COMPUTER SIMULATION OF EUTROPHICATION

by

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General Approach

The proposal for the research project reported herein was principally prepared during 1968 and the starting date for this study was established as September 1, 1969. In the approximately four years from the preparation of this proposal to the completion of this final report, the state of the art for the subject, computer simulation of eutrophication, has undergone a dramatic development. The development of this area has in general, followed the expansion of the Riley mass balance equations and the Michaelis-Menten equation as described in the original proposal. This development, however, has been more rapid than implied by the proposal and the contributions to this development have come from a variety of sources. The works of Thomann, O'Connor and Ditoro (1970) and Chen (1970) are among the best examples of the models developed during this time period. Similar models are being employed in a wide range of environmental studies and environmental management approaches. An extensive modeling effort is also being pursued for the study of terrestrial ecosystems. Few subject areas in the environmental sciences can match the rapid development and exapansion of ecosystem modeling that has occurred in the past few years.

The original proposal was written as a relatively self-contained project. The broad expansion of ecosystem modeling, which rapidly progressed in a manner quite similar to that outlined in the original proposal, made it necessary to view the project goals and approaches from a perspective which recognized the many developments occurring in this area. The research was thus one of active participation in a rapidly expanding field with a strong emphasis given to avoiding unnecessary duplication and providing the maximum contribution for the resources available.

A number of workshops and informal exchanges provided for meaningful information exchange among investigators in this field prior to the appearance of formal publications in the literature. The workshop entitled "Modeling the Eutrophication Process" held in November, 1969 under the sponsorship of the University of Florida and the U.S. Department of the Interior (FWQA) was attended by approximately forty persons, including the author, and provided particularly important information exchange. The author participated in a number of such workshops. As a result of these informal information exchanges, a number of meaningful subject areas were pursued throughout the course of this study so as to contribute to this rapidly expanding field without wasteful duplication or poor utilization of recent (though often unpublished) information.

The body of this report will provide, under five principal headings, and overall record of the accomplishments, conclusions and recommendations of this study. Reference will be made to the publications developed under this study which are listed in a separate section of this report.

Algal Sinking and Mixing

The most common mathematical models of the eutrophication process treat the phytoplankton as a single component. That is, the model output provides a measure of the total phytoplankton biomass. A major problem in eutrophic waters, however, is often not the total biomass but rather the nature of the biomass. Specifically, eutrophic lakes are often characterized by blue-green algae which result in objectionably high surface concentrations and which may not provide a suitable primary food source for a more desirable ecosystem.

Field studies (reported during the last several years) from lakes which had been artifically mixed provided interesting results. In general, these results (from separate sources) demonstrated that, artificial mixing alone very often removed the most objectionable aspects of cultural eutrophication and in some of the more specific reports, declines in blue-green algae were noted. Though these results were recognized as having strong implications for the eutrophication process, they could not be reasonably examined through the use of the more common models of eutrophication because such models were either completely vertically homogeneous or they were divided into several homogeneous segments. A task established under this project was, thus, to examine possible factors which contribute toward a change in species composition with particular emphasis given to the influence of vertical mixing. The following guidelines were established so as to provide results which would complement the current research and avoid unnecessary duplication.

1. A clearly defined mathematical model of the mechanism being examined would be developed.
2. The model should be as simple as possible in order to clearly define the concepts examined without becoming unnecessarily

involved with other controversies associated with the eutrophication process.

3. The model should be such that it might be combined with the vertically homogeneous models of greater biological and chemical detail.
4. The model results should indicate where some future experimental research might provide more meaningful information.

