Rep. Suwa Hydrobiol., *11* : 87-98 (1999)

A CIRCULATION DYNAMICS MODEL IN THE ECOSYSTEM FOR THE WEST LAKE, HANGZHOU

Pei Hongping, He Jingtu, Wang Weiwei, Zhou Hong, Wu Dexiu, Wang Lihong and Chen Junwei
(Hangzhou university)

Abstract:
This paper focuses the researches on an eutrophication model after drainage of wastewater and drawing water from the Qiantang River to West Lake. The model describes the circulation of nutritive matters (such as phosphorus, nitrogen, and carbon) in the ecosystem of the Lake. The model was established according to observed values of water quality and relevant parameters in 1995. The results of model calibration and verification show that the model can reasonably respond to the changes of forcing functions for drawing quantity and temperature of water. The model has been used to forecast the water quality in different drawing quantities. The predictions given by the model are also believed to be useful to comprehensively harness the West Lake.

Key words: Eutrophication model, Drawing water, West Lake.

Introduction

Lake eutrophication is a very complicated process. According to research results, there are many factors which interfere with lake eutrophication, such as phosphorus, nitrogen, carbon and so on. Eutrophication is a phenomenon whereby primary productivity is unusually enlarged. The nutritive matter, which dominates the primary productivity, is an important index of eutrophication and also is a primary control factor. In order to provide data material for harnessing the West Lake comprehensively, the model attempts to forecast the change of water quality and studies the benefit of drawing water by describing the dynamic change in phosphorus circulation after drawing water.

General description of West Lake

West Lake is located in the west of downtown Hangzhou, which is situated in southeast China. It's a relatively small shallow lake, with a water area of 5.66 km^2 and an average depth of 1.56m. According to available data, the average diversion is about 1.96×10^7 m^3/yr after drainage of wastewater, excluding the evaporation loss of 4.17×10^6 m^3 /yr. Before drawing water, the amount of sluicing is 1.54×10^7 m^3/yr. After the establishment of a drawing water project in 1986, the average amount of drawing water was 1.3×10^7 , while the amount of drawing water was 1.55×10^7 m^3 in 1995.

Structure of Model

The model focuses on the West Lake's ecosystem, taking into account phosphorus, nitrogen, carbon circulation and budget. Seven rooms including four trophic levels (phytoplankton, zooplankton, benthon and fish) and three nutritive salt pools (water body, detritus and sediment) were set-up. Each nutritive salt had a relatively independent circulation, forming an eutrophical cycling model of West Lake (see Figure 1). This model consisted of state variables, forcing functions, state equations, rate equations and parameters.

Twenty state variables are used. These were phytoplankton biomass (PHYT), phosphorus in phytoplankton (PC), nitrogen in phytoplankton (NC), carbon in phytoplankton (CC), zooplankton biomass (ZOO), proportion of nitrogen in zooplankton (FNZ), proportion of phosphorus in zooplankton (FPZ), benthon biomass (BBIO), proportion of nitrogen in benthon (FNB), proportion of phosphorus in benthon (FPB), fish biomass (FISH), proportion of nitrogen in fish (FNF), proportion of phosphorus in fish (FPF), soluble nitrogen (NS), soluble phosphorus (PS), nitrogen in detritus (ND), phosphorus in detritus (PD), phosphorus in interstitial water (PI), exchangeable phosphorus in sediment (PE) and nitrogen in sediment (NSED).

