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AQUAMOD: AN INTRODUCTORY PURPOSE SIMULATION MODEL OF PLANKTON DYNAMICS

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Abstract: An easy to use numerical simulation model of plankton dynamics in aquatic environments is described. The model simulates growth of two phytoplankton and two zooplankton groups on the basis of physical and trophic data from field measurements collected in the investigated environment. AQUAMOD may specially be of help to users who are being introduced to ecological modelling, since the interactions between variables are easy to understand.

Introduction

The low trophic levels of aquatic environments have been widely analyzed and modelled (Scavia 1980, Jorgensen et al., 1982, Fontaine et al., 1988), and many computer programs for the dynamic simulation of biotic entities have been developed. However, almost all programs are written in FORTRAN.

The advantages of writing a simulation model for phyto and zooplankton growth in BASIC is in the interactive facilities this programming language offers, an advantage for training purposes.

The numerical simulation model AQUAMOD has been inspired by others like those of Di Toro, O'Connor and Thomann (1971), Kremer and Nixon (1978), and specially by that in UNESCO (1983), which deal with plankton dynamics related to physical and trophic features of the investigated environments.

In the present paper a brief description of the model itself and of its use, with an example, is given. The purpose is to outline its distinctive features and capabilities.

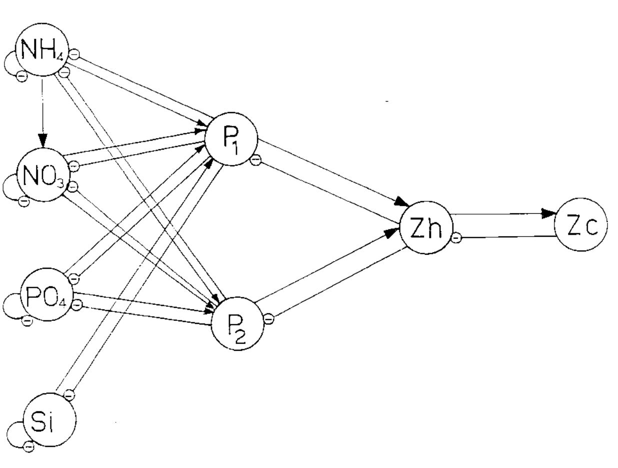


Fig. 1. Variables and interactions in the model.

The model

A qualitative loop model (Puccia and Levins, 1985) is represented in Fig. 1 to symbolize in a graph the variables and their interactions, as they are also involved in the simulations.

The graph explains the predation interaction of phytoplankton on nutrients, that of herbivorous zooplankton on phyto plankton and that of the carnivorous on the herbivorous. The result is a positive effect of the nutrients on phytoplankton growth rates (symbolized with the arrow) and a negative effect of phytoplank-

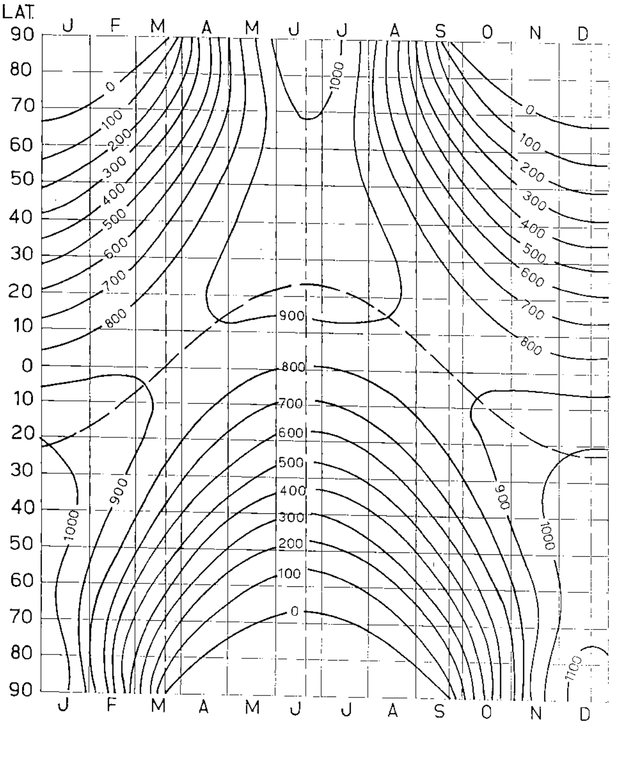


Fig. 2. Clear sky solar radiation at all latitudes. Redrawn after Smithsonian Meteorological Tables (1958).

