CONCEPTS AND UTILITIES
OF AN
ECOLOGIC MODEL

A Position Paper

by

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INTRODUCTION

From a cursory analysis of the environmental problems facing cities in general and water resources systems in particular, one finds several things in parallel. In the cities, there are "slums" and occasionally a "summer riot" occurs. Cities may also die and become "ghost towns". Similarly, the pollution of natural and artificial water bodies has given rise to "eutrophication" and riot-like "algal blooms". Eutrophication, which is characterized by the excess growth of algae, detritus accumulation, exhaustion of dissolved oxygen, fishkills and other associated nuisances, has threatened to shorten the life span of the nation's water bodies and to destroy the utility of the water resources.

In the past, the study of eutrophication has been concerned primarily with a fundamental understanding of its component processes, with emphasis on field and laboratory work. "Neat little problems", concerned with a special aspect of eutrophication, have been isolated and studied in a piece-meal approach to the investigation of the total environment.

Recently, the public's concern about responsible stewardship of the nation's water resources has created an intensifying demand on the scientific community for a more enlightened understanding of environmental problems. This demand opens up a new horizon of research with a scope beyond that of any traditional field of science. Now, today and tomorrow, laboratory results gathered under well controlled conditions must be transferred outdoors to predict changes in the "real" ecologic system where parameters vary in time and space. Therefore, a multi-disciplinary background is required to bring the scattered bits and pieces of information that have been accumulated to bear on the broader problem of management of aquatic environments.

This paper describes a method that seeks to integrate the fundamental principles from all fields including chemistry, biology, ecology, limnology, meterology, hydrology, hydrodynamics, and sanitary engineering. Such a method, characterized by a mathematical model of ecologic processes, may serve as a quantitative means of assessing the state of eutrophication, predicting its trends, and evaluating methods for its control.

THE ECOSYSTEM AND ECOLOGIC PROCESSES

Model development begins with a definition of the system. Within the aquatic environment, four major components can be identified:

1. Abiotic Substances which include basic elements and compounds such as H_2O, CO_2, NO_3, PO_4, Fe, and other water quality constituents.
2. Producers which include autotrophic organisms such as algae.
3. Consumers which include hetertrophic organisms such as zooplankton and animals (benthos and fish).
4. Decomposers which include bacteria and fungi.

These components are interrelated through complex ecologic processes. Figure 1 is a schematic diagram showing the basic components of an ecosystem (boxes) and their interrelationships (lines).

The system receives abiotic substances from various external sources including air, soil and adjoining waters. The producers, with the aid of solar energy, manufacture complex organic materials from the abiotic

