CLEANER, THE LAKE GEORGE MODEL

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ABSTRACT

CLEANER, an ecosystem model based on the International Biological Program model CLEAN, has a number of characteristics useful to environmental management. It represents functional physiologic and ecologic relationships for major compartments of the ecosystem, with disaggregation of trophic levels appropriate for studying competition among dissimilar forms. It exhibits good calibration and has few data requirements, facilitating transferability. It is programmed for use in interactive mode from remote terminals, with user-oriented output - including transformation of biomass values to turbidity, scum, and taste and odor indicators. It is currently implemented as a one-dimensional model without physical mixing terms, but it can be coupled with existing hydrodynamic models.

As a research tool CLEANER can be used to test hypotheses concerning complex ecosystem linkages and to guide data collection. As a management tool it can be used to provide scenarios and to extract bivariate relationships between pollutants and ecosystem effects. The model can be used by citizen groups as an educational tool, by advisory groups as a means of examining environmental trade-offs, and by regulatory agencies as a means of determining sensitivities and evaluating environmental impacts. CLEANER will eventually be coupled with adjunct models that predict nutrient loadings and tourist response, permitting simulation of long-range environmental, social and economic impacts.

INTRODUCTION

The ecosystem model CLEANER (Comprehensive Lake Ecosystem ANalyzer for Environmental Resources) has been developed by Rensselaer's Fresh Water Institute at Lake George in response to the need for a resource management model with ecologic realism. It is based on the model CLEAN, which was formulated by a multidisciplinary team in the Eastern Deciduous Forest Biome, U.S. International Biological Program (Park and others, 1974) and implemented by the Fresh Water Institute (Scavia and others, 1974).

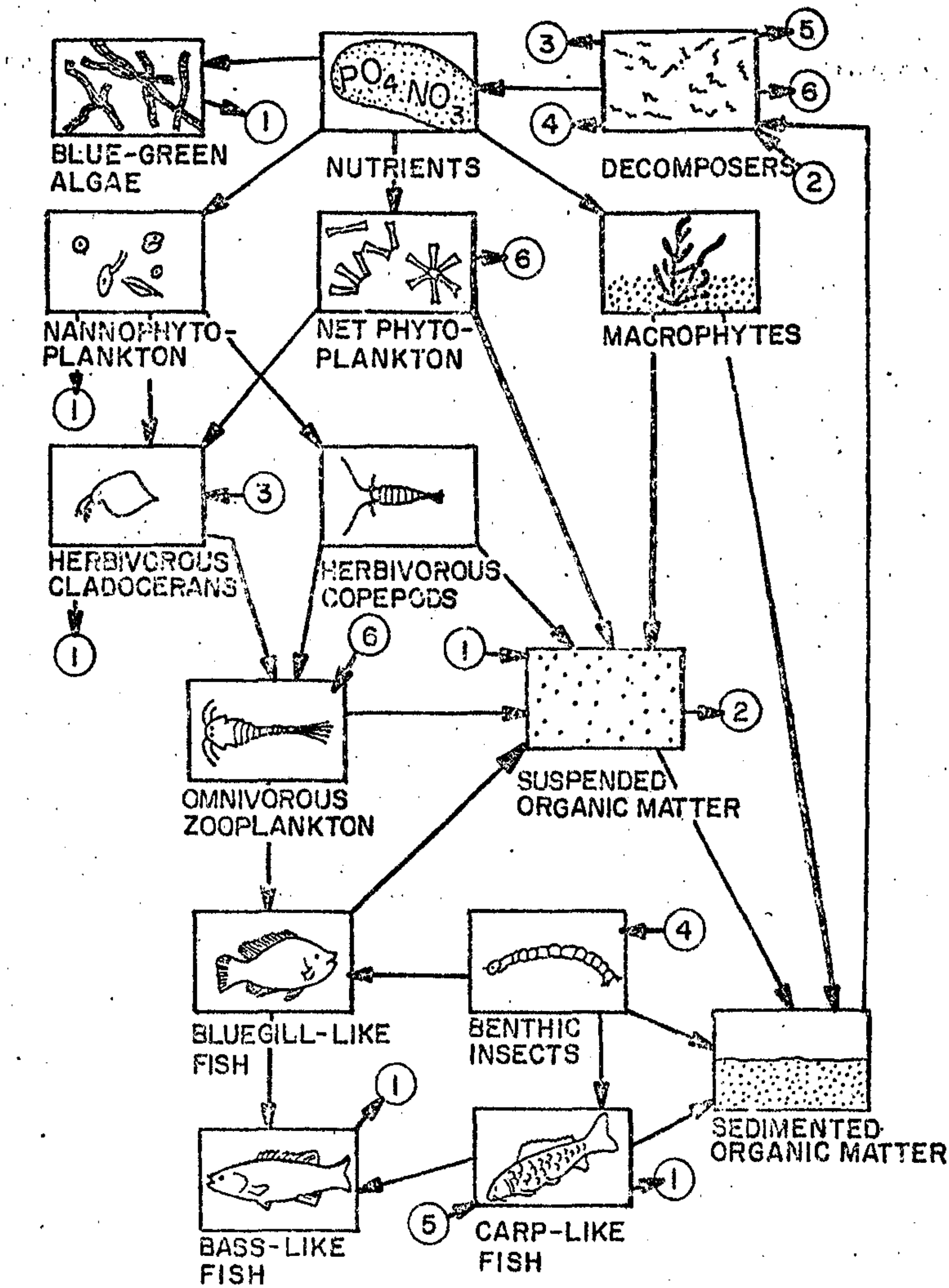
CLEAN presently comprises 29 coupled ordinary differential equations representing the more important compartments of lake ecosystems (Figure 1). Several versions have been implemented, including CLEANER and WINGRA[2] which is specific to the Lake Wingra, Wisconsin, IBP site (MacCormick and others, 1972). CLEANER presently consists of the 14 equations in CLEAN specific to the pelagic (open-water) portions of lakes, especially Lake George, New York, with output designed particularly for environmental managers.

Although CLEAN was developed primarily as a scientific tool to study ecosystem dynamics, the implementation of CLEANER has been guided by careful consideration of the characteristics that would be most useful in the application of the model to problems of environmental management. The principal objective of this paper will be to describe these characteristics.

FUNCTIONALITY

Probably the single most important characteristic of CLEAN is its embodiment of our current understanding of functional relationships. Model development has attempted to represent the more important aspects of key ecologic and physiologic processes in the

FIGURE 1. Ecosystem compartments represented in CLEAN.



BLUE-GREEN ALGAE
PO_4 NO_3
NUTRIENTS
DECOMPOSERS
NANNOPHYTO-PLANKTON
NET PHYTO-PLANKTON
MACROPHYTES
HERBIVOROUS CLADOCERANS
HERBIVOROUS COPEPODS
OMNIVOROUS ZOOPLANKTON
SUSPENDED ORGANIC MATTER
BLUEGILL-LIKE FISH
BENTHIC INSECTS
SEDIMENTED ORGANIC MATTER
BASS-LIKE FISH
CARP-LIKE FISH

mathematical formulation (Bloomfield and others, 1973; see also, Shugart and others, 1974). Of necessity these representations are greatly simplified, but they are based on a consideration of underlying biologic principles. The result is a biomass model that exhibits a strong degree of ecologic realism and that is capable of being applied to a wide range of aquatic environments, with appreciable utility in environmental management.

Furthermore, the equations are formulated in such a way that they can be modified very easily. Each process is represented by a maximum-rate parameter (measured at optimal conditions) multiplied by reduction factors for the effects of non-optimal conditions. For example, net photosynthesis is formulated as:

$$P_{net} = (P_{max} n / [\sum_i 1/\mu_i] - R) f(T)$$

P_{max} = maximum photosynthetic rate

n = number of limiting factors

μ_i = ith limiting factor: μ_1 = light, μ_2 = soluble nitrogen, μ_3 = phosphate

R = respiration rate

$f(T)$ = complex function for effect of temperature

Rates can be changed by changing parameter values and by changing the formulation of the factors; additional factors can be incorporated simply by including them in the process equations. Thus, pesticide inhibition of photosynthesis could be represented as:

$$P_{net} = (P_{max} n / [\sum_i 1/\mu_i] - R) f(T) f(p)$$

$f(p)$ = function for effect of pesticide with range from 0 (complete inhibition) to 1 (no inhibition)

SCOPE

Implicit in the development of CLEAN has been the realization that the whole ecosystem should be modeled, as also noted by Patten (1973). This has a direct bearing on the application of the model because environmental decision-making is increasingly being required to consider effects at all levels of the ecosystem. For example, the Federal Water Pollution Control Act (Public Law 92-500) calls for the restoration and maintenance of the biological integrity of the Nation's waters, with particular attention to the support of fish, shellfish, and wildlife and to the protection of public water supplies and waterbased recreational activities. If models of aquatic ecosystems are to be useful in investigating and forecasting the far-ranging consequences of pollution and physical disruption (including dredging, shoreline construction, and dumping) on such varied aspects of the ecosystem, they will have to represent not only algal growth, but the dynamics of zooplankton, fish, benthos, and bacteria as well.

The choice of compartments dictates the ultimate usefulness of the model. The use of too few compartments limits the way in which the model can represent the dynamic interactions found in the real world; the use of too many compartments results in undue requirements for parameter values and unnecessarily large computational loads. Very seldom would one want to simulate at the species level (Walters and Efford, 1972); but likewise, it is unrealistic to expect applicable results by modeling whole trophic levels, thereby reducing the food web to an overly simplified food "chain."