ton on nutrient concentrations (symbolized with the little circle including a dash). There is a positive effect of phytoplankton on herbivorous zooplankton growth rates and a negative effect of zoo on phytoplankton growth rate: the last interaction concerns the carnivorous zooplankton which shows its negative effect on hervivorous growth rate and the positive of herbivorous on carnivorous, all including the same kind of symbolic notations. Two phytoplankton groups consume nutrients, one herbivorous zooplankton group consume phytoplankton and one carnivorous zooplankton group consume the herbivorous. Nutrients are self-depleted as they are not self-reproducing variables (Puccia and Levins, 1985).

The trophic dynamic qualitative model just described is relatively simple. In the numerical simulation water temperature and light are included as limiting factors for plankton growth. All species suffer a certain yield loss due to respiration and natural mortality. The model works on one single station point per time, this limitation reduces the need for large data inputs.

Variables include nitrogen flux, expressed in micrograms of N/lt, phosphorus and silicon fluxes which are treated in terms of relevant parameters of conversion (UNESCO, 1983).

Since the model lacks hydrodynamical formulations, the milieu type it works on most satisfactorily is that which does not present unexpected changes in equilibriums. The differential equations describing the dynamics of biological simulated entities are formuled in Table 1. In Table 2 the processes involved in computations are given.

AQUAMOD and the three associated programs (AQUATEMP, AQUAINPUT, AQUAPLOT) are written in GW-BASIC under MS-DOS operating system and should run easly on any IBM-compatible microcomputer.

Physical and chemical properties of the environment

Water temperature is simulated in the well known cosine algorithm (Kremer and Nixon, 1978) on the basis of field measurements. An ad-hoc program has been written (AQUATEMP) for those not familiar with simulation. The program performs calculations of parameters and a graphs the results.

