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ESTIMATION OF TROPHIC STATES IN WARM TROPICAL LAKES AND RESERVOIRS OF LATIN AMERICA BY USING GPSS SIMULATION

MARIO A. ORTIZ-JIMÉNEZ, JOSÉ DE ANDA and ULRICH MANIAK

SUMMARY

This paper proposes a stochastic simulation model to determine the boundaries of the trophic states of warm-water tropical lakes and reservoirs in Latin America based on statistical correlation and MonteCarlo techniques. The model was developed using GPSS as a discrete simulation language and calibrated by correlating a set of state variables of 27 Latin American lakes and reservoirs monitored by the Pan American Center of Sanitary Engineering and Environmental Sciences (CEPIS). In order to warrant a better stability in the resultant probabilistic behavior of the dependent variable, 10000 new virtual water bodies with different trophic states were generated to produce a trophic state index based on the total phosphorus concentration. Based on the obtained results, it is concluded that the applied methodology is appropriate to determine the boundaries of the trophic states of warm-water tropical lakes and reservoirs and is also able to generate results similar to those obtained using the existing applied estimation techniques.

n the last 50 years the extensive construction of dams and reservoirs in Latin America has produced a large number of artificial water bodies that have interfered with the hydrology and ecology of several basins, sub-basins and rivers. Most dams were built initially to generate electricity, but were later also used for other purposes, like fishery, irrigation, transportation, water supply source, sports, and recreation. Artificial and natural fresh water bodies have suffered under nutrient contamination, especially nitrogen and phosphorus, originated from point and diffuse sources, mainly municipal and industrial sewages and agriculture runoff. When an excessive amount of nutrients enter to the system, contaminating the water body, their elimination is technically difficult and costly (DVWK, 1988; UNEP, 1999). The quantity of organic matter in aquatic ecosystems defines their trophic state, which serves as an indicator of the contamination grade of the system. The trophic state depends on several biotic and abiotic factors. One of this factors is the in-lake total P concentration, which compared to other water quality parameters, could be considered as the most studied indicator to determine the trophic state in lakes and reservoirs (Konesky *et al*., 1999). In freshwater bodies the total P is widely accepted as the limiting nutrient, and controlling the total P inputs is regarded as essential in reversing freshwater eutrophication (OECD, 1982; Hecky and Kilham, 1988). There are numerous case studies of the reversal of eutrophication processes resulting from the reduction of P loadings (Willander and Personn, 2001).

The OECD (1982) determined the boundary values between oligotrophic and mesotrophic states for temperate lakes as 0.008mg·l^{-1} P, and the boundary values between mesotrophic and eutrophic states was fixed at 0.267mg·l^{-1} P. But these boundaries values are not applicable to warm tropical lakes and reservoirs in Latin America (Castagnino, 1983). Salas (2003) proposed a methodology to assess the eutrophication grade in warm tropical lakes, and a new alternative is proposed herein to improve the assessment process by using a simulation model.

Due to the requirement of a higher grade of mathematical complexity, few environmentalists use simulation techniques to model ecological problems. For example, Romeu (1995, 1997) briefly outlines a GPSS simulation model

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of an aquatic ecosystem. Some statisticians are already actively working in ecological problems using GPSS which are regularly publishing their work in refereed journals (Baltzer, 1996). GPSS is a consolidated discrete simulation language focused on the flow of transactions and is usually applied to simulate manufacturing processes (Chisman, 1992). A GPSS simulation consists of a network of blocks, which represents actions linked with a set of transactions, arranged sequentially in different blocks. Therefore the whole simulation is simply a sequence of one transaction entering to one or more blocks, then a new transaction starts, and so on. Modeling a real system is to piece together a set of blocks that cause transactions to behave in a manner resembling the real system (Minuteman Software, 2000).