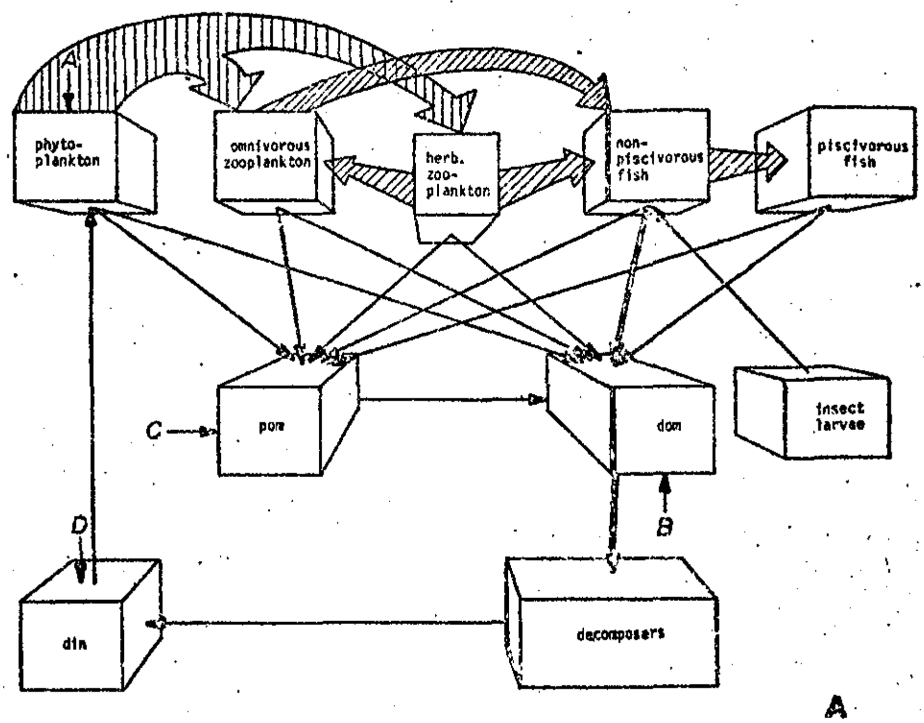
The choice of compartments modeled in CLEANER was based on a consideration of the principal modes of resource utilization and ecologic interaction found in the Lake George ecosystem. Therefore, the primary trophic level represented by phytoplankton was subdivided into three groups that reflect differences in nutrient utilization and susceptibility to grazing by zooplankton. In turn, zooplankton were divided into three groups on the basis of differences in feeding. The fish compartments also represent major feeding strategies, with additional compartments currently being added.

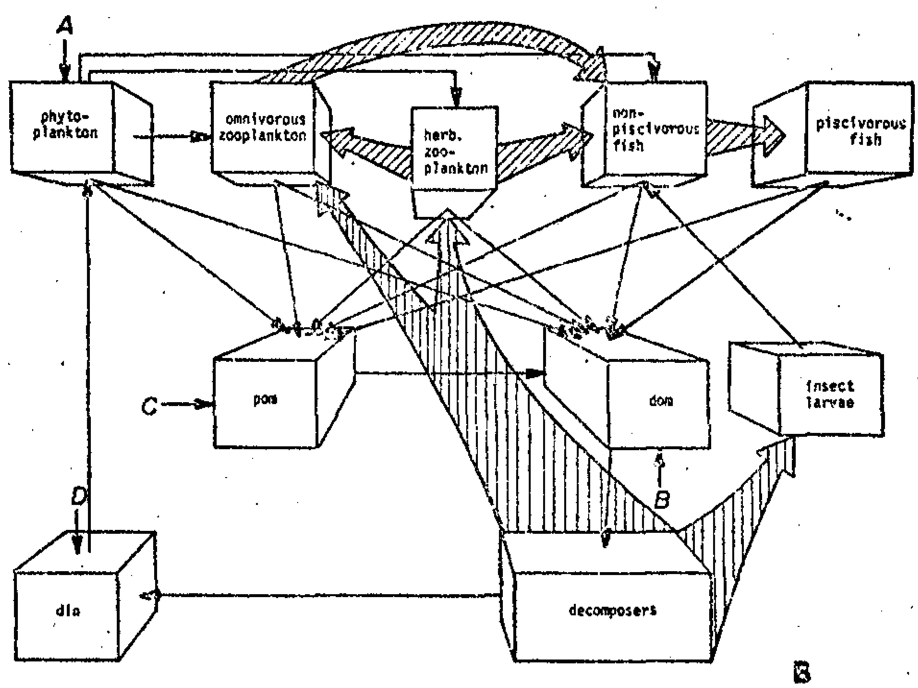
This degree of disaggregation permits environmental managers to observe the effects that man's impact will have on competition among ecologic groups, including both desirable and undesirable forms. For example, nutrient enrichment can favor the replacement of relatively innocuous nannophytoplankton by taste- and odor-producing large diatoms, which in turn may be replaced by scum-forming blue-green algae. The ascendency of these different types will affect the higher levels of the food web and can lead to a change in the fisheries - all of which can be represented to some degree by CLEANER. Likewise, the degree of disaggregation exhibited by CLEANER can permit the examination of the effects of alternate food pathways, such as plankton- and detritus-based systems, on the biological concentration and magnification of hazardous materials, including pesticides, heavy metals, and PCBs (Figure 2).

The equations are expressed in a general format (Park and others, 1974), so that if additional compartments are needed for a particular study they can be added with relative ease. Elaboration of the model is primarily a problem of parameterization.

In its present form CLEANER does not include a compartment for dissolved oxygen. Lake George is aerobic at all depths (Aulenbach, 1972); therefore, as a simplification, we have ignored the effects of dissolved oxygen. However, to ensure general applicability of the model, we are presently implementing dissolved oxygen as a state variable.

FIGURE 2. Flowchart of CLEANER showing: A. plankton-based food chain, and B. detritus-based food chain.


A
phyto-
plankton
omnivorous
zooplankton
herb.
zoo-
plankton
non-
piscivorous
fish
piscivorous
fish
C
pom
dom
insect
larvae
D
B
din
decomposers
A


A
phyto-
plankton
omnivorous
zooplankton
herb.
zoo-
plankton
non-
piscivorous
fish
piscivorous
fish
C
pom
dom
insect
larvae
B
D
din
decomposers
B

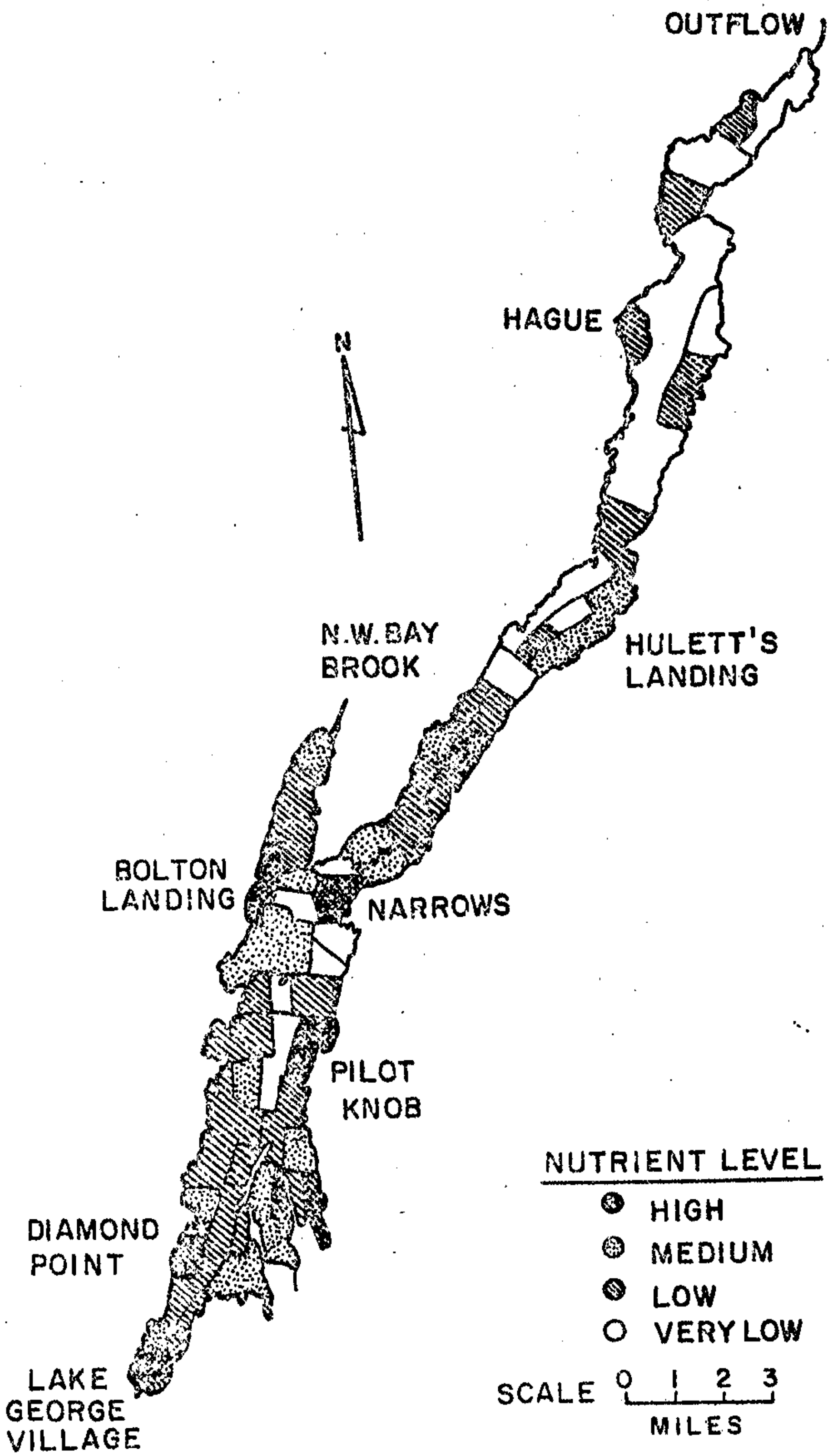
SPATIAL REPRESENTATION

CLEANER has been implemented as a one-dimensional model representing a m^2 column of water, which may be considered as indicative of average conditions for the lake or for a portion of the lake. The model differs from several popular ecosystem management models (for example, Chen, 1970; DiToro, O'Connor, and Thomann, 1971; Lombardo, 1971) in not including physical mixing terms, reflecting the emphasis on biologic processes in the IBP. Furthermore, as discussed below, it is felt that the resolution necessary for management of Lake George does not require continuous spatial modeling.