The parameters to simulate clear sky solar radiation

VARIABLES AND PARAMETERS	PROCESSES	EQUATIONS	REFERENCE
TEMP	Water temperature	TM - TSC * COS(6.28*(DAY+H)/365)	Kremer & Nixon (1978)
TM	Mean of highest and lowest TEMP value		
TSC	Maximum departure from mean value		
DAY	Day of the year in computation		
H	phase constant		
PHYTOPLANKTON (P)			
GROWTH	Phytoplankton specific growth rate	GMAX * LUX * NUTR * TLIM	
GMAX	Phytoplankton maximum growth rate	0.59 EXP^0.0633*TEMP	Eppley (1972)
LUX	Light limiting factor	LF * FOTOP	
LF	3 options	LF1(t)=[(Ia/Io)*EXP(1-Ia/Io)-r]*(1-r)	Steele (1962)
r	Steele's modified factor	0.027	idem
		LF2(t)=2.718[EXP[-(Ia/Io)EXP(-C*H]-EXP(-Ia/Io)]/(C*H)	Ditoro et al.(1971)
h	depth	C(t)=0.04 + 0.054*CHLA^(0.667) + 0.0088*CHLA	Riley (1956)
C	extinction coefficient (2 options)	CHLA = 0.476 * P(t)	UNESCO (1983)
CHLA	Chlorophyll a	C(t)=0.16 + 0.039*P(t)^(0.667) + 0.0053*P(t)	Walsh (1975)
		LF3(t)=[1-EXP(-a*Ia/p)]*exp(-b*Ia/p)	Gallegos et al. (1983)
a	dimensionless factor	0.05	Lagonegro & Hull(1987)
p	idem	0.00147	Lagonegro & Hull(1987)
b	idem	0.85	Lagonegro & Hull(1987)
Io	Optimal acclimation light intensity	=0.7*Ia(DAY+3) + 0.2*Ia(DAY+2) + 0.1Ia(DAY+1)	Kremer, Nixon (1978)
Ia	Average light intensity	Is(t)*[1-EXP(-C*H)]/C*H	
Is	Corrected total insolation	RADMAX * REF *LW	UNESCO (1983)
RADMAX	Total insolation	600 - 340 * COS(6.28*(DAY+10)/365)	
REF	Reflected fraction factor	0.85	UNESCO (1983)
LW	Long wave factor	0.45	idem
FOTOP	Photoperiod	0.5 - 0.125 *COS(6.28*(DAY+10)/365)	idem
NUTR	Nutrients limiting factor	NUTLIM / (KS + NUTLIM)	Dugdale (1967)
NULIM	Limiting nutrient concentration		Liebig
KS	Half saturation costant		Michaelis-Menten
TLIM	Temperature limiting factor	EXP^(K1*(TEMP-TMAX) FOR TEMP<=TMAX	UNESCO (1983)
TMAX	Temperature of maximum growth		
	Temperature limiting factor	EXP^[K1((TEMP-TMAX)/DT)^N] FOR TEMP>TMAX	Lagonegro & Hull(1987)
K1	Growth constant		Eppley (1972)
RESPP	Phytoplankton respiration rate		UNESCO (1983)
DEATHP	Phytopl. natural mortality rate		idem
ZOOPLANKTON (Z)			
Herbivorous			
GRAZ	Specific feeding rate	FMAX * FOODLIM * THLIM	UNESCO (1983)
FMAX	Maximum feeding rate		
FOODLIM	Vegetal biomass limitation	PTOT / (KF + PTOT)	idem
PTOT	Total phytoplankton biomass	P1 + P2	
KF	Phyto biomass conc.at which feeding is half of max		
THLIM	Temperature limitation factor	TEMP / TOPTH EXP(1-TEMP/TOPTH)	idem
TOPTH	Optimal growth temperature	RH * EXP(KRH * TEMP)	idem
RESPZH	Herbivorous respiration rate		
RH	Respiration rate at 0xC		
KRH	Slope of the curve describing respiration as a function of water temperature		
DEATZH	Herbivorous mortality rate		
Carnivorous			
FOOD	Specific feeding rate	HMAX * HLIM * TCLIM	UNESCO (1983)
HMAX	Maximum feeding rate		
HLIM	Herbivorous biomass limitation	ZH / (KH + ZH)	idem
KH	Herbivorous biomass concentration at which feeding is half of max		
TCLIM	Temperature limitation factor	TEMP/TOPTC * EXP(1-TEMP/TOPTC)	idem
RESPZC	Carnivorous respiration rate	RC * EXP (KRC * TEMP)	idem
RC	Respiratory rate at 0xC		
KRC	Slope of the curve describing respiration as a function of water temperature		
DEATHZC	Carnivorous natural mortality rate		

at the top of the atmosphere has been determined for environmental areas located between 40 and 45 northern latitudes. For different latitudes it is possible to deduce values using Fig. 2 that has been redrawn from the Smithsonian Meteorological Tables (1958). Corrections are also included for photoperiod (Kremer and Nixon 1978), reflected fraction and long wave fraction (UNESCO, 1983). Ligth extinction coefficient, on whic phytoplankton biomass depends is computed by Riley's (1956) or Walsh's (1975) formulas, on request by the user.

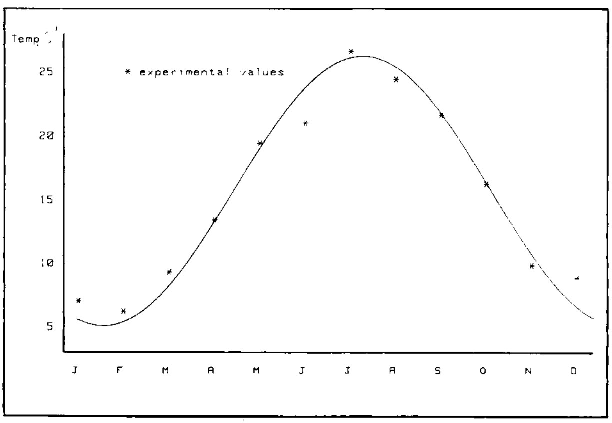
The nutrients included in the model are ammonia and nitrate (plus nitrite) as nitrogen sources, reactive phosphorus and silicon. Nutrients are considered to be discrete inputs in to the system, hence the model interpolates concentrations and computes phytoplankton uptakes. Ammonia is preferred by phytoplankton to nitrate (Dugdale, 1967) when available in concentrations higher than a determined quantity specified as in put in the simulation program.

Phytoplankton

The model supports computations for up to two groups (or species) which require nutrients, light and favourable temperatures. Respiration and natural mortality, given as input by the user, are considered to be constant but can be changed if experimental measurements are available. Light limitation to phytoplankton growth is computed on option by the user; the choice is on three different equations due to: Steele (1962), Di Toro, O'Connor and Thomann (1971) and Gallegos, Platt, Harrison and Irwin (1983).

Zooplankton

Two zooplancton groups are included: the first is herbivorous grazing on the phytoplankton, the second being carnivorous feed on the herbivorous. The herbivorous group is considered to graze independently on the relative presence of two phytoplankton species. Mortality is kept constant, but can be changed if experimental data are available. Respiration is temperature dependent.



Output from AQUATEMP.

The computer programs

AQUAMOD contains four programs. AQUATEMP which performs calculations to determine parameters for temperature simulation on the basis of field measurements. The program returns the results of computations and presents them in graphical form in terms of the fit of experimental data on the computed curve. It also returns a statistical parameter (chi square) to measure the goodness of fit. AQUAINPUT is used to create the data base file or, to up-date an existing one, of constants and experimental data inputs for AQUAMOD. AQUAINPUT operates with large interactive capabilities to facilitate use. AQUAMOD computes all simulations, prints out results and stores a second data file for graphics. AQUAPLOT returns results of AQUAMOD's simulations in terms of graphics: growth curves for the biotic entities and interpoled curves for the nutrients.

The simulations, conducted on a single station point at one depth only for one year, the longest time span the model can support takes over 2 hours of machine time in the interpreted version of the BASIC language and about 20 minutes in the compiled BASIC. More details about programs and mathematical formulations can be found in a technical report by Lagonegro and Hull (1987) and in Hull, Lagonegro and Puccia (1988).

Sample run

The data for the sample run were collected over one year in a coastal lagoon used for fishery purposes in Sardinia.

The experimental measurements of temperature are given in Table 3. The data are relative to the observation point located at the center of the lagoon at the depth of one meter; this is the only depth considered in the sample. The model can support more depths.

Table 3. Temperature data.

Day	13	58	86	115	163	178	203	224	253	276	336	363
Temp (xC)	10.9	12.6	12.3	14.4	26.3	26.7	27.9	22.5	23.9	22.7	12.7	9.9

The temperature data in Table 3 were submitted to AQUATEMP with which the simulation of temperature was performed and parameters for AQUAMOD selected; Fig. 3 shows the result.

Nutrients were analyzed monthly; phyto and zooplankton biomass were measured seasonally. Bioassayes were also conducted to estimate half-saturation constants of nutrients (Eppley et al., 1969), and uptake ra-

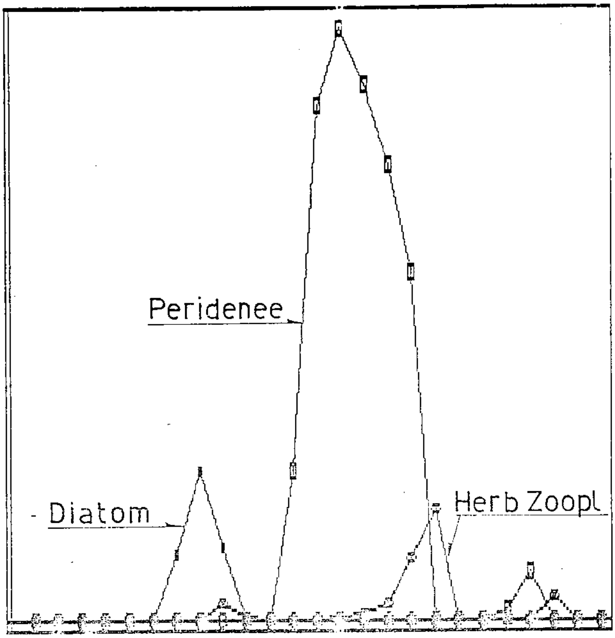


Fig. 4. Model calibration results for different types of planktons.