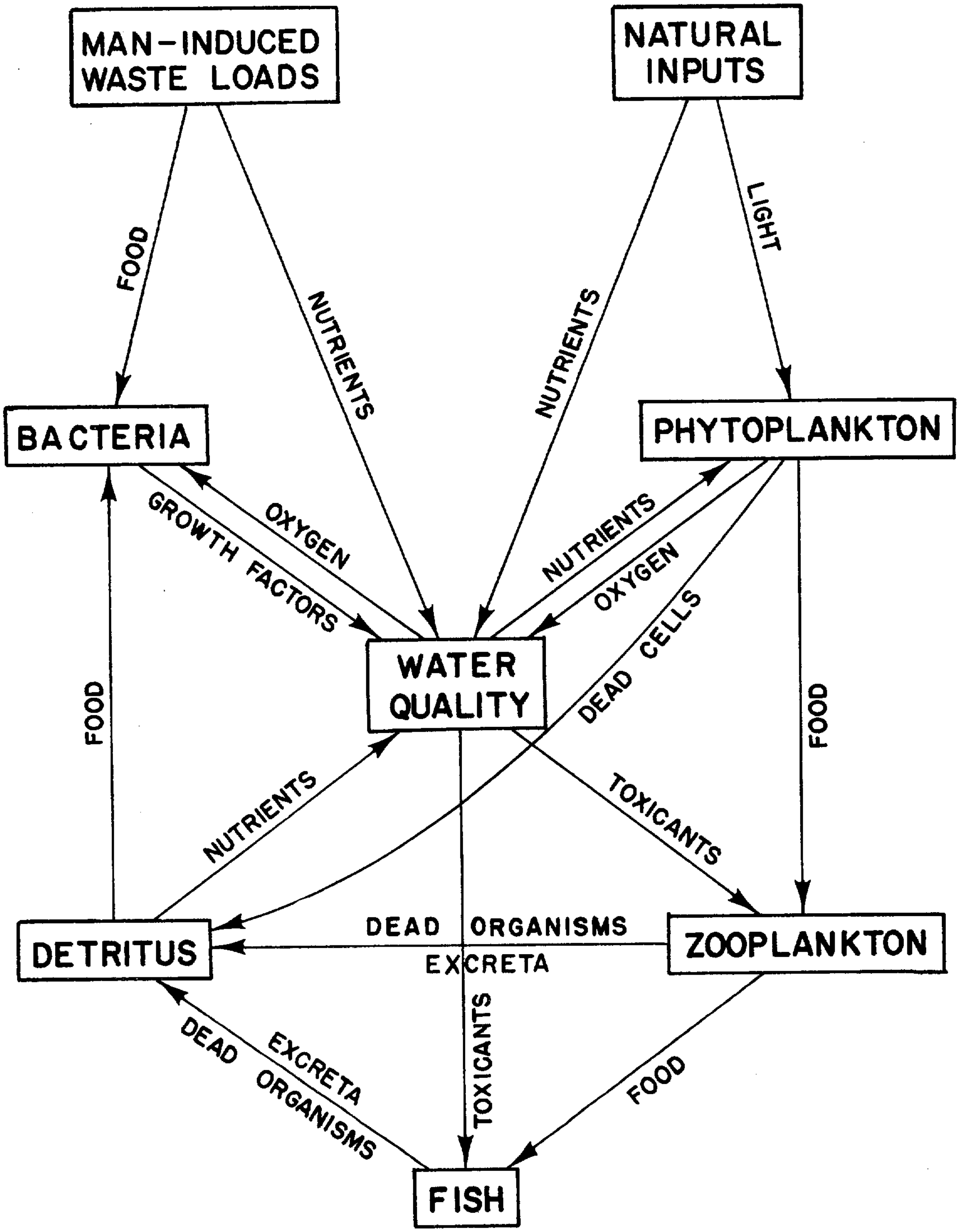


FIGURE 1. DEFINITION OF AN ECOSYSTEM

substances through a photosynthetic reaction. These organic materials serve as primary food sources for herbivorous animals, such as zooplankton, which in turn are consumed by carnivores, such as fish. All of these biological activities generate detritus which consists of dead cell material and excreta or undigested food stuffs. Bacteria and fungi, the decomposers, operate on the detritus to release simple abiotic substances for use by the producers, thus completing the "cycle".

Thus, it is that a water resources system may serve as a giant reactor for the biological cycle. Bacteria oxidize or demineralize organic matter to liberate nutrients, and phytoplankton reduce the minerals and resynthesize the organic materials to support other life. When these two processes are in balance, the rate of eutrophication is at a virtual minimum (Oswald, _et_. _al_., 1966). An unbalanced situation tends to stimulate excess algal growth and create nuisances. Likewise, on the bacterial side, an imbalance may tend toward deoxygenation and anaerobic conditions.

Such an imbalance in the ecologic system may result from either one or a combination of two causes: an extraordinarily large organic input to the system, especially in streams or estuaries, and/or thermal stratification in the case of lakes and reservoirs (Fruh, _et_. _al_., 1966). Thermal stratification in a reservoir causes the two biological processes to react in separate zones--planktonic activity in the epilimnion and bacterial activity in the hypolimnion. After the seasonal overturn, the nutrient rich water from the hypolimnion is mixed with the epilimnal water, resulting in an enrichment that tips the biological balance.

AN ECOLOGIC MODEL

The ecologic phenomena in the real world have been shown to vary dynamically in space, influence greatly by the hydrodynamic behavior of the aquatic system. A comprehensive ecologic model must therefore describe not only the biological processes, but also the transport phenomena of the water and its quality constituents.

A model with such capability has been envisioned after a literature review of some 100 papers and reports (FWPCA, 1968). The general method of approach will be described briefly in the following paragraphs.

Prototype Geometry

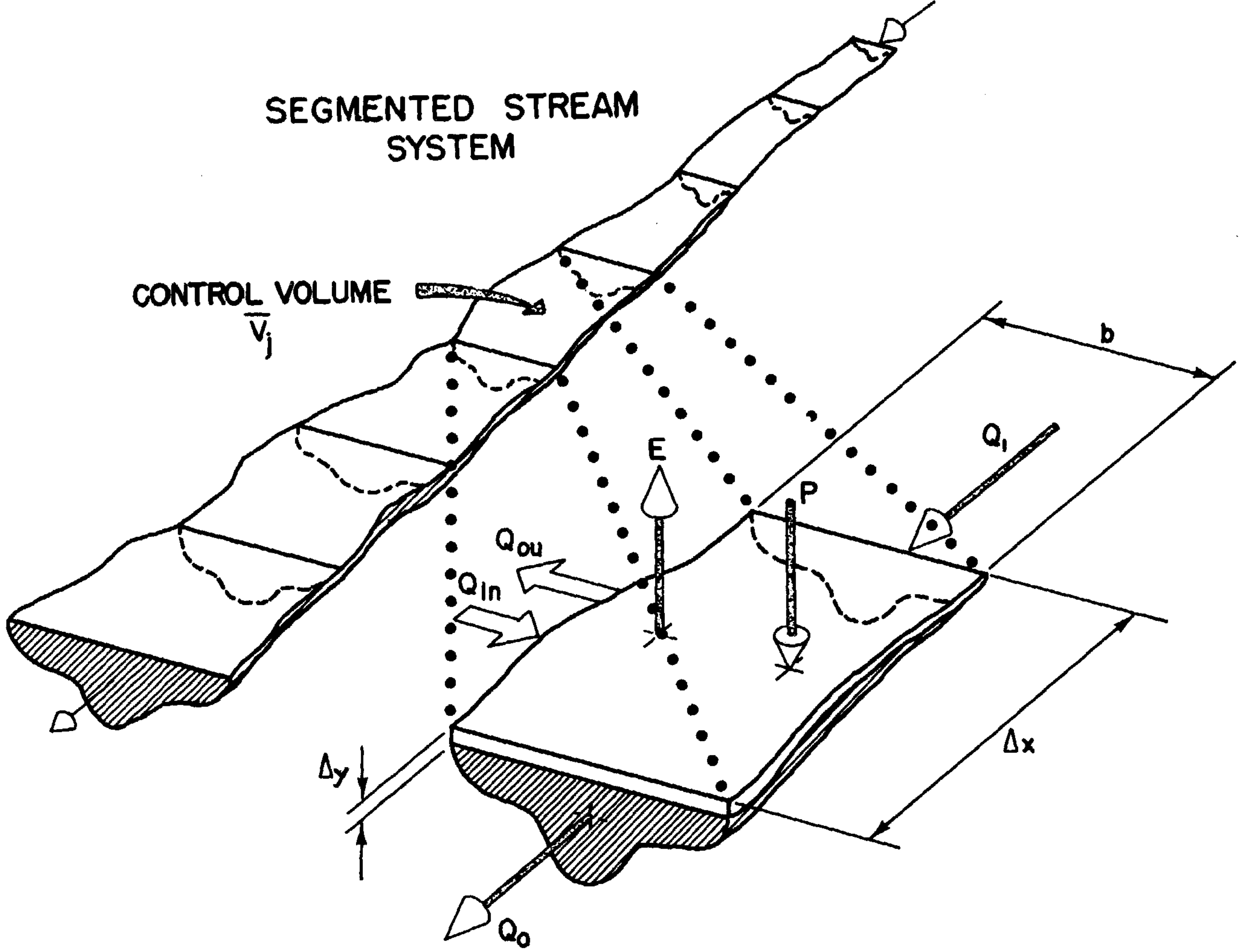
The model represents the water system by a network of discretized "elements" chosen to be representative of characteristic components of the water body. Figure 2 shows such an element as it may be defined for a stream or estuary. For reservoirs or lakes where the primary hydrodynamic concern is stratification, elements can be taken horizontally as shown in Figure 3.