In the Lake George study multivariate analysis of the distributions of diatom frustules (siliceous skeletons) in bottom sediments has indicated the heterogeneity of nutrient enrichment of the lake (Bloomfield, 1972). As shown in Figure 3, the heterogeneity is relatively complex in the southern portion of the lake, but a basic pattern of enrichment adjoining the lakeside communities is evident. This information has suggested modelling the lake as homogeneous sub-basins. With this simplification, we can run the model for each major nutrient-enrichment segment of the lake, using sub-basin loadings and estimates of import and export values for nutrients. Furthermore, Lake George does not exhibit chemical stratification (Aulenbach, 1972); and renewal of the epilimnion by nutrient-rich hypolimnetic water during overturn is not a problem. Therefore, the effects of vertical mixing have been ignored.

On the other hand, there are management problems where spatial differences are of particular interest or where the complexities of shifting current patterns and stratification necessitate greater attention to the physical setting. Fortunately, physical modeling is relatively advanced. Therefore, one can either use existing

FIGURE 3. Nutrient-enrichment map of Lake George based on multivariate analysis of diatom death assemblages. After Bloomfield, 1972.


OUTFLOW
HAGUE
N
N.W. BAY
BROOK
HULETT'S
LANDING
BOLTON
LANDING
NARROWS
PILOT
KNOB
NUTRIENT LEVEL
HIGH
MEDIUM
LOW
VERY LOW
SCALE 0 1 2 3
MILES
DIAMOND
POINT
LAKE
GEORGE
VILLAGE

hydrodynamic models to determine import-export rates from one spatial compartment to another through a given span of time for subsequent use in the ecosystem model, or one can couple the ecosystem model to a particular hydrodynamic model and run them simultaneously. For example, it is possible to use CLEANER in place of the biologic production term in the IBP transport model developed by Hoopes and others (In: Park and others, 1974).

CALIBRATION

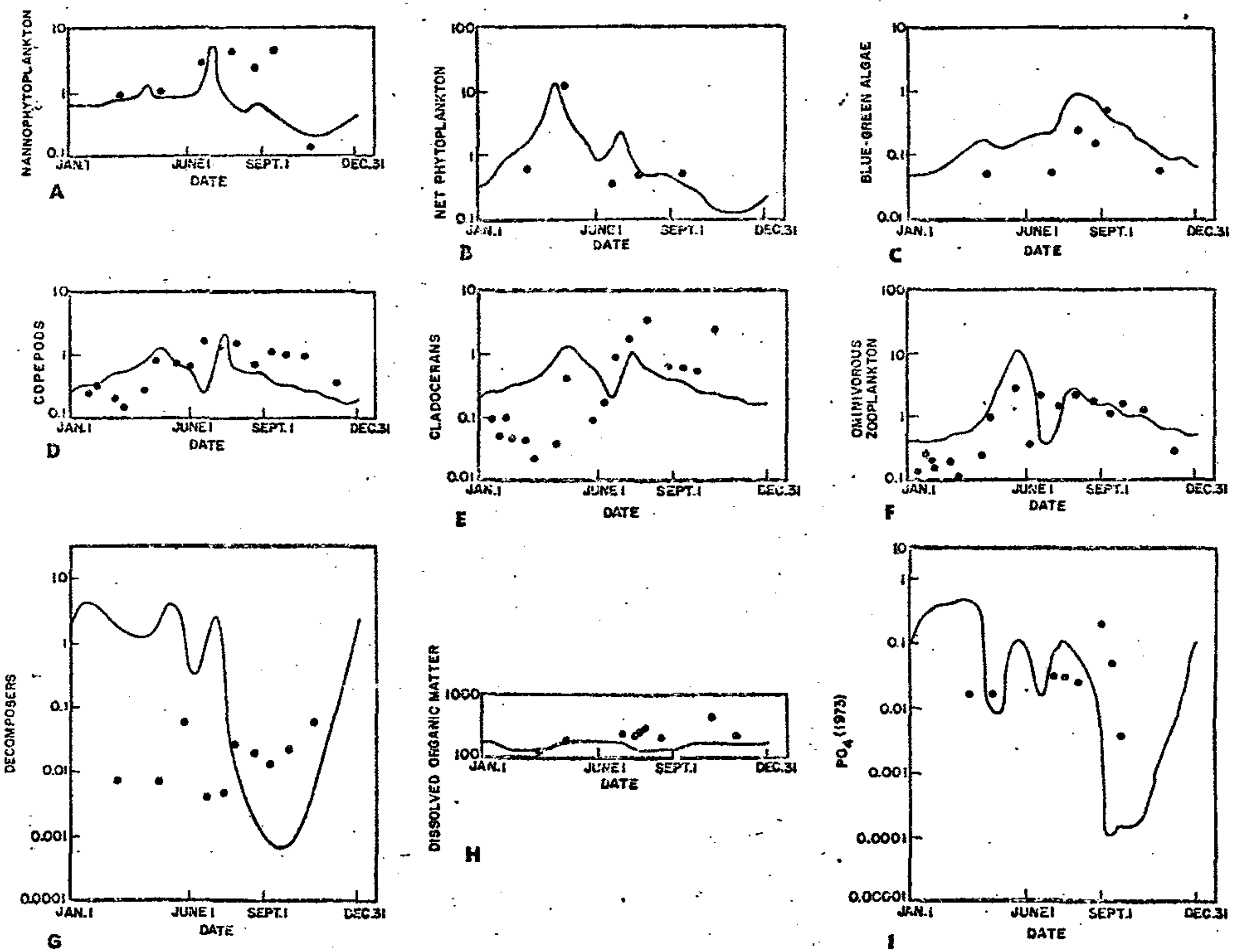
The model has been calibrated using data from Lake George. The objective has been to approximate the seasonal patterns and mean levels of biomass for each of the compartments by varying parameter values within the ranges suggested by laboratory experimentation. No attempt was made to get an exact fit to the observations, especially in view of the sampling errors and stochastic variations inherent in the data.

The results are relatively good (Figure 4) with the exception of the decomposer simulation, which overestimates decomposer biomass. The difficulty here is probably one of parameterization: it does not seem to be feasible to obtain valid parameter estimates for all decomposer processes under controlled laboratory conditions. Additional field data will probably be required before this part of the model can be calibrated satisfactorily.

TRANSFERABILITY

Implementation of the model has emphasized those aspects that would insure its transferability. Although CLEANER has been implemented specifically for Lake George, it is based on a core of ecologically sound functions and is, therefore, expected to be

FIGURE 4. Comparison of results of simulation (solid lines) with data from Station 1, Lake George, New York (dots) for six compartments. Biomass and nutrients are in grams/m^2. Phytoplankton data from H. H. Howard, zooplankton data from D. C. McNaught, phosphate data from D. B. Aulenbach, dissolved organic matter data from S. Kobayashi, decomposer data from L. S. Clesceri and M. Dazé.


NANNOPHYTOPLANKTON
NET PHYTOPLANKTON
BLUE-GREEN ALGAE
COPEPODS
CLADOCERANS
OMNIVOROUS ZOOPLANKTON
DECOMPOSERS
DISSOLVED ORGANIC MATTER
PO4 (1973)
JAN.1
JUNE 1
SEPT.1
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A
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adaptable to other sites. During adaptation to a new site, the inclusion of hydrodynamic transport, vertical mixing, sediment resuspension and other mechanics should be included where necessary, as previously discussed.

Site Calibration - Since there are often differences in physiologic and ecologic responses at different sites, the model should be reevaluated for each site. In addition to construct modification, it may be necessary to reparameterize the model to better represent endemic populations. We view this as a proper procedure where the present state of the lake is known and the objective is to forecast the results of perturbations.

By partitioning lake types that can be represented by specific model versions and particular sets of parameters, the fine-tuning phase can be reduced in many studies and the model can be applied even more readily. Some success has already been achieved with a related model using separate parameters for warm- and cold-water lakes (Walters, Park, and Koonce, in press).

Data Requirements - One of the difficulties in applying ecosystem models to various sites is that data are usually sparse. This was recognized early in the development of CLEANER and, accordingly, every effort has been made to reduce the amount of data required to run the model. At present, the driving variables include incident solar radiation (corrected for ice cover), water temperature (averaged for the water column), and loadings for nutrients and organic matter. Time-series for the first two can be approximated for a given site. The loadings can be measured directly or approximated using literature values (for example, Shannon and Brezonik, 1972). They can also be simulated using a separate model (see "Adjunct Models" below).