A one-dimensional mathematical model which simulated the combined effects of algal growth, sinking of algae and vertical mixing in a lake was developed (1). Combinations of different growth rates, sinking velocities, euphotic zone depths, and vertical dispersion coefficients were incorporated into the model. Both algal sinking velocity and vertical mixing had pronounced effects on the tendency of different algae to increase. Reduction of the euphotic zone depth favored algae with lower sinking velocities, whereas increased mixing favored algae with higher sinking velocities. Experimental results reported in the literature indicate that nearly all freshwater diatoms and most other phytoplankton, except blue-green algae, sink in undisturbed water. Moreover, it appears that the sinking velocities of many algae increase when a nutrient becomes limiting. Most blue-green algae, by producing gas vacuoles, can reduce sinking velocities or even become bouyant. Thus the concepts described by this model do appear to be relevant, in general, to the dominance of blue-green algae in eutrophic lakes which do not receive artificial mixing. Subsequent research (not under this project) indicates that carbon limitation at high pH values contributes to such dominance of blue-green algae. In actual lakes, both of the above concepts, and others, interrelate to result in such domination. These concepts can lead to more effective control and corrective measures within eutrophic lakes.

In conjunction with the above model study, field studies were partially supported by this project to better understand the natural vertical mixing that occurs in the surface waters of lakes. Field results indicate that diel (24 hr) temperature variations provided a large portion of the mixing by resulting in a nocturnal density overturning extending to about 3 meters in depth (2)(3).

Dissolved Oxygen in Stratified Lakes

The most commonly used water quality models have, until very recently, dealt principally with the dissolved oxygen, DO, within flowing streams. These models have been one-dimensional, considering only the variations in water quality along the length of the stream. Cultural eutrophication, however, has been a major problem in lakes and the depletion of DO from the deeper waters of eutrophic lakes has been a common problem of major concern. Though attempts had been made to utilize the stream equations for the DO variations within eutrophic lakes and impoundments, the results were not very meaningful due to the distinct differences between lakes and flowing streams. An improvement of the qualitative and quantitative understanding of DO variations in stratified lakes was therefore established as a task to be pursued under this project.

To accomplish this task, in a manner that would provide general information rather than a narrow definition of a particular problem, several guidelines were established early in the study. Among these guidelines were the following:

1. A clearly defined mathematical model of the DO variations in lakes should be developed.
2. This model should take maximum advantage of the knowledge previously obtained from stream models.
3. The basic assumptions of the model should be examined in the light of field measurements.
4. The model should indicate which factors were most controlling and where future experimental research might most profitably be directed.

A mathematical model describing the DO variations in a stratified lake was developed (4). The basic model was one-dimensional including DO variations with depth and time. The model describes the combined effect of photosynthesis, reaeration, vertical mixing and total respiration. A method of using the model to determine hypolimnetic oxygen uptake rates was presented. The model study indicated that the DO concentrations within the hypolimnetic waters of lakes were more sensitive to vertical mixing and total respiration than to photosynthetic oxygenation or reaeration.

A companion field study on an eutrophic lake was partially supported by this project in order to better relate actual field results to the capabilities and limitations of the model (3). The temporal and spacial variations of temperature and dissolved oxygen were measured in Triangle Lake, Oregon. The lake was found to be relatively uniform in the horizontal direction and significantly vertically stratified.

Maximum diel DO variations were found to be less than 0.5 mg/L. These results did indicate that the principal model assumption of horizontal uniformity could be justified to describe the major DO variations. Each lake, of course, would have to be examined and where horizontal variations were found to be significant, a horizontally segmented model with vertical variations might have to be employed (the literature does demonstrate that horizontal variations in impoundments with larger river flows can be significant though vertical variations are usually larger).

The specific results and conlcusions for this phase of the project are presented in the cited references.

Expanded Phytoplankton Model

A central feature of nearly all of the recently developed mathematical models of the eutrophication process is the use of the Michaelis-Menten (Monod) equation for algal growth. Experimental approaches to the determination of the coefficients of this equation usually involve chemostat (flow through) or batch laboratory experiments. Because of the importance and wide-spread use of this equation, opinions concerning the adequacy (relevance, reality, suitability, etc.) of this equation were solicited from available persons most familiar with chemostat and batch phytoplankton experiments. The basic concepts and assumptions expressed in this equation were described in the most favorable manner possible to a group of biologists from the Department of Oceanography, Oregon State University. The support of the equation and its concepts and assumptions from this group fell just slightly less than total rejection. The objections were pursued, principally by William Grenney, and an improved model of phytoplankton growth was developed. Dr. Herbert Curl, Department of Oceanography, Oregon State University was a major contributor to this effort. This model forms the basis of a Ph.D. dissertation by William Grenney and publications based on this work have been prepared (5)(6)(8).