For any given time interval, the element behaves like a completely mixed reactor, allowing the mass of water quality constituents (including biota) to be transported in and out by both advection and diffusion. The "state" of the system is described at any desired time over the space continuum formed by the aggregation of discrete elements.

Hydrodynamic Characterization

The hydrodynamic description of the aquatic environment is a complex problem, for which the ideal solution technique has yet to be developed. However, methods are available for two classes of problems which may be applicable for a great number of water systems.

A hydrodynamic program has been developed to solve the equations of



WATER FLOW

FIGURE 2. CONCEPTUAL REPRESENTATION OF A VERTICALLY MIXED SYSTEM

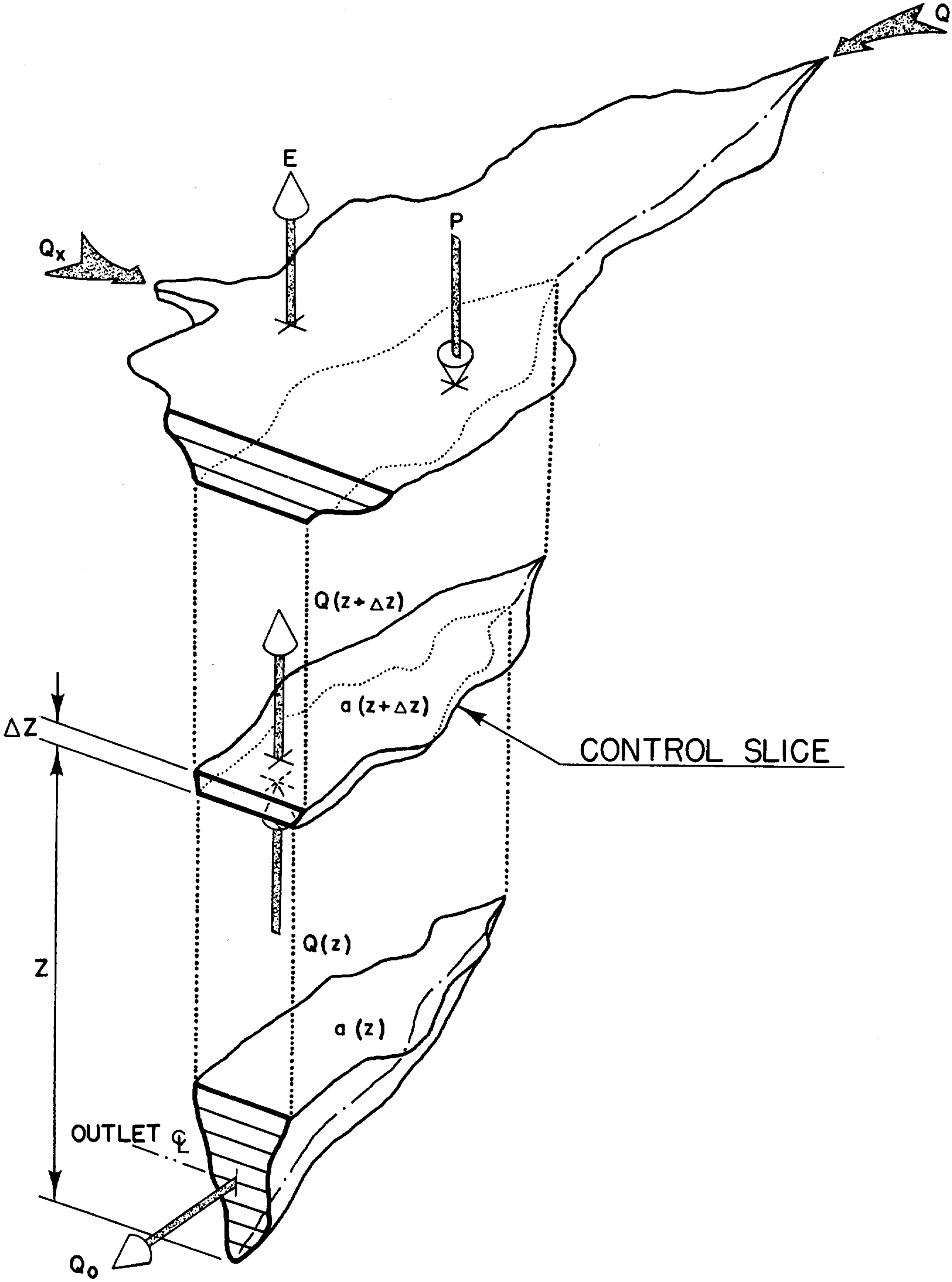


FIGURE 3. CONCEPTUAL REPRESENTATION OF A RESERVOIR

motion and continuity simultaneously for discretized systems such as vertically mixed streams or estuaries (Shubinski, et. al., 1965 and FWPCA, Mar. 1966). A reservoir temperature program has also been developed to simulate the density-dependent temperature and flow conditions in the impoundment throughout an annual cycle (Orlob, et. al., 1967 and Calif. Dept. of Fish and Game, 1968). This program is capable of predicting thermal stratification and seasonal overturn, exemplified by a typical simulation shown in Figure 4.