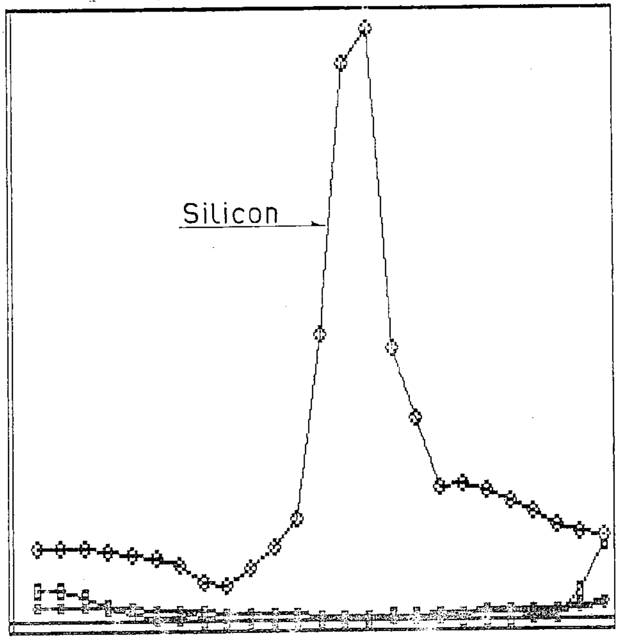


Fig. 6. Model calibration results for silicon.

tios (UNESCO, 1983). The phytoplankton group was found to be of Diatoms mainly *Scelethonema costatum* and *Rhizosolenia sp.* which have a Spring bloom. The second group contained Peridenees mainly *Prorocentrum micans* and *Gymnodimium sp.* which has a late Summer bloom. The herbivorous zooplankton groups, was represented mainly by Copepods (*Acartia clausi*) and larval forms of the same group.

Carnivorous zooplanktons species or groups were not found in significant quantities. All parameters for this variable, were zeroed in the input data file.

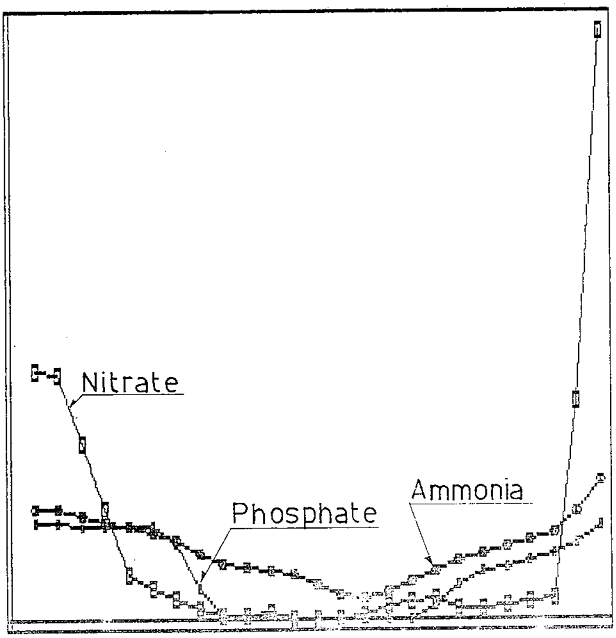


Fig. 5. Model calibration results for different nutrients.

The complete set of the constants and parameters used in the simulations are given in Table 4. These are input in AQUAINPUT and printed out in AQUAMOD's first processing step. The input file TEST was submitted to AQUAMOD program for computations. Table 4 has the first simulation step as from AQUAMOD's print out. Span time is 360 hours = 15 days.

Discussion of results and conclusions

The results produced by the model calibration are shown in Figs. 4, 5 and 6. The first reports growth curves of the biotic entities, and the second and the third give the nutrient interpolations. The peaks of computed plankton growth curves agree with those doserved during the experimental work. Only the Diatoms peak lags compared to field data. Absolute values of measured and simulated eptities have about 10-15% disagreement but, if we consider that the model is substantially qualitative, the mentioned differences appear to be acceptable. AQUAMOD is capable to estimate satisfactorily ecological properties trend, and relative importance of the components affecting the system. The model works on a one single station point at a time, hence the required field data and parameters necessary to run it are not excessive.

We are of the opinion that models are conceptual tools with specific ranges of validity. As such, AQUAMOD should be applied for instructional purposes in ecological modelling of aquatic environments. To better define and/or estimate components and parameters, which are important for system evolution, seems also to be a suitable utilization of the model. Copies of the technical report of Lagonegro and Hull (1987) can be obteined from the authors. The computer programs, on 5.25 in diskettes, are in Hull, Lagonegro and Puccia (1988).

Table 4. Complete set of model constants and a first bit of output.

Program AQUAMOD-1987: 1 surface point from 1 to 1 depths
Step by step input for nutrients at every depth considered

Computation date: 10-21.1987 - hour: 11:38:50
Data file: test - computation time-step 1 hours
considered n. of planktonic species 2
Chosen light lim. factor is Steele
Chosen ext. coeff. formula Riley
File for plot is testplot
Min. light level for acclimation is 40
Nutrients data in input are true input
NH4 lowest limit before switching to NO3 14
Interpolated phase for temp. is = —32
Month. day of starting time for simulation 1 1
time interval for output in hours 360
computation time span. in days 365

respiration and mortality for phyto sp 1 .05 .1
Max, growth temp. for phyto sp. 1 14 growth const. = .05
Half saturat. const. of phyto sp 1 for N, P, Si 4 2 1.3

respiration and mortality for phyto sp 2 0.5 .1
Max, growth temp, for phyto sp 2 26 growth const. = .06
Half saturat. const. of phyto sp 2 for N, P, Si .1 .05 0

*** depht n. 1 is 1 meters
average tm (1) and fluctuation tsc (1) are 18.9 8.8
starting value for phyto sp 1 is 80
for phyto sp 2 is 25
for herb. zoopl. is 20
for carn. zoopl. is .0
Optimal I for phyto sp 1 at starting time is 40
Optimal I for phyto sp 2 at starting time is 40
Time 14 values for NH4, N03, P04, Si (mg—At/m3) 1134 2940 2883 13300
Time 59 values for NH4, N03, P04, Si (mg—At/m3) 1092 546 2418 11956
Time 87 values for NH4, N03, P04, Si (mg—At/m3) 1078 252 2201 10220
Time 116 values for NH4, N03, P04, Si (mg—At/m3) 42 42 1457 5208
Time 164 values for NH4, N03, P04, Si (mg—At/m3) 42 84 1240 15904
Time 179 values for NH4, N03, P04, Si (mg—At/m3) 42 196 961 47684
Time 204 values for NH4, N03, P04, Si (mg—At/m3) 14 196 496 128240
Time 225 values for NH4, N03, P04, Si (mg—At/m3) 98 238 775 48692
Time 254 values for NH4, N03, P04, Si (mg—At/m3) 154 252 1240 23772
Time 277 values for NH4, N03, P04, Si (mg—At/m3) 546 84 1643 24080
Time 337 values for NH4, N03, P04, Si (mg—At/m3) 784 252 2294 16128
Time 364 values for NH4, N03, P04, Si (mg—At/m3) 1162 8078 3844 14476

Herb, z, max, feeding rate, food half sat, const., mortality .45
8 .1
Carn, z, max, feeding rate, food half sat. const., mortality . 0
8 .10

phyto sp 1—NP factor 5
phyto sp 1—NSi factor 1
phyto sp 2—NP factor 5
phyto sp 2—NSi factor 0

....

day = 15 time = 24 depth (m) = 1 Temp (°C) 10.47375 (C (1/m) = 4.250899E—02
phyto type 1 growth = .0134176 /lim. nut, nitrogen/fr. = 1
phyto type 2 growth = 7.0077163—03 /lim. nut. nitrogen/fr. = 1
Residuals: NH4 = 1133.047 N03 = 2885.692 P04 = 2872.451 SI = 13269.51
Photoperiod = .3863864 Itop = 114.2518 Io = 109.4968 Iav = 111.8574
phytopl sp 1 = .01 sp 2 = .01 zoopl. herb. = 47.2334 carn. = .01
phytopl N+P+Si mass-sp 1. .014 sp 2. .01

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