ECOLOGICAL MODELING AND ESTIMATION OF STRESS

By

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ABSTRACT

Examples of the application of ecological modeling in studying environmental impact are given for Lake George, New York. Multivariate analysis, including cluster analysis and ordination, is useful in determining patterns of nutrient enrichment as shown by diatom death assemblages. CLEANER, an aquatic ecosystem model, represents functional ecologic and physiologic relationships and gives realistic simulations. Stresses, such as changes in nutrients, temperature, and turbidity, can be examined. LAND, a terrestrial ecosystem and land-use model is being developed; it will be coupled to CLEANER to provide basin-wide analyses.

INTRODUCTION

The estimation of ecological stress can be facilitated by a variety of modeling procedures. Such procedures include 1) multivariate analysis, which makes it easier for investigators to perceive the intensity of impact that man has had on the natural environment, and 2) simulation modeling, by which one can gain a better understanding of complex environmental relationships and can therefore make a better prognosis of potential impacts. In particular, simulation modeling has advanced to the stage in the United States where it can be used to examine the potential effects of stresses on both terrestrial and aquatic systems.

In this paper the application of these techniques will be demonstrated by a series of examples taken from the long-term study of Lake George, New York. The study began several years ago with a multivariate analytical survey, followed by the development and implementation of an aquatic ecosystem model; it is presently being completed with the development of a terrestrial ecosystem and land-use model that will be coupled with the aquatic model.

Lake George is of particular interest because it has been a principal site in the U. S. International Biological Program. It is a long, narrow, moderately deep lake (50 km long, 5 km wide at the widest point, and 18 m average depth). The watershed consists of mountainous metamorphic terrane and is approximately 492 km^2, in comparison with the lake area of 114 km^2. Consequently the lake is naturally oligotrophic. However, a heavy concentration of tourists at the southern end of the lake could be expected to have a detrimental impact on the water quality.

MULTIVARIATE ANALYSIS

In order to rapidly and efficiently determine the stress that tourism has been placing on the lake, multivariate analysis was performed on diatom death assemblages from 125 sample stations located systematically throughout the lake (Fig. 1) (Bloomfield, 1972). Numerous prior studies of diatoms suggested that they would be suitable indicators of nutrient enrichment, and by studying the diatom frustules contained in the top several mm of sediment a time-averaged indication of impact would be obtained.

The multivariate analytical strategy was designed to obtain the best environmental interpretation (See Park, 1974). R-mode (variable-by-variable) cluster analysis of the diatom data showed that there was no appreciable redundancy among the diatom types. Q-mode (sample-by-sample) cluster analysis showed that the samples grouped in a number of classes at high levels of similarity (Fig. 2).

Ordination emphasized the environmental gradients among the samples and made it possible to interpret the relationships of the clusters shown in Figure 2. Particular attention was given to the distribution of those diatom types that were known to be indicators of oligotrophic or eutrophic conditions. An example is the distribution of the genus Cyclotella (Fig. 3), which in general indicates oligotrophic, or nutrient-poor conditions. By noting the concordant gradients of the various indicator types, the general trend of nutrient enrichment among the samples was determined. A gradational series of patterns was assigned to the clusters to represent their positions along the nutrient gradient in the model (Fig. 4).

These same patterns were plotted on the map of Lake George in polygons enclosing each of the respective sample stations. The result is a map showing the nutrient stress on each part of the lake (Fig. 5). As one might expect, the nutrient-enriched areas are adjacent to the centers of population, moderately-enriched areas are in more sparsely populated parts of the drainage basin, and nutrient-poor areas are in the undeveloped parts.

SIMULATION MODELING

Aquatic

Understanding of the complex relationships of the Lake George ecosystem has been increased greatly by implementation of the aquatic model CLEANER. This comprehensive ecosystem model was developed by 25 investigators in the Eastern Deciduous Forest Biome, U.S. International Biological Program (Park and others, 1974); it is being improved continuously, especially with the addition of environmental-management capabilities (Park, Scavia, and Clesceri, 1975).

The model simulates 20 compartments, most of which are illustrated in Figure 6. Each of these is represented by one or more equations; mathematical functions are incorporated for each significant ecologic and physiologic process. Such functionality in the modeling ensures generality and permits greater application for management purposes.

CLEANER demonstrates adequate fits of predicted curves to observed data (Fig. 7). Parameter values, such as optimal temperatures and maximum photosynthetic rates, were based on the literature and cooperative IBP studies (Scavia and Park, 1975). No attempt was made to obtain perfect fits by changing these well established parameter values.

Analysis of detailed environmental relationships is enhanced by the use of plots showing the predicted time-courses of the modeled process rates (Scavia and Park, 1975). For example, Figure 8 shows that the concentration of orthophosphate in Lake George at any given time is predominantly the result of the biotic processes of uptake by phytoplankton and remineralization by decomposers and animals; the contribution from streams is insignificant. Assuming that the functionalities of the model are reasonably correct, one can infer that decreasing the phosphate loadings in the streams would have little effect on the dynamics of phosphate in the lake.

Perturbation of the driving variables, such as phosphate loadings, results in simulations that estimate the complex effects of environmental stress on all major components of the ecosystem. Most American modelers recognize that the estimations cannot be considered as precise predictions, but they do believe that useful insights can be derived.

Figures 9-11 exemplify the simulations that can be obtained in less than five minutes each, using the time-sharing capability of a fast computer available to personnel of the Environmental Protection Agency from remote terminals anywhere in the United States.

In the first example (Fig. 9) phosphate loadings to Lake George have been decreased to one-fifth of normal. The ecosystem is slow to respond, but blue-green algae and the fish gradually decrease in biomass over a period of several years. In the next example (Fig. 10) a sustained increase in temperature of 5°C results in an increase in blue-green algae and a slight decrease in lake trout. In the last example (Fig. 11) an increase in the extinction coefficient of the water, comparable to the effect of moderate siltation, causes a slight decrease in biomass of net and nannophytoplankton, but again the noxious blue-green algae increase.

The validity and potential applicability of CLEANER is being tested with data from several European lakes. Of particular interest at this time of renewed U.S.-U.S.S.R. cooperation is the adaptation of the model to Slapy Reservior, Czechoslovakia. Extensive changes have been made, including development of a two-layered version to represent stratification, changes in parameter values to represent European species, and addition of throughflow terms (Fig. 12).

Terrestrial

In order to fully understand the potential threat of stresses on Lake George and other freshwater ecosystems, it is advisable to utilize terrestrial models as well. This was recognized by the Lake George group, and a case study was recently completed, demonstrating the applicability of combining terrestrial and aquatic models (Park and Carlisle, 1975).

As a part of the case study, LAND, a model to simulate land-use changes and vegetational succession, is being developed (Carlisle and Park, 1975). The model combines the approach to studying land-use changes of Hett (1971) and the forest succession model of Shugart and others (1973). However, it is more applicable to problems of environmental impact because it subdivides a study area into km^2 cells and considers the site-specific soil, slope, vegetational, aesthetic and cultural characteristics of each. It is anticipated that simulation results can be represented by maps such as those of the calibration data (Fig. 13).

