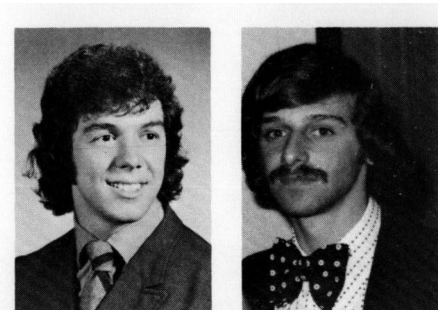

by

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Documentation of CLEANX: a generalized model for simulating the open-water ecosystems of lakes*

FOREWORD

In the lead article in this issue, CLEAN, a generalized lake ecosystem model, was described by the 25 investigators in the Eastern Deciduous Forest Biome, U.S. International Biological Program, who were responsible for its formulation.[1] Because of the interest in this model, the team that implemented it as a user-oriented interactive package has consented to make the software available through one of the authors, Richard A. Park, or from SCS. The version described here is CLEANX; it is used to simulate the open-water (pelagic) portions of lakes, as described in the previous paper.

Don Scavia (above, left), who had primary responsibility for implementation of CLEANX, has a BS and an MS in environmental engineering; he is currently a research assistant in the Fresh Water Institute. Jay Bloomfield (above, right), who worked closely with Scavia in the implementation and was instrumental in developing the original program code for the overall CLEAN model, also has BS and MS degrees in environmental engineering and is currently completing his PhD (his dissertation research is on modeling the decomposition process). John Fisher has a BS in mathematics and is in the graduate mathematics program at Rensselaer Polytechnic Institute. He and James Nagy, currently a programmer at National Computer Software Systems, worked closely with the rest of the team in programming the model. Richard Park is an Associate Professor of Geology at Rensselaer Polytechnic Institute and is Chief Mathematical Ecologist of the Fresh Water Institute; his dual role was to supervise the implementation of the model and to serve as liaison with the multidisciplinary group involved in its formulation.

SUMMARY

This paper outlines the software for an open-water version of CLEAN, an ecosystem model for lakes. The modular program structure is described, examples of driving variables are given, and the output (including values of several parameters) is shown. The program, with extensive annotations to facilitate adaptation by potential users, is available from author Richard A. Park or from SCS.

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* Contribution No. 168 from the Eastern Deciduous Forest Biome, U.S. International Biological Program

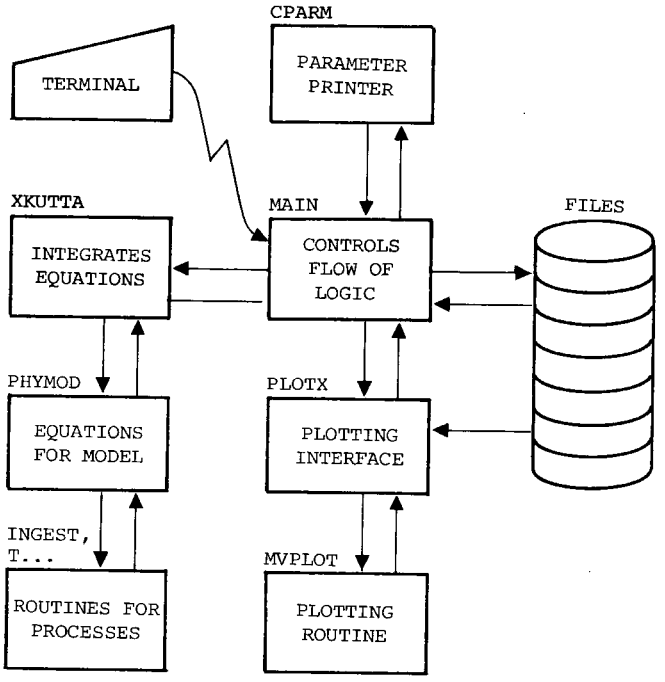

Figure 1 - Flow diagram of program logic

PROGRAM STRUCTURE

The model has been implemented in FORTRAN V on a UNIVAC 1108 as an interactive program. The program has a modular structure to increase computational efficiency and to permit addition of compartments and processes with minimal effort. The main routine is responsible for delegating control to integrating, plotting, and parameter-printing routines; also, it handles the editing of parameters, site constants, initial conditions, and perturbations, and it manipulates files (Figure 1).

