COMMENTS

The LSA Phase I report has been generally well received and supported in the Great Lakes Basin. Those critical comments received were mostly directed toward specific details of the Phase I report or towards a fundamental disagreement about the utility of modeling as a means of helping responsible officials make decisions. With regard to the first point, Hydroscience, Inc. carefully considered the level of detail of the Phase I study and strove to give it balance, recognizing that it was intended as an overall assessment of the feasibility of systems analysis application to the Great Lakes. On the second point, one of the authors' general conclusions from the Phase I study was that an important class of problems exists in the Great Lakes for which the application of existing modeling technology will produce results that will be a significant aid to decision making. It seems that conclusion is still valid, particularly in view of the recent successful applications of Great Lakes models, some of which were proposed by Hydroscience, Inc. New model developments which have occurred since the Phase I report was completed will be discussed in a subsequent section.

More specific comments and the response to them by Hydroscience, Inc. are given below.

Existing Data

Several reviewers commented that an exhaustive, detailed assessment of all Great Lakes water resource data was not made. However, as Hydroscience, Inc. pointed out, the purpose of reviewing data in the Phase I report was to provide an overview of available data and to determine the adequacy of data for modeling purposes. Numerous visits were made to agencies and universities to assess the data base. However, there was no attempt to be exhaustive and undoubtedly some data were excluded from the Phase I report. In addition, new data have become available since the Phase I report was completed. The fact that there are additional data over that considered in the Phase I report further supports the conclusion of Hydroscience, Inc. that a sufficient data base exists for modeling efforts.

There were several specific comments by reviewers that dealt with the adequacy or inadequacy of the data on circulation in the lakes. Circulation patterns inferred from primary variables (e.g. temperature and depth) were not considered data but rather results of data analysis. One comment indicated that not enough was known about the circulation patterns due to lack of basic information about factors such as the over-lake wind field. However, it was the judgment of the contractors that for a wide class of practical and meaningful water resource problems, knowledge of general Great Lakes circulation is really quite good and relatively more is known about circulation than any other variable or problem. This is partly due to the fact that lake circulation has been observed for about seventy years. There are, of course, aspects of the circulation in specific lakes that are poorly known. However, in the opinion of the contractor, there are sufficient Great Lakes circulation data and data analyses for use in other water resource modeling efforts.

Finally, several comments indicated that the data base was not sufficient for the construction and validation of mathematical models. This is often a source of controversy and appears to reflect a desire for more information before predictions or analyses are made. Hydroscience, Inc. felt that structuring of analysis frameworks through mathematical modeling should proceed simultaneously wherever possible with the gathering of field data. Obviously, at least some data must be available in order to even begin the analysis and determination of a mathematical model. The contractor's analysis indicated that there are several classes of water resources problems where such a data base does exist. This is not to say that field data should no longer be collected. It simply means that the activities of data gathering, data analysis, and prediction of possible consequences of proposed decisions should proceed more or less simultaneously. It should be recalled that the purpose of the Phase I report was to "present an assessment of the feasibility of applying a Limnological Systems Analysis (LSA) to the water resource problems of the Great Lakes." Based on the analysis of the situation in the Great Lakes, it was concluded that sufficient data do indeed exist, in varying degrees, for application of limnological systems analysis to the Great Lakes for planning purposes.

Adequacy of Mathematical Models

Several comments on the Phase I report revolved about either the adequacy of existing understanding as embodied in state-of-the-art mathematical models or the supposed impossibility or futility of modeling certain problem areas. The first type of comment was directed primarily at the adequacy of existing circulation models. However, there are probably more circulation models existent for the Great Lakes than any other types of models. In the case of circulation models, as the level of modeling increases, the depth and complexity of the questions about the model increase. However, lake circulation models have progressed to the point where they can be useful in water resource problems. In the determination of model status (see Figure 14 and page 921 of Appendix A) several important criteria were used: (1) basic understanding and knowledge, (2) data availability, (3) degree of model verification, and (4) degree of model application. Based on evaluations of these categories in some depth, a weighted score for Lake Circulation and Mixing (and other modeling frameworks) was determined by the contractors. These scores were the subject of several intensive discussions with the Board of Technical Advisors and the scores generally reflected the consensus opinion of that Board. As noted in Table 16 of Appendix A, the Lake Circulation and Mixing Models were rated highest in terms of development and planning application compared to the ten other modeling frameworks considered. In other words, it was felt that this modeling framework is sufficiently developed for use in a variety of water resource problem contexts. On the other hand, it is not meant to imply that additional work should not be done on the modeling of circulation in the Great Lakes.

The other major area of discussion on mathematical models was the feasibility of constructing models of biological phenomena. One comment stated that it is not possible to construct such models because of the great complexity of the biological world. That the aquatic ecosystem is complex and diverse is not denied; however, the essence of any mathematical approach is to attempt to organize the major features, i.e., to properly aggregate a complex phenomena so as to display the key interactions between variables. If we do not attempt to aggregate or organize the complexity (which in essence is what is done with a well-structured mathematical model), then the complexity of the system obscures all vision and one easily runs the risk of saying "the system is just too complex to say anything meaningful in a predictive sense."