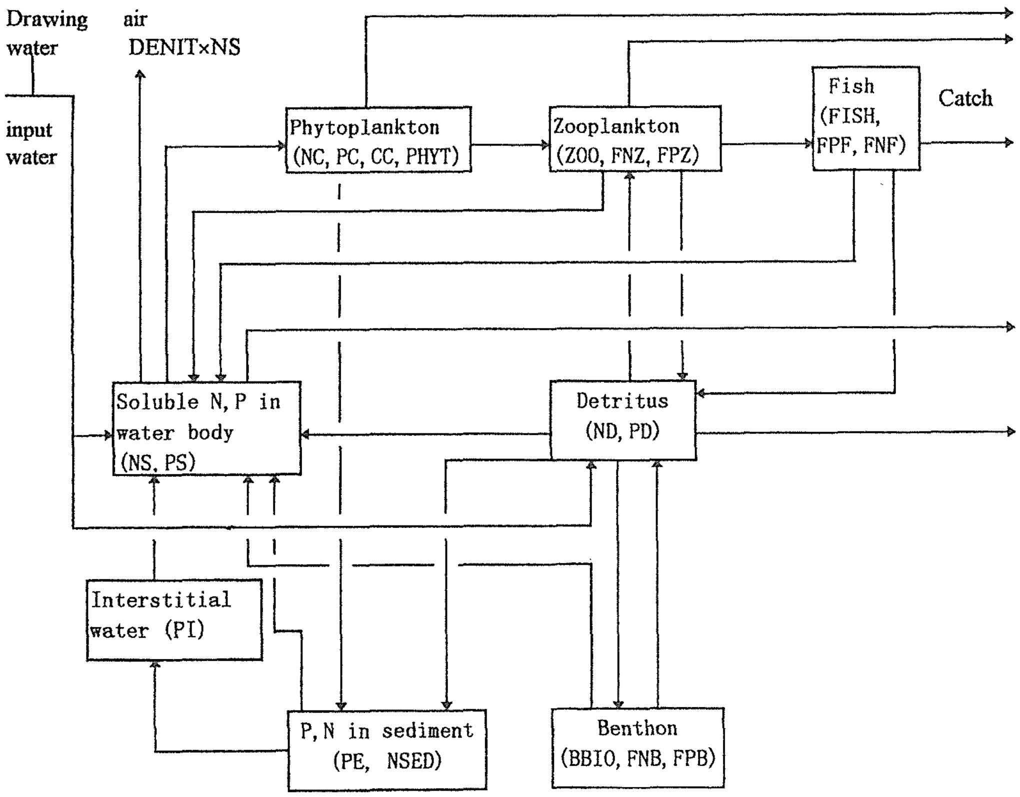


Figure 1. The nutrition matter circulation model of the ecosystem of the West Lake

State equations are equations, which describe physical, chemical and biological courses in phosphorus circulation. They consist of definite differential equations, which are set up according to the law of conservation of matter. Each equation describes the relationship between one state variable and other state variables, forcing functions or parameters. The equation groups are described as follows:

1. dPC/dt=UP*PHYT-(SA+GZ/Y1+(Q1+Q2)/V)*PC
2. dPD/dt=L1*GZ*PC+MZ*PZOO+L2*PRED*PFISH-(KDP+SD+(Q1+Q2)/V)*PD+(MB-MYB)*PB
3. dPS/dt=KDP*PD+RZ*PZOO+PRED*PFISH-UP*PHYT+QDIFF+QPSIN1-(Q1+Q2)/V*PS+AB*QDSORP
4. dPE/dt=F*SA*PC-QSED+SD*PD-(AE/AI)*KE*PE
5. dPI/dt=(AE/AI)*KE*PE-QDIFF/AE
6. dFPB/dt=MYB*(FPD-FPB)
7. dFPF/dt=PRED/Y2*(FPZ-FPF)
8. dFPZ/dt=MYZ*(FPA-FPZ)
9. dNC/dt=UN*PHYT-(SA+GZ/Y1+(Q1+Q2)/V)*NC
10. dND/dt=L1*GZ*NC+MZ*NZOO-(KDN+SD+(Q1+Q2)/V)*ND+(MB-MYB)*NB
11. dNS/dt=KDN*ND+RZ*NZOO+PRED*NFISH+NREL/AE+RB*NB-UN*PHYT
12. dNSED/dt=SA*NC+SD*ND-NREL/AE
13. dFNB/dt=MYB*(FND-FNB)
14. dFNF/dt=PRED/Y2*(FNZ-FNF)
15. dFNZ/DT=MYZ*(FNA-FNZ)
16. dCC/dt=(UC-RC)*PHYT-(SA+GZ/Y1+(Q1+Q2)/V)*CC
17. dPHYT/dt=(CDR-SA-GZ/Y1-(Q1+Q2)/V)*PHYT
18. dZOO/dt=(MYZ-RZ-MZ-(Q1+Q2)/V)*ZOO-PRED*FISH/Y2
19. dFISH/dt=(PRED-RF)*FISH
20. dBBIO/dt=(MYB-RB-MB)*BBIO