Obtaining reasonable initial-condition values for all compartments can be difficult. However, CLEAN has been shown to have good stability through successive years (Park and others, 1974); and, by using a "spin-up" period of three or more years, transient conditions caused by inappropriate initial conditions can be avoided. As shown in Table 1, the compartments in CLEANER will seek their proper levels even when the initial conditions are far from the actual values. Therefore, the only need for data on the individual ecosystem compartments is so that the model can be calibrated for a given site prior to perturbation analysis.

INTERACTIVE CAPABILITY

In order to maximize its accessibility and flexibility, CLEANER has been programmed for use on time-sharing systems from remote terminals. Thus, we are able to access the model from virtually any location. As a result, the model has been used to some advantage in seminars, workshops, and meetings at a variety of locations. Aside from its availability on one of our local computers, the model is being implemented on a commercial time-sharing system that is under contract to the Environmental Protection Agency, thus making it available to their personnel from anywhere in the country.

Equally important is the fact that users can interact with CLEANER by on-line editing of driving variables, site constants (such as water depth), initial conditions, and parameters. The time-series for nutrients, light, and temperature can be changed merely by setting the appropriate perturbation parameter. Consequently, entering a single statement:

PERT(1) = 2

on the terminal will double the phosphate loading for the period of

Table 1 - Initial and Final Biomass Levels After Eight Year Simulation (g/m^2)

	INITIAL Run 1	INITIAL Run 2	INITIAL Run 3	FINAL Run 1	FINAL Run 2	FINAL Run 3
NANNOPLANKTON	.59	1.0	1.5	.18	.18	.18
NET PLANKTON	.34	1.0	1.5	.08	.08	.08
BLUE GREEN ALGAL	.05	.09	.002	.044	.047	.044
CLADOCERANS	.22	.1	.05	.11	.11	.11
COPEPODS	.26	.1	.05	.11	.12	.11
OMNIVORES	.37	.1	.05	1.03	.99	1.03
NON-PISCIVORES	.011	.3	.5	.02	.02	.02
PISCIVORES	.556	.3	.5	.767	.744	.767
PO_4	.07	1.0	.2	.005	.004	.005
NITROGEN	2.28	.5	.2	2.65	2.63	2.65
POM	.22	5.0	3.0	.13	.13	.13
DOM	150.8	150.0	190.0	156.4	156.1	156.4
DEC	1.858	5.0	.8	.096	.069	.096

the simulation. Likewise, the user can explore the effects of a wide variety of perturbations such as halving the nitrogen input, raising the mean annual temperature by 10°C, removing all lake trout, and inhibiting photosynthesis in blue-green algae.

User-oriented Output - Considerable attention has been devoted to programming CLEANER so that the output would be meaningful to users other than the aquatic-specialist. The integration results are given in tabular form (Figure 5). Plots can be obtained in linear, semi-log, scaled or unscaled form showing any or all state variables (Figure 6).

It is not enough to create a model capable of mimicking these aquatic systems. If watershed managers and other non-specialist groups are to use the model, output must be in a more meaningful form. As optional output, therefore, a tabulation of key environmental-perception characteristics is available (Figure 7). These informative transformations of the biomass values include: predicted fish catches, transparency, and concentrations of scum-forming blue-green algae and taste- and odor-producing net phytoplankton, as well as algal ratios and concentrations of chlorophyll a with which environmental managers are accustomed to working.

APPLICATION

Although it is difficult to avoid using the word "predict," we prefer to think of CLEANER as being a "diagnostic" tool: one that is capable of diagnosing effects of man-induced perturbations. Ecosystems are very complex, characteristically with non-linear linkages among compartments; and it is not uncommon to find that perturbations produce counter-intuitive results. By using ecosystem models one can symbolically explore ecologic relationships and gain

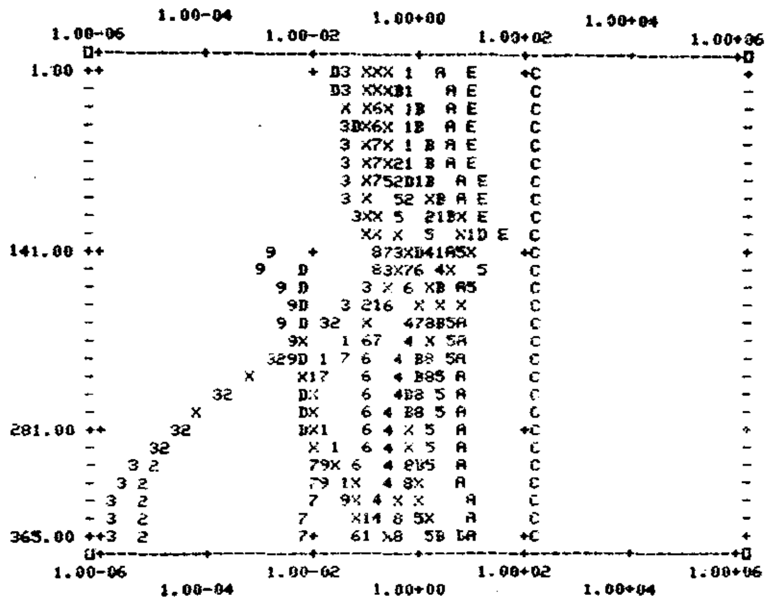
FIGURE 5. Tabular output of integration results from CLEANER.

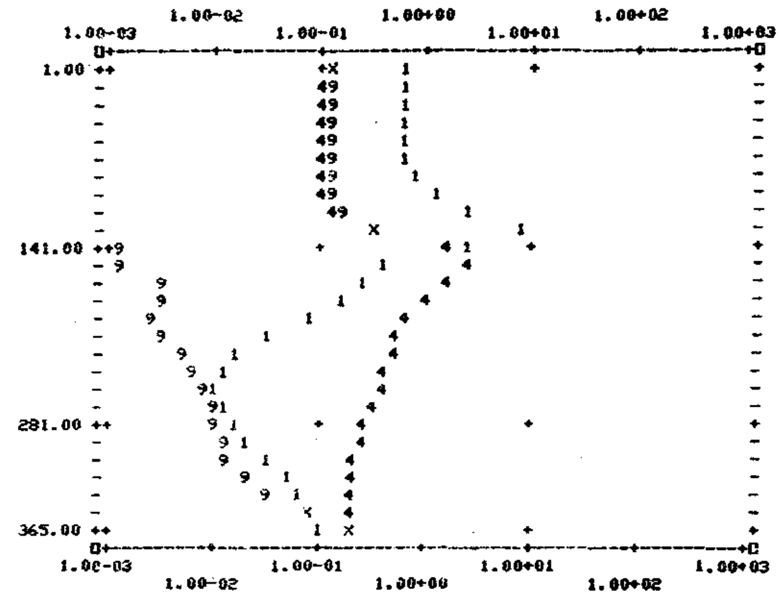
◆INT
READY
DATE: 090374 (MMDDYY) TIME: 095521 (HHMMSS) LAKE: GEO

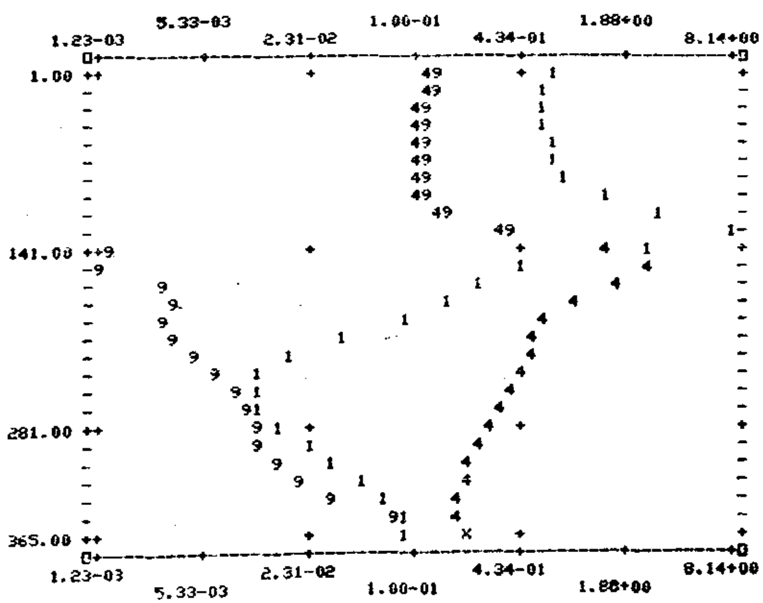
TIME	NAN	NET	B-GRN	CLAD	COPE	OMNIZ	NON-P	PISC	PO4	NIT	POM	DOM	DEC
1	.59	.34	.050	.22	.26	.37	.011	.556	.070	2.28	.22	150.8	1.858
15	.63	.39	.045	.22	.26	.35	.010	.519	.201	3.73	.26	142.6	4.614
29	.68	.51	.043	.21	.27	.35	.009	.488	.356	5.39	.35	133.7	5.271
43	.76	.71	.042	.21	.27	.34	.008	.461	.457	6.56	.40	130.3	3.747
57	.85	1.04	.042	.21	.27	.33	.007	.437	.507	7.22	.36	131.5	2.423
71	.99	1.61	.043	.21	.27	.32	.007	.415	.524	7.51	.29	134.1	1.766
85	1.25	2.94	.044	.21	.27	.32	.006	.393	.500	7.36	.28	136.3	1.527
99	2.08	7.77	.046	.24	.29	.34	.005	.368	.335	5.55	.53	141.5	1.736
113	3.46	16.04	.045	.38	.40	.50	.005	.340	.024	1.74	1.58	150.1	3.625
127	4.00	18.17	.039	.94	.87	1.34	.005	.312	.022	.60	3.54	139.9	9.437
141	1.77	7.97	.043	2.04	1.78	6.16	.016	.283	.114	.20	9.10	126.7	3.930
MAX TIME. STEP= 2.6250 MAX ERR= .06%													
155	.79	1.66	.048	.98	.91	9.47	.045	.254	.156	.38	4.08	128.6	.706
169	.73	.75	.052	.56	.55	9.35	.112	.226	.158	.45	1.19	131.6	.182
183	.78	.62	.056	.49	.49	8.21	.264	.202	.138	.42	.57	134.4	.058
197	.78	.57	.059	.43	.43	6.62	.559	.187	.110	.30	.51	136.3	.022
211	.76	.54	.058	.36	.37	4.74	.964	.184	.086	.22	.54	137.3	.010
225	.78	.51	.055	.28	.29	3.01	1.281	.193	.066	.19	.45	138.9	.005
239	.85	.50	.048	.22	.23	1.81	1.366	.208	.047	.20	.31	141.3	.003
253	.95	.47	.039	.17	.19	1.11	1.266	.222	.026	.20	.22	143.3	.002
267	.99	.42	.031	.14	.15	.72	1.087	.228	.010	.22	.16	144.9	.003
281	.89	.35	.023	.11	.13	.50	.899	.227	.003	.30	.12	146.0	.004
295	.73	.27	.017	.10	.11	.37	.732	.218	.002	.44	.13	147.3	.012
309	.65	.22	.014	.08	.10	.29	.597	.208	.004	.64	.12	149.4	.053
323	.70	.20	.011	.07	.09	.23	.492	.196	.021	1.00	.09	151.2	.354
337	1.00	.25	.009	.07	.08	.20	.411	.184	.118	2.04	.11	146.8	2.282
351	1.52	.42	.009	.07	.08	.19	.348	.174	.358	4.19	.14	131.4	5.046
365	1.82	.61	.010	.07	.09	.18	.300	.165	.524	5.78	.17	123.2	3.258