For example, biological systems, especially the aggregate behavior of phytoplankton are, in the opinion of the contractor, much more deterministic than some biologists believe. Again, this does not imply that there are not significant random fluctuations in the biological world, it simply means that for decision making at the present time, a sufficient degree of determinism exists to provide an additional basis for assessing the impact of nutrient removal.

Several comments were made about the validating of the models in the Phase I report. In particular, the validation exercise was criticized as being really nothing more than statistical "curve fittings." The validity of the models as presented in the Phase I report (Appendix A) can only be judged at the present time by the degree to which the solutions that are generated provide reasonable estimates of biomass and growth dynamics. This was one of the reasons for using the model to make the hindcast to 1930 conditions in western Lake Erie. The results of the analysis further buttressed the confidence in the model to display the major interactions between nutrient and phytoplankton biomass. The fundamental difference between the mathematical model in the Phase I report and statistical regression analysis is in the structuring of causal relations based on physical and biological reasoning. For example, the mathematical models are founded on basic principles such as the conservation of mass momentum and energy. As such, they provide a basis for predicting or extrapolating beyond the available data range. Such is not the case with statistical curve fittings, which can obscure or confound effects and interactions in overall coefficients and sometimes tend to produce extrapolated results that are patently inconsistent with known laws.

Eutrophication Model

Several specific comments were also made on the details of the eutrophication model. One comment suggested that temperature dependence changes species composition and therefore the dependency that is built into the model is not representative. However, the dependence of maximum growth rate on temperature has been shown to be virtually independent of species (Eppley[1]). This is a good example of the aggregation of complex phenomena mentioned earlier.

Another reviewer commented that the contractor ignored the vertical structure of the aquatic ecosystem. However, the vertical structure of the Phase I report was not ignored (see for example, Figure 21, Equation 9-11, page 217; page 233; and page 346, Appendix A). The demonstration model does not include verticle structure in detail, simply because it was exactly that, a demonstration model or illustration, and as such was not intended to incorporate all possible considerations. However, vertical structure is discussed frequently throughout the modeling section and is explicitly recognized through light extinction even in the western Lake Erie demonstration model.

A comment was made on the lack of specific sediment-nutrient feedback in the demonstration model. This is an important problem and an area in which understanding of just how and when to include such sediment feedback is undergoing rapid expansion. For western Lake Erie, however, which is almost always aerobic, such feedback is not significant. Models of the central basin of Lake Erie would, of course, have to include this phenomenon.

Another comment revolved about "whole ecosystem field experiments" as a substitute or "different" approach to understanding eutrophication in the lakes. Such experiments would be highly desirable and useful and would provide significant information on the complex interactions of the aquatic ecosystem. By themselves, however, such experiments are simply not sufficient, just as mathematical models without input data on interactions are not sufficient. The data from ecosystem field experiments must be analyzed in order to unravel the causal chains. In fact, a viable framework for such analyses of the field experiment data is the type of model reviewed in the Phase I report. Furthermore, such experiments by themselves do not provide a sufficient basis for prediction.

SECTION VII

CURRENT STATUS OF GREAT LAKES LIMNOLOGICAL SYSTEMS ANALYSIS

Many changes in Great Lakes planning, management, and research activities, including research in modeling, have taken place since the time the limnological system analysis program was first conceived by the Great Lakes Basin Commission. These include external changes in state, federal, and international policies and programs. The purpose of this section is to briefly review the external changes and the new developments in modeling which have occurred in the last few years and which will affect the Phase I study results as they relate to the Phase II program.

MAJOR EXTERNAL EVENTS

During the course of the Phase I project and during the period of the GLBC report review and deliberations on future Great Lakes environmental planning needs, progress on solving Great Lakes problems accelerated at the state, provincial, national, and international levels. The major events briefly outlined below continue to have a major influence on implementation of the integrated modeling-planning recommendations of the Great Lakes Basin Commission.

In August, 1971, the Second Environmental Conference of Great Lakes Governors and Premiers was co-hosted by the State of Michigan and the Great Lakes Basin Commission. Thirteen specific resolutions related to the water quality improvement in the Great Lakes were passed and submitted to the Canadian and U.S. governments. This led to the U.S.-Canada Great Lakes Water Quality Agreement signed on April 15, 1972. The Agreement authorized new pollution studies in the Great Lakes Basin coordinated by the International Joint Commission and established procedures and mechanisms to deal with research and management needs affecting international waters. Major studies include:

(1) Report on "Regulation of Great Lakes Water Levels" by the International Great Lakes Levels Board, December, 1973

(2) Upper Lakes (Superior and Huron) Reference Group Study

(3) Pollution from Land Use Activities Reference Group Study

(4) Research Needs Reports and Great Lakes Research Directory, Great Lakes Research Advisory Board.