V, Q1, Q2 in the equation groups represent the lakes volume, amount of sluicing without drawing water and the amount of drawing water, respectively. LIP and LPG stand for the loads of orthophosphate and phosphorus in detritus in one unit volume without drawing water, respectively. DPI and dPD stand for the loads of orthophosphate and phosphorus in detritus in one unit volume with drawing water, respectively.

Rate equations give a quantitative description of the birth, growth, death and decomposition processes of aquatic organisms in a lake ecosystem. The current model uses 35 rate equations which are shown below.

UP=UPmax*(FPAmax-FPA)/(FPAmax-FPAmin)*PS/(PS+KP)

SA=SVS/D*FT2**0.5

GZ=MYZmax*FPH*FT1*ZOO/PHYT

FPH=max(0,(PHYT-0.5)/(PHYT+KA))

PZOO=FPZ*ZOO

PRED=PREDmax*FT1*FZ

PFISH=FPF*FISH

KDP=KDP10*FT3

SD=SVD/D*FT2**0.5

MYB=MYBmax*FT12

PB=FPB*BBIO

RZ=RZmax*FT1

QDIFF=FT4*(1.21*(PI-PS)-1.70)/(1000*D)

AB=DB/D*DMU

QDSORP=(0.60*LOG(PS)-2.27)/(1000*DB)

QSED=min(SA*PC,5.06*E-3)

AE=LUL*DMU/D

AI=LUL*(1-DMU)/D

KE=KE20*FT3

MYZ=MYZmax*FPH*FT1

UN=UNmax*(FNAmax-FNA)/(FNAmax-FNAmin)*NS/(NS+KN)

NZOO=FNZ*ZOO

KDN=KDN10*FT3

NFISH=FNF*FISH

NREL=FT5*(KREL*NSED+0.08)/(1000*D)

RB=RBmax*FT12

NB=FNB*BBIO

FNA=NC/PHYT

UC=UCmax*(FCAmax-FCA)/(FCAmax-FCAmin)*C/(KC+C)*FRAD

RC=RCmax*CC/CCmax*FT1

FRAD=LOG((RAD+KL)/(RAD*EXP(-OMEGA)+KL))/OMEGA

OMEGA=(ALPHA+BETA*PHYT)*D

CDR=CDRmax*FT1*(1-CCmin/CC)*(1-NCmin/NC)*(1-PCmin/PC)

RF=RFmax*FT10

FZ=max(0,(ZOO-KS)/(ZOO+KZ)

Forcing functions indicate the influence of rate variables or horizontal variables by each parameter

FT1=EXP(-2.3*ABS(T-16.5)/15)

FT2=THEAT**(T-20)

FT3=THEAT**(T-10)

FT4=(T+273)/280

FT5=EXP(0.151*T)

FT6=EXP(0.203*T)

FT10=EXP(-2.3*ABS(T-25)/15)

FT12=EXP(-2.3*ABS(T-22.5)/15)

Model parameters

The model used 51 parameters, some of which were obtained experimentally while were obtained experimentally while others were taken from the literature. These parameters are shown in Table.

Table 1. Model parameters

Symbol	Definition	Unit	Values	Values based upon
	Temperature coefficient for degradation of detritus	d	1.072	Constant
ALPHA	Extinction coefficient of water	/M	1.170	Calibration
BETA	Specific extinction coefficient of phytoplankton	M^2/G	0.180	Calibration
	Temperature coefficient for decomposition of PE	/D	1.030	Constant
C	Concentration of inorganic carbon	G/M^3	100	Calibration
CCmin	Minimum carbon content in phytoplankton	G/M^3	0.01	Calibration
CCmax	Maximum carbon content in phytoplankton	G/M^3	0.59	Calibration
CDRmax	Maximum growth rate of phytoplankton	/D	1.5	Calibration
D	Depth of the West Lake	M	1.56	Measurement
DB	Depth of biological active layer	M	0.002	Measurement
DENIT	Denitrification rate	/D	0.03	Calibration
DMU	Dry matter in sediment	d	0.1	Measurement
FCAmin	Minimum quantity of C in phytoplankton biomass	%	1.5	Calibration
FCAmax	Maximum quantity of C in phytoplankton biomass	%	9.4	Calibration
FNAmin	Minimum quantity of N in phytoplankton biomass	%	1.5	Calibration
FNAmax	Maximum quantity of N in phytoplankton biomass	%	0.6	Calibration
FPAmin	Minimum quantity of P in phytoplankton biomass	%	0.2	Calibration
FPAmax	Maximum quantity of P in phytoplankton biomass	%	1.4	Calibration
KA	Michaelis constant for zooplankton grazing phytoplankto	G/M^3	0.475	Calibration
KB	Michaelis constant for benthon feeding	G/M^3	0.076	Calibration
KC	Michaelis constant for carbon uptake	G/M^3	0.5	Calibration
KDN10	Decomposition rate of detritus nitrogen at 10□	/D	0.005	Calibration

KDP10	Decomposition rate of detritus phosphorus at 10□	/D	0.005	Calibration
KE20	Decomposition rate of PE at 20□	/D	0.002	Calibration
KL	Michaelis constant for light	G/M^3	400	Calibration
KN	Michaelis constant for nitrogen uptake	G/M^3	0.023	Calibration
KP	Michaelis constant for phosphorus uptake	G/M^3	0.023	Calibration
KREL	Rate constant for release of nitrogen	/D	0.004	Calibration
KS	Threshold zooplankton biomass	G/M^3	0.013	Measurement
KZ	Michaelis constant for fish feeding on zooplankton	G/M^3	0.350	Calibration
LUL	Unstable sediment layer	M	0.100	Measurement
MB	Mortality of benthon	/D	0.015	Measurement
MYBmax	Maximum growth rate of benthon	/D	0.019	Measurement
MYFmax	Maximum growth rate of fish	/D	0.200	Calibration
MYF	Growth rate of fish	/D	0.040	Measurement
MYZmax	Maximum growth rate of zooplankton	/D	0.165	Measurement
MZ	Mortality of zooplankton	/D	0.040	Measurement
NCmin	Minimum nitrogen content in phytoplankton	G/M^3	0.0035	Measurement
PCmin	Minimum phosphorus content in phytoplankton	G/M^3	0.0006	Measurement
PREDmax	Maximum feeding rate of fish on zooplankton	/D	0.043	Calibration
RBmax	Maximum respiration rate of benthon	/D	0.002	Measurement
RCmax	Maximum respiration rate of phytoplankton	/D	0.086	Calibration
RZmax	Maximum respiration rate of zooplankton	/D	0.071	Measurement
SVD	Setting rate of detritus	M/D	0.001	Calibration
SVS	Setting rate of algae	M/D	0.190	Calibration
UCmax	maximum rate of carbon uptake by algae	/D	0.700	Calibration
UNmax	maximum rate of nitrogen uptake by algae	/D	0.010	Calibration
UPmax	maximum rate of phosphorus uptake by algae	/D	0.002	Calibration
V	Volume of the West Lake	M^3	$9.0*10^6$	Measurement
Y1	Yield of feeding phytoplankton	/D	0.219	Measurement
Y2	Yield of feeding zooplankton	/D	0.241	Measurement

Implementation and calibration of the model

The model was used with Runge-Ketta numerical integration and the operation was executed using FORTRAN language by a Dell 486 microcomputer. A step length of 24 hours was adopted, in accordance with the ecological model.

The model was calibrated on a monthly basis according to observed values of west Lake in 1995. Data obtained in December 1994 was adopted as the initial values (Table 2). In this table, phosphorus, nitrogen and carbon in phytoplankton was obtained from the dry weight of phytoplankton biomass. The dry weight of the phytoplankton biomass was obtained from observed values of chlorophyll a, assuming that 0.05mg carbon = 1g chlorophyll a.

Table 2. Initial values of the state variables in the model (g/m^3)

order	state variable	initial value	order	state variable	initial value
1	PC	0.0225	11	NS	0.6508
2	PD	0.0779	12	NSED	0.0861
3	PS	0.0080	13	FNB	0.0852
4	PE	0.5750	14	FNF	0.1060
5	PI	0.0705	15	FNZ	0.0823
6	FPB	0.0050	16	CC	0.9000
7	FPF	0.0277	17	PHYT	2.2500
8	FPZ	0.0223	18	ZOO	0.3590
9	NC	0.1324	19	FISH	1.6670
10	ND	1.1418	20	BBIO	24.000

The model conducted sensitivity analyses and observed the relevant reactions of state variables to calibrate the model parameters through changing parameters.

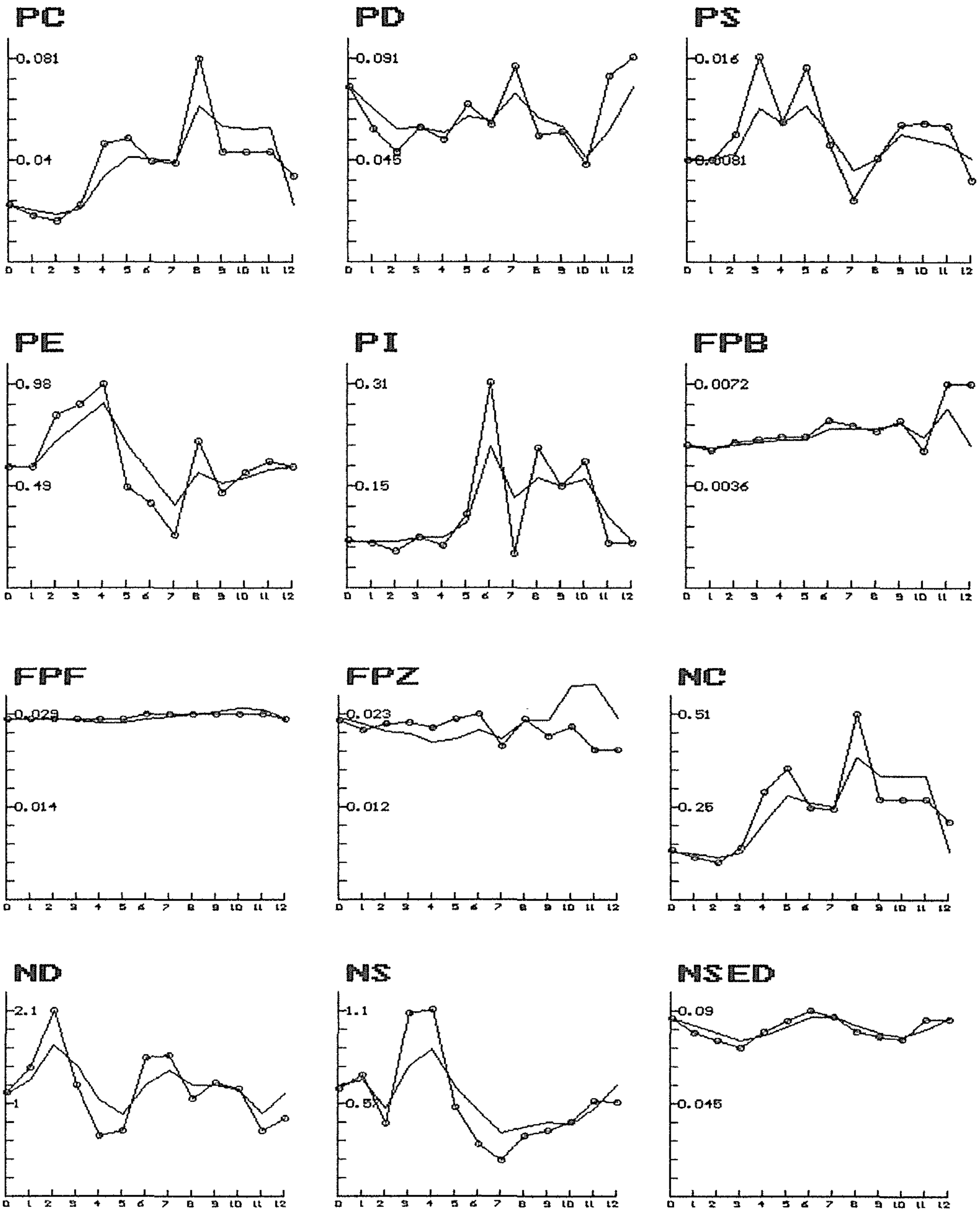
Simulated and observed values of each index are listed in Figure 2. In this figure, transparency was obtained from the statistically proven relationship between transparency and total phosphorus content of the West Lake, $\ln(SD) = 8.777 - 1.025*\ln(TP)$. Figure 2 shows that the model correctly describes the dynamic course changes of phosphorus circulation in the ecosystem after drawing water. Though simulated values and observed values do not completely coincide in some indexes, the variation trends are almost identical. This can be shown by three indexes; the calibration errors of state variables in the calibration period (Y), calibration errors of average state variables (R) and the calibration errors of the largest state variable (A). Their formulas are given below.

$$Y\,(\%) = \{[(Y_c - Y_m)^2]^{1/2}/n / Y_m\} \times 100$$

$$R\,(\%) = \{(Y_c - Y_m)/Y_m\} \times 100$$

$$A\,(\%) = \{(Y_{c,max} - Y_{n,max})/Y_{m,max}\} \times 100$$

Y_c, Y_c and $Y_{c,max}$ are the simulated values of the calibration period, the average simulated values and the largest simulated value, respectively. Y_m, Y_m and $Y_{m,max}$ are the observed values of the calibration period, the average observed value and the largest observed value, respectively.


PC
0.081
0.04
PD
0.091
0.045
PS
0.016
0.0081
PE
0.98
0.49
PI
0.31
0.15
FPB
0.0072
0.0036
FPF
0.029
0.014
FPZ
0.023
0.012
NC
0.51
0.25
ND
2.1
1
NS
1.1
0.57
NSED
0.09
0.045

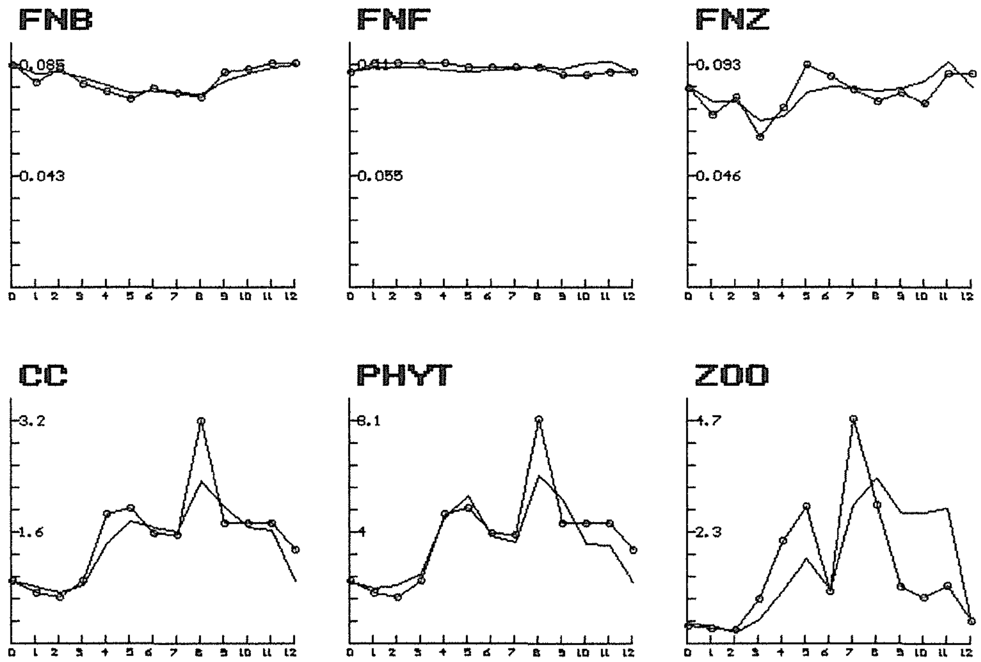


Figure 2. Comparison between observed (—) and simulated(----------) monthly values of state variables in the West Lake, during 1995.

These three indexes were calculated for each of state variables, and are shown in Table 3. From these tables, we can see that the results are closely matched and that the model is a valuable forecasting tool.

The beneficial evaluation of artificial measurements

In order to study the developing trend of eutrophication after drawing water, we evaluated the benefit of the drawing project with the model. The calculated result shows that drawing water reduced the content of chlorophyll a in the water body, but the benefit was not very good. For 1.55×10^7 or 3.10×10^7 tons/yr of drawing water, the average content of chlorophyll-a was reduced by 1.5 or 2.1□g/l, (or 2.4% and 2.7%), respectively. The chlorophyll-a content is most obviously reduced in July, the content of which was reduced by 3.2 and 4.1□g/l, respectively. According to these results, water-drawing plays no significant role in the reduction of chlorophyll a content of West Lake, suggesting a direct relationship to the high concentration of nitrogen and orthophosphate in Qiantang River.