The three-compartment mathematical model that was developed represented a phytoplankton population having the capability to store nitrogen in a nitrate limited environment. Parameters were estimated by fitting the model to data from two chemostat experiments reported in the literature. The model was used to simulate growth dynamics observed in chemostat and batch experiments. The model demonstrated the changes which may occur in the nitrogenous constituents of phytoplankton population with time and environmental conditions. Three phenomena were demonstrated which have been observed in field and laboratory experiments but which are not represented by the customary Michaelis-Menten model: 1) uptake rates may significantly exceed net growth rates, 2) high growth rates may be encountered at very low environmental nitrate concetrations, and 3) the ratio of internal nitrogen to population size may change significantly during a study period. It is suggested that the amount of nitrogen in storage may be used as an indicator of the physiological state of the population.

Parameters for the one-compartment Michaelis-Menten (Monod) model were estimated by customary methods from data generated by the three-compartment model. It was shown that difficulties encountered in estimating the yield coefficient and the decay coefficient may be attributed to the intracellular storage phenomenon. It was also demonstrated that the one-compartment Monod model was inadequate to accurately represent population growth in chemostat experiments when intracellular storage is a significant factor.

The model was applied to a completely mixed system to demonstrate the succession of blooms and coexistence of species in phytoplankton communities as influenced by temporal variations in the environmental conditions. The model was then expanded to include the one-dimensional vertical distribution of the phytoplankton in the water column. The influences of light, temperature, and water turbulence on the growth and distribution of the population were included in the model.

It is not intended that this model replace the simpler Michaelis-Menten model but rather that these models, representing different levels of resolution, might complement each other. The three compartment nitrogen model could be expanded to include phosphorous and carbon. Such an expanded high level resolution model could complement the more simple models used for management purposes.

Temporal Variations

A characteristic feature of eutrophic waters is a decline in the species diversity of the phytoplankton (a diversity decline can also be apparent at other levels). Models of the eutrophication process nearly all quantify the phytoplankton by some single measure of biomass, thus, changes in biological diversity have not, in general, been examined through the use of the more common models. The importance of biological diversity is generally recognized and a decline of diversity is generally associated with increased ecological instabilities. The algal "bloom," characteristic of eutrophic lakes, can be considered a feature of such instabilities.

Water bodies which are not highly eutrophic or stressed by other factors do contain a variety of phytoplankton. A question that was pursued in this study was how can a wide variety of phytoplankton, which compete for a relatively few number of limiting resources in an environment which interdisperses the varieties, coexist? That is, what environmental conditions prevent competitive exclusion among the phytoplankton?

The study was directed primarily at the influence of temporal variation of environmental conditions. A simple model was developed in which two species competed for a single nutrient within a homogeneous environment (7). The first species had a higher average efficiency of nutrient uptake but was not able to adjust to environmental variations. The second species was not influenced by environmental variations but was less efficient with regard to nutrient uptake. When no environmental fluctuations were present, the first species competitively excluded the second. Both species, however, were able to coexist when sufficient environmental fluctuations were present. Thus, the coexistence of the two species depended upon the environmental fluctuations. The model described in the previous section of this report was also used to examine the influence of temporal variations upon coexistence (8). Again, it was shown that the coexistence of competitor species depended on the presence of temporal variations.

Though the models used in these studies were highly simplified in comparison to actual ecosystems, the results do suggest that the long term ecological impact of a variety of man's activities (e.g.; streamflow regulation, waste heat disposal, regulation of estuarine salinity intrusion, artificial mixing of lakes, weather modification, etc.) which tend to reduce temporal variations warrents further study.