In the U.S., a sweeping federal-state campaign to prevent, reduce, and eliminate water pollution was begun in October of 1972 with the passage of Public Law 92-500, the Federal Water Pollution Control Act Amendments of 1972. All Great Lakes states were affected, while several federal agencies began programs directed to Great Lakes water quality problems.

Under P.L. 92-500, the U.S. Environmental Protection Agency began a major Great Lakes Initiative Program and eleven areas (Ashtabula, Ohio; Black River, New York; Buffalo-Niagara, New York; Calumet, Illinois/Indiana; Duluth-Superior, Minnesota/Wisconsin; Detroit River, Michigan; Erie, Pennsylvania; Fox River-Green Bay, Wisconsin; Maumee, Ohio; Rochester-Genesee, New York; Saginaw Bay, Michigan) were selected for study. Other EPA work was carried out in support of the International Joint Commission. Specific Great Lakes research was initiated at the Large Lakes Research Station at Grosse Ile, Michigan and at the Environmental Research Laboratory in Duluth, Minnesota. Under Section 108(d) of P.L. 92-500 the U.S. Army Corps of Engineers launched the Lake Erie Wastewater Management Project for the design and development of a demonstration wastewater management program for the rehabilitation and environmental repair of Lake Erie. Under Section 208, EPA is conducting Areawide Wastewater Management Studies with special emphasis on non-point sources of pollution. There are just a few of the programs initiated under P.L. 92-500 which will affect the Great Lakes.

Another major development occurred in October 1972, when Public Law 92-583, the Coastal Zone Management Act of 1972, was passed. This law encourages Great Lakes states to develop long-term planning and management programs for the wise use of coastal resources. Other significant events include:

(1) demonstration study on extension of the Great Lakes navigation season under P.L. 91-611 by the U.S. Army Corps of Engineers

(2) the International Field Year for the Great Lakes, a U.S.-Canadian study of Lake Ontario

(3) Sea Grant research on Great Lakes problems under University of Wisconsin, Michigan, and State University of New York

(4) the establishment of the Great Lakes Environmental Research Laboratory by the National Oceanic and Atmospheric Administration

(5) the Great Lakes Basin Framework Study and a Level B planning study of the Maumee River Basin by the Great Lakes Basin Commission

(6) the activities of the National Commission on Water Quality, established to study the technological capabilities and the economic, social, and environmental impact of meeting (or not meeting) Public Law 92-500. A regional assessment study of Lake Erie was performed using available data and predictions were made of Lake Erie's water quality if certain provisions of the 1972 law are met or not met.

Other events have occurred which have not been discussed here. Progress in understanding the Great Lakes system continues to shape the future action required for Great Lakes environmental planning.

RECENT MODELING ACTIVITIES

Since the Phase I report was completed, much progress has been made in mathematical modeling of the Great Lakes. A number of the modeling activities listed in the Specifications report (Appendix B) have actually been accomplished or are in the process of being developed. New laboratories have been formed (NOAA's Great Lakes Environmental Research Laboratory and EPA's Large Lakes Research Station) whose missions have a major orientation towards systems modeling. Many models designed for or with application to the Great Lakes have been developed at universities. Much of the recent modeling effort is a direct outgrowth from the limnological systems analysis Phase I reports and meetings and deliberations on modeling sponsored or supported to encourage the development of modeling methodologies to assist planners in the Great Lakes Basin.

One of the most significant recent reports on Great Lakes mathematical modeling is a review of models or modeling methodologies by Tetra Tech, Inc.[2]. This report was prepared for the Lake Erie Wastewater Management Study of the U.S. Army Corps of Engineers. The report provides a convenient update of the review of the modeling literature prepared in the Phase I report.

Tetra Tech's assessment of the present state-of-the-art of water quality monitoring agreed with the conclusions of the Phase I report in that they believed rational modeling methodologies are currently available for the Great Lakes. The main job that has to be accomplished is integrating these models into workable, practical programs of utility to planners and managers.

Another pertinent review work entitled Systems Analysis in Water Resources Planning was recently conducted by Meta Systems, Inc. [3]. The report was prepared for the National Commission on Water Quality to (1) examine systems analysis in water and related land resources planning to describe the potential role of this approach for water resources planners rather than for systems analysis or operations research professionals, and (2) make recommendations on the use of systems analysis in water resources planning, including mechanisms for its promotion in this field and areas of further research needs. One of the major conclusions of this report was that the balance of evidence overwhelmingly favors the use of system analysis techniques for water resources planning problems. Again, this supports the use of systems analysis as part of a Great Lakes environmental planning strategy.

Another recent modeling review is Modeling Biochemical Processes in Aquatic Systems.[4]. This book has some key papers on current Great Lakes modeling activities.

The Environmental Protection Agency is sponsoring the development of lake effect models for Lake Ontario, Lake Erie, and the Saginaw Bay area of Lake Huron. Consultants for these modeling activities have been the same individuals who prepared the Phase I report. Thus, the Phase I report served as the impetus for this work. The models for Saginaw Bay, Lake Erie, and Lake Ontario were all discussed as part of a recommended program described in the Specifications report (Appendix 2). The Lake Ontario model is now operational and the preliminary predictions from this model[5] already have had a major effect on some Great Lakes programs.