Integration is performed by XKUTTA, a Runge-Kutta-Merson algorithm[2] modified to operate at a local relative error specified by the user. It is a fourth-order, variable-step method, carried out in extended precision. XKUTTA calls the subroutine PHYMOD, which evaluates the differential equations by extended-precision arithmetic manipulations. PHYMOD, in turn, calls additional subroutines and functions that define the process-level relationships and driving variables. After each interval in the simulation, control is returned to the main routine and the results are tabulated.

Upon completion of the integration, control can be passed to PLOTX, where control parameters which specify the plot format are set; plotting is initiated by the routine MVPLOT. Subsequently, control is passed back through the main routine to the user.

Other subroutines called by the main program at the user's discretion are for printing parameter values (CPARM) and saving edited parameter values (PRES). The main routine also prints initial conditions, messages that have been saved on a file, and a list of usable commands (Table 1).

The use of files is an integral part of this program. Parameter values are saved on file 9 and initial conditions are saved on file 10. During the execution of the program, temporary copies of these files are used for editing. Free-form editing is done using file 4. If the program is terminated by a *RES command, the temporary files are copied into the permanent files. Broadcast messages are saved on file 2, and a more detailed message listing is on file 3. Broadcast messages are displayed each time the program is executed; the detailed messages are obtained using a *MSG command (Table 1). The detailed list of commands is saved on file 11 and can be displayed by using a *HEL command. Unit 8 is used to store the integration data for subsequent plots and is retrieved by PLOTX.

Table 1
Program commands

Command	Options/Syntax	Description
*PRP, options	Parameter sections 1-9, A-E. No separators for a list.	Print parameters.
*PRI		Print initial conditions.
*RES		Save all changes made during current run (terminates program).
*END		Terminates program without saving changes.
*LAK, option	Lake Code: GEO, WIN default - GEO	Set driving variables for desired lake.
*MSG		Print all saved messages.
*EDP	Enter: ¢&EDIT *param* = xx &END	Edit a parameter value.
*EDI	Enter: ¢&BEGIN *param* = yy &END	Edit an initial condition.
*HEL, option	B = brief listing default = extensive listing	List usable commands.
*READY		Check to see if program is expecting input.
*PLT,*ab*	*a*: S - scaled log U - unscaled log (default) L - linear *b*: F - forced axis length C - constrain plot to maximum and minimum values of biomass as preset by user	Plot results of last integration.
*INT		Integrate equations.
None	*Param* = xx where *Param* is any parameter, site constant, or initial condition (see Table 2)	Edit parameters and initial conditions in free-form format.

DRIVING VARIABLES

Time-series of values of temperature and nitrogen are stored in the program in the form of equations utilizing Fourier series. Linearly interpolated values for other driving variables are returned from the routine CHART. Because of the application of this model to lakes of interest to the International Biological Program (IBP) and the Fresh Water Institute, data are included for Lake George in New York, Lake Wingra in Wisconsin, and Saratoga Lake in New York. The code also includes some data for Vorderer Finstertaler See, Austra, and Char Lake, Canada. However, only the data for Lake George have been checked for accuracy.

Data from Lake George were used in the example presented by Park and others[1] and in generating the output presented in this paper. Figure 2 shows the yearly variation of incident solar radiation, based on data corrected for ice cover and snow pack.[3] The yearly pattern for water temperature (Figure 3) was derived from data averaged over the water column.[3] The inputs of available phosphate and particulate and dissolved organic matter from streams and precipitation are shown in Figure 4.[3,4] This version of the model is also driven by the nitrate-N and ammonia-N concentrations in the water column as shown in Figure 5.[3] An important food source for the nonpiscivorous fish (perch, cisco, and bluegills) is bottom-dwelling insects; the insect submodel in CLEAN is not used in this pelagic version; rather, insect biomass is used as a driving variable (Figure 6).[5]