Chemical and Biological Simulation

For a chemical or biological constituent of the ecosystem, a differential equation can be written to express the rate of change of each constituent as a function of the other variables and coefficients describing the ecologic process. For example, the biomass of phytoplankton is transported by the movement of water. In addition, phytoplankton will increase by growth depending on the light, temperature and nutrient conditions. It also decreases as result of continuous respiration, settling, and grazing by zooplankton. Terms to account for these effects can be put together to form the differential equation

$$\frac{d(\bar{V}P_i)}{dt} = T + AE\frac{dp_i}{dx} + (\mu_i - r - s)\,P_i\bar{V} - \frac{1}{Y_z}\,gp_{fi}z\bar{V}.$$

where

$\bar{V}$ = volume of the element, L^3;

P_i = mass concentration of algae in group i, M/L^3;

t = time, T;

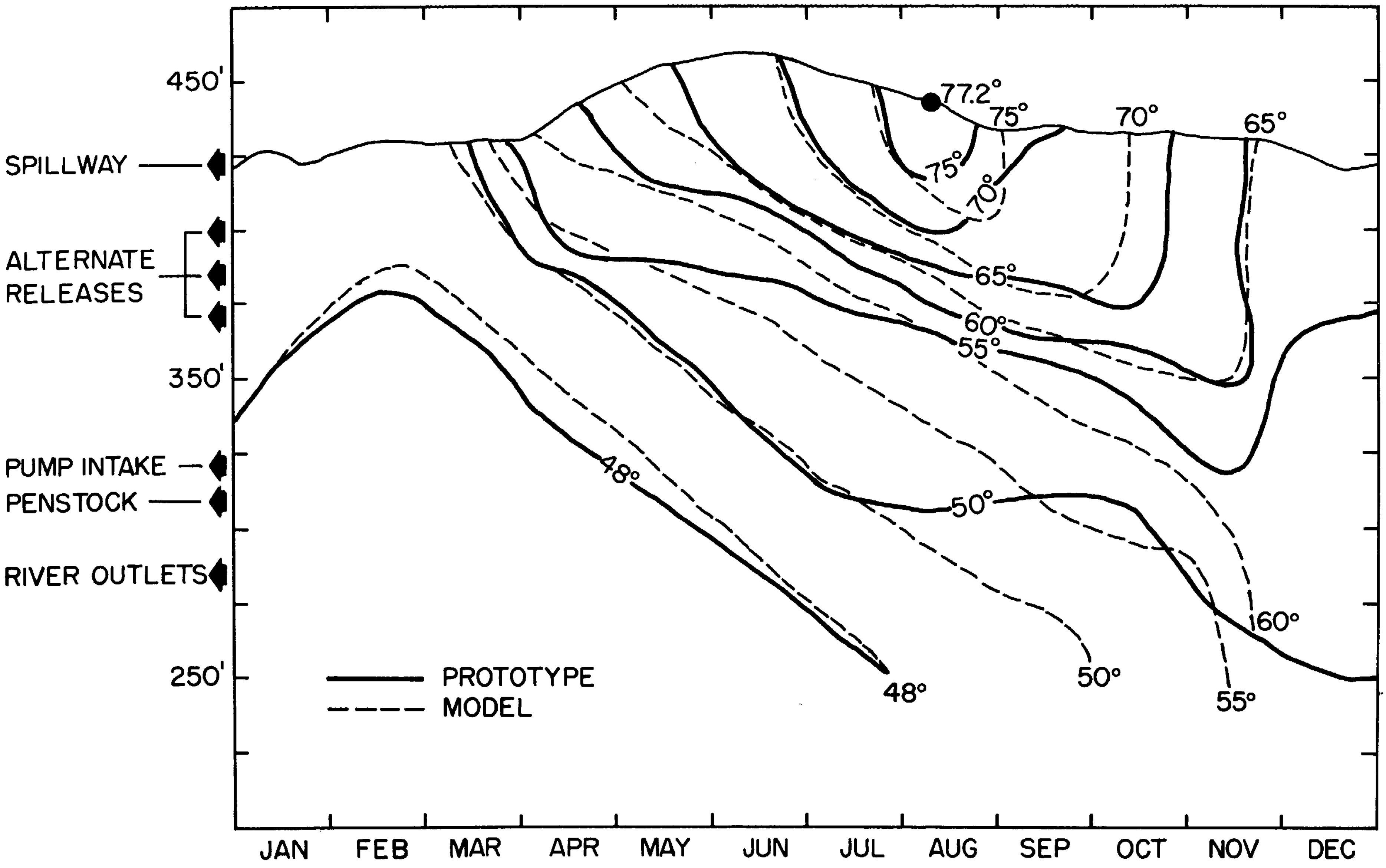


FIGURE 4. ENERGY DISTRIBUTION IN FOLSOM RESERVOIR, CALIFORNIA, 1966

T = total advective mass transfer of biomass, M/T;

A = cross sectional area of the element, L^2;

E = effective diffusion coefficient, L^2/T;

x = distance, L;

μ_i = specific growth rate of algae in group i, $^1/T$;

r = percent respired per unit time, $^1/T$;

s = percent of mass settling per unit of time, $^1/T$;

Y_z = yield coefficient of zooplankton, M/M;

g = specific growth rate of zooplankton, $^1/T$;

P_{fi} = preference factor for algae; group i, dimensionless; and

z = zooplankton biomass concentration, M/L^3.