As part of the Level B Study of the Maumee River Basin, coordinated by the Great Lakes Basin Commission, a mathematical model was developed for Maumee Bay. This model is designed to measure the impact of alternative plans for the Maumee watershed on the Maumee Bay. Traverse Bay in Lake Michigan has also undergone extensive study by the University of Michigan. Models developed include limnological, sociological, and economic models.

The Lake Erie Regional Assessment of the U.S. National Commission on Water Quality has recently utilized a phosphorus model[6] for projecting water quality changes in Lake Erie according to different management schemes. This model is part of an overall effort at the Systems Research Center of Case Western Reserve University to model regional phosphorus pollution control. Many other universities in the basin have active Great Lakes modeling programs.

The Lake Erie Wastewater Management Study of the U.S. Army Corps of Engineers is currently utilizing a different phosphorus model to project water quality changes in Lake Erie which would result from different management schemes. Thus, there are a number of modeling methodologies specifically for Lake Erie that are currently available. For planning applications it would perhaps be useful to use different methodologies which model the same parameter or process to set probable output ranges.

The recent activity in mathematical modeling is also reflected in the number of papers presented in recent years at the annual conferences on Great Lakes research sponsored by the International Association for Great Lakes Research. Separate sessions of this conference are now devoted entirely to modeling.

Any overall model for the water quality of the Great Lakes must include submodels for tributary loadings, or at least consider submodels as exogenous inputs. Among the major efforts at watershed modeling, the Pollution from Land Use Activities Reference Group of the International Joint Commission is sponsoring some model development related to tributaries to the Great Lakes. Similarly, the U.S. Army Corps of Engineers' Lake Erie Wastewater Management Study is developing Lake Erie watershed models. The Upper Lakes Reference Group of the International Joint Commission is sponsoring the development of general waste generation models which consider economic, legislative, and sociological factors as well as water quality factors. Finally, the 208 programs sponsored by U.S. EPA often have watershed modeling components.

The modeling papers and reports discussed above, as well as other recent, pertinent literature not discussed here, are compiled in the references (Section IX) and the bibliography (Section X). These lists are intended to provide an update of the reference list provided in the Phase report (Appendix A).

SECTION VIII

GREAT LAKES ENVIRONMENTAL PLANNING STUDY (GLEPS)

Environmental planning and program implementation for Great Lakes resource problems have received increased attention since the initiation of the Phase I study. As discussed in previous sections, progress in research, data collection, and analyses continues to be reflected in improved policy and resource management decisions affecting portions of the lakes. However, there continues to be a need to establish a systematic framework for Great Lakes planning which will give planners quantitative tools to evaluate the effectiveness of many resource management strategies on different segments of the entire Great Lakes system. In order to develop a comprehensive coordinated joint plan for the Great Lakes region, a GLEPS program would be an extremely useful, if not essential, tool.

The Great Lakes Environmental Planning Study (GLEPS) represents Phase II in the limnological systems analysis program. GLEPS will furnish the basis for detailed assessments of the effects of alternative courses of resource management strategies on the Great Lakes themselves. These assessments will be used in completing and maintaining a comprehensive coordinated joint plan for the region. The proposed planning study will not investigate and propose final solutions to all conceivable resource problems and needs within the entire Basin. Instead, it will serve as a tool to allow planners and managers in the Great Lakes area to realistically evaluate the effects on the lakes of appropriate action programs focused to meet middle-term (15-25 years) needs and desires.

The major objective of the GLEPS study is to integrate currently available analytical methodologies and utilize this integrated framework to model certain physical, chemical, and biological processes of the Great Lakes. The utility of the modeling effort lies in its ability to evaluate the consequences of alternative planning and resource development strategies. This effort is not designed to replace "best judgment" planning, but only to develop an additional means for planners, engineers, or economists to evaluate alternatives.

Planning for the entire Great Lakes system requires a special and unique planning approach. GLEPS will be characterized by: (1) an integration of proven planning approaches with the increasingly useful technique of applying systems analysis to large-scale, multidisciplinary water resource problems; (2) successive planning iterations to insure responsiveness of GLEPS to governmental and non-governmental objectives for the lakes; and (3) development of a planning framework which will be the basis for continuous planning processes for the Great Lakes system.

The GLEPS program as it is currently conceived is not designed to develop extensive new models. The Phase I report (Appendix A) and other studies discussed in Section VII agree that rational modeling methodologies are currently available for application to the Great Lakes. Of major importance is the molding of these models into workable programs relevant to planning and program evaluative needs. The GLEPS program will conduct modeling applications programs and apply the results to current planning efforts and approaches. A major portion of the study will be devoted to formulating in an iterative fashion alternative planning strategies for the Great Lakes, using the modeling program as an evaluative methodology. An assessment of the usefulness and limitations of the modeling program in comparison to other planning techniques will finally be made. Thus, emphasis will be on "applied modeling", using existing methodologies which could potentially yield information of practical importance to planners. The development of new models, the refinement of old models, or the verification or negation of existing models by other agencies or organizations will serve to update the total GLEPS effort. Where applicable, the results of several different methodologies which model the same parameter or problem will be used in GLEPS to set the probable output ranges.