A simulation model is a representation of the behavior of a set of variables in a system, performed with a computer and reflects, in a single way, the activities in which the variables are related. The simulated system in this work it is not the physical system itself, but it is a system which "generates" a great number of virtual lakes and reservoirs having similar characteristics to that encountered in the Latin American region with the objective of establishing the total P concentration limits between their different trophic states. To cover the goals of this work, the "transaction" is a virtual water body that flows through the system, while a block is defined as any operation that performs that transaction within the simulation model, such as its own generation (GENER-

ATE), its transfer toward a specific block (TRANSFER), assignment of a value to one of its parameters (ASSIGN), evaluation of an arithmetic condition to modify its flow (TEST), and its own 'destruction' (TERMINATE). Since transactions take up memory space, all transactions that are no longer needed in the model should be removed in a TERMINATE block. Additionally, the system requires some control instructions such as definition of variables having floating point (FVARIABLE), definition of initiators to generate random numbers (RMULT), start up of the simulation processes (START), etc.

The data requirements of a GPSS simulation model include both parameters and variables. The parameters include particular values of the predictive variables: mean depth, P load and residence time of every water body and of every trophic state, in addition to the predicted total P value calculated from a regression model in function of the three previously mentioned variables. Variables are divided in input and output variables, and both sets of variables are classified as statistical ones.

Input variables include the probabilistic distributions of each one of the predictive variables corresponding to each trophic state, and are obtained from a set of 27 lakes and reservoirs located in the studied region. The output variables include the probabilistic distribution of the total P concentration and the trophic state of each one of the simulated water bodies.

Methodology

Table I shows a database from 27 Latin American lakes and reservoirs collected by the Pan American Center of Sanitary Engineering and Environmental Sciences (CEPIS, 2001). The information in the database was obtained on the basis of the Clark method to quantify the nutrient load from the tributary streams (Sonzogni *et al.*, 1978), the nutrient export coefficients developed by Rast and Lee (1978), the contribution of living beings considered by Castagnino (1982), and the laboratory APHA standards (13th to 16th eds.). For the trophic state classification of the lakes in Table I, the criteria applied by the Organization for Economic Cooperation and Development (OECD; Vollenweider and Kerekes, 1982, 1983; Salas, 2003) were used. However, the validity of these classification criteria is under discussion (Kietpawpan *et al.*, 2003). According to these authors, out of the total lakes and reservoirs included in Table I, 55.88% would be classified as eutro-

TABLE I
MONITORED PARAMETERS OF SOME LATIN AMERICAN LAKES AND RESERVOIRS

Lake/Reservoir	Year	Country	Z	Tw	Lp	TP	Classification
Salto Grande	1982	Argentina	7.80	0.097	12.6000	0.082	E
Salto Grande	1981-83	Argentina	8.40	0.032	14.5000	0.046	M
Descoberto	1980	Brazil	6.90	0.280	0.6500	0.016	O
Paranoá	1980	Brazil	14.30	0.731	2.9300	0.040	E
Funil	1978-79	Brazil	22.80	0.151	9.1900	0.041	M
Funil	1987	Brazil	22.80	0.131	18.6000	0.048	E
Funil	1988-89	Brazil	21.00	0.081	29.3000	0.066	E
Vigario	1988-89	Brazil	9.80	0.008	142.9000	0.084	E
Lajes	1988-89	Brazil	13.60	0.760	0.7950	0.018	O
Americana	1982	Brazil	9.20	0.047	37.7000	0.081	E
Americana	1986	Brazil	7.80	0.084	31.6200	0.098	E
Atibainha	1986	Brazil	12.50	0.388	1.2900	0.023	O
Barra Bonita	1978-79-80	Brazil	8.30	0.269	3.4300	0.058	M
Barra Bonita	1983	Brazil	9.20	0.073	23.0000	0.115	E
Barra Bonita	1982-84	Brazil	9.30	0.211	7.4500	0.094	E
Barra Bonita	1986	Brazil	8.60	0.221	6.9600	0.059	M
Cachoeira	1986	Brazil	10.70	0.130	4.1400	0.032	O
Guarapiranga	1982-83	Brazil	4.90	0.238	1.4000	0.052	E
Guarapiranga	1986	Brazil	4.90	0.331	1.7000	0.044	M
Itupararanga	1986	Brazil	7.80	0.660	2.1100	0.029	M
Jaguarí	1986	Brazil	16.80	1.225	3.2800	0.036	O
Paiva Castro	1982-83	Brazil	5.70	0.059	7.3000	0.040	M
Paiva Castro	1986	Brazil	5.40	0.028	5.4800	0.023	O
Paraibuna	1986	Brazil	26.40	1.923	0.7900	0.016	O
Ponte Nova	1982-83	Brazil	8.90	0.615	0.5500	0.027	O
Ponte Nova	1986	Brazil	8.30	0.806	0.4700	0.025	O
Taiaçupeba	1986	Brazil	2.20	0.135	0.6400	0.031	M
Laguna de Sonso	1988	Columbia	1.00	0.041	6.5800	0.210	HE
Pozo Honda	1981	Ecuador	20.00	4.845	5.0600	0.400	HE
Pozo Honda	1982	Ecuador	20.14	1.574	15.1000	0.200	HE
Livingston	1975	USA	6.30	0.243	14.6000	0.200	E
Chapala	1983-84	Mexico	4.20	11.050	0.9320	0.426	M
Chapala	1986-87	Mexico	4.43	15.940	1.5080	0.680	E
Tequesquitengo	1986	Mexico	16.00	98.500	0.0460	0.023	-
Requena	1986-87	Mexico	5.00	0.260	13.229	0.383	-
La Plata	1981-82	Puerto Rico	10.00	0.090	34.900	0.220	E
Loiza	1973-74	Puerto Rico	6.14	0.054	52.910	0.330	E
Tortuguero	1974-75	Puerto Rico	1.20	0.133	0.300	0.010	O
Laguna Grande	1980	Venezuela	3.50	0.120	13.700	0.290	E