Eventually models such as CLEANER and LAND, as well as hydrologic models, can be coupled to estimate basin-wide effects of environmental stress (Fig. 14). At Lake George, use of information from 7,000 returned questionnaires on environmental perception will permit evaluation of the cultural and economic implications of these environmental effects (Park, Scavia, and Clesceri, 1975).

SUMMARY

Ecological modeling is useful in estimating the impacts of environmental stresses. A multivariate-analytical approach facilitates interpretation and delineation of biotic responses to stresses such as nutrient enrichment. Aquatic and terrestrial simulation models provide insights

into complex relationships and, through perturbation analysis, permit evaluation of the consequences of environmental impact. The full potential will be realized when these models can be coupled.

ACKNOWLEDGEMENTS

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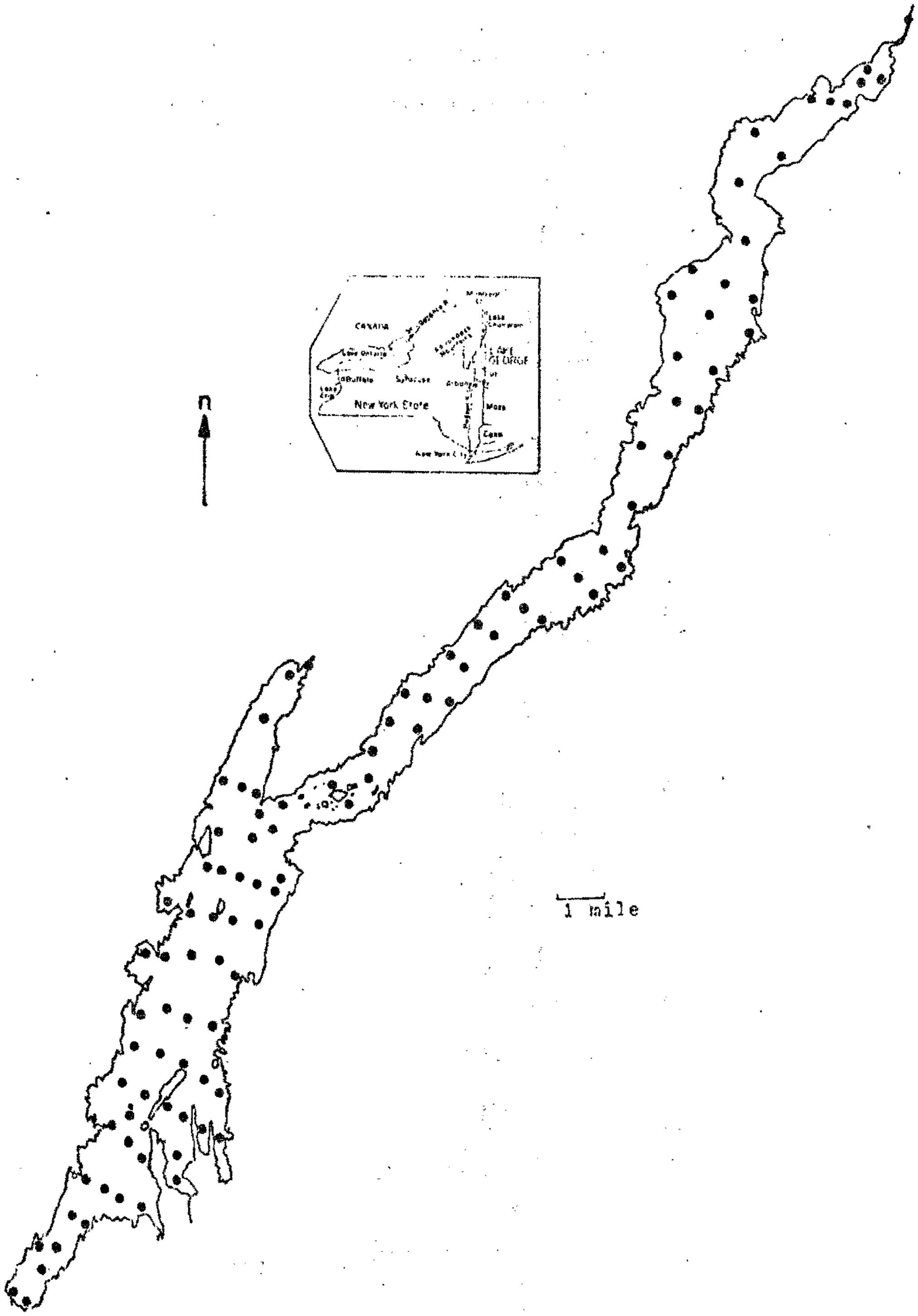
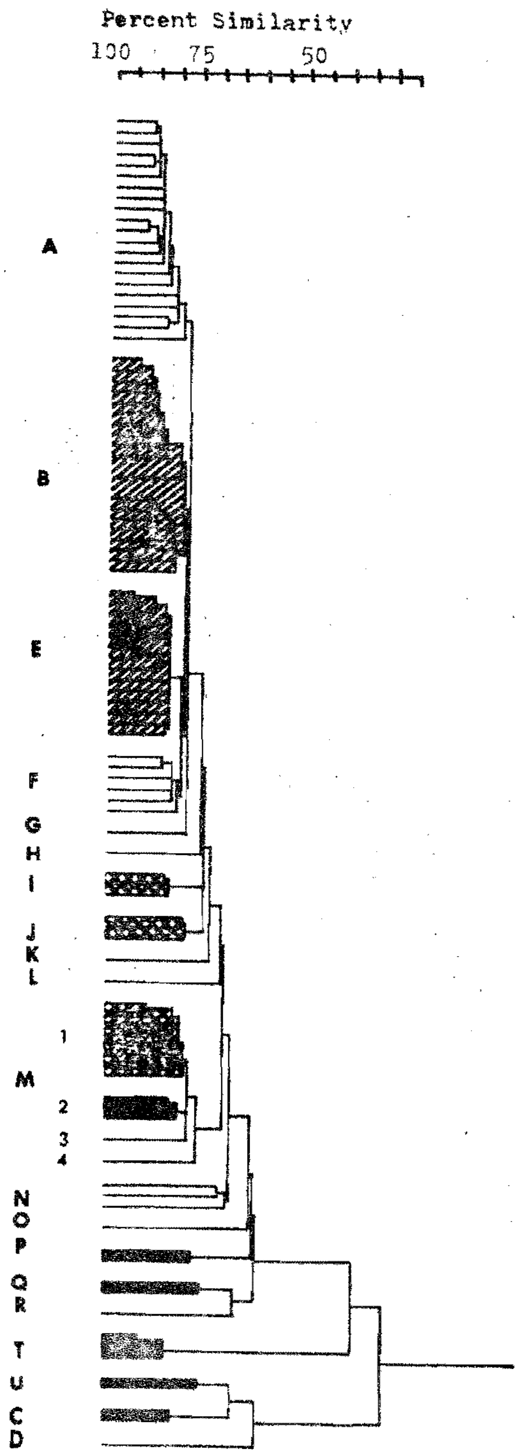
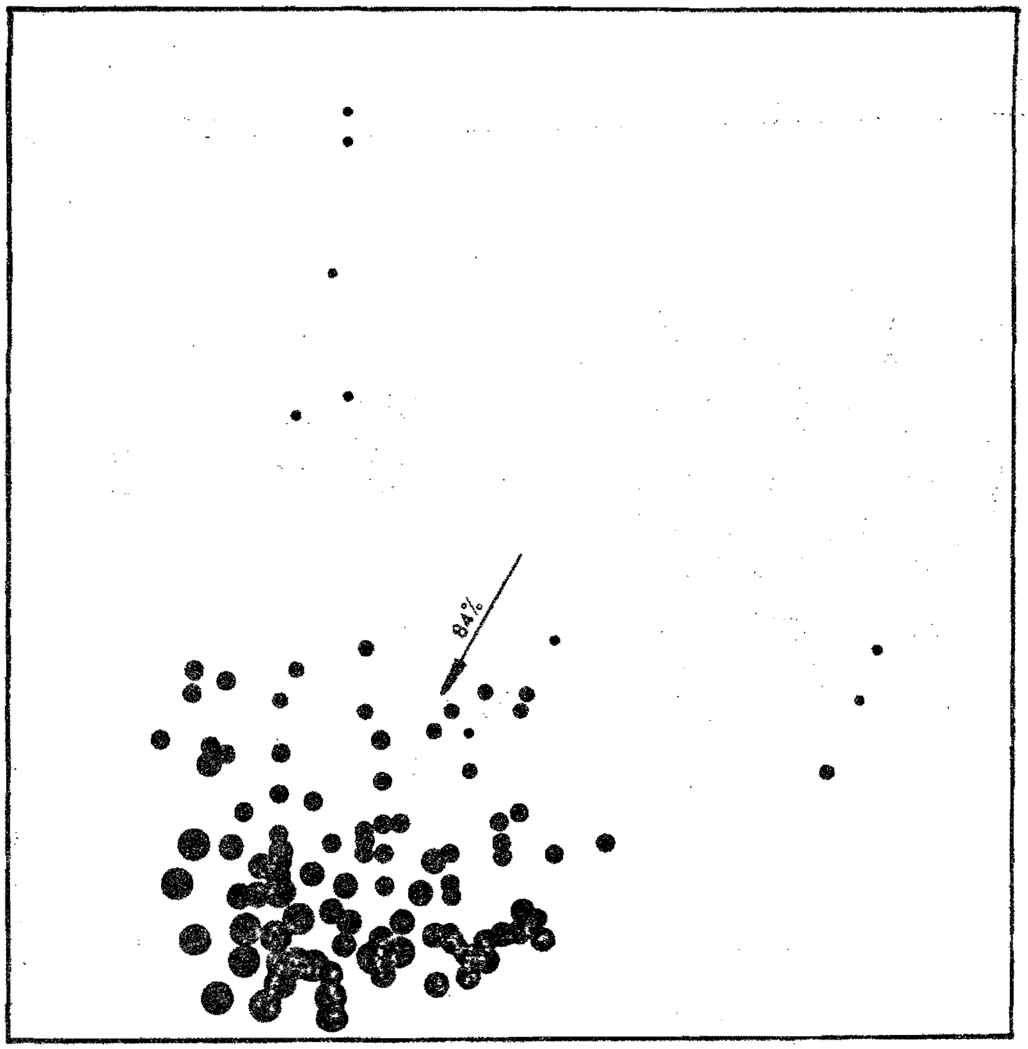