Comprehensive Environmental Management

The rapid development and acceptance of mathematical models of aquatic and terrestrial ecosystems has been previously described. A broader more recent concern for comprehensive environmental planning has arisen at federal, regional and state levels. Comprehensive land use legislation is being pursued at both the federal and state levels and Oregon is no exception. The "systems approach to environmental planning" has become a popular (though most often poorly understood) phrase and there has been a tendency to rely partially upon a mathematical model approach. The subject of comprehensive planning and the role of mathematical models in comprehensive planning, however, has been nearly entirely omitted from the environmental engineering and management literature. The relatively few contributions to comprehensive planning have not been further analyzed and continued in the literature with the same degree of technical aggressiveness as subjects of a more limited and narrow scope. There is a real danger that comprehensive planning will be attempted by merely extrapolating methods and approaches which have been useful for the solution of narrowly defined problems of limited scope.

In the final phase of the project, the task of examining the problems of comprehensive environmental management and the role of mathematical models in comprehensive planning was pursued. It was decided to accomplish this phase by initially drawing upon the recent experiences obtained from the development of models for both aquatic and terrestrial ecosystems. The principal investigator of this report and Dr. W. Scott Overton jointly examined this broad, but increasingly important, topic. Dr. Overton has a broad experience in systems ecology and general systems theory and has actively participated in the modeling of terrestrial ecosystems through the International Biological Program.

The concepts resulting from this investigation are given in a published paper (9). No attempt at this time will be made to summarize this work and the interested reader should refer directly to the original paper.

Admittedly, the material covered in this paper does depart substantially from the original proposal, yet, at the time the proposal was written, the rapid developments previously described could not be clearly foreseen. The author believes that this work is a natural outgrowth from the more limited proposed work and it may eventually have the most significant impact on environmental management.

Publications Supported by Project

(1) Bella, D. A. "Simulating the Effect of Sinking and Vertical Mixing on Algal Population Dynamics," Journal of the Water Pollution Control Federation, 42:5, Part 2, May 1970. pp. R140-152.

(2) Smith, S. L. and D. A. Bella. "Diel Overturning in Lakes," Presented at the Pacific Northwest AGU Conference, Oregon State University, Corvallis, Oregon. 1971.

(3) Smith, S. A. and D. A. Bella. "Dissolved Oxygen and Temperature in a Stratified Lake," Journal of the Water Pollution Control Federation, 45:1, January 1973. pp. 119-133.

(4) Bella, D. A., "Dissolved Oxygen Variations in Stratified Lakes," Journal of the Sanitary Engineering Division, ASCE, 96:SA5 Proc. Paper 7628, October 1970. pp. 1129-1146.

(5) Grenney, W. J., D. A. Bella, and H. C. Curl, Jr. "A Mathematical Model of the Nutrient Dynamics of Phytoplankton in a Nitrate Limited Environment." Biotech. and Bioeng., 15:225, 1973.

(6) Grenney, W. J. and D. A. Bella. "A Mathematical Model of the Effects of Intracellular Nutrient Pools in Phytoplankton on Community Growth Dynamics." Presented at 3rd Annual Environmental Engineering and Science Conference, University of Louisville, Louisvilled, Kentucky, March 5-6, 1973, publication pending.

(7) Bella, D. A. "Ecological Importance of Temporal Variations," (Technical Note), Journal of the Sanitary Engineering Division, ASCE, 98:SA4, August 1972. pp. 685-691.

(8) Grenney, W. J., D. A. Bella, and H. C. Curl, Jr. "A Theoretical Approach to Interspecific Competition in Phytoplankton Communities." American Naturalist, in publication.

(9) Bella, D. A. and W. S. Overton. "Environmental Planning and Ecological Possibilities," Journal of the Sanitary Engineering Division, ASCE, 98:SA3, June 1972. pp. 579-592.

Additional References

Chen, C. W. "Concepts and Utilities of Ecological Models," Journal of the Sanitary Engineering Division, ASCE, 96:SAS, October 1970, pp. 1085-1097.

Thoman, R. V., D. J. O'Connor, and D. M. Ditoro. "Modeling of the Nitrogen and Algal Cycles in Estuaries," Presented at the Fifth International Water Pollution Research Conference, Paper III-9, July-August 1970.