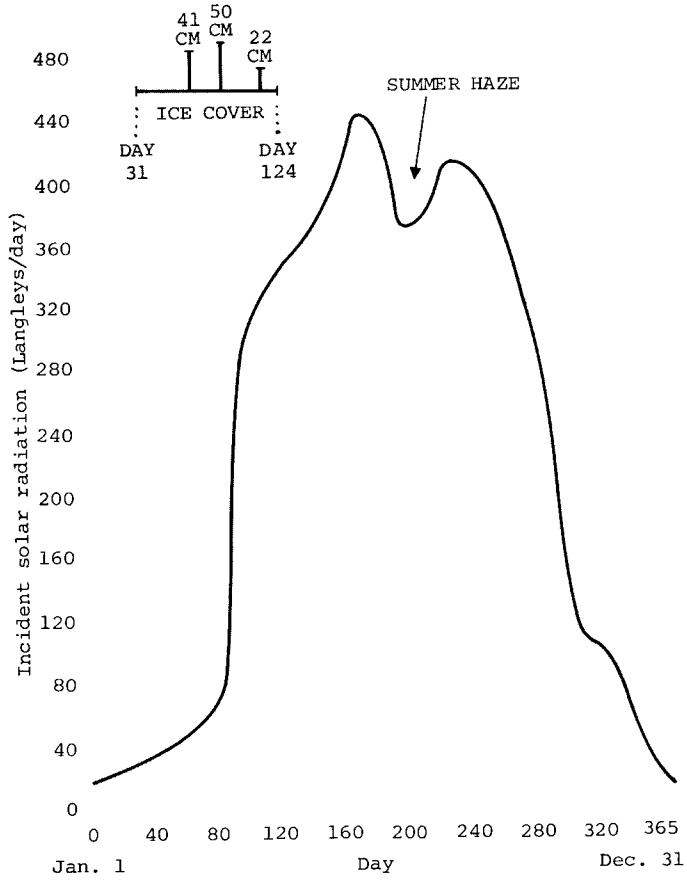

Figure 2 - Incident solar radiation, corrected for ice and snow pack

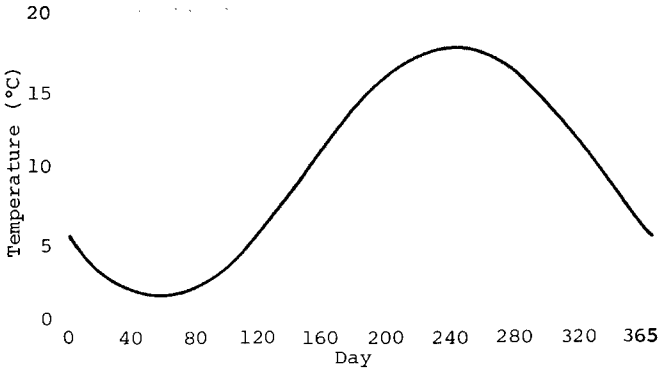

Figure 3 - Mean water-column temperature

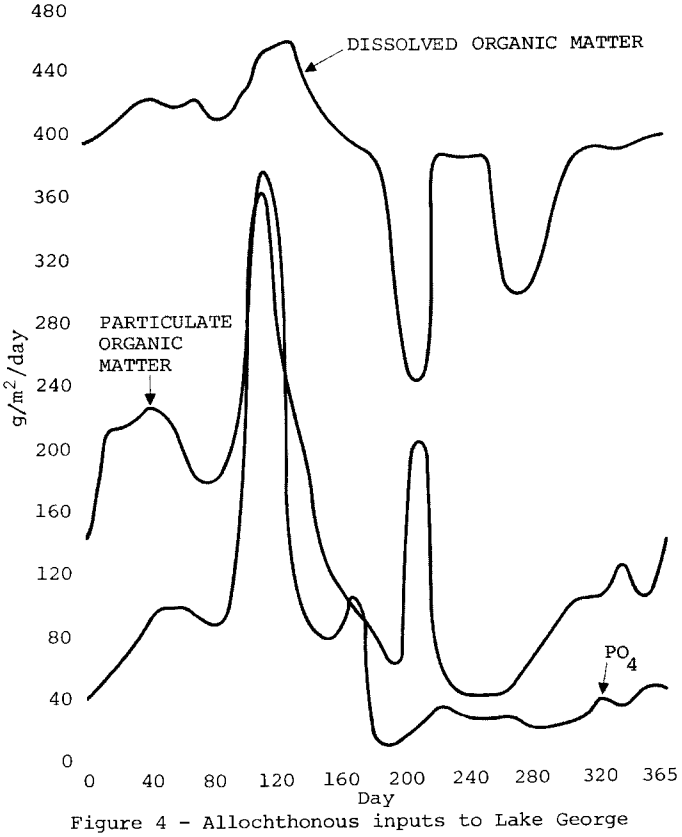

Figure 4 - Allochthonous inputs to Lake George

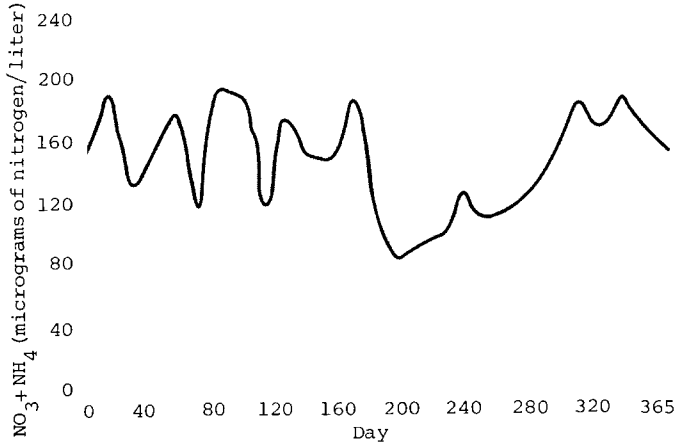

Figure 5 - Nitrate-N and ammonia-N concentration in Lake George

Table 2
Parameters and site constants

Name of variable in program	Name of variable in differential equation[1]	Units
ALPHA1	b	g/g/day
ALPHA2	a	g/g/day
BMIN	B_{min}	g/m^2
CMAX	C_{max}	g/g/day
CROWD	d	unitless
CROWDR	c	unitless
DEPTH	z	m
DOMMIN	DOM_{min}	g/m^2
E	f	unitless
EPS	e	1/m
HMAX	H_{max}	g/g/day
ISAT	I_s	ln/day
KBEH	$a_{j,n}$	unitless
KCAP	K_j	g/m^2