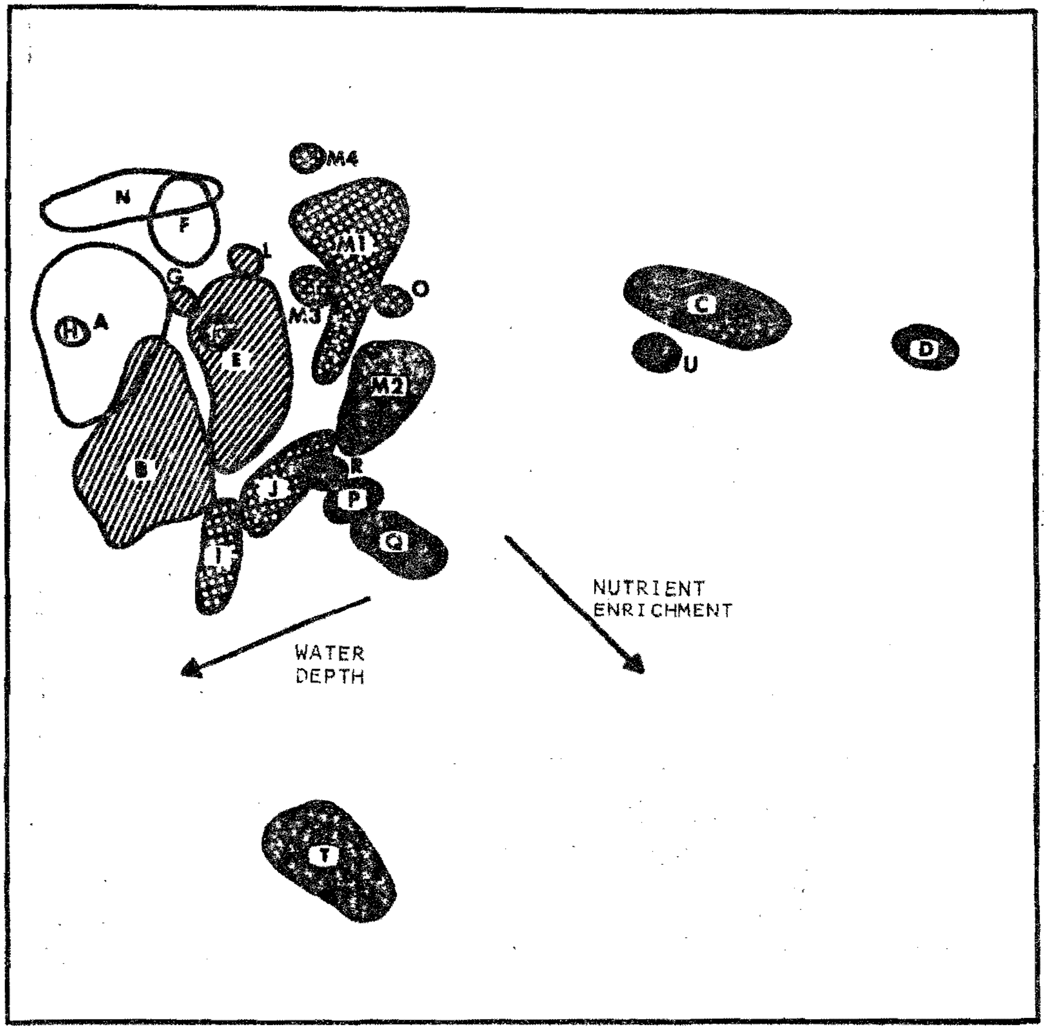
1. Diatom sample stations, Lake George, New York