The model approach used by GLEPS will use as a basis the recommended framework developed as a result of the Phase I investigation and summarized in "Great Lakes Systems Analysis: Model Specifications" (Appendix B). In the Specifications report it is recommended that:

(1) existing subsystem models, parameter values, and inputs be gathered into interactive modeling frameworks;

(2) generalized computer programs be developed and modifications be made to existing models to accommodate recently evolved numerical and software techniques; and

(3) applications be made of existing systems technology to those problem categories for which a reasonable degree of success for the application is assured.

These recommendations are still timely and would be major aspects of the Phase II study (GLEPS).

The following specific problems were also recommended for inclusion in the Phase II study (see Appendix B):

(1) Water Quality
  (a) Dissolved oxygen
  (b) Chemical interactions

(2) Public Health

(3) Eutrophication--biomass problems

(4) Food Chain--toxic or harmful substances

The effect of different management strategies would be measured through these different problem contexts.

The Specifications report (Appendix B) recommended that the Phase II study (GLEPS) be directed toward three spatial scales:

(1)	Comprehensive Great Lakes	All lakes interconnected
(2)	Lakewide	Lakes Erie and Ontario
(3)	Regional	Duluth, Minnesota area, Southern Lake Michigan, Green Bay, Saginaw Bay, Lake St. Clair.

These spatial scales would still be appropriate for the GLEPS effort. As discussed previously, comprehensive modeling activities are already well under way for lakewide studies of Lakes Erie and Ontario and a regional study of Saginaw Bay. Further, as part of the Great Lakes Basin Commission's two-year Fox-Wolf Level B study, scheduled to begin in late 1976, detailed modeling activities will be conducted on Green Bay. Other Great Lakes and regional models, including regional models of areas not suggested above, are available which could be incorporated in the GLEPS effort.

Examples of specific resource planning or management questions that could be addressed in a quantitative fashion by GLEPS are listed below:

(1) What would be the effect on the Great Lakes of reducing loading by regulating point and non-point sources of certain substances (e.g., phosphorus)? How fast and to what extent would different areas of the Great Lakes respond?

(2) What would be the effect on the food chain of increasing metal concentrations in the Great Lakes through industrial waste discharge or through effluents from mining operations?

(3) What might be the effect of major oil spills from wells or ships on the Great Lakes in terms of organic pollution or light shading of phytoplankton?

(4) What might be the effect on fish stocks from the killing of larval fish by cooling water intakes? Where can intakes be best placed to have the least ecological impact and the greatest overall benefits?

(5) What zones in a lake are particularly sensitive to different ecological factors? What zones have a high productivity potential? What zones have long recovery rates, etc.?

(6) What would be the social, economic, ecological, and public health effects of limiting or prohibiting the use of PCBs? To what extent and at what rate would the different lakes respond?

(7) What effect would reduction of shoreline erosion have on Great Lakes water quality?

(8) What would be the effect of water diversions on water levels or water quality?

(9) What influence would regulating water levels have on water quality, biological production (e.g., fish spawning), and physical erosion?

Despite the great amount of work that has been devoted to individual aspects of the above questions, a systems analysis approach will be necessary to integrate the data into an overall picture of the Great Lakes environment.

SECTION IX

REFERENCES

[1] Eppley, R. W., "Temperature and Phytoplankton Growth in the Sea", Fish. Bull., 70, 4, p. 1063-1085, 1972.

[2] Tetra Tech, Inc., "Final Report, Lake Erie Wastewater Management Study", Tetra Tech Report No. TC-413, 1974.

[3] Meta Systems, Inc., Systems Analysis in Water Resources Planning, Water Information Center, Inc., Port Washington, N. Y., 393 p., 1975.

[4] Canale, R. P., ed., Modeling Biochemical Processes in Aquatic Ecosystems, Ann Arbor Science, Ann Arbor, Michigan, 1976.

[5] Thomann, R. V., D. M. DiToro, R. P. Winfield and D. J. O'Connor, "Mathematical Modeling of Phytoplankton in Lake Ontario", EPA Report 660/3-75-005, U. S. EPA, Corvallis, Oregon, 177 p., 1975.

[6] Richardson, J. M. and J. G. Klabbers, "A Policy-Oriented Model of the Eutrophication Problem in the Lake Erie Ecosystem", SRC Report 74-1, Systems Research Center, Case Western Reserve University, 115 p., 1974.

SECTION X

BIBLIOGRAPHY

Additional or recent references not cited in Section IX or in the Appendices.

Baca, R. G. and R. C. Arnett. 1975. "A Limnological Model for Eutrophic Lakes and Impoundments." Battelle Pacific Northwest Laboratories, Richland, Washington, 158 p. (mimeo).