KDIF	K_{dif}	g/g/day
KDMORT	$K_{d,m}$	unitless
KDOM	K_{DOM}	g/m^2
KEXCR	U	1/day
KFISH	Z_f	1/day
KGON	$Z_g \kappa_g$	g/g/day
KMORT	Z_m	g/g/day
KN	N	g/m^3
KPMORT	$K_{p,m}$	unitless
KPOM	K_{pom}	g/m^2
KPOP	$b_{j,n}$	unitless
KO2	K_{r,O_2}	unitless
KP04	N	g/m^3
KRESP	K	unitless
KSED	K_{sed}	m/°C
KSV	K_{sv}	
KTEMP	*	°C^{-1}
KU	U_j	unitless
OFMAX	*	°C
O2MIN	$O_{2,min}$	g/m^2
PHOPT	pH_{opt}	pH units
PHYTEX	K_2	m^2/g
PMAX	P_{max}	g/g/m^2
PSI	ψ	g/g/day
Q	Q	g/m^2
Q10	S_Q	e°C^{-1}
R	r	unitless
RMAX	R_{max}	g/g/day
SIGMA	σ	pH units
TCRIT	*	°C
TMAX	T_{max}	°C
TOPT	T_{opt}	°C
TREF	*	°C
TSPAWN	$C_{f,g}$	°C
TSTOP	$C_{f,g}$	°C
URES	K_{resp}	unitless
VMAX	V_{max}	g/g/day
W	w	unitless

* Parameters used for acclimation to temperature, not used in Reference 1.