2. Q-mode cluster analysis of Lake George diatom samples



3. Distribution of Cyclotella in ordination model



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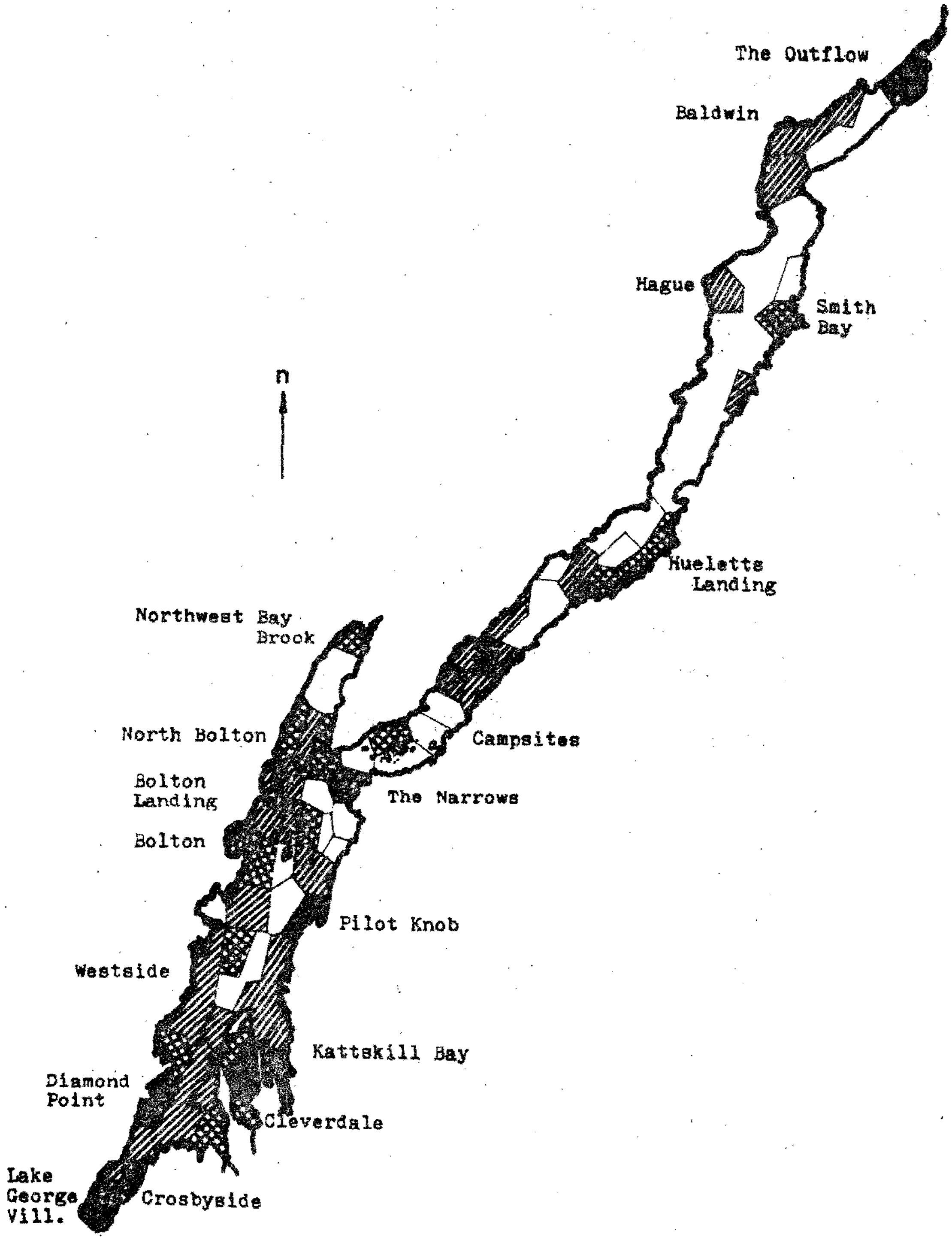
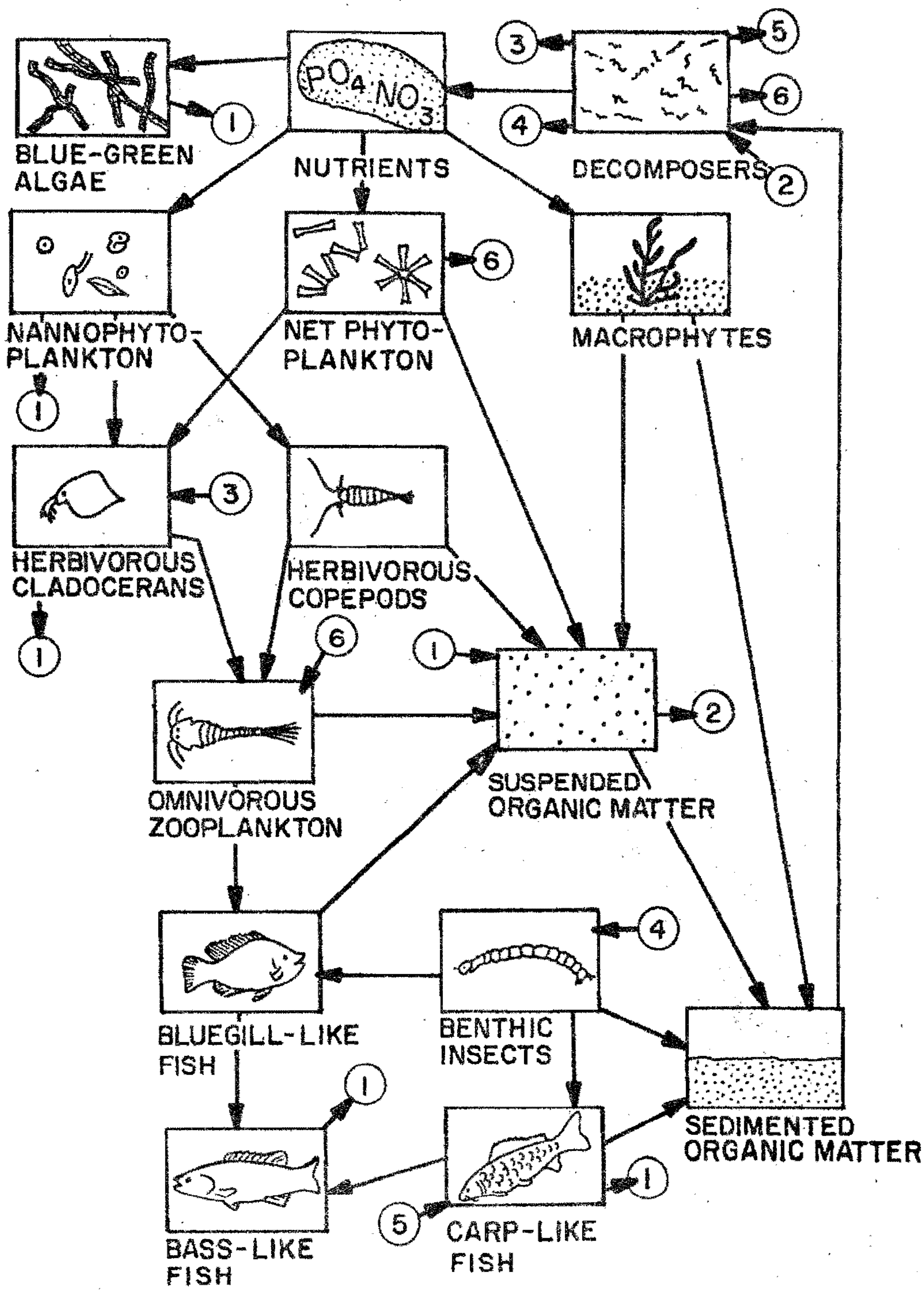
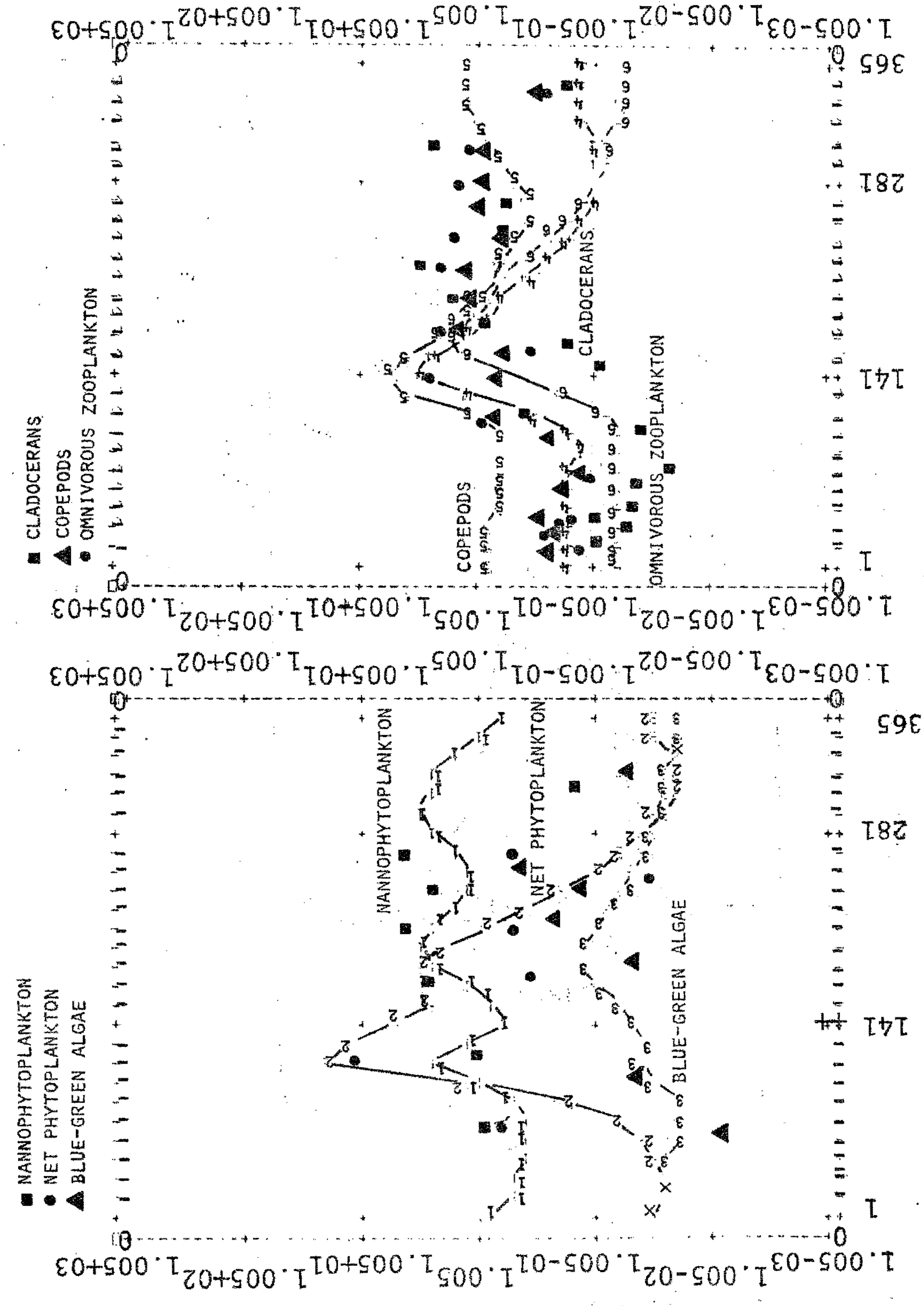