Benedict, B. A., J. L. Anderson and E. L. Yandell, Jr. 1974. "Analytical Modeling of Thermal Discharges - A Review of the State of the Art." Argonne National Laboratory ANL/ES-18, April.

Bloomfield, J. A., R. A. Park, D. Scavia and C. S. Zaborcah. 1973. "Aquatic Modeling in the Eastern Deciduous Forest Biome, U. S. International Biological Program." In Workshop Proceedings of Modeling the Eutrophication Process, Utah State University and EPA, November, p. 139-158.

Bonham-Carter, G. and J. H. Thomas. 1973. "Numerical Calculations of Steady Wind-Driven Currents in Lake Ontario and the Rochester Embayment." Proc. 16th Conference, Great Lakes Research, International Assoc. Great Lakes Research, p. 640-662.

Buechi, P. J., and R. R. Rumer. 1969. "Wind Induced Circulation Pattern in a Rotating Model of Lake Erie." Proc. 12th Conf. Great Lakes Research, International Assoc. Great Lakes Research, p. 406-414.

Canale, R. P. 1971. "A Methodology for Mathematical Modeling of Biological Production." University of Michigan, Sea Grant Program.

Canale, R. P. and A. W. Green. 1972. "Modeling the Spatial Distribution of Coliforms in Grand Traverse Bay." Proceedings of the 15th Conference on Great Lakes Research, International Assoc. Great Lakes Research.

Canale, R. P., S. Nachiappan, D. J. Hineman and H. E. Allen. 1973. "A Dynamic Model for Phytoplankton Production in Grand Traverse Bay." Proceedings of the 16th Conference on Great Lakes Research, International Assoc. Great Lakes Research, p. 21-33.

Canale, R. P., D. F. Hineman and S. Nachiappan. 1974. "A Biological Production Model for Grand Traverse Bay." University of Michigan, Sea Grant Program Report No. 37, February.

Chapra, S. C. and S. J. Tarapchak. 1976. "A Chlorophyll *a* Model and Its Relationship to Phosphorus Loading Plots for Lakes." GLERL Contribution No. 44, Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, Ann Arbor, Michigan, 20 p. (mimeo).

Chapra, S. C. 1976. "Total Phosphorus Model for the Great Lakes." Publication of the Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, Ann Arbor, Michigan, 31 p. (mimeo).

Chen, C. W. and G. T. Orlob. 1972. "Ecologic Simulation for Aquatic Environments." Report to the Office of Water Resources Research, Water Resources Engineers, Inc., Walnut Creek, California, December, 156 p.

Chen, C. W., S. S. Lee and M. Lorenzen. 1974. "Water Quality Studies for the Proposed Lakeport Lake." Report to the Corps of Engineers, Sacramento District, Tetra Tech, Inc., June.

Cheng, R. T., and C. Tung. 1970. "Wind Driven Lake Circulation by the Finite Element Method." Proceedings of the 13th Conference on Great Lakes Research, International Assoc. Great Lakes Research.

Dillon, P. J. 1974. "A Critical Review of Vollenweider's Nutrient Budget Model and Other Related Models." Water Resources Bulletin, 10, p. 969-989.

Dillon, P. J. and F. H. Rigler. 1974. "A Test of a Simple Nutrient Budget Model Predicting the Phosphorus Concentration in Lake Water." Journal of Fisheries Research Board of Canada, 31, p. 1771-1778.

Di Toro, D. M., D. J. O'Connor and R. V. Thomann. 1970. "A Dynamic Model of Phytoplankton Populations in Natural Waters." Environmental Engineering and Science Program, Manhatton College, Bronx, New York, June.

Feigner, K. D. and N. A. Jaworski. 1972. "Mathematical Model Applications for Water Quality Management in the Potomac Estuary." In International Symposium on Mathematical Modeling Techniques in Water Resources Systems, K. Biswas, ed. Ottawa, May, pp. 129-138.

Friedman, J. H. 1973. "Eutrophication: A Mathematical Model." Reports on Natural Resource Systems, No. 21, University of Arizona, Tucson.

Gallagher, R. H., J. A. Liggett and S. T. K. Chan. 1973. "Finite Element Shallow Lake Circulation Analysis." Journal of the Hydraulics Division, ASCE, 99, HY 7, July, p. 1083-1098.

Gedney, R. T., F. B. Molls and W. Lick. 1973. "A Simplified Stratified Lake Model for Determining Effects of Wind Variation and Eddy Diffusivity." Proceedings of the 16th Conference on Great Lakes Research, International Assoc. Great Lakes Research, p. 710-722.

Gupta, N. N. and J. Houdeshell. 1975. "A Differential-Difference Equations Model of a Dynamic Aquatic Ecosystem." Int. J. Systems Sci., 0, p. 1-12.

Hall, R. W., H. E. Westerdahl and R. L. Eley. 1974. "A Review of Ecosystem Modeling Methodology with Recommendations for Application to the Dredged Material Research Program." Draft Report by U.S. Army Engineers Waterways Experiment Station, June.