O: oligotrophic, M: mesotrophic, E: eutrophic, HE: hypertrophic.

phic, 29.41% as oligotrophic, and the remainder is mesotrophic.

This work also considered P as the limiting nutrient in Latin American lakes and reservoirs (Salas, 2003). A Kolmogorov-Smirnov test was applied to the TP, Z, Lp, and Tw values showed in Table I. It was found that only their respective natural logarithms underwent a normal behavior (P>0.40). If TP', Z', Lp' and Tw' are the natural logarithms of TP, Z, Lp, and Tw , respectively, it is possible to adjust the next multiple linear regression model to the data showed in Table I, so that

$$TP'=\beta_0+\beta_1 Z'+\beta_2 Lp'+\beta_3 Tw' \qquad (1)$$

where, β_0, β_1, β_2, β_3 are the regression coefficients corresponding to the ordinate at the origin, Z', Lp', and Tw', respectively. The model could be represented as a matrix form as follows:

$$\mathbf{TP' = Xb+e} \qquad (2)$$

where

$$\mathbf{TP'} = \begin{bmatrix} TP'_1 \\ TP'_2 \\ ... \\ TP'_{39} \end{bmatrix} \quad \mathbf{X} = \begin{bmatrix} 1 & Z'_1 & Lp'_1 & Tw'_1 \\ 1 & Z'_2 & Lp'_2 & Tw'_2 \\ ... & ... & ... & ... \\ 1 & Z'_{39} & Lp'_{39} & Tw'_{39} \end{bmatrix} \quad \boldsymbol{\beta} = \begin{bmatrix} \beta'_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} \quad \boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ ... \\ \varepsilon_{39} \end{bmatrix} \qquad (3)$$

and TP'_i, Z'_i, Lp'_i, Tw'_i (i = 1, 2, …, 39) are the values of the state variables shown in Table I and ε_i (i = 1, 2, …, 39) is the error term of TP'_i. For the data reported in Table I, it could be verified that MSE= 0.1222 and the variance-covariance matrix $\mathbf{(X'X)^{-1}}$ is

$$\mathbf{(X'X)^{-1}} = \begin{bmatrix} 0.310616 & -0.129933 & 0.019908 & 0.034499 \\ -0.129933 & 0.063974 & -0.015860 & -0.015941 \\ 0.019908 & -0.015860 & 0.020912 & 0.014313 \\ 0.034499 & -0.015941 & 0.014313 & 0.017920 \end{bmatrix} \qquad (4)$$