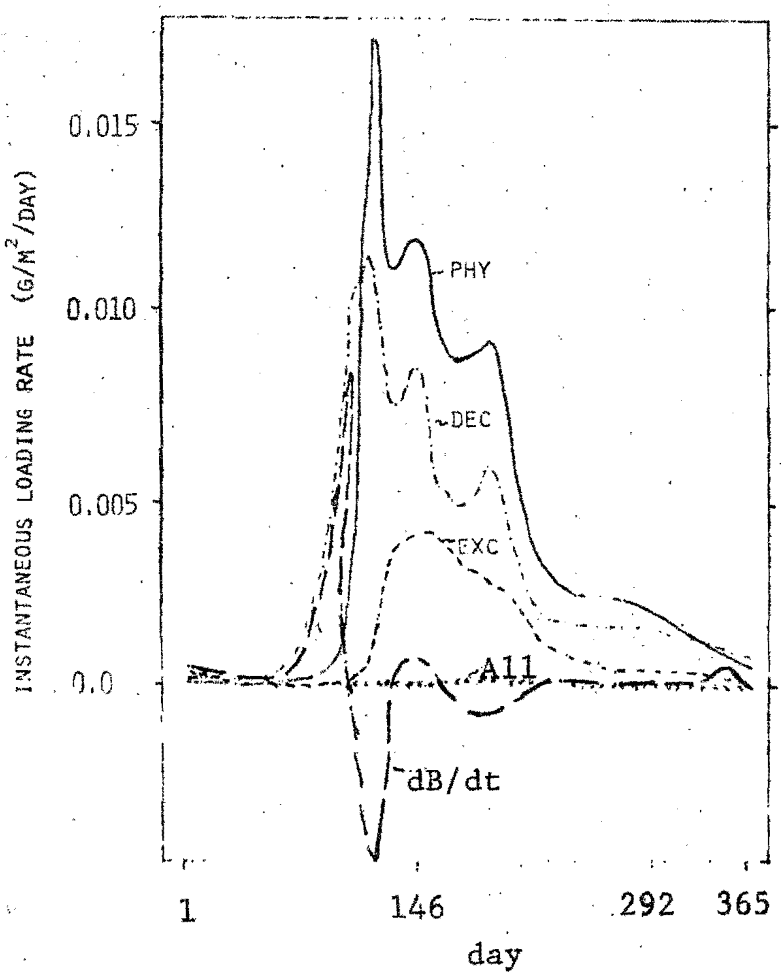
5. Distribution of clusters, Lake George