Hamblin, P. F. 1974. "A Simple Dispersion Model of the Mean Concentration Field in the Western and Central Basins of Lake Erie." J. Great Lakes Res., 1, 1, p. 92-100.

Harper, M. E. 1972. "Development and Application of a Multi-Parametric Mathematical Model of Water Quality." Ph.D. Thesis, University of Washington, June.

Imboden, D. M. 1974. "Phosphorus Models of Lake Eutrophication." Limnol. and Oceanog., 119, 2, p. 297-304.

Kirchner, W. B. and P. J. Dillon. 1975. "An Empirical Method of Estimating Retention of Phosphorus in Lakes." Water Resour. Res., 11, 1, p. 182-183.

Lassiter, R. R. 1975. "Modeling Dynamics of Biological and Chemical Components of Aquatic Ecosystems." EPA-660/3-75-012, National Environmental Research Center, Corvallis, Oregon.

Lee, K. K., and J. A. Liggett. 1970. "Computation for Circulation in Stratified Lakes." Journal of the Hydraulic Division, ASCE, 96, HY 10, pp. 2089-2115.

Leendertse, J. J. 1967. "Aspects of a Computational Model for Long-Period Water-Wave Propagation." Rand Corporation, Report No. RM-5294-PR, May, 165 p.

Leendertse, J. J.- R. C. Alexander and S. K. Liu. 1973. "A Three-Dimensional Model for Estuaries and Coastal Seas: Volume I: Principles of Computation." Rand Corporation, Report No. R-1417-OWRR, December, 57 p.

Lerman, A. 1972. "Strontium 90 in the Great Lakes; Concentration-Time Model." J. Geophys. Res., 77, 18, p. 3256-3264.

Lick, W. 1976. "Numerical Models of Lake Currents." Ecological Research Series Report, U.S. EPA, EPA-600/3-76-020, 140 p.

Lombardo, P. S. 1971. "A Mathematical Model of Water Quality in an Impoundment," M. S. Thesis, University of Washington, Seattle, Washington, March.

Lombardo, P. S. 1972. "Water Quality Simulation Model Discussion," Journal of the Sanitary Engineering Division, ASCE, Vol. 98, No. SA 2, April, pp. 468-470.

Lombardo, P. S., and D. D. Franz. 1972. "Mathematical Model of Water Quality in Rivers and Impoundments," Hydrocomp, Inc., Palo Alto, California, December.

Lorenzen, M. W. 1973. "Predicting the Effects of Nutrient Diversion on Lake Recovery." In Workshop Proceedings of Modeling the Eutrophication Process, Utah State University and EPA, November, pp. 205-210.

Lorenzen, M. W., and R. Mitchell. 1973. "Theoretical Effects of Artificial Destratification on Algal Production in Improvements." Environmental Science and Technology, Vol. 7, No. 10, pp. 939-944, October.

Lorenzen, M., Smith, D. J., Kimmel, L. V. 1976. "A Long-Term Phosphorus Model for Lakes: Application to Lake Washington." Modeling Biochemical Processes in Aquatic Ecosystems, R. P. Canale, ed., Ann Arbor Science Publishers, Inc., Ann Arbor, MI., 1976, pp. 75-92.

Markofsky, N., and D. R. F. Harleman. 1971. "A Predictive Model for Thermal Stratification and Water Quality in Reservoirs." EPA Report No. 161-30-DJH 3/71 Water.

Meredith, D. D. 1974. "Hydrologic Models of the Great Lakes." WRC Res. Rep. No. 81, Water Resources Center, University of Illinois, Urbana, 38 p.

Newbold, J. D., and J. A. Liggett. 1974. "Oxygen Depletion Model for Cayuga Lake," Journal of the Environ. Engineer. Division, ASCE, 100, EE 1, p. 41-59.

O'Connor, D. J., Di Toro, D. M. and R. V. Thomann. 1975. "Phytoplankton Models and Eutrophication Problems." In Ecological Modeling, C. S. Russel, ed., Resources for the Future, Inc., Washington, D. C., p. 149-209.

O'Melia, C. R. 1972. "An Approach to the Modeling of Lakes." Swiss Journal of Hydrology, 34, p. 1-34.

O'Neill, R. V. 1975. "Management of Large-Scale Environmental Modeling Projects in Ecological Modeling." C. S. Russel, ed., Resources for the Future, Inc., Washington, D. C., p. 251-282.

Paskaysky, D. F. 1969. "A Barotropic Prognostic Numerical Model of the Circulation in the Gulf of Mexico." Ph.D. Thesis, Texas A and M University.

Patterson, R. L. undated. "A Progress Report on Mathematical Models for Natural Resource Systems Analysis." University of Michigan, Sea Grant Program, 49 p.

Paul, J. F. and W. J. Lick. 1973. "A Numerical Model for a Three-Dimensional, Variable-Density Jet." Proceedings of the 16th Conference on Great Lakes Research, International Assoc. Great Lakes Research, p. 818-830.