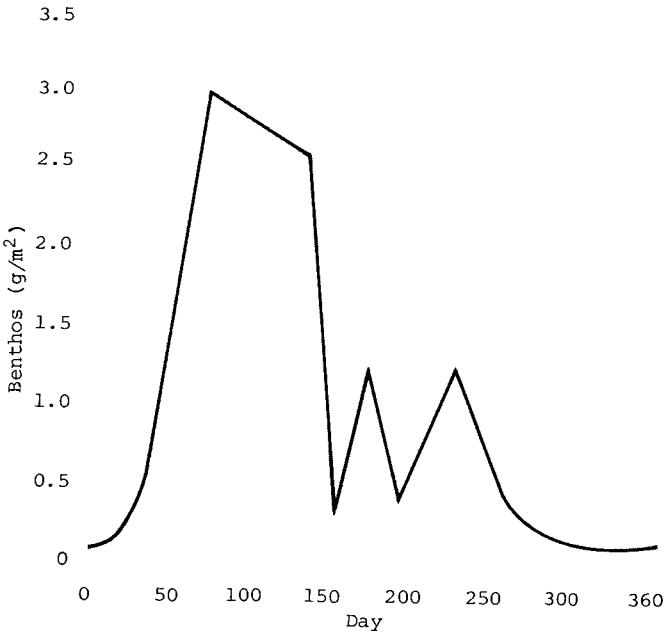

Figure 6 - Benthic insect biomass in Lake George

Table 3
Subscript definitions for parameters

Ecosystem Compartments

1. Nannophytoplankton
2. Net phytoplankton
3. Cladocerans
4. Copepods
5. Omnivorous zooplankton
6. Nonpiscivorous fish
7. Benthic insects
8. Piscivorous fish
9. Particulate organic matter
10. Dissolved organic matter
11. Decomposers
12. Phosphate

Process

1. Primary production, consumption, decomposer uptake
2. Decomposer hydrolysis
3. Respiration
4. Mortality
5. Gamete loss, decomposer excretion
6. Gamete loss
7. Fishing stress

```
 ♦♦♦♦♦  PELAGIC MODEL (CLEANX)  ♦♦♦♦♦
DATE: 030674 (MMDDYY)  TIME: 000609 (HHMMSS)

FWI TIME/SHARE MODELS      (SUNYA)

LAST UPDATE 3/4/74

FOR PERTURB. DO A ♦MSG.

READY
♦MSG
  NEW MSGS

 3/4/74    THE FOLLOWING PARAMS ALLOW CHANGES IN THE
             DRIVING FUNCTIONS:
                   KPOP(7,1)      L. GEORGE PO4IN
                   KPOP(7,2)      L. WINGRA PO4IN
                   KPOP(7,3)      L. GEORGE TEMP.
                   KPOP(7,4)      L. WINGRA TEMP.
           FORM:
                   PO4IN=KPOP(    )♦(EXISTING FUNCTION)
                   TEMP.=KPOP(    )+(EXISTING FUNCTION)

 2/21/74    MVPLOT CHANGE: THE FORMAT FOR THE X-AXIS IS
              IS NOW DYNAMICALLY SELECTED TO AVOID THE
              THE ♦♦♦♦♦ PROBLEM FOR FIVE YEAR SIMULATIONS.
              SOURCE IS NAMED 'MVPLOTX'. OLD SOURCE IS
              STILL 'MVPLOT',   JSF
 2/20/74    THERE ARE NEW PARAM VALUES IN THE PELAGIC MODEL...
              A COPY OF YOUR VALUES IS ON MY DESK.

 1/ 9/74    KUTTA NOW DEBUGGED...JAY

 1/ 9/74    DEFAULT FOR LAKE CODE IS NOW LAKE GEORGE.

12/26/73    THE ♦PRP COMMAND NOW TAKES UP TO 6 OPTIONS:
              FOR EXAMPLE  ♦PRP,1A45
              ♦PRP,I GIVES INITIAL CONDITIONS
              ♦PRP GIVES ALL SECTIONS (EXCEPT INITIAL CONDITIONS)

12/26/73    THE ♦LAK COMMAND NOW TAKES AN OPTION:
              FOR EXAMPLE ♦LAK,G IS LAKE GEORGE.

12/26/73    A NEW VERSION OF KUTTA IS UP UTILIZING
              RELATIVE LOCAL ERROR. ACCURC=.01 NOW
              REPRESENTS A 1% LOCAL ERROR. CHECK RESULTS
              CAREFULLY. IT'S NOT DEBUGGED.

12/13/73    USE ADD SOURCE.DIAG AFTER A 'FOR' TO SEE DIAGNOSTICS.

12/13/73    BENFSH, CLEANX AND MACRO ALL UP.

12/13/73    CLEANX NOW HAS ALL COMPARTMENTS DYNAMIC FOR PELAGIC
                  MODEL EXCEPT NO3-NH4.

READY
```