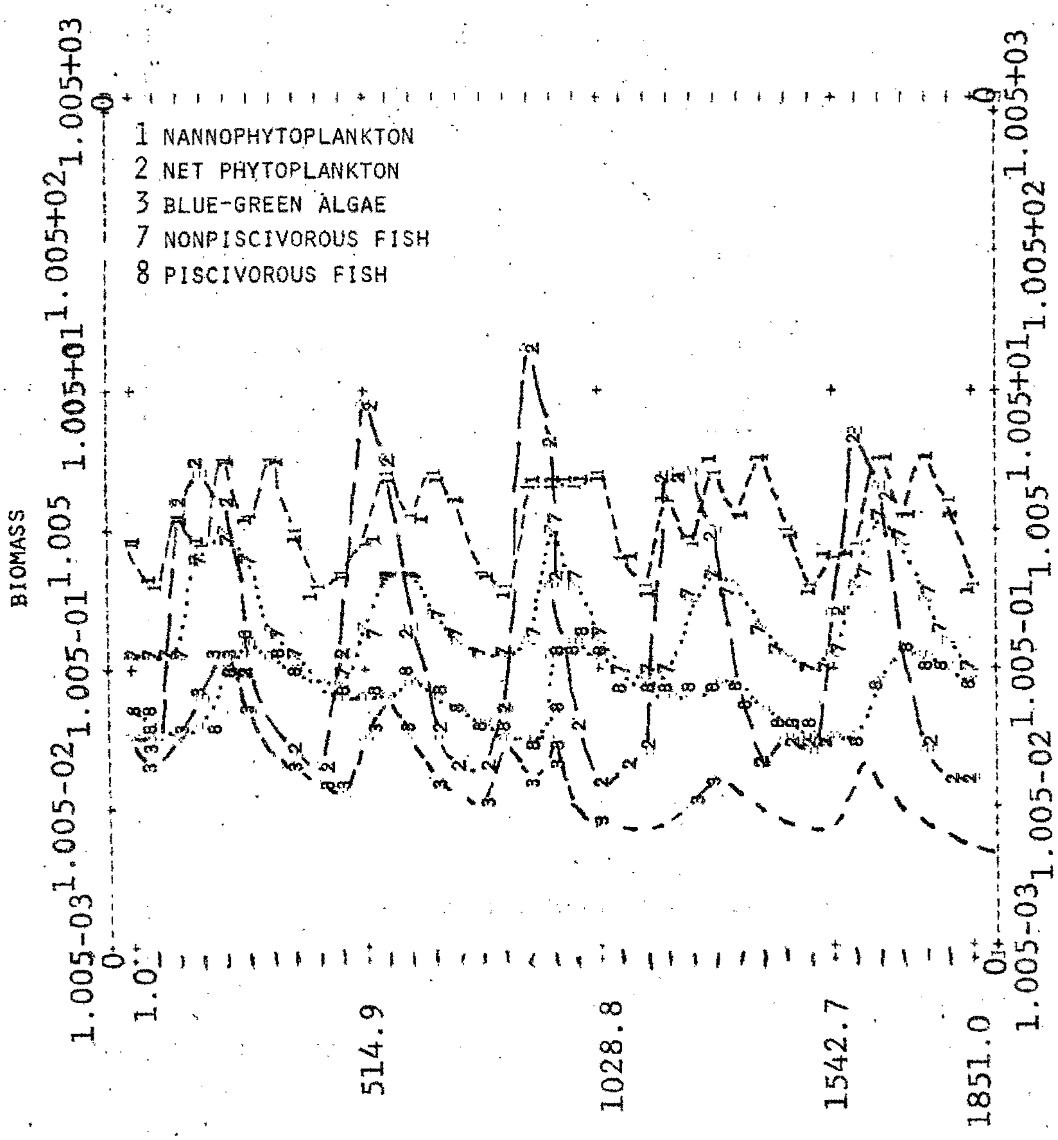
6. Compartments in the aquatic model CLEANER



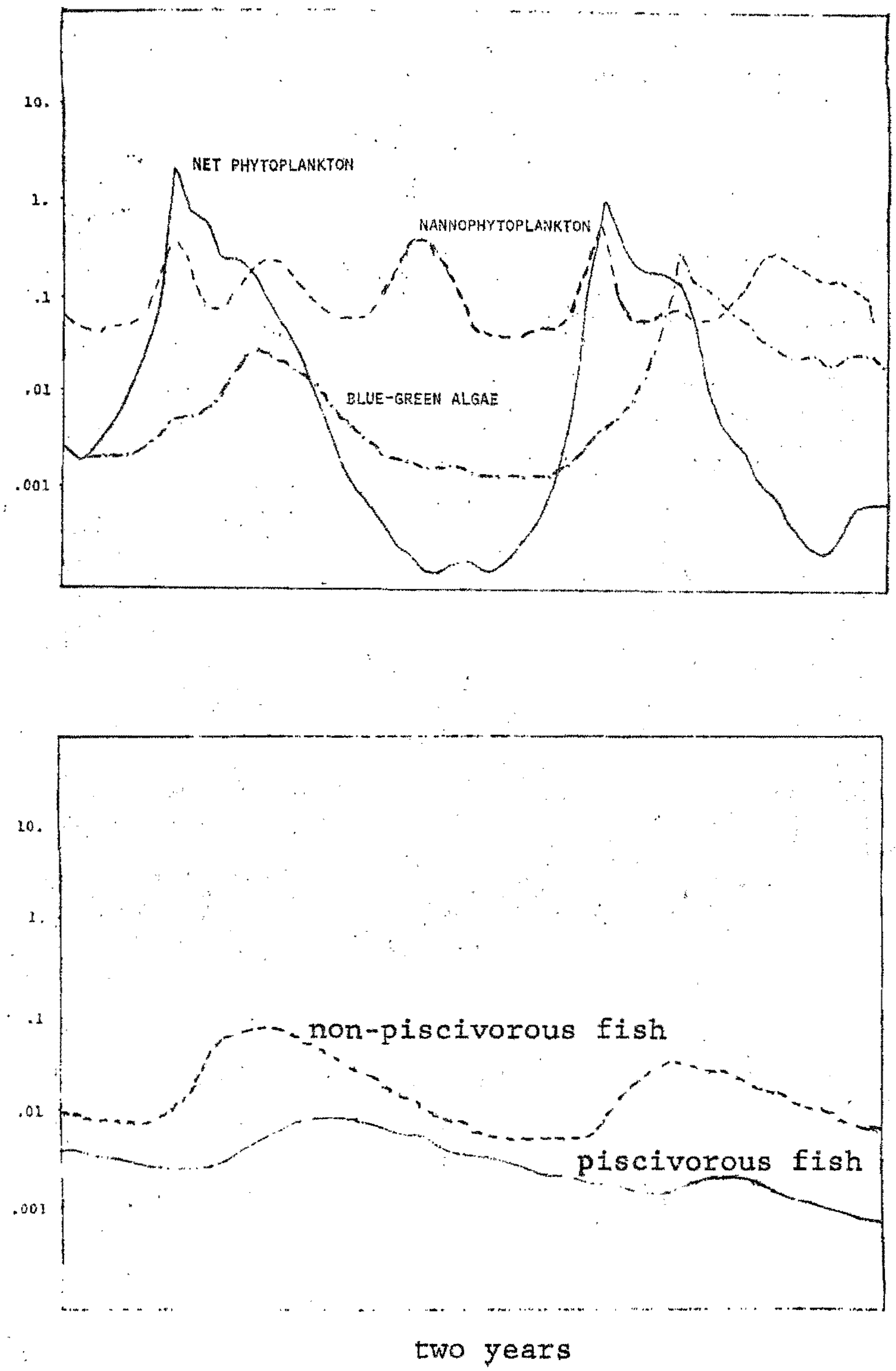
7. Comparison of predicted and observed values using CLEANER