Since the factors controlling algal growth may vary in time at various locations, a general "limiting-factor equation" has been developed for dynamic determination of μ_i, the specific growth rate of phytoplankton (FWPCA, 1968):

$$\mu_i = \hat{\mu} \left(\frac{L}{k_1 + L}\right) \left(\frac{C}{k_2 + C}\right) \left(\frac{N}{k_3 + N}\right) \left(\frac{P}{k_4 + P}\right)$$

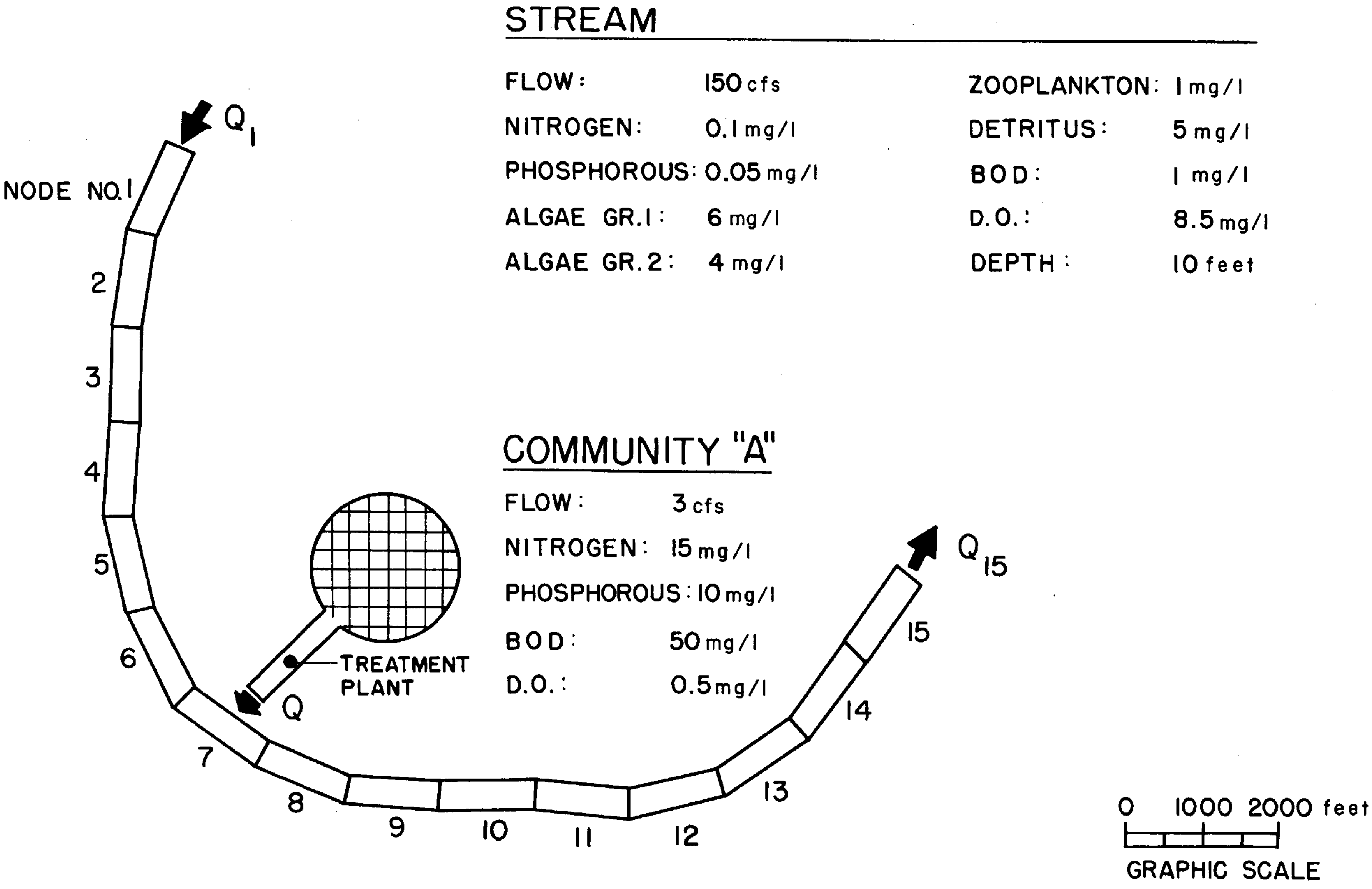
where $\hat{\mu}$ is the maximum possible growth rate, k_1, k_2, k_3, and k_4 are coefficients and L, C, N, and P are respectively light intensity, carbon dioxide, nitrate, and phosphate concentrations. Since light intensity is nonuniform with depth, the Beer-Lambert equation was modified to treat light attenuation with depth, resulting in part from the self-shading effect of the phytoplankton. (The light intensity and the specific growth rate can be calculated dynamically for every foot and then averaged for use in the differential equation.)

In a similar fashion, a series of differential equations was formulated to describe the changing rates of zooplankton, fish, detritus, BOD, nutrients and DO. In the case of DO, terms were included to account for the decrease by BOD exertion and the increases by photosynthesis and surface reaeration. Following this approach, a dozen differential equations were written to describe the behavior of the ecosystem in each discretized element.

A computer program developed to solve the set of simultaneous differential equations will simulate the eutrophication phenomena dynamically. The interactions between biota and their environment are pursued continuously in both trophic directions, since the environmental conditions may either stimulate or inhibit the growth of biota, and the biota may both consume nutrients and/or release by-products to modify the environment. In this sense, the quality and biological relationships are seen to be "coupled", i.e., interdependent.