Figure 7 - Model output — broadcast and detailed messages

```
♦KPOP(7,1)=.5
 READY
TLAST=365
 READY
♦INT
 DATE: 030674 (MMDDYY)  TIME: 001126 (HHMMSS) LAKE: GEO
-------------------------------------------------------------------------------
 TIME   NAN    NET   CLAD   COPE OMNIZ NON-P PISC   PO4    POM    DOM    DEC
-------------------------------------------------------------------------------
    1   .64    .30    .12    .30   .13   .30   .10  .129   1.50 100.00   .020
   15   .64    .40    .12    .30   .17   .25   .10  .130    .89 102.78   .031
   29   .65    .54    .11    .30   .16   .21   .09  .131    .63 106.16   .056
   43   .69    .73    .11    .29   .15   .18   .09  .133    .54 109.90   .119
   57   .73   1.01    .11    .29   .14   .16   .09  .135    .47 113.17   .305
   71   .79   1.40    .11    .30   .14   .14   .08  .141    .35 114.76   .913
   85   .90   2.09    .12    .32   .13   .12   .08  .155    .25 110.67  2.648
   99  1.23   3.74    .14    .39   .14   .10   .08  .171    .33  98.37  4.293
  113  1.84   6.88    .20    .55   .16   .09   .07  .162    .77  90.59  2.658
  127  2.67  12.19    .36    .94   .18   .08   .07  .121   1.55  91.82  1.211
  141  3.08  16.16    .87   2.06   .27   .07   .06  .057   3.54  96.29   .818
  155  1.30   9.21   2.17   4.05   .71   .08   .06  .024   6.38 100.70   .864
  169   .68   2.05   2.48   1.99  2.45   .14   .05  .026   5.66 103.03   .955
  183  1.01   1.01    .88    .54  3.54   .26   .05  .031   2.85 101.40  1.045
  197  1.43    .79    .57    .54  3.27   .52   .05  .026   1.92  97.88   .789
  211  1.61    .62    .56    .55  2.50   .90   .05  .016   1.97  95.27   .593
  225  1.26    .47    .56    .56  1.63  1.19   .06  .008   1.79  94.03   .506
  239   .89    .34    .53    .54  1.02  1.19   .08  .005   1.29  93.44   .443
  253   .71    .23    .50    .52   .71   .98   .10  .004    .88  93.03   .352
  267   .64    .16    .47    .50   .56   .72   .12  .004    .62  92.60   .268
  281   .60    .11    .42    .47   .48   .50   .13  .004    .48  92.17   .188
  295   .57    .08    .38    .43   .42   .35   .13  .003    .40  92.31   .130
  309   .56    .06    .34    .40   .37   .26   .12  .004    .34  93.07   .098
-------------------------------MAX TIME. STEP= 14.0000 MAX ERR=     .02%
  323   .56    .04    .31    .37   .33   .19   .11  .005    .30  94.39   .087
  337   .57    .03    .29    .35   .29   .15   .11  .006    .27  95.94   .092
  351   .57    .03    .27    .33   .27   .12   .10  .007    .24  97.57   .112
  365   .56    .03    .26    .31   .25   .10   .09  .009    .21  99.37   .150
-------------------------------------------------------------------------------
READY
```

Figure 9 - Model output — free-form editing and integration (time is in days, biomass is in grams per m^2 column of water, and available phosphate concentration is in grams per m^3)

```
♦PRP
 DEPTH= 20.0 EPS=  .2 PHYTEX=  .1

          ♦SPECIES♦                          ♦SPECIES♦
♦PARAM♦   (1)    (2)     ♦PARAM♦    (3)  (4)  (5)  (6)  (7)  (8)
 PMAX=    2.20 2.00       CMAX=    1.00 1.30 1.60 1.50  .00 1.00
 ALPHA1= .0500  .0500     Q=         .2   .2   .2   .5   .0   .5
 ALPHA2= .0010  .0010     R=         .0   .0   .0   .0   .0   .0
 KN=     10.00  50.00     CROWDP=    .10  .10  .10  .10  .00  .10
 KPO4=     .01    .15     KEXCR=     .05  .01  .01  .01  .00  .01
 ISAT=  550.00 350.00     KMORT=     .001 .001 .002 .005 .000 .001
 KRESP=    .01   .01      PMAX=      .01  .01  .01  .01  .00  .01
 KPMORT=   .70   .70      KCAP=    50.0 50.0 20.0  5.0   .0  5.0
 KDMORT=   .30   .30      CROWD=     .010 .010 .010 .001 .000 .001
                          TCRIT=   40.0 40.0 40.0 40.0   .0 40.0
                          KPMORT=    .50  .50  .50  .40  .00  .40
                          KDMORT=    .50  .50  .50  .40  .00  .40

                      (SPECIES,PROCESS)
♦PARAM♦ 1,1 2,1 3,1 4,1 5,1 6,1 7,1 8,1 1,3 2,3 3,3 4,3 5,3 6,3 7,3 8,3
KTEMP=   0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.
OFMAX=   0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.
TREF=    0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.
TOPT=   28. 28. 22. 22. 22. 22. 20. 20. 20. 28. 22. 22. 22. 22. 20. 20.
TMAX=   35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35.
Q10=   2.5 2.0 2.2 2.2 2.2 2.2 2.2 2.2 2.5 2.0 2.2 2.2 2.2 2.2 2.2 2.2

TSPAWN= 18.0  18.0    TSTOP= 21.0  21.0
 KGON= .001  .010    KFISH= .000  .100

W(I,J)          (J)                        (J)          (I,J)
       (3) (4) (5) (6) (7)        (5) (6) (7)    (6,8)  (7,6)
   (1) .33 .45 .05 .00 .00   (3) .20 .10 .00       .90 .45
(I)(2) .33 .10 .01 .00 .00   (4) .55 .15 .00
   (9) .16 .22 .05 .00 .00   (5) .00 .30 .00
  (11) .17 .23 .14 .00 .00

E(I,J)          (J)                        (J)          (I,J)
       (3) (4) (5) (6) (7)        (5) (6) (7)    (6,8)  (7,6)
   (1) .65 .65 .65 .00 .00   (3) .70 .40 .00       .70 .30
(I)(2) .65 .65 .65 .00 .00   (4) .70 .40 .00
   (9) .80 .80 .80 .00 .00   (5) .00 .40 .00
  (11) .80 .80 .80 .00 .00

BMIN(I,J)              (J)                        (J)          (I,J)
       (3)   (4)   (5)   (6)   (7)        (5)   (6)   (7)   (6,8) (7,6)
   (1).5000 .5000 .5000 .5000 .5000   (3).5000 .5000 .5000  .0010 .5000
(I)(2).5000 .5000 .5000 .5000 .5000   (4).5000 .5000 .5000
   (9).5000 .5000 .5000 .5000 .5000   (5).5000 .5000 .5000
  (11).5000 .5000 .5000 .5000 .5000

KPOP(J,PROCESS)        (PROCESS)
       (1)  (2)  (3)  (4)  (5)  (6)  (7)
   (3) .10  .10  .10  .10  .10  .10  .10
   (4) .10  .10  .10  .10  .10  .10  .10
(J)(5) .10  .10  .10  .10  .10  .10  .10
   (6) .10  .10  .10  .10 -.10  .10  .10
   (7)1.00 1.00  .00  .00  .10  .10  .10   --- PERTURBATION PARAMS
   (8) .10  .10  .10  .10 -.10  .10  .10

KBEH(J,PROCESS)        (PROCESS)
       (1)  (2)  (3)  (4)  (5)
   (3)1.00 1.00 1.00 1.00 1.00
   (4)1.00 1.00 1.00 1.00 1.00
(J)(5)1.00 1.00 1.00 1.00 1.00
   (6)1.00 1.00 1.00 1.00 1.00
   (7)1.00 1.00 1.00 1.00 1.00
   (8)1.00 1.00 1.00 1.00 1.00


  ♦♦DECOMPOSER PARAMS♦♦

       (1) (2) (3) (4) (5)
 TOPT= 15. 14. 15. 21. 17.
 TMAX= 35. 35. 35. 35. 35.
  Q10= 2.2 2.2 2.2 2.2 2.2
KTEMP=  0.  0.  0.  0.  0.
OFMAX=  0.  0.  0.  0.  0.
 TREF=  0.  0.  0.  0.  0.
  KO2=  0.  0.  0.  0.  0.

        (SPECIES 11)
VMAX=  5.0000  KMORT=   .0100  KSED=   .8000
KDOM=300.0000  PHOPT=   .0000  KPOM= 50.0000
RMAX=   .4500  SIGMA=   .0000  KDMORT=   .5000
HMAX=  4.0000  KPMORT=  .5000  KSV=   1.0000
PSI=     .0500 DOMMIN= 60.0000

KDIF(10)=   .0000  KSED(9)=   .8000  PSI(9)=   .0500
KU(1)=      .0700    KU(2)=     .0050    KU(3)=     .0050
                   O2MIN=   .0000
 READY
♦PRI
 BIC=   .64    .30    .12    .30    .18    .30  10.00    .10   1.50 100.00
      .02    .13
 TFIRST=  1.00  TLAST=365.00  STEP=14.000  ACCURC=  .500-002  IMAX= 9
 READY
```