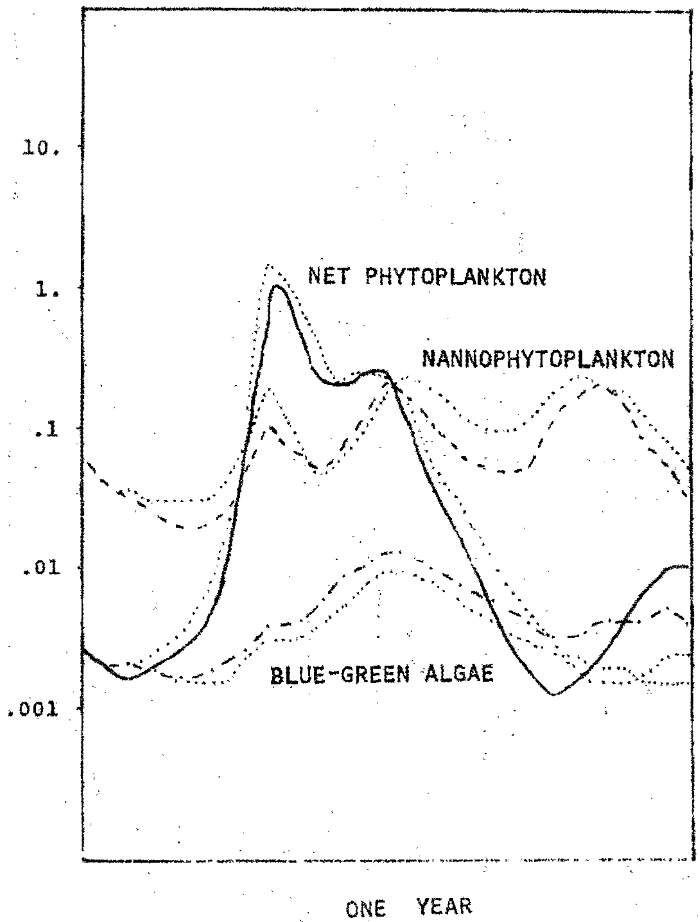
8. Time-series of orthophosphate process-rates predicted by CLEANER



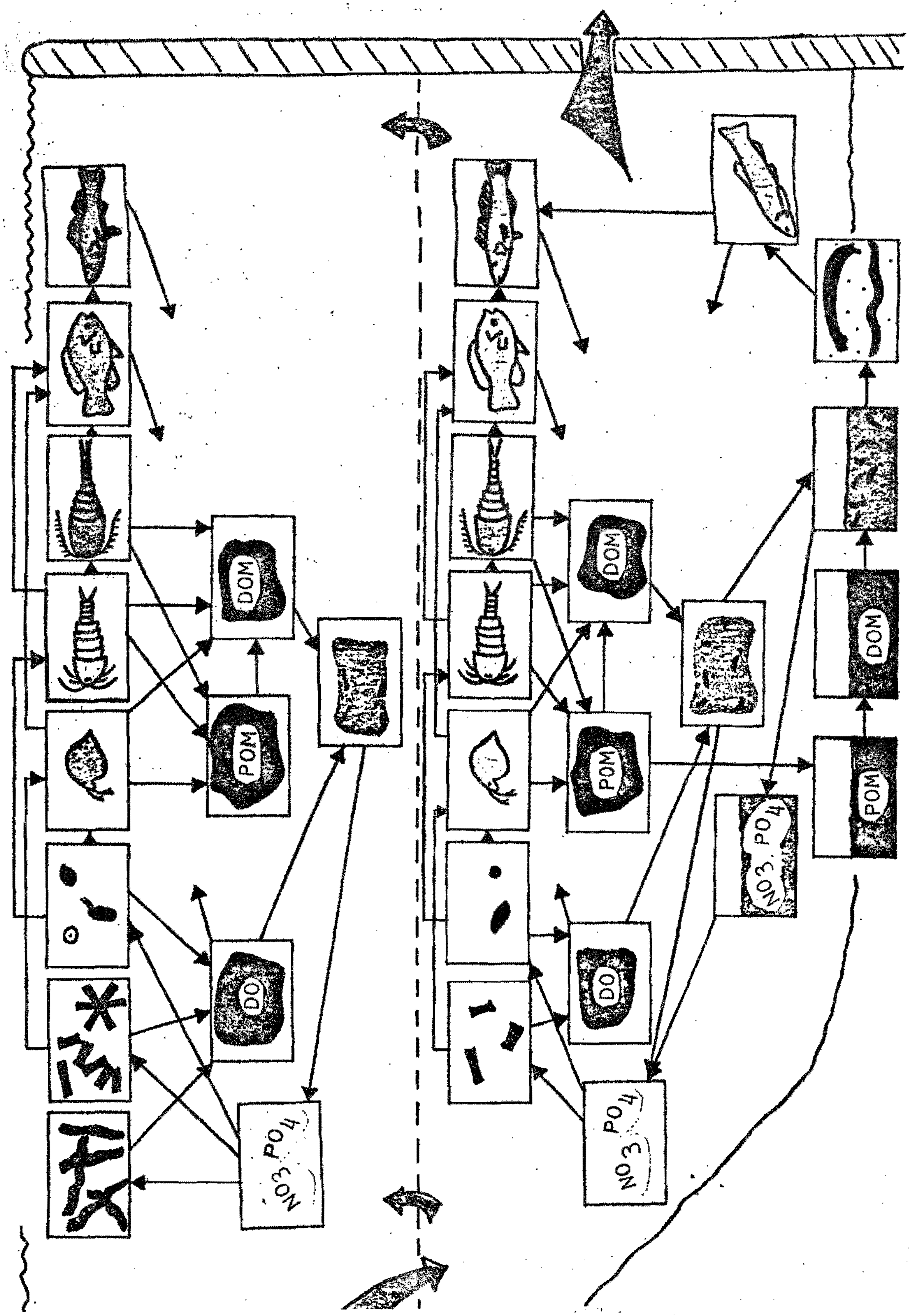
9. Simulation using 0.2 normal phosphate loadings