Functional Test of the Model

The applicability of the ecological concepts outlined above has been tested preliminarily for a simple uni-directional stream. A hypothetical stream with a mean depth of 10 feet and mean width of 500 feet was segmented into 1200-foot elements. The stream, with a flow of 150 cfs, was assumed to receive a waste discharge of 3 cfs at an intermediate element. Water quality characteristics of both the river and the waste in this example are given in Figure 5. Solar insolation was assumed to be 0.2 langleys/min at the outer atmosphere, with a cloud cover of 30 percent throughout the day. Other necessary coefficients were obtained from the literature or assumed, and the calculations were performed for every six



STREAM

FLOW:	150 cfs	ZOOPLANKTON:	1 mg/l
NITROGEN:	0.1 mg/l	DETRITUS:	5 mg/l
PHOSPHOROUS:	0.05 mg/l	BOD:	1 mg/l
ALGAE GR.1:	6 mg/l	D.O.:	8.5 mg/l
ALGAE GR.2:	4 mg/l	DEPTH:	10 feet

COMMUNITY "A"

FLOW:	3 cfs
NITROGEN:	15 mg/l
PHOSPHOROUS:	10 mg/l
BOD:	50 mg/l
D.O.:	0.5 mg/l

FIGURE 5. SEGMENTED STREAM SYSTEM FOR THE TEST CASE

hours to illustrate the diurnal variation of each parameter.

Figure 6 shows several resulting concentration profiles of important parameters, as calculated by the model. They appear to be in reasonable agreement with limited field observations in similar prototype situations. Also, detritus production showed a steady increasing rate of 0.2 mg/l per day which was consistent with the "aging" process of the ecosystem as it has been observed in the field.

The results of the simulation are indeed very preliminary and need further refinement. However, they do demonstrate the reasonableness of the technique and suggest the myriad possibilities for analysis, decision-making, and management that this developing tool provides.

The Utility of Ecologic Models

Since the ecologic model integrates all the physical, chemical, and biological factors together in one package, one obvious utility of the model is to provide a unified interpretation of data collected in the field. Aside from that, the model as described herein may serve to:

1. develop a better understanding of the behavior of the ecosystem, and
2. assist in the intelligent planning and management of water resources systems.

These two utilities actually go hand in hand, because comprehensive planning can only come from an intimate knowledge of the system's behavior.

Because the ecosystem is intricately balanced, ecologic responses are usually subtle, especially when they are attributable to several factors which may be varying either individually or jointly. Assessment of ecologic response becomes extremely difficult and has relied heavily on