And, therefore, the vector of least squares estimates is

$$\hat{\boldsymbol{\beta}} = \begin{bmatrix} \hat{\beta}'_0 \\ \hat{\beta}_1 \\ \hat{\beta}_2 \\ \hat{\beta}_3 \end{bmatrix} = \mathbf{(X'X)^{-1}X'TP'} = \begin{bmatrix} -1.237 \\ -0.934 \\ 0.891 \\ 0.676 \end{bmatrix} \qquad (5)$$

Finally, the multiple linear model in terms of natural logarithm of total phosphorus (TP') is

$$TP'=-1.237-0.934Z'+0.891Lp'+0.676Tw' \qquad (6)$$

$$R^2=0.902; \ SE=0.056)$$

If Z'_0, Lp'_0 and Tw'_0 are the particular values of Z', Lp' and Tw' respectively, the standard deviation of the mean value of TP' can be written (Younger, 1979) as

$$SD(TP')= \sqrt{MSE \times [1 \ Z'_0 \ Lp'_0 \ Tw'_0] \times (X'X)^{-1} \times \begin{bmatrix} 1 \\ Z'_0 \\ Lp'_0 \\ Tw'_0 \end{bmatrix}} \qquad (7)$$

Table II shows the descriptive statistic values of the state variables of the water bodies reported in Table I for each trophic classification.

Because Volenweider and Kerkes (1981) assumed homogeneous standard deviations of TP' for the different trophic status, the standard deviation of TP' was calculated by applying Eq. 6 regardless of the trophic state. Table III shows the programming code of the simulation model carried out on GPSS World Version 4.3 (Minuteman Software, 2000). The goal of the simulation model is to simulate a number of water bodies in each trophic state where the state variables undergo random variations in relationship with their population means. In this way it is possible to warrant a better stability in the probabilistic behavior of the dependent variable from the distributions curves of the predictive variables obtained in the sample of 27 warm tropical lakes and reservoirs. According to the Kolmogorov-Smirnov test applied to the selected sample, it is assumed that such variations follow a normal distribution in relation to the means of the standard deviations reported in Table II. Additionally, it is also assumed that TP' follows a normal distribution in relationship with the mean and standard deviations given by Eqs. 6 and 7, respectively.

To add more realism to the simulation process, only positives values are used for Ks, which was obtained from the mass balance equation proposed by Vollenweider (1976),

$$TP= \frac{Lp}{Z \left(\dfrac{1}{Tw}+Ks \right)} \qquad (8)$$

so that all the transactions (lakes and reservoirs) that did not satisfy the restriction

$$\frac{Lp}{ZP\lambda} > \frac{1}{Tw} \qquad (9)$$

were excluded.

Results and Discussion

Figure 1 shows the results (outputs) of the simulation model as a probability distribution function of natural logarithm of total phosphorus (TP') for each trophic level. The distribution curves are very close to the normal distribution pattern, and they have the same variance.

TABLE II
DESCRIPTIVE STATISTICS OF EACH TROPHIC CLASSIFICATION

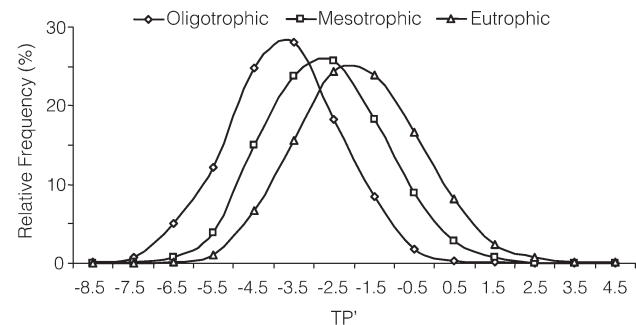| State variables	Oligotrophic Mean	SD	Mesotrophic Mean	SD	Eutrophic Mean	SD
Z'	2.17	0.83	1.90	0.64	2.15	0.52
Tw'	-1.00	1.27	-1.35	1.67	-1.95	1.64
Lp'	0.11	1.00	1.20	1.08	2.71	1.30

Figure 1. Distribution curves of the probability of TP' for each trophic state from the simulated data.

Abbreviations and Notations	
GPSS	General Purpose Simulation System
Z	Average depth, m
As	Surface area, km^2
Tw	Residence time, yr
Lp	Phosphorus load, $g/m^2 yr$
Ks	Overall loss rate of total phosphorus, yr^{-1}
TP	Total phosphorus concentration, mg/l
TP'	Natural logarithm of TP
Z'	Natural logarithm of Z
Lp'	Natural logarithm of Lp
Tw'	Natural logarithm of Tw
MSE	Mean Square Error
SD	Standard Deviation
y	Column vector of the observed Tp' values (39×1)
$\boldsymbol{\beta}$	Column vector of the regression parameters (4×1)
$\mathbf{X}$	Model specification matrix (39×4)
$\boldsymbol{\varepsilon}$	Column vector o the random errors (39×1)
$\hat{\boldsymbol{\beta}}$	Vector of least squares estimates of $\boldsymbol{\beta}$ (4×1)

To validate the simulation model, the Z test is used to compare the mean values of TP' of the simulation model with the mean values of the real data. Non-significant differences between the compared means (P>0.32) were encountered. Table IV indicates the estimated 95% of the confidence intervals for the TP' means of each trophic state based on the simulated data.

The limit between the oligotrophic and mesotrophic levels was obtained by averaging the upper limit of the 95% confidence interval for the TP' mean of the oligotrophic state and the lower limit of the 95% confidence interval for the TP' mean of the mesotrophic state. Similarly, the limit between the mesotrophic and eutrophic levels was obtained by averaging the upper limit of the 95% confidence interval for the TP' mean of the mesotrophic state and the lower limit of the 95% confidence interval for the TP' mean of the eutrophic state. According with Table V, the limit between the oligotrophic and mesotrophic states was established as the antilog (-3.22)= 0.04mg·l^{-1} P and the limit between the mesotrophic and eutrophic states was established as the antilog (-2.27) = 0.10mg·l^{-1} P. Vollenweider (1968) established the limits for temperate lakes as 0.01 and 0.03 mg·l^{-1} P, respectively.

The proposed GPSS simulation model seems to represent a useful technique to predict the trophic condition of warm tropical lakes and reservoirs. The results are not significantly different from those reported by CEPIS (2001). Utilizing the data reported on Table I, they fixed the limit between the oligotrophic and mesotrophic states as 0.03mg·l^{-1} and the limit between the mesotrophic and eutrophic states as 0.07 mg·l^{-1} P, respectively. In contrast, the USEPA (1974) fixed these limits as 0.01 and 0.02mg·l^{-1} P, and the OECD as 0.008 and 0.0267mg·l^{-1} P, respectively (Vollenweider and Kerekes, 1982).

The boundaries values predicted in this work for the trophic states in Latin American warm tropical lakes were 4 times higher than the corresponding values estimated in the temperate lakes located in the north hemisphere; nevertheless, they show the same trophic features. According with the OECD and USEPA criteria, a hypertrophic temperate lake has the same total P concentration than a warm tropical mesotrophic lake. This demonstrates that OECD criteria are largely inapplicable to warm tropical lakes. This is because the relative distributions of nutrient N and P in Latin American lakes and those of the OECD study are different in several ways. The main limnological feature to the OECD findings is that P is the nutrient lim-