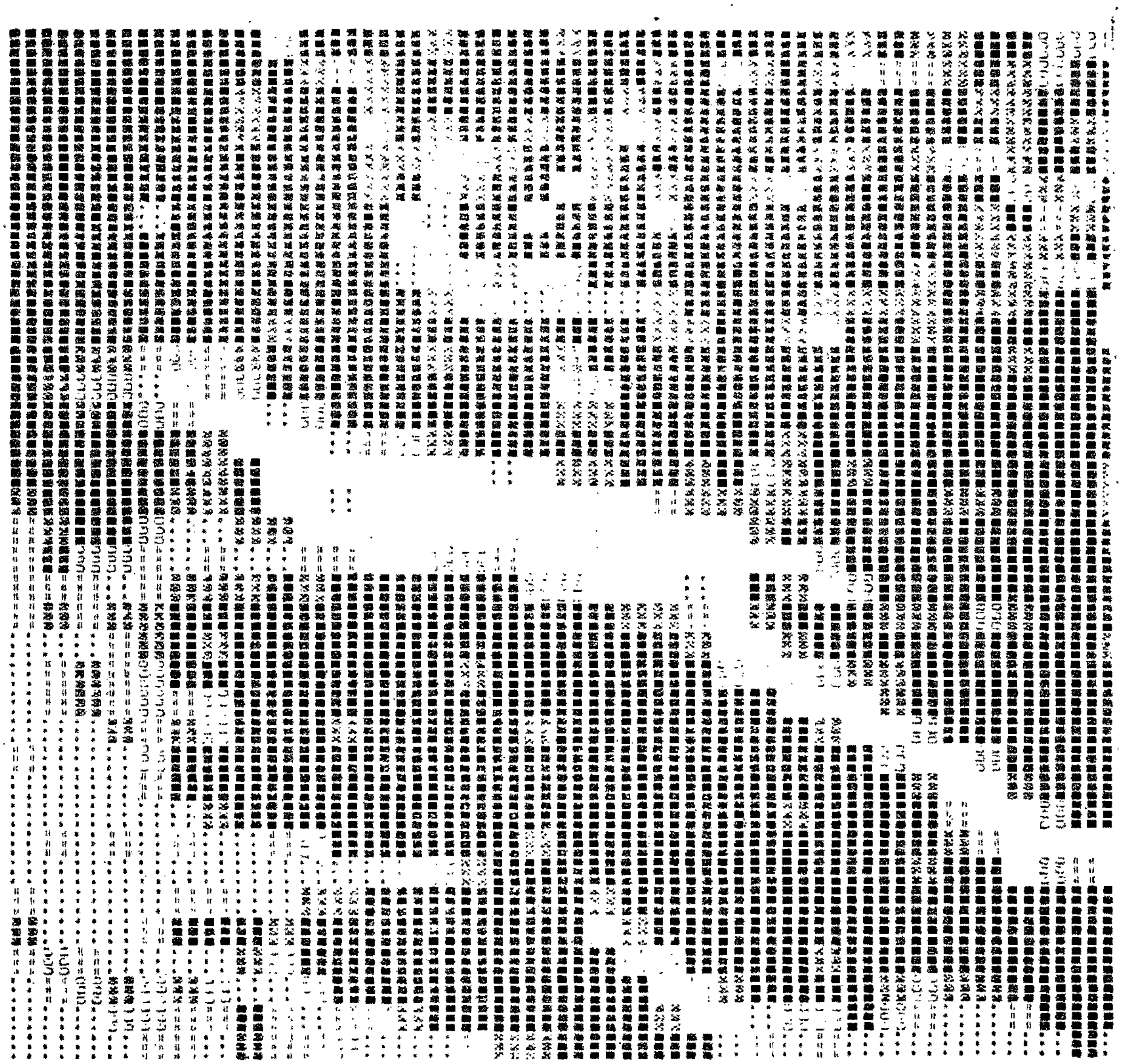
10. Simulation with temperature increased 5° above normal



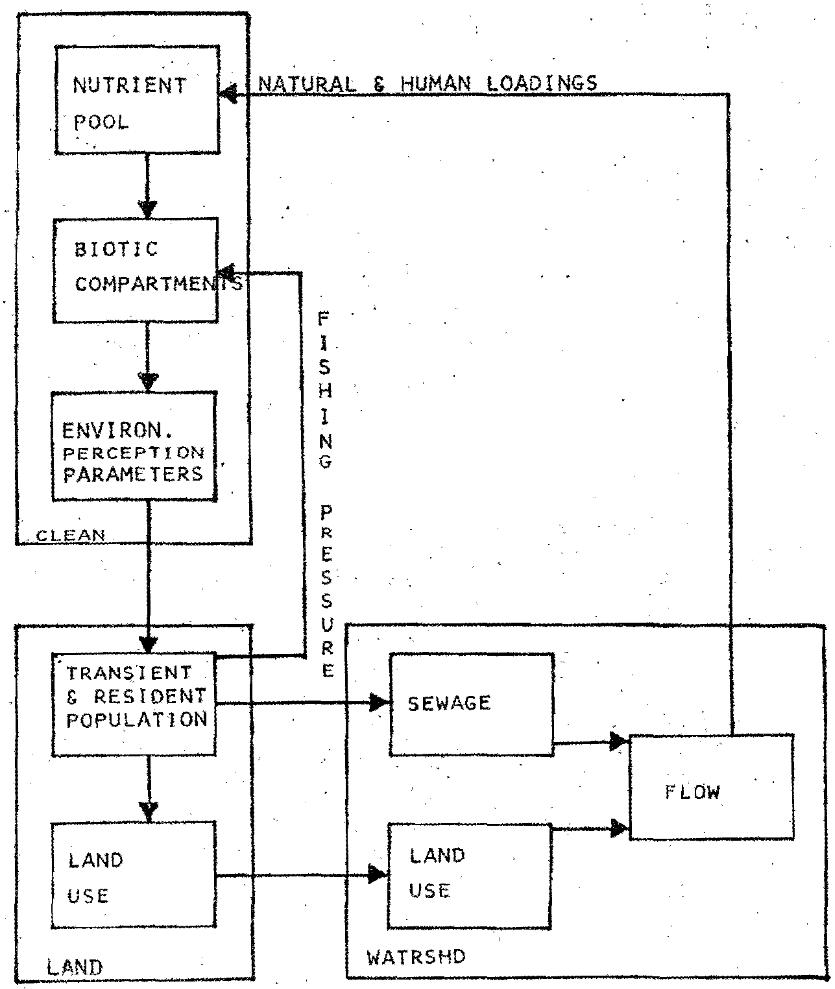
11. Simulation with extinction coefficient of 0.4 (instead of 0.2 as is normal for Lake George); dotted lines represent normal simulation results



12. Structure of version of CLEANER adapted for Slapy Reservoir, Czechoslovakia



13. Distribution of natural forests in Lake George region



14. Coupling of simulation models for basin-wide analysis