READY

FIGURE 6. Plot output from CLEANER, demonstrating various options for scaling and for suppressing state variables. Simulation is for one year (vertical axis): biomass values are given on the horizontal axes.


1.00-06
1.00-04
1.00-02
1.00+00
1.00+02
1.00+04
1.00+06
1.00
141.00
281.00
365.00


1.00-03
1.00-02
1.00-01
1.00+00
1.00+01
1.00+02
1.00+03
1.00
141.00
281.00
365.00


1.23-03
5.33-03
2.31-02
1.00-01
4.34-01
1.88+00
8.14+00
1.00
141.00
281.00
365.00

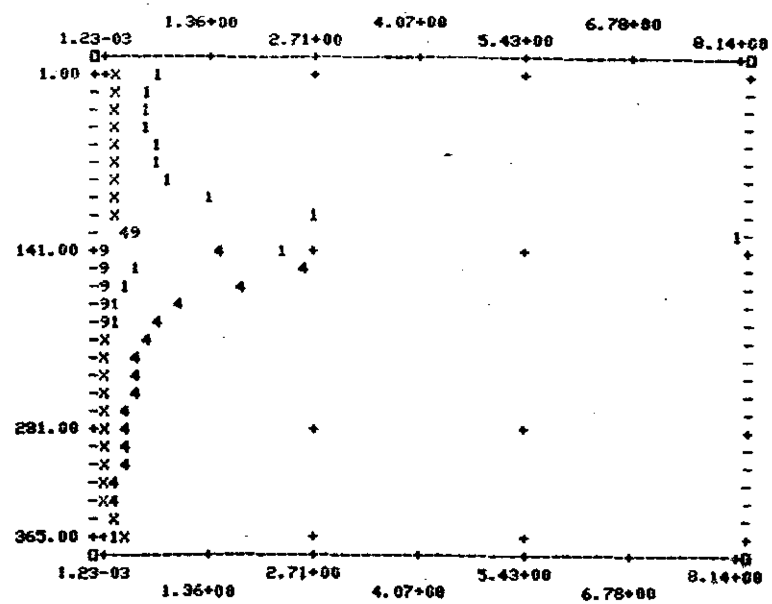

1.23-03
1.36+00
2.71+00
4.07+00
5.43+00
6.78+00
8.14+00
1.00
141.00
281.00
365.00

FIGURE 7. Tabular output of environmental-perception characteristics from CLEANER.

*TAB;A

ENVIRONMENTAL PERCEPTION PARAMETERS; LAKE CODE=GEO AVG DEPTH=30.0

TIME	2-WEEK FISH CATCH N-PISC #	PISC #	SECCHI DISC METERS	ALGAE MG/L	NET/NAN	BLGRN/OTHER	NET MG/L	BLGRN MG/L	CHLA MG/L
1.	9.	0.	40.31	.07	.576	.054	.005	.050	.001
15.	8.	0.	46.92	.06	.629	.044	.005	.045	.001
29.	7.	0.	46.08	.06	.748	.036	.007	.043	.001
43.	7.	0.	47.49	.06	.939	.029	.010	.042	.001
57.	6.	0.	48.65	.07	1.214	.022	.014	.042	.001
71.	5.	0.	48.67	.08	1.628	.016	.022	.043	.001
85.	5.	0.	46.94	.10	2.353	.010	.041	.044	.001
99.	4.	37.	39.39	.21	3.733	.005	.128	.046	.002
113.	4.	34.	24.31	.57	4.638	.002	.429	.045	.005
127.	4.	32.	9.72	1.52	4.548	.002	1.218	.039	.013
141.	13.	29.	15.60	.45	4.517	.004	.333	.043	.004
155.	37.	26.	32.55	.10	2.112	.019	.033	.048	.001
169.	92.	23.	38.58	.08	1.036	.035	.013	.052	.001
183.	217.	20.	40.74	.08	.793	.040	.010	.056	.001
197.	461.	19.	42.67	.08	.729	.043	.009	.059	.001
211.	794.	19.	45.11	.08	.704	.045	.008	.058	.001
225.	1055.	19.	47.75	.07	.661	.042	.007	.055	.001
239.	1126.	21.	49.99	.07	.585	.036	.006	.048	.001
253.	1043.	22.	51.76	.06	.495	.028	.006	.039	.000
267.	895.	23.	53.27	.05	.426	.022	.005	.031	.000
281.	740.	23.	54.64	.04	.391	.019	.004	.023	.000
295.	603.	22.	55.71	.03	.373	.017	.003	.017	.000
309.	492.	0.	56.41	.02	.341	.016	.003	.014	.000
323.	405.	0.	56.42	.02	.291	.012	.002	.011	.000
337.	338.	0.	53.70	.02	.248	.007	.003	.009	.000
351.	287.	0.	49.26	.03	.276	.005	.006	.009	.000
365.	247.	0.	50.85	.04	.335	.004	.008	.010	.000

TOTAL NON-PISC CATCH FROM THE BASIN IS 8909.
TOTAL PISCIVOROUS CATCH FROM THE BASIN IS 369.
READY

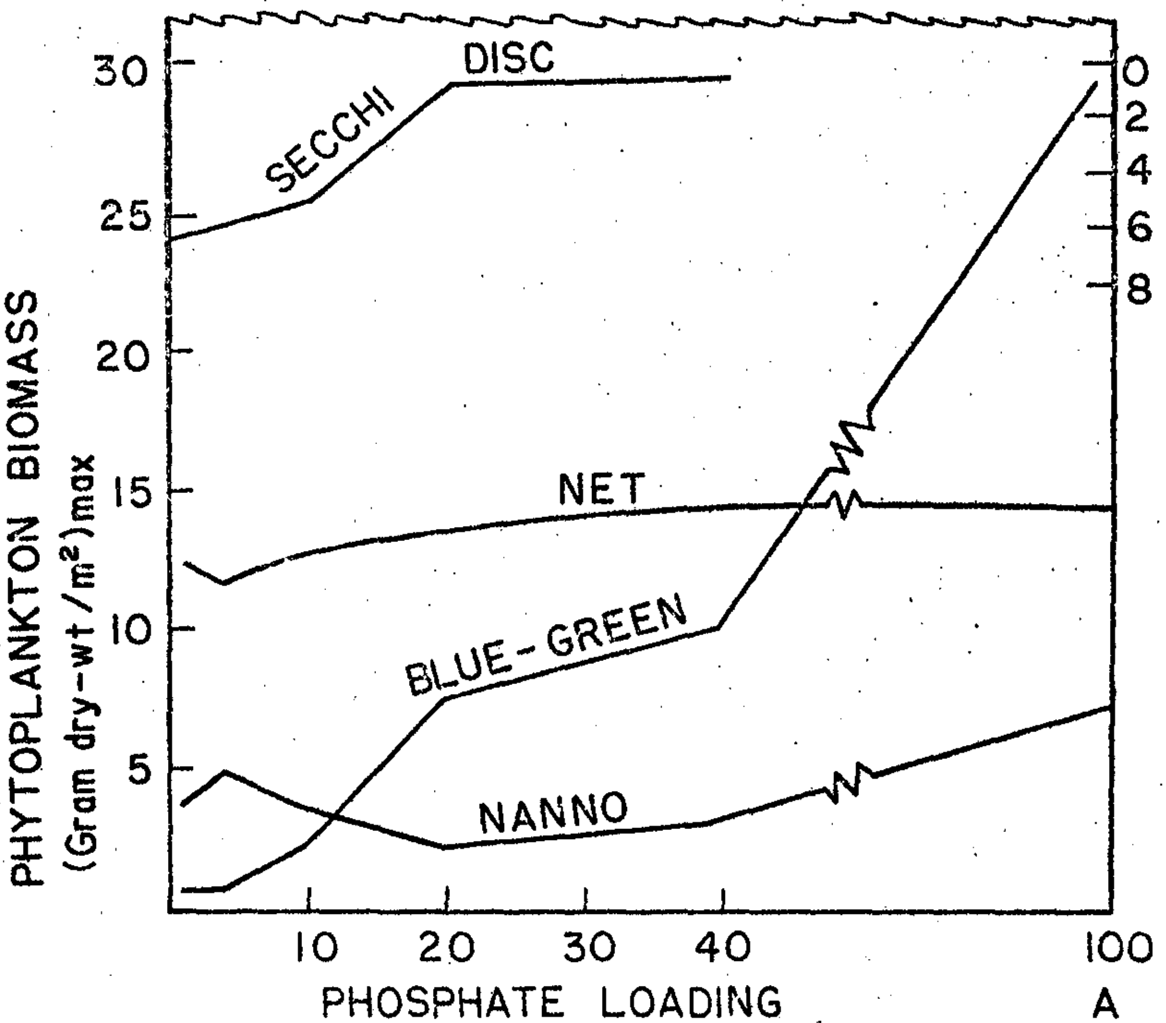
a feeling for the way the system probably would react to a particular perturbation.

As a research tool, CLEAN can be used to test hypotheses concerning the ecosystem linkages that are not otherwise amenable to experimentation. It can also guide future research and data collection by explicitly defining those areas needing further description (Park and others, 1974). The history of development of CLEAN amply demonstrates this (Park and Wilkinson, 1971a, 1971b; Park and others, 1972, 1973; Bloomfield and others, 1973).

After several years of development, CLEAN, as manifested in CLEANER is reaching the stage where it can be used as a management tool as well as a research and educational tool. It does not provide answers, but it does provide a wealth of information on the effects of alternative management schemes, permitting interested groups to make their own value judgments. In effect, the model provides scenarios that can supplant the very slow feedback that characterizes the actual management and monitoring of the ecosystem. Furthermore, by varying the intensity of perturbation one can gain an understanding of the sensitivity of the model - and, by extension, of the real world - in that particular factor-space.

As an example, consider the use of the model in studying the effects of phosphorous enrichment. Various intensities of phosphorous loadings were used in a series of simulations of the south end of Lake George. Maximum phytoplankton biomass and minimum transparency were plotted against phosphorous loads (Figure 8). It can be seen that, in the extreme case, blue-green algae completely dominated the system; and even in less extreme situations the most dramatic change is in the ascendency of those noxious algae. Also, the water quality decreased markedly with increasing phosphorous loadings, as indicated by the simulated secchi disc readings. In

FIGURE 8. Maximum predicted biomass of net phytoplankton, nannophytoplankton, and blue-green algae and minimum predicted secchi disc readings plotted against phosphate loadings (multiplicative with normal phosphate loading from the drainage basin of the southern portion of Lake George.)


PHYTOPLANKTON BIOMASS
(Gram dry-wt/m²)max
30
25
20
15
10
5
SECCHI
DISC
NET
BLUE-GREEN
NANNO
0
2
4
6
8
10
20
30
40
100
PHOSPHATE LOADING
A

this way, the model can be used to establish simple relationships between algal problems and phosphorous loadings that can be readily applied by environmental policymakers and managers. It is interesting to note that when excess nitrogen loadings were simulated, there was little response (Figure 9), as would be expected in that Lake George has been shown to be primarily phosphorous-limited for much of the growing season (Stross, 1971).

We anticipate that CLEANER will be used somewhat differently by various elements of the environmental management system (Figure 10). For instance, we have found that interested citizens tend to respond to the model output according to their particular interests, with fishermen looking for increased productivity and cottage owners worrying about water clarity and taste (especially on Lake George where most drinking water is pumped directly from the lake). For these special-interest groups the model can be used as an educational tool, giving them more objective insights into the intricacies of the aquatic ecosystem and their relationships to it.

Similarly, CLEANER is appropriate for legislative advisory groups that are concerned with the trade-offs involved in managing the environment. The model should facilitate the formulation of goals by providing scenarios based on alternative policies. Advisory groups seem to be particularly interested in cost-benefit relationships; therefore, linkages of a socio-economic model to the ecosystem model, as discussed below under "Adjunct Models," would be invaluable.

Theoretically, CLEANER and similar models should be quite useful to environmental managers. At the present time the implementation of regulations seems to be manifested primarily in the review of environmental standards and the evaluation of effects; it would appear that the model would be most helpful in differentiating

FIGURE 9. Same as in Figure 8, except that nitrogen loading was varied instead of phosphate.

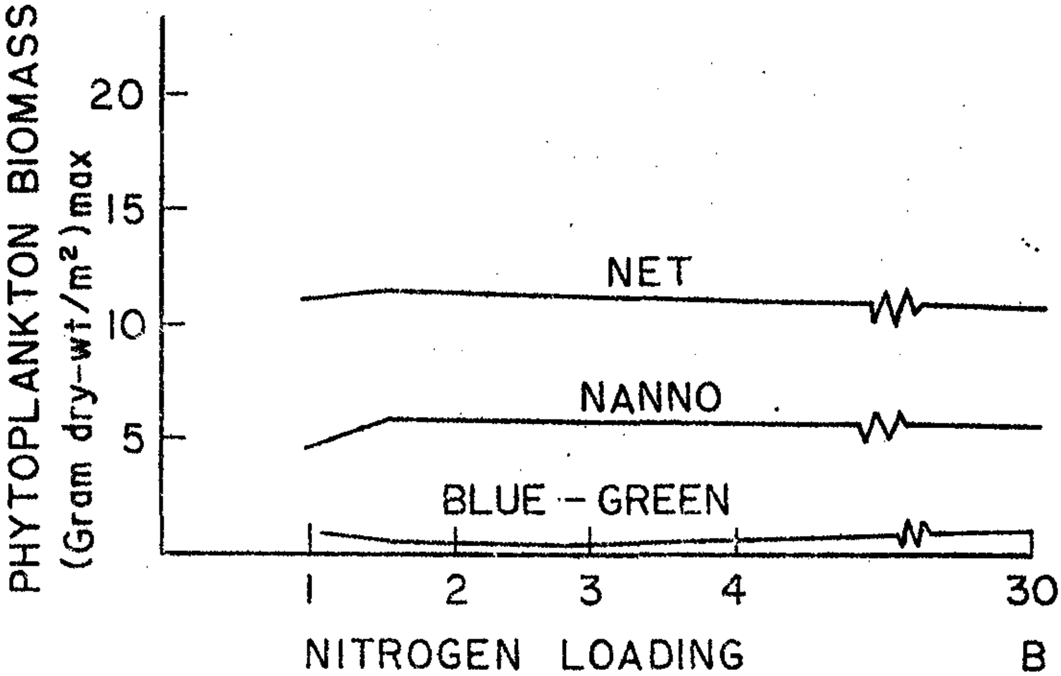
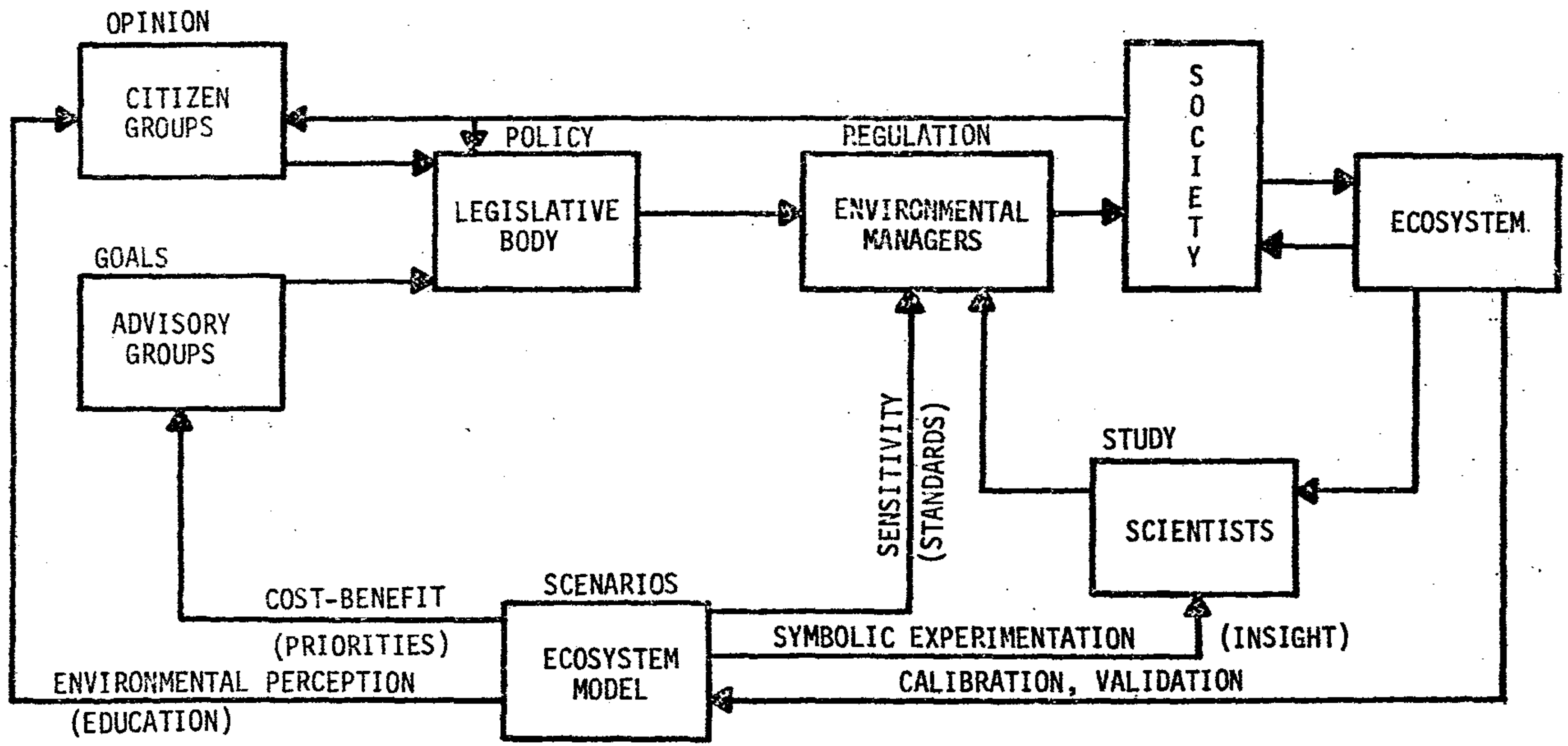

PHYTOPLANKTON BIOMASS
(Gram dry-wt/m²) max
20
15
10
5
NET
NANNO
BLUE - GREEN
1
2
3
4
30
NITROGEN LOADING
B

FIGURE 10. Relationship of elements of the environmental management system to CLEANER.


OPINION
CITIZEN GROUPS
POLICY
REGULATION
SOCIETY
LEGISLATIVE BODY
ENVIRONMENTAL MANAGERS
ECOSYSTEM
GOALS
ADVISORY GROUPS
SENSITIVITY
(STANDARDS)
STUDY
SCIENTISTS
COST-BENEFIT
(PRIORITIES)
SCENARIOS
ECOSYSTEM MODEL
SYMBOLIC EXPERIMENTATION
(INSIGHT)
ENVIRONMENTAL PERCEPTION
(EDUCATION)
CALIBRATION, VALIDATION

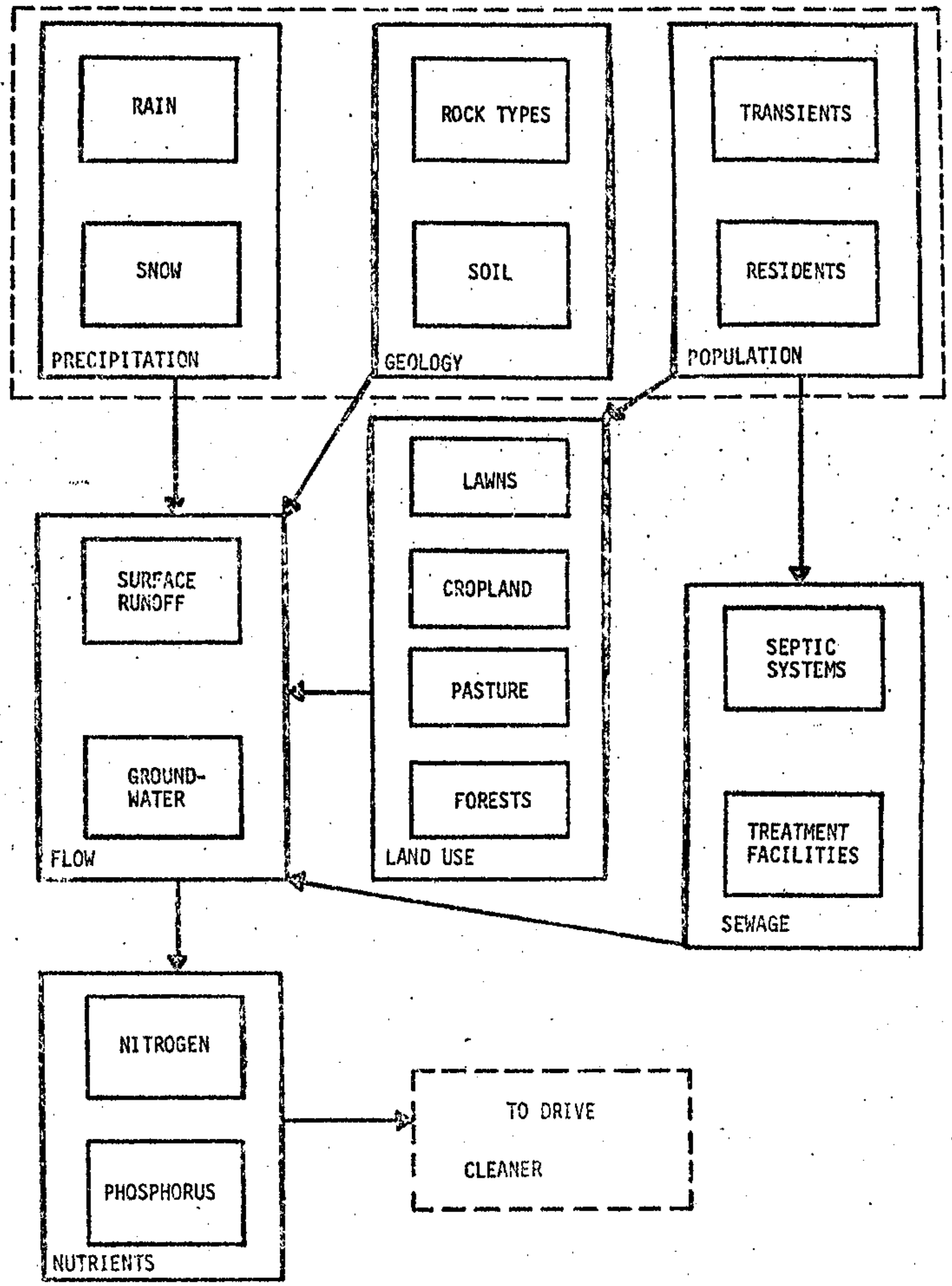
between sensitive and insensitive ranges of pollutants, based on whole-ecosystem response. The perturbation analysis described above would be useful in determining these sensitive ranges and critical points. In the same fashion, CLEANER can be used either directly or indirectly in the evaluation of environmental impact statements (EIS). The effects of perturbations on the system can be investigated and results can be expressed as simple bivariate relationships, whereby a relatively expedient assessment of the EIS can be made. In writing an EIS, where more time and manpower is often available, the model can provide an in-depth diagnosis of the ecosystem responses to the anticipated stresses. In this way the effects throughout the food web can be examined, and a thorough assessment of the impact can be delineated.

ADJUNCT MODELS

The usefulness of CLEANER as an environmental management tool will be enhanced when it is coupled with adjunct models developed in the course of the Lake George study (Park and Wilkinson, 1971a; Clesceri and Ferris, 1971). The concept of the linkages among these models might well serve as an example for modeling programs in general.

In order to examine the effects that changing land-use patterns and construction of waste-treatment facilities will have on nutrient input in a given basin, we are implementing WTRSHD, a nutrient/hydrology model (Holberger, personal communication). The model considers both point and non-point sources of nutrients and the transport of these nutrients as a function of surface and groundwater flow (Figure 11). The final version of WTRSHD will obviate the need for data on nutrient loadings; it will require time-series data on precipitation and populations of permanent residents and

FIGURE 11. Major components of the nutrient/hydrology model WATRSHD.


RAIN
SNOW
PRECIPITATION
ROCK TYPES
SOIL
GEOLOGY
TRANSIENTS
RESIDENTS
POPULATION
LAWNS
CROPLAND
PASTURE
FORESTS
LAND USE
SURFACE RUNOFF
GROUND-WATER
FLOW
SEPTIC SYSTEMS
TREATMENT FACILITIES
SEWAGE
NITROGEN
PHOSPHORUS
NUTRIENTS
TO DRIVE
CLEANER

transients and data on areal extent of major rock and soil types, and land usage - all of which can be obtained relatively easily for most lake basins.

A second model, POPUL, provides a means for predicting the growth of populations of transients and permanent residents and the resulting changes in land-use patterns (Figure 12). At present, the model calculates nutrient loadings and represents negative feedback to transient population by means of overly simplified formulations (Stern, 1971). However, POPUL can provide the land-use and population input for WTRSHD which, in turn, can calculate the nutrient input to CLEANER using well established functionalities.

Many people have expressed concern regarding the quantification of the intangible aspects of water-quality aesthetics. Because little is known about this important subject, environmental perception by recreationists, cottage and homeowners, and businessmen has been extensively studied at Lake George and three other lakes with dissimilar characteristics (Kooyoomjian and Clesceri, 1974). The recreationists were subdivided into boating, camping, fishing, picnicking, swimming, sightseeing, and amusement-park categories. Data are available showing how each of these groups perceive numerous aspects of the lake environment; considering that the response may be positive or negative, the data can be used to predict differential usage patterns for a range of water-quality states. Therefore, response to water quality can be modeled with some assurance. With prediction of water quality by CLEANER, the feedback loop to POPUL is formed and the linkage of the three models is complete (Figure 13).

Furthermore, the perception data show spending patterns by categories and water-quality states; these will eventually be used in developing an economic model to predict the economic consequences

FIGURE 12. Major components of the population model POPUL.