Figure 8 - Model output — parameter and initial-condition list (as given in Table 2)

PROGRAM OUTPUT

Upon execution, the model prints all broadcast messages and passes control to the user. The first command used, *MSG, is to print out all messages inserted by previous users (Figure 7). This allows colleagues to keep one another informed of recent changes. The parameters and initial conditions are printed using *PRP and *PRI (Figure 8). (Parameter names and subscript definitions are given in Tables 2 and 3.) As shown in Figure 9, a perturbation parameter (in this example, phosphate loading for Lake

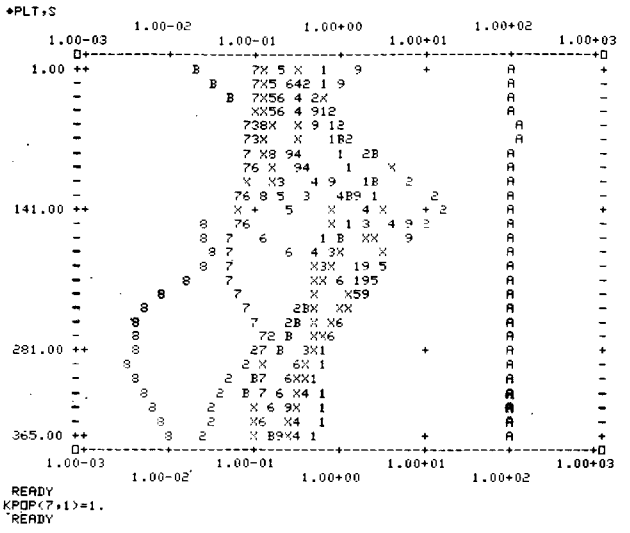

Figure 10 - Model output — plotting. Vertical axis represents time in days (beginning with January 1 and ending with December 31 in this example); horizontal axis represents biomass, expressed as grams per m^2 column of water. 1 = nannophytoplankton, 2 = net phytoplankton, 3 = herbivorous cladocerans, 4 = herbivorous copepods, 5 = omnivorous zooplankton, 6 = nonpiscivorous fish, 7 = piscivorous fish, 8 = available phosphate (in grams per m^3), 9 = particulate organic matter, A = dissolved organic matter, B = decomposers.

George) is changed using the free-format editing feature, and an initial condition (TLAST) is changed. Also shown in Figure 9 are the tabulated results of an integration following the command *INT; the results are given for the user-specified interval (STEP) of fourteen days. The state variables, corresponding to those given by Park and others,[1] are nannophytoplankton, net phytoplankton, herbivorous cladocerans and copepods, omnivorous zooplankton, nonpiscivorous fish (including perch, cisco, and bluegills), piscivorous fish (including lake trout and bass), available phosphate, particulate organic matter, dissolved organic matter, and decomposers. Because of the time required for the simulation, the user is given the option to abort the integration (using the command KILL) after twenty-five seconds of central processing unit (CPU) usage have elapsed (at "MAX. TIME"). In this example a 'carriage return' is used to continue the integration. Upon completion of the integration the plotting routine is called with the scaled plot option (*PLT,S) as shown in Figure 10. The compartments, numbered in the order in which they are displayed in the tabulation, are then plotted versus day of the year. After the plot, the perturbation parameter is reset.

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