The result of calculations also showed that drawing water can improve the transparency of the West lake. Drawing 1.55×10^7 or 3.10×10^7 tons/yr from Qiantang River, could potentially raise

Table 3. Three main calibration indexes of state variables (%)

order	state variable	Y	R	A	order	state variable	Y	R	A
1	PC	6.7	−3.7	−23.9	11	NS	8.4	8.6	−20.7
2	PD	4.5	−2.1	−14.1	12	NSED	1.1	0.5	−3.4
3	PS	5.1	−5.3	−23.5	13	FNB	0.7	0.3	0.1
4	PE	5.2	0.1	−9.7	14	FNF	0.8	0.2	1.3
5	PI	10.3	−2.0	−31.3	15	FNZ	2.2	0.5	1.2
6	FPB	3.6	−4.9	−12.5	16	CC	6.5	−6.5	27.8
7	FPF	0.5	−0.3	3.2	17	PHYT	6.0	−6.6	−25.1
8	FPZ	4.6	4.8	15.9	18	ZOO	20.0	5.9	−26.1
9	NC	7.1	−6.4	−23.5	19	FISH	1.8	−1.4	−6.7
10	ND	5.7	2.8	−18.3	20	BBIO	5.5	3.3	−14.2

the yearly average transparency by 3.1 or 4.3 cm (or 5.8 or 8.4%), respectively, with the transparency being highest in March to June (7.9, 9.6, 5.3 and 7.1 cm, respectively).

From the above analysis, we can see that drawing water has some benefit in improving the water quality, but the degree of improvement is not high. Even if the amount of drawing water is increased to a small degree of a result of the quality in Qiantang River (it is impossible to increase the actual drawing water), it is still difficult to improve the water quality massively. The analysis of the model suggests that the main reason for eutrophication may be related to nutritive salts in sediments in the nutritive pool. Investigations of data from many lakes have shown that because residual nutrient salts remain in the sediment after the external source of pollution has been controlled, eutrophication may again occur in lake.

Simulated calculations were conducted according to the quantity and temperature of drwing water in 1995, and the assumption that one-third to half of the sediment was removed.