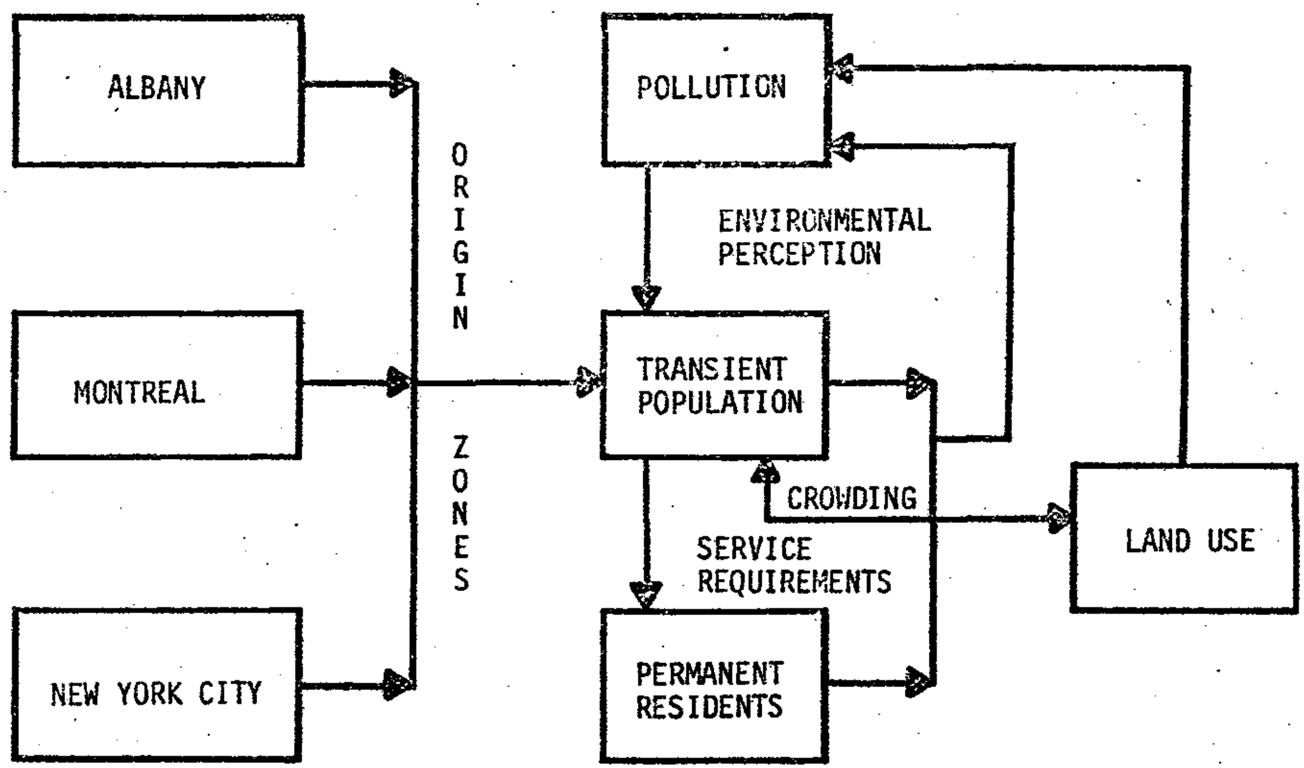
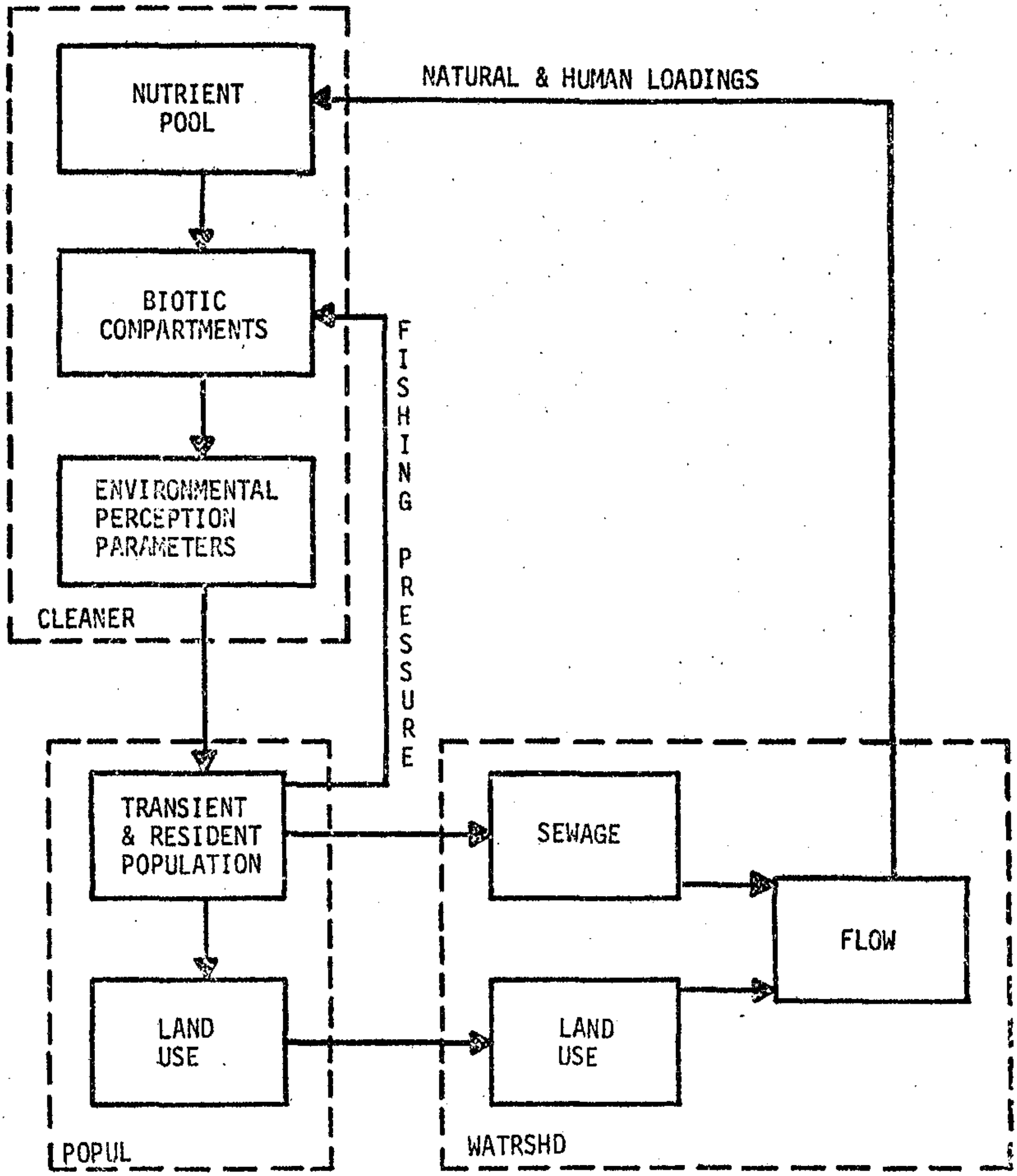

ALBANY
MONTREAL
NEW YORK CITY
ORIGIN ZONES
POLLUTION
ENVIRONMENTAL PERCEPTION
TRANSIENT POPULATION
CROWDING
SERVICE REQUIREMENTS
PERMANENT RESIDENTS
LAND USE

FIGURE 13. Conceptual linkage of the models CLEANER, POPUL and WATRSHD.



NUTRIENT POOL
BIOTIC COMPARTMENTS
ENVIRONMENTAL PERCEPTION PARAMETERS
CLEANER
NATURAL & HUMAN LOADINGS
FISHING PRESSURE
TRANSIENT & RESIDENT POPULATION
LAND USE
POPUL
SEWAGE
FLOW
LAND USE
WATRSHD

of changing water qualities. For example, we know that recreationists, other than fishermen, at oligotrophic (nutrient-poor) lakes spend more per year than recreationists at eutrophic (nutrient-rich) lakes (Kooyoomjian, 1974); thus the "cost" of degrading water quality can be assessed.

By developing this family of compatible models, a sophisticated, objective management tool can be created to examine the long-range environmental, social, and economic impacts at recreational lake sites.

SUMMARY

CLEANER exemplifies several characteristics that are useful in applied modeling efforts. These include: 1) functionality, embodying the more important aspects of key ecologic and physiologic processes in a formulation that can be modified easily; 2) broad scope, including simulation of the major ecosystem compartments, with enough disaggregation to permit observation of competition between desirable and undesirable forms and examination of the effects of concentration of hazardous substances through alternate food pathways; 3) transferability, with few data requirements and with a formulation that facilitates reparameterization; 4) interactive capability, permitting on-line editing of driving variables, site constants, initial conditions, and parameters from remote terminals; and 5) user-oriented output, including a variety of plotting options, and tabulations of biomass values and of environmental-perception characteristics.

The model is a useful tool for scientific research, for education, and for environmental management. It is capable of providing detailed scenarios for numerous types of perturbations and can help in 1) diagnosing basic ecologic relationships, 2) providing a learning experience for concerned citizenry, 3) examining environmental trade-offs, 4) determining critical values of pollutants, and 5) evaluating environmental impacts of man-induced stresses.

The modeling program has also led to the development of adjunct models to simulate hydrology and nutrient loadings and citizen response; and data are available for development of an economic model. These will eventually be coupled to CLEANER in order to simulate long-range environmental and socio-economic impacts.

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