Pinsak, A. P. and T. L. Meyer. 1976. "Environmental Baseline for Maumee Bay." Maumee River Basin Level B Study, Technical Report No. 9, Great Lakes Basin Commission, 194 p.

Platzman, G. W. 1963. "The Dynamical Prediction of Wind Tides on Lake Erie." Meteorological Monographs, 4, 26, p. 1-44.

Ridley, J. E. and J. M. Simons. 1972. "New Approaches to Water Quality Control in Impoundments." Water Pollution Microbiology, Ralph Mitchel (ed.), p. 389-412.

Rumer, R. R., Jr., D. D. Merideth, C. C. Chien and R. P. Apmann. 1974. "Chlorides in Lake Erie." Water Resources and Environmental Engineering Report No. 74-1, State Univ. of New York at Buffalo, Buffalo, 82 p.

Simons, T. J. 1971. "Development of Numerical Models of Lake Ontario." Proceedings of the 14th Conference on Great Lakes Research, International Assoc. Great Lakes Research.

Simons, T. J. 1973. "Comparison of Observed and Computed Currents in Lake Ontario During Hurricane Agnes." Proceedings of the 16th Conference on Great Lakes Research, International Assoc. Great Lakes Research, p. 831-844.

Simons, T. J. 1973. "Development of Three-Dimensional Numerical Models of the Great Lakes." Canada Centre for Inland Waters, Scientific Series No. 12.

Simons, T. J. 1973. "Continuous Dynamic Computations of Water Transports in Lake Erie for Year 1970." Canada Centre for Inland Waters, Internal Report, July.

Simons, T. J. 1974. "An Operational Framework for Interfacing Physical and Biochemical Computer Models of Large Water Bodies." Canada Centre for Inland Waters, June.

Smith, F. E. 1969. "Efforts of Enrichment in Mathematical Modeling." In Eutrophication - Causes, Consequences, Corrections, National Academy of Science, Washington, D. C., p. 631-645.

Snodgrass, W. J. and C. R. O'Melia. 1974. "A Predictive Model for Phosphorus in Lakes." Draft, August.

Sonzogni, W. C., P. D. Uttormark and G. F. Lee. 1976. "A Phosphorus Residence Time Model: Theory and Application." Water Research, 10, p. 429-435.

Vollenweider, R. A. 1969. "Possibilities and Limits of Elementary Models Concerning the Budget of Substances in Lakes." Archives of Hydrobiology, Vol. 66, p. 1-36.

Vollenweider, R. A. 1975. "Input-Output Models." Schweiz. Z. Hydrology, 37, p. 53-84.

Vollenweider, R. A. and P. J. Dillon. 1974. "The Application of Phosphorus Loading Concept to Eutrophication Research." N.R.C. Tech. Rep. 13690, National Research Council of Canada, 42 p.

Welander, P. 1957. "Wind Action on a Shallow Sea: Some Generalizations of Ekman's Theory." Tellus, 9, 45-52.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/3-77-126a	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Great Lakes Environmental Planning Using Limnological Systems Analysis: Summary		5. REPORT DATE November 1977 issuing date 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Hydroscience, Inc., 363 Old Hook Road, Westwood, New Jersey 07675		8. PERFORMING ORGANIZATION REPORT NO
9. PERFORMING ORGANIZATION NAME AND ADDRESS prepared for the Great Lakes Basin Commission P.O. Box 999 3475 Plymouth Road Ann Arbor, Michigan 48106		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. DACW-35-71-C0030
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Research Laboratory-Duluth, MN 55804 Office of Research and Development U.S. Environmental Protection Agency Duluth, MN 55804		13. TYPE OF REPORT AND PERIOD COVERED Final 14. SPONSORING AGENCY CODE EPA-600/03
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

The report documents the deliberate decision making process used by the Great Lakes Basin Commission in concluding that rational modeling methodologies could be used to evaluate the effect of different planning alternatives on the Great Lakes and that planning for specific problems affecting the Great Lakes system can be technically and economically supported through mathematical modeling and systems analysis. It assesses the technical and economical feasibility of developing mathematical models to assist in making selections from among alternative management strategies and structural solutions proposed for solving water resource problems of the Great Lakes. The study reviews, evaluates and categorizes present and future water resources problems, presently available data, problem-oriented mathematical models and the state of models and model synthesis for large lakes. A demonstration modeling framework for planning is developed and applied to western Lake Erie and the Great Lakes system. The report evaluates four widely ranging alternatives for future modeling efforts in the Great Lakes and recommends the modeling level most feasible to answer planning questions on scales ranging from the Great Lakes to regional areas. Also discussed is a proposed Commission study which will apply limnological systems analysis to the planning process.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Limnology, Systems, Mathematical Models, Water Resources, Planning, Hydrology, Ecology	systems analysis, Great Lakes, ecosystems, long term planning, environmental effects, large lakes	08 H 13 B

18. DISTRIBUTION STATEMENT Release unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 36
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE