Use Of Models For Evaluating Aquatic Weed Control Strategies[1]

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ABSTRACT

Literature values provide estimates of some general ecosystem parameters which are used in a model to demonstrate the effects of two different kinds of control programs on an aquatic ecosystem. The steps one follows in conceptualizing, programming, simulating, and evaluating a model are described.

INTRODUCTION

In determining the impact of aquatic weeds and aquatic weed control practices on a body of water, it is important to be able to assess the changes that are brought about in the whole ecosystem, since chemical, physical, and biological properties of the ecosystem are interrelated. Too frequently, however, these changes and their impacts on the ecosystem are disregarded in light of the urgency of the aquatic weed problem and the desire for immediate action. In addition, experience in working with entire ecosystems, such as lakes and streams, has shown that it is extremely difficult to perform broad ecosystem analyses along with experiments on these weeds and with their associated controls, allowing suitable variation in treatments within a reasonable time period. The size of an affected body of water, the species involved, and the various ecological effects of the control mechanisms that can be used may be important variables, but their significance cannot be thoroughly assessed experimentally because of the time and money involved.

The analysis of an aquatic weed problem generally includes field work, when the chemical and physical attributes of the environment of the weed are investigated, and laboratory work, in which data on such processes as rates of nutrient uptake and growth are obtained. A third phase that could prove to be extremely useful in such an analysis is modelling, the use of computers to reconstruct the important variables in a system as a series of interrelated equations. Modelling allows us to use information that has been collected over the span of a normal field project to predict the possible behavior of the system under different environmental or biological conditions.

Extensive field work and careful laboratory analyses and tests are necessary to obtain the information needed for the model. Occasionally, however, information from previous studies can be used to construct a single comprehensive model. Nevertheless, in order to validate the predictions of the model, it is generally useful to have sufficient experimental data to provide a range of acceptability for the results of the simulation.

The construction of the model itself is useful in the identification of important components and processes in the system being studied. Subsequent simulation may prove or disprove initial assumptions often indicating relationships which are not obvious in a component-by-component analysis. In this way, modelling can effectively be used to indicate the most important directions that should be taken in continuing research on a particular ecosystem.

A GENERAL MODEL AS AN EXAMPLE

To demonstrate some of these points, a model was devised using values in the literature as well as estimates for certain parameters to indicate how an aquatic system overtaken by waterhyacinths (*Eichhornia crassipes* (Mart.) Solms) might be affected by the plants and how control measures might affect the system.

In the process of modelling an ecosystem, the first step is the definition of the limits of the system. The ecosystem diagrammed in Figure 1 is assumed to be a lake with an average depth of 5 m, containing plants rooted in the detritus on the bottom, phytoplankton, and invading waterhyacinths. It is assumed that the size and shape of the lake are such that the wind does not have an effect on the growth of the plants. Dissolved nitrates and phosphates are the key nutrients considered here, since they are usually considered the main factors controlling the growth rates of both algae and macrophytes. Again, it is assumed that the other potentially limiting factors are present in adequate supply. These nutrients are introduced from outside the system and are recycled within it. The dissolved oxygen level in the water is affected

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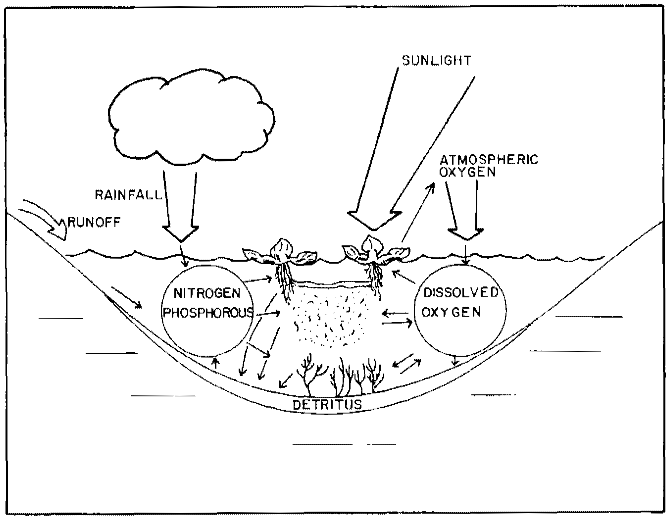

Figure 1. Schematic drawing of the main components of a pond eco-system.

by diffusion from the air and by respiration of the bottom-dwelling bacteria responsible for the remineralization of the organic matter. Waterhyacinths affect the ecosystem by shading out the bottom plants and the phytoplankton and by decreasing the rate of diffusion of oxygen from the air into the water.

The important pathways in this model are listed in Table 1. Average growth rates and death rates were estimated from values in the literature for the plant populations, while the inputs and outputs of the nutrient and oxygen compartments were estimated. Because of the simplicity of the model, several flows, such as nutrient inputs from sewage effluent, runoff, and rainfall were lumped together as one.

The model in Figure 2 is an energy flow model indicating more precisely the relationships discussed above; the symbols used were developed by Odum (6). The tank-like symbols indicate storages of oxygen, phosphorus, nitrogen, and detritus. Changes in these storages are brought about by differences between the inputs and outputs shown. The three bullet-shaped symbols at the bottom designate energy stored in plant populations: algae, bottom-rooted plants, and waterhyacinths are included as three general categories. The circles at the left are forcing functions from outside the ecosystem: air available for diffusion, phosphates and nitrates from rainfall, runoff, etc., and solar radiation. The lines connecting the symbols are flows of nutrients, oxygen, or energy. The arrow-shaped

TABLE 1. NUMERICAL VALUES USED IN A MODEL OF A HYPOTHETICAL AQUATIC ECOSYSTEM.

Compartment or Pathway in Model	Designation in Model	Value	Source of Value
Dissolved phosphorus	P	1.01 $g \cdot m^{-3}$	5
Phosphorus input*	P_0 (k_1)	5.82 $g \cdot m^{-3} \cdot yr^{-1}$	estimated[a]
Phosphorus uptake by waterhyacinths	k_4WP	2.88 $g \cdot m^{-3} \cdot yr^{-1}$	see note [b]
Phosphorus uptake by phytoplankton	k_6AP	2.26×10^{-1} $g \cdot m^{-3} \cdot yr^{-1}$	estimated[c]
Remineralization of phosphorus	k_3O	2.5 $g \cdot m^{-3} \cdot yr^{-1}$	7
Dissolved nitrogen	N	1.75 $g \cdot m^{-3}$	5
Nitrogen input*	N_0	2.59×10^{1} $g \cdot m^{-3} \cdot yr^{-1}$	estimated[a]
Nitrogen uptake by waterhyacinths	$k_{11}WN$	1.77×10^{1} $g \cdot m^{-3} \cdot yr^{-1}$	see note [b]
Nitrogen uptake by phytoplankton	$k_{12}AN$	1.39 $g \cdot m^{-3} \cdot yr^{-1}$	estimated[c]
Remineralization of nitrogen	$k_{10}O$	1.64×10^{1} $g \cdot m^{-3} \cdot yr^{-1}$	1
Effective solar radiation	S	8.32×10^{1} $kcal \cdot m^{-3} \cdot yr^{-1}$	4
Biomass of phytoplankton	A	8.65×10^{2} $kcal \cdot m^{-3}$	3
Net primary productivity of phytoplankton	$k_{14}APSN/W$	747.5 $kcal \cdot m^{-3} \cdot yr^{-1}$	3[d]
Death rate of phytoplankton	$k_{15}A^2$	747.5 $kcal \cdot m^{-3} \cdot yr^{-1}$	3[d]
Biomass of bottom plants	B	2.66×10^{3} $kcal \cdot m^{-3}$	3
Net primary productivity of bottom plants	$k_{17}BS/W$	55 $kcal \cdot m^{-3} \cdot yr^{-1}$	3[d]
Death rate of bottom plants	$k_{18}B^2$	55 $kcal \cdot m^{-3} \cdot yr^{-1}$	3[d]
Biomass of waterhyacinths	H	1.10×10^{4} $kcal \cdot m^{-3}$	see note [b]
Net primary productivity of waterhyacinths	$k_{20}WPSN$	3020 $kcal \cdot m^{-3} \cdot yr^{-1}$	see note [b]
Death rate of waterhyacinths	$k_{21}W$	2 $kcal \cdot m^{-3} \cdot yr^{-1}$	estimated[e]
Oxygen in air	Air	2×10^{6} $g \cdot m^{-3}$	estimated[f]
Diffusion from air	$k_{43}Air/W$	175.2 $g \cdot m^{-3} \cdot yr^{-1}$	estimated[g]
Benthic respiration	$k_{40}O$	175.2 $g \cdot m^{-3} \cdot yr^{-1}$	2

*Indicates that this number was varied in the different simulations of the model.

[a] Inputs of nutrients from the outside were calculated by balancing the inputs with all outputs.

[b] Estimate from unpublished manuscript: Brown, S., T. Center, K. Duggar, and W. Mitsch. 1975. Management model and associated field measurements of Lake Alice.

[c] Nutrient uptake values for phytoplankton were estimated by using the same ratio to phytoplankton biomass as is found in waterhyacinths.

[d] Values for temperate areas were multiplied by 1.25 to account for the longer growing season.

[e] The death rate for waterhyacinths was adjusted to simulate a rapid growth rate.

[f] This value is an upper estimate of the density of oxygen in air.

[g] Diffusion of oxygen from the air was assumed to be equal to benthic respiration under the initial conditions.

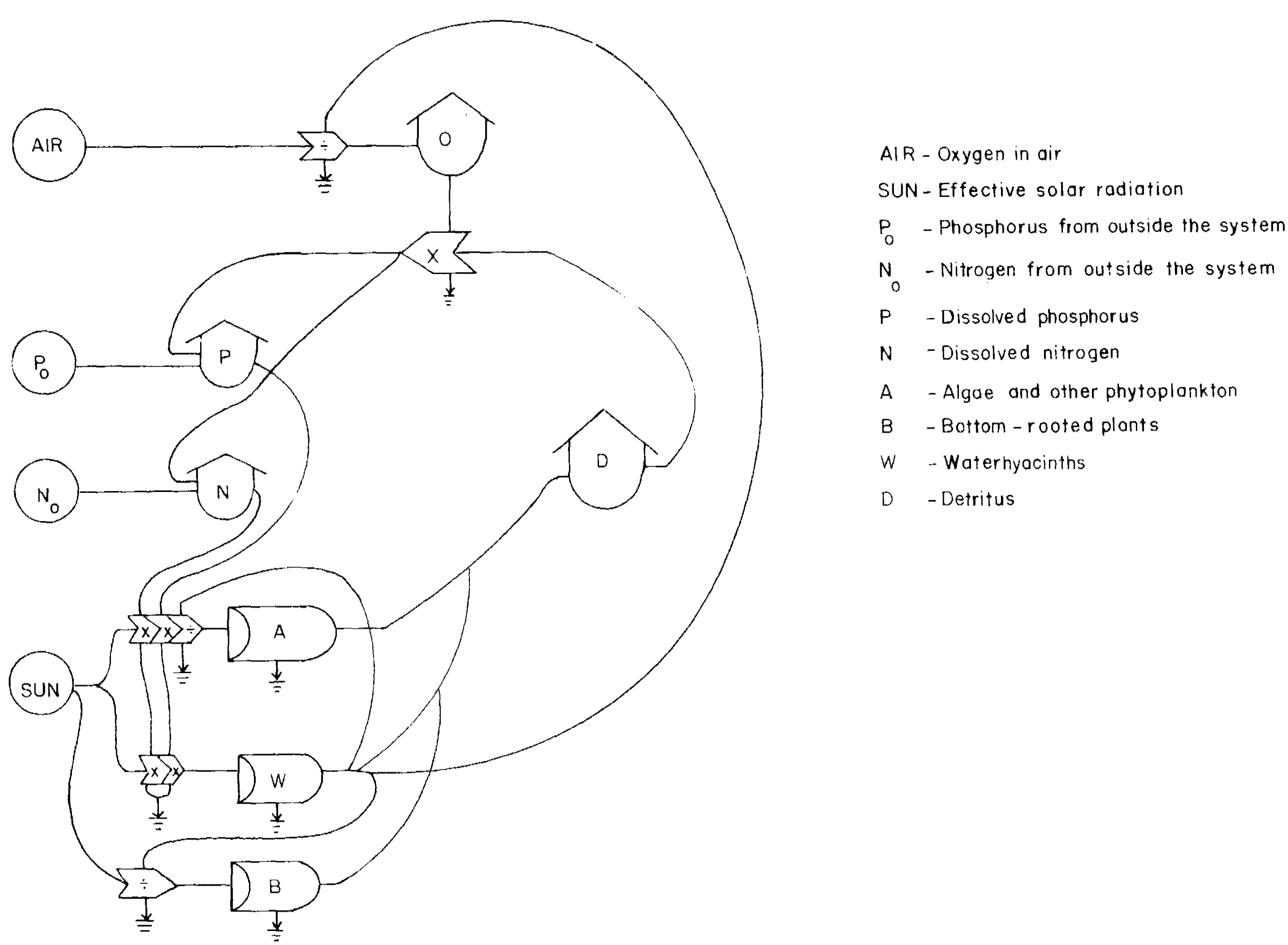

Figure 2. Energy flow model of a hypothetical pond ecosystem.

symbols are work gates indicating the interactions of these flows. Waterhyacinths, for instance, are shown to inhibit both diffusion of air into the water and growth of the other plants in this ecosystem. The growth of waterhyacinths is in turn affected by solar radiation and by the supply of nitrogen and phosphorus.

The relationships formalized in this model can be readily translated into differential equations (Table 2).

TABLE 2. DIFFERENTIAL EQUATIONS WHICH EXPRESS THE RELATIONSHIPS DEMONSTRATED IN THE ENERGY FLOW MODEL.[a]

$$dP/dt = k_1 + k_3O - k_4WP - k_6AP$$
$$dN/dt = k_2 + k_{10}O - k_{11}WN - k_{12}AN$$
$$dA/dt = k_{14}\ APSN/W - k_{15}A^2$$
$$dB/dt = k_{17}\ BS/W - k_{18}B^2$$
$$dW/dt = k_{20}\ WPSN - k_{21}W$$
$$dD/dt = k_{13}A^2 + k_{18}B^2 + k_{21}W - k_{30}O$$
$$dO/dt = k_{43}AIR/W\ (1 - 0/\text{satn.}) - k_{40}O$$

[a] The term to the left of the equality sign indicates that a change in a storage, or amount of a quantity, overtime is brought about according to the inputs and outputs designated on the right-hand side of the equation.