The results of these calculations indicated that in comparison to the index value of 1995, the yearly average value of transparency was increased by 13.3 and 23.2 cm (or increased by 24.9 and 43.4%), respectively. The yearly average content value of chlorophyll-a decreased by 15.7 and 22.3 □g/L (or 20.5 and 29.2%), respectively. In view of this calculation, the water qualities would benefit more by removing the sediment than by drawing water.

Conclusions

The dynamic description of nutritive matter circulation of the West Lake made by this model, was co,pared to observations detected once a month, with each observed value being an average of 8 samples. Thus the observed data are statistically sound believable. There was some discrepancy between the model and the observed data. It may be that the model was too simple in its description of the definitiveness of the ecosystem, with some factors not accounted for which may have resulted in these discrepancies. The calibrated and tested indexes of the model, however, revealed that it reflected the practical changes in the water body quite well, with the trends of the imitated values being basically the same as those of the observed values.

Because the main floating matter in Qiantang River is sand, especially in periods of spring tide and rain, the large quantities of sand influenced the amount of drawing water. According to a survey, there are approximately 135 days in which the transparency of Qiantang River water is high up to 90 cm. Although the Pump Station can offer 300,000 tons water per year, for several reasons the highest quantity of actual yearly drawing water is estimated to be between only 2.50×10^7 tons and 3.10×10^7 tons. In this paper, the quantity of drawing water was found to have doubled compared to that observed in 1995, which lies in the interval, so we investigate benefit of drawing water by taking 3.10×10^7 tons as high quantity of drawing water in one year. From our results, we revealed that the quantity indexes of water rose slowly from 1.55×10^7 tons/year to 3.10×10^7 tons/year, due to many factors. From analyses of the model, it was apparent that the main cause of eutrophication may be sediment, as the content of nutritive salt was very high in the sediment of the West Lake. In particular, the mineralization of sediment and the release of nutritive material were the most significant factors in the change in nutritive content in the shallow lake. So in order to improve the quality of the water body and to avoid eutrophication, so as to satisfy the needs of the tourist, drawing water is insufficient. Other countermeasures must also be carried out. Removing sediment is certainly one beneficial way to improve the water quality. Meanwhile, we should try our best to improve our countermeasures in force.

References

1. Jin Xiangchan et al.: Eutrophication of China Lake. Environmental Science Press of China, 31-50 (1990)

2. Gu Dingxi and Shu Jinghua: Pollution Forecast of Lake Water and Its Method of Prevention and Control. Environmental Science Press of China, 38-69 (1888)

3. Jin Xiangchan et al.: The Investigative Standard of Lake Eutrophication. Environmental Science Press of China, 303-317 (1990)

4. Ruan Jiangrong et al. : Acta Hydrobiologica Sinica, 12(4):289-307 (1988)

5. Pei Hongping: Biometer,. Zhejiang Education Press, :96-125 (1991)

6. Pei Hongping: A Phosphorus Circulation Dynamics Model for the Ecosystem of the West Lake, Hangzhou. Collected Papers on Life Science, Hangzhou University Press, (1992)

7. Jogensen.S.E.: An Eutrophication Model for a Lake. Ecol Modelling. (2),147-165 (1976)

8. Jogensen.S.E., Mejer,H.F. and Frils,M.: Examination of a Lake Model. Ecological Modelling. (4), 253-278 (1978)

9. Jogensen.S.E.: Application of Ecological Modelling in Environmental Management,.Part A. Elsevier Scientific Publishing Company, 227-282 (1983)

10. Jogensen.S.E.: Fundamental of Ecological Modelling, Elsevier, 220-245 (1986)

11. Jogensen.S.E., Kamp-Nielsen,L. and Jogensen.L.A.: Ecological Modelling. (32) 237-240 (1986)

12. Nyholm,N.: A Simulation Model for Phytoplankton Growth and Nutrient Cycling in Eutrophic, Shallow Lakes. : Ecological Modelling, (4) 279-310 (1978)

13. Schnoor,J.L.: A Steady State Eutrophication Model for Lakes. Water Research, (14) 1651-1665 (1980)