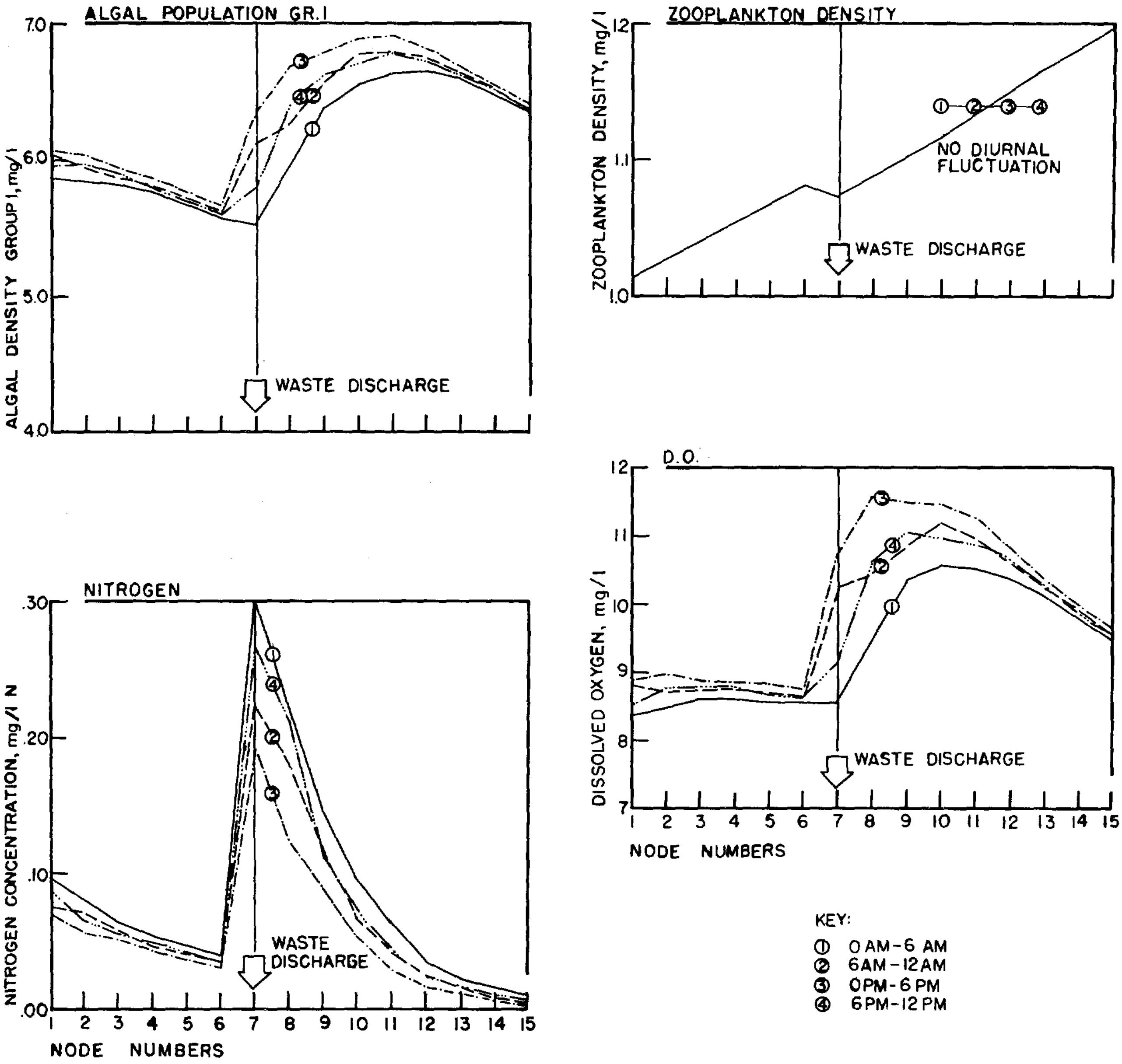


FIGURE 6. SOME TYPICAL CONCENTRATION PROFILES IN THE HYPOTHETICAL ECOSYSTEM

statistical approaches typified by multivariate analysis. However, statistical analysis, which is basically a "block-box" approach, is not particularily enlightening for depicting in a comprehensive way what is actually taking place in the system.

The model described should enable ecologists to gain an insight to the complex system, notwithstanding the simplifications and idealizations used. Intermediate results of model output may be used to evaluate both the final state and the process of ecologic responses. This in itself may stimulate scientists for further theoretical developments which are an important ingredient for the advancement of science.

Another way in which the model may contribute to the understanding of eutrophication phenomena is through sensitivity analysis. Once the accuracy of the model has been determined, it can be used to assess the effect of changing the assumed or derived rate coefficients. For example, one may wish to examine the relative importance of nutrient resolubilization from detritus. This may be accomplished by operating the model with different coefficients for detritus decay.

Figure 7 shows the responses of such a sensitivity analysis for the test case described previously. The results indicate that resolubilization of nutrients from detritus will support higher algal growth. For a thermally stratified reservoir, it may also show that the decay of detritus can deplete oxygen in the hypolimnion, allow resolubilization under the anaerobic conditions, and hence permit an algal bloom during or just after the seasonal overturn of the lake.

In a similar fashion, sensitivity analysis can be made for respiration rate, sedimentation rate, photosynthesis oxygenation factor, or the

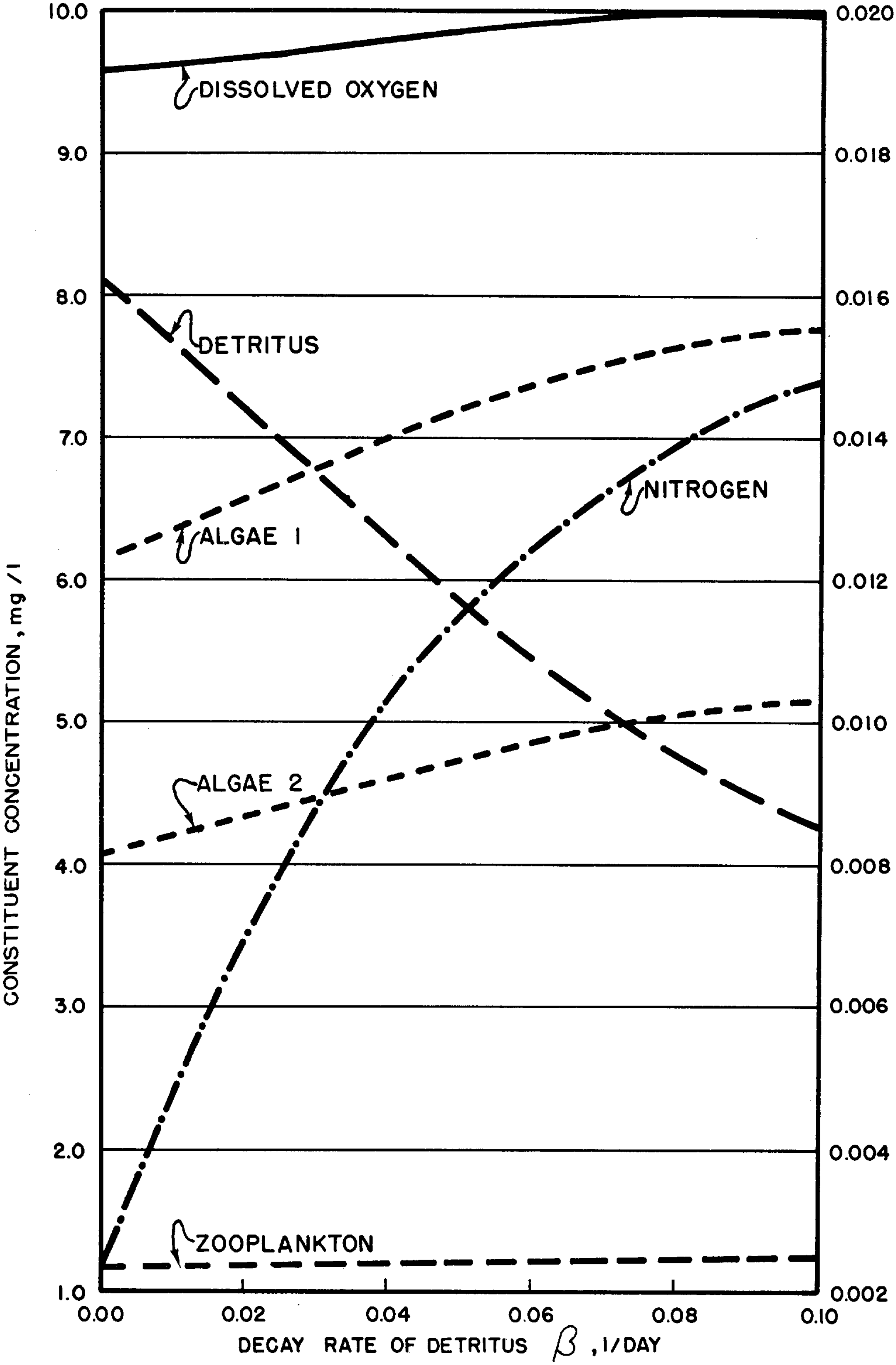


FIGURE 7. ECOLOGIC RESPONSES TO VARYING DECAY RATE OF DETRITUS (0-6 P.M., 10 TH DAY, NODE 15)

surface reaeration coefficient. Through an organized review of the responses, one may identify important parameters for additional study.