The "k" values are transfer coefficients which determine the magnitude of the effect of each expression on the right-hand side of the equation on the overall change calculated on the left-hand side. The change in the level of phosphorus, in the first equation, is therefore affected by a constant input (k_1), by the rate of remineralization, which is in turn dependent on the amount of available oxygen (k_3O), and by the rate of uptake by waterhyacinths and phytoplankton (k_4WP and k_6AP).

The values for each of the expressions and the differential equations are then programmed in a computer, and as the values are substituted, the levels change, affecting each of the other levels according to their equations. Digital computers are commonly used for large-scale models, although the differential equations must be translated into difference equations which provide less accurate solutions when simulated for longer time periods. Computer languages such as FORTRAN, DYNAMO, and CSMP are well-adapted and flexible enough to handle difference equations and plotting routines. Analog computers solve differential equations simultaneously, allow direct interaction with the program, and are ideal for situations requiring solutions over long time periods.

The results of the simulation of the model (in DYNAMO) are shown in Figures 3 to 6. These figures illustrate both the effect of a large population of waterhyacinths on the ecosystem, and the reaction of the ecosystem to a variety of policies which might be implemented to control the waterhyacinths. The graphs in Figure 3 show changes that occur in the system when waterhyacinths are allowed to multiply without any control measures. High levels of phosphorus and nitrogen coming into the system from the outside are taken up by waterhyacinths, which in turn shade out bottom plants and phytoplankton. The increase in the waterhyacinth biomass may be expected to level off eventually. The pulses evident particularly in the phytoplankton reflect seasonal changes in solar radiation and therefore in temperature as well. The increase in the cover of waterhyacinths causes a decrease in the oxygen level, which in turn affects the rate of remineralization of the nutrients. Detritus on the bottom of the lake builds up slowly.

Reducing the rate of nutrient inputs, as was done for the simulation shown in Figure 4, would solve the problem, according to the constraints of this model, causing waterhyacinths to decrease and bottom plants and phytoplankton to assume dominance. Oxygen levels would then

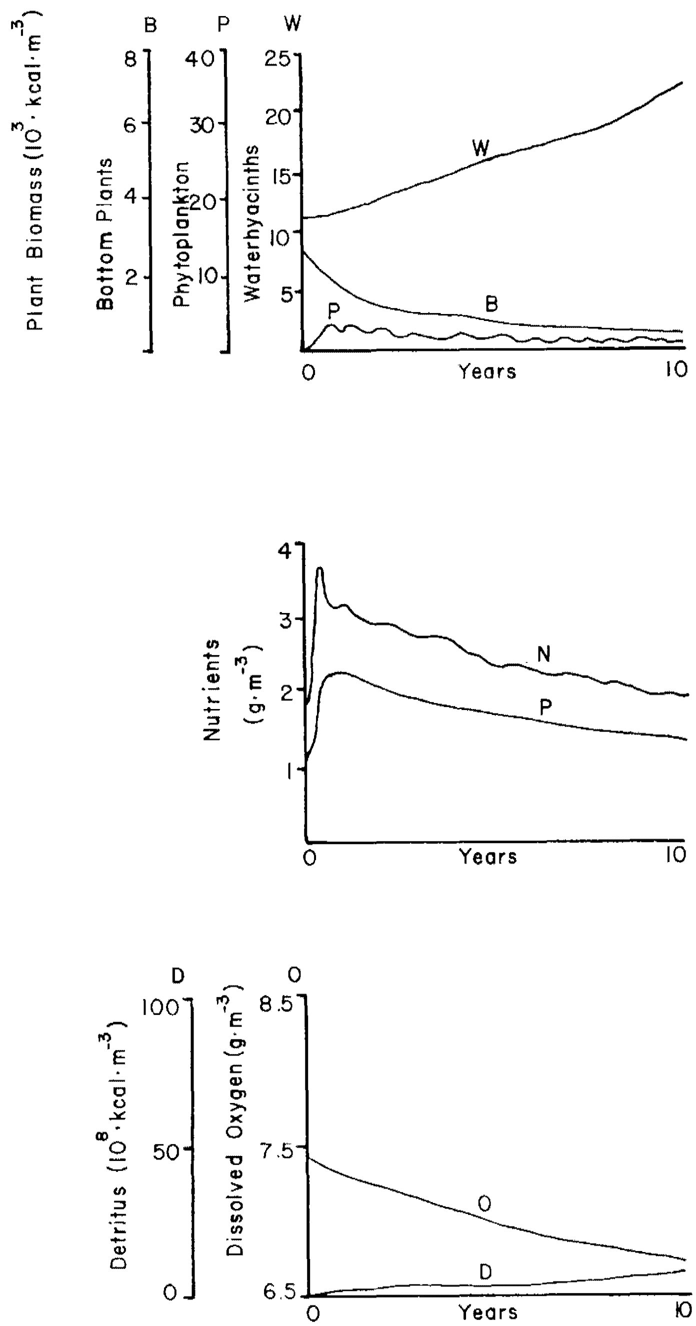

Figure 3. Simulated changes in a hypothetical pond ecosystem that are induced by the programmed increase of a waterhyacinth population.

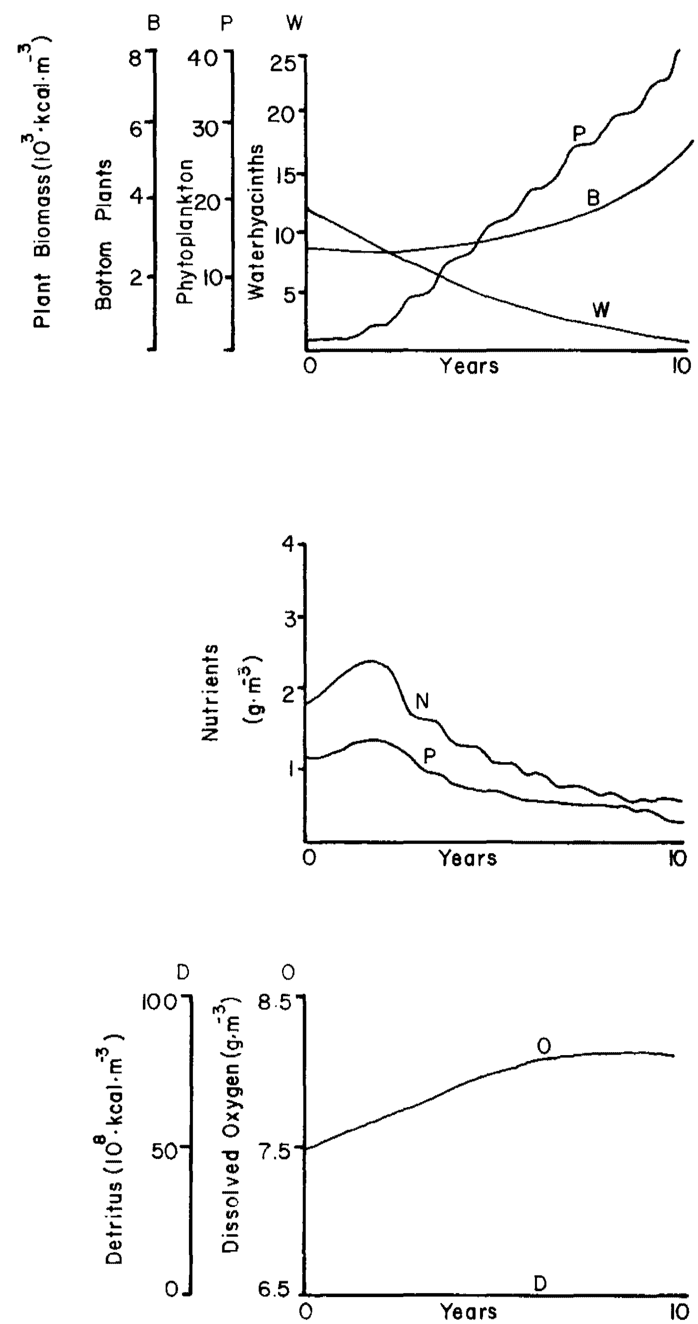

Figure 4. Effect on the hypothetical pond ecosystem of a reduction in the programmed nutrient input.