Finally, the ecologic model may serve as a tool for resources planning. The normal process of resources planning entails:

1. formulation of planning objectives,
2. design of alternative plans,
3. evaluation of the feasibility of alternatives,
4. modification of planning objectives, if required, based on the objectives' technical and economical attainability, and
5. selection of optimum plans.

Figure 8 is a schematic diagram of the planning procedure for regional water and land resources development. An ecologic model is depicted an "analytical balance" for resources planning. It weighs all the factors to ensure that the socio-economic design of the region will be compatible with the water quality and ecologic objectives.

SUMMARY AND CONCLUSIONS

An ecologic model based on fundamental principles of biology, chemistry and physics has been described. Basic ecologic processes including photosynthesis, respiration, zooplankton grazing, fish predation, sedimentation, nutrient recycling, and others were shown to be capable of representation by mathematical functions. These functions can be assembled and operated together to simulate simultaneously, the physical, chemical and biological behaviors of an ecosystem.

Preliminary tests of the ecologic model indicate the reasonableness

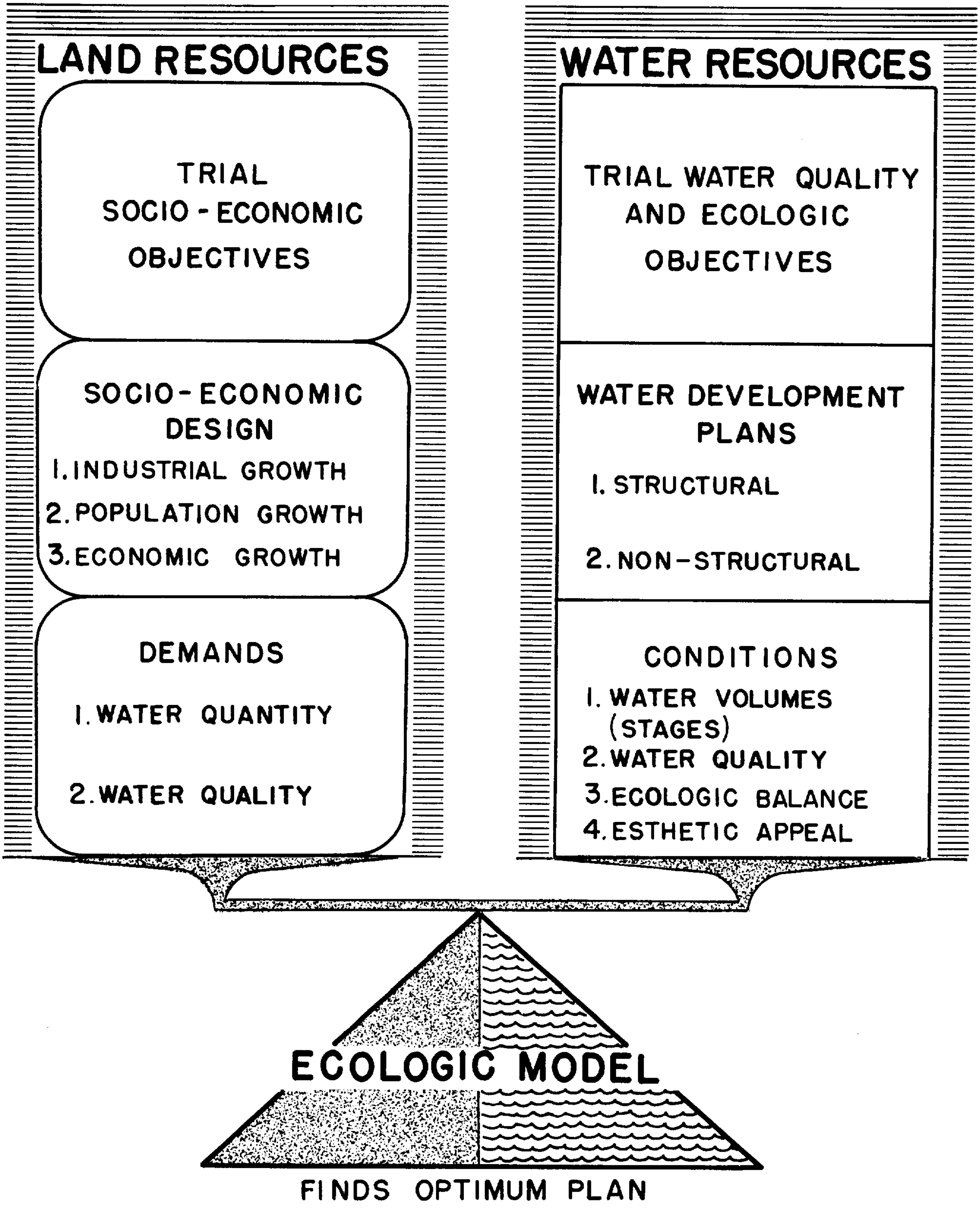


FIGURE 8. "ANALYTICAL BALANCE" FOR RESOURCES PLANNING

of the technique. It is concluded that model development and application will aid greatly in the development of a more fundamental understanding of eutrophication processes and their control.

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