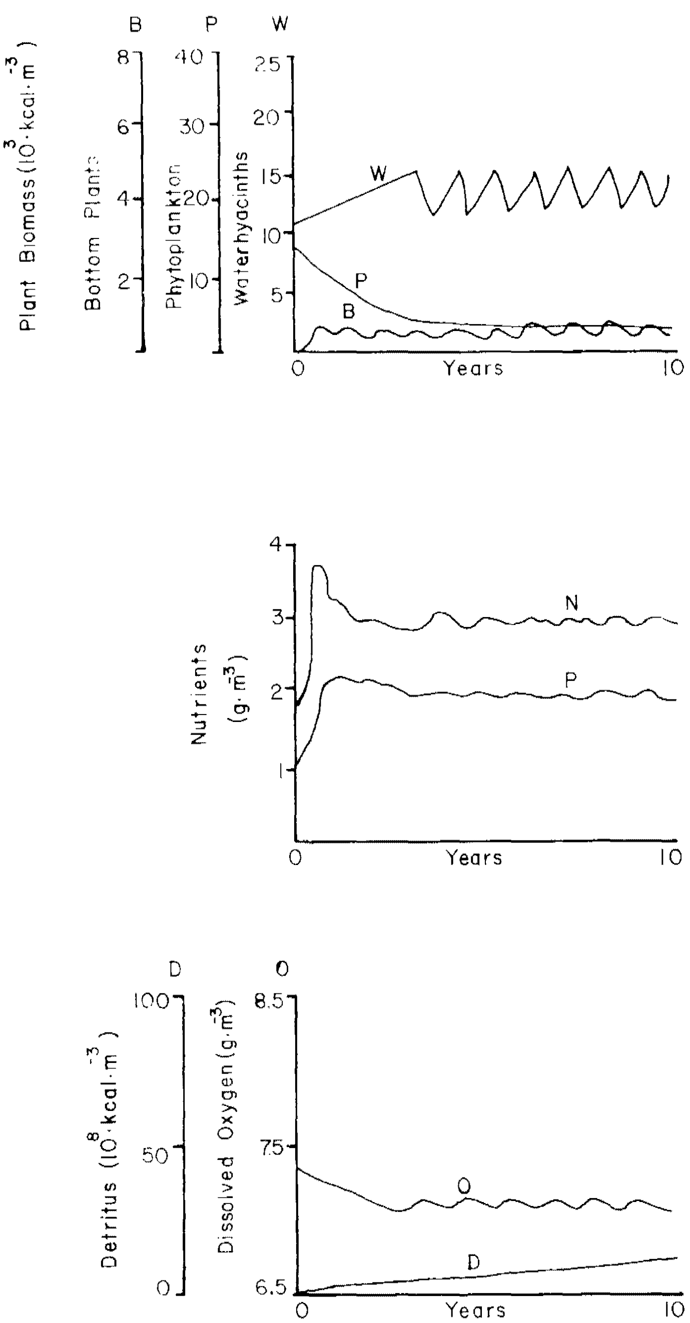

Figure 5. Effectiveness of a moderate control program in containing a simulated waterhyacinth population.

increase to near saturation level; the amount of detritus remains nearly constant in this case.

Chemical control of waterhyacinths would bring about the results diagrammed in Figure 5. Use of a partial-kill spray could result in rapid regrowth of the water-hyacinths, necessitating an annual reapplication. The other components of the system are maintained in a fairly constant state under this treatment, although the dead water-hyacinths do cause a more rapid increase in detritus.

The effects of a single large dose of herbicide, driving the waterhyacinth level to a fraction of its previous level, would result in an immediate increase of the phytoplankton and a subsequent stabilization of both the algal and the

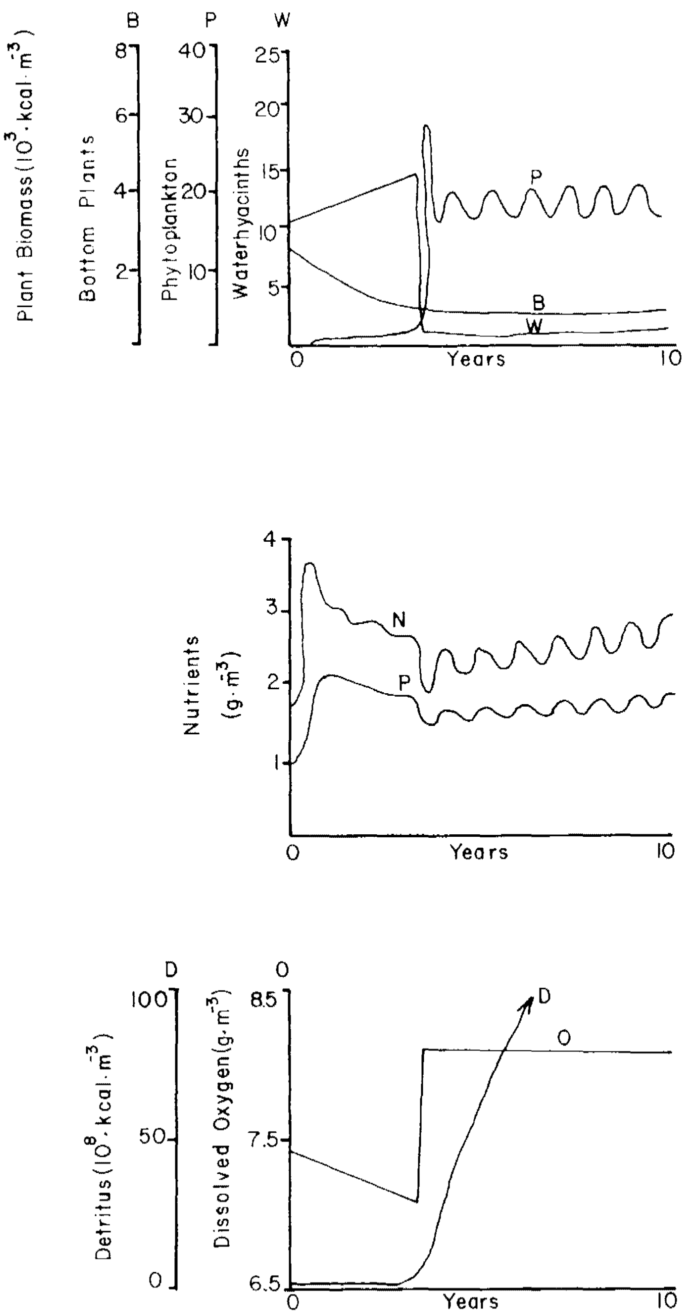

Figure 6. Effectiveness of an intensive control program in containing a simulated waterhyacinth population.

bottom plant populations, as shown in Figure 6. The killing of so many waterhyacinths causes the detrital layer to thicken appreciably. Return of the waterhyacinths would be considerably slower than before, suggesting a possible economic benefit in that control might then only be required at infrequent intervals.

The implementation of mechanical controls would probably not cause significant differences among the plant populations when compared with the effects of chemical controls; the dead waterhyacinths, however, would not sink to the bottom and so would represent a removal of nutrients from the system, thereby affecting not only the nutrient levels but the oxygen level and detrital pool as well.

FURTHER DEVELOPMENT OF THE MODEL

Because of the simplicity of this model and the lack of sufficient data from a single source, firm recommendations could obviously not be made on the basis of the simulations described above. Considerable detail is still needed to include such important aspects of the system as the use of nitrates, nitrites, and ammonia by the plant community, as well as the remineralization rates for both nitrogen and phosphorus compounds. The effects of varying depths in the body of water, of the size of the lake, and of the presence of aerobic and anaerobic zones within the lake are also important considerations.

In addition, several factors which might affect the outcome of the model have not been taken into account. The timing of a kill to coincide with winter frosts might increase the effectiveness of the partial-kill spray. Removing the weeds mechanically might help keep the regrowth under control.

An evaluation of waterhyacinth control methods in such a system should include a consideration not only of the biological system but of the economic system as well, taking into account inflationary rates which we are now experiencing in the prices of herbicides and which we might expect to continue. One approach to this would be to include in the model a set of pathways that would outline the expenditures of energy, human energy as well as energy used in manufacturing, to indicate a baseline energetic cost per hectare of different waterhyacinth control methods. Included in this sub-model might be the energy conserved in the system by utilization of mechanically harvested waterhyacinths as food, fodder, or fertilizer.

It is hoped that this general model demonstrates that it is possible not only to investigate a wider variety of situations than might be feasible under field conditions but also to determine which of several proposed experiments might yield the most useful information. In diagramming the system and identifying the most important variables, therefore, it is possible to emerge with a more complete understanding of the system. Just as important, a better idea of the critical measurements that are necessary may be obtained, enabling one eventually to reach more valid decisions on control policies.

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The Ecology Of Waterhyacinth In The White Nile, Sudan

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ABSTRACT

Infestation of the White Nile system by waterhyacinth (*Eichhornia crassipes* (Mart.) Solms) can be classified into three major consecutive phases of a cyclical nature. These phases are related to seasonal changes in certain important environmental factors, resulting in an annual cycle. It is shown here that the periodic rise and fall of infestation is based on the responses of waterhyacinth to the optimum conditions of high flood season and adversities of low flood, respectively. In the former case, the whole stretch of the White Nile becomes littered with vigorous populations. This dense infestation gives rise to great difficulties for navigation, fishing, and irrigation. In the latter, however, waterhyacinth populations retreat and become confined to sporadic occurences in the perpetually infested swamps of the Sudd-Sobat complex.

INTRODUCTION

Waterhyacinth has been infesting the Sudanese White Nile system since 1958 (4). Throughout its short history in the Sudan, waterhyacinth has been found to follow a rhythmic annual cycle of infestation. The critical part of the cycle occurs when the greater portion of the White Nile system is subject to epidemic infestation which lasts over a period of 3 months. Under the optimum conditions of high flood (August to October), the infestation soars to its peak. At this time, the distribution of the plant reaches its maximum extent, and the remarkable vitality of populations results in a massive cover of floating waterhyacinth. This picture contrasts strongly with the insignificant vegetational aspect which prevails during the low flood season, when the infestation declines to its minimum both in space colonized and overall vegetative vigor. At its