TABLE III
PROGRAMMING CODE OF THE SIMULATION MODEL FOR 10000 WARM
TROPICAL LAKES AND RESERVOIRS

```
100  ;MYLAKES.GPS – By Mario A. Ortiz-Jiménez
110  ;MEAN AND STANDARD DEVIATION OF EACH TROPHIC STATE
120  PLO        FVARIABLE (-1.2370-0.9335#P$Z+0.891#P$LP+0.67634#P$TW)
130  SUMA1      FVARIABLE 0.3106-0.1299#P$Z+0.0199#P$LP+0.0345#P$TW
140  SUMA2      FVARIABLE P$Z#(-0.1299+0.0640#P$Z-0.0159#P$LP-0.0159#P$TW)
150  SUMA3      FVARIABLE P$LP#(0.0199-0.0159#P$Z+0.0209#P$LP+0.0143#P$TW)
160  SUMA4      FVARIABLE P$TW#(0.0345-0.0159#P$Z+0.0143#P$LP+0.0179#P$TW)
170  DEPLO      FVARIABLE 0.3495762#SQR(V$SUMA1+V$SUMA2+V$SUMA3+V$SUMA4)
180  ;CALCULO DE Ks
190  TERM1      FVARIABLE EXP(P$LP)/EXP(P$PL)#EXP(P$Z))
200  TERM2      FVARIABLE 1/EXP(P$TW)
210  KS         FVARIABLE LOG(V$TERM1-V$TERM2)
220  ;LAKES AND RESERVOIRS GENERATION
230             RMULT 9999,6666,7777,3333
240             GENERATE 0
250             OPEN («MISDAT0S.TXT»),,
260             TRANSFER .5588,EUTRO,INTER
270  ;EUTROPHIC LAKES AND RESERVOIRS
280  EUTRO      ASSIGN Z,(NORMAL(1,2.1453,0.5247))
290             ASSIGN LP,(NORMAL(2,2.711,1.2973))
300             ASSIGN TW,(NORMAL(3,-1.95,1.6374))
310             ASSIGN PL,(NORMAL(4,V$PLO,V$DEPLO))
320             ASSIGN 1,3
330             TEST G V$TERM1,V$TERM2,SALE
340             TRANSFER ,REGIS
350  INTER      TRANSFER .5263,MESO,OLIGO
360  ;MESOTROPHIC LAKES AND RESERVOIRS
370  MESO       ASSIGN Z,(NORMAL(5,1.9033,0.6388))
380             ASSIGN LP,(NORMAL(6,1.2015,1.0815))
390             ASSIGN TW,(NORMAL(7,-1.3452,1.6706))
400             ASSIGN PL,(NORMAL(8,V$PLO,V$DEPLO))
410             ASSIGN 1,2
420             TEST G V$TERM1,V$TERM2,SALM
430             TRANSFER ,REGIS
440  ;OLIGOTROPHIC LAKES AND RESERVOIRS
450  OLIGO      ASSIGN Z,(NORMAL(9,2.1703,0.8331))
460             ASSIGN LP,(NORMAL(10,0.1112,0.9964))
470             ASSIGN TW,(NORMAL(11,-0.9972,1.2656))
480             ASSIGN PL,(NORMAL(12,V$PLO,V$DEPLO))
490             ASSIGN 1,1
500             TEST G V$TERM1,V$TERM2,SALO
510  REGIS      WRITE (POLYCATENATE(P$PL,» «,P1)),,SALE
520             CLOSE
530             TERMINATE 1
540  SALE       CLOSE
550             TERMINATE 1
560  SALM       CLOSE
570             TERMINATE 1
580  SALO       CLOSE
590             TERMINATE 1
600             START 10000
```

TABLE IV
UPPER AND LOWER LIMITS OF THE POPULATION PARAMETERS
OF TP' BY TROPHIC CLASSIFICATION

Classification	N	Mean	SD	95% Conf.	LCL	UCL
Oligotrophic	2804	-3.75	1.41	±0.05	-3.80	-3.70
Mesotrophic	2455	-2.67	1.46	±0.06	-2.73	-2.61
Eutrophic	4055	-1.87	1.54	±0.05	-1.92	-1.82

TABLE V
TROPHIC CLASSIFICATION LIMITS

Trophic state	Average (TP')	Trophic limit (TP)
Oligotrophic/mesotrophic	[(-3.70)+(-2.73)]/2=-3.22	0.04
Mesotrophic/eutrophic	[(-2.61)+(-1.92)]/2=-2.27	0.10

The main lines of the programming code given in Table III are:

120   Definition of the mean of TP' according to Eq. 6.

170   Definition of the standard deviation of TP' according to Eq. 7. The expression V\$SUMA1+...+ V\$SUMA4 represents the result of the following matrix product:
[1 Z'_0 Lp'_0 Tw'_0]$\times(X'X)^{-1}\times$[1 Z'_0 Lp'_0 Tw'_0] where Z'_0, Lp'_0 and Tw'_0 are random values normally and independently distributed with the mean and standard deviation of every trophic state.

210   Definition of the natural logarithm of the variable Ks starting from the mass balance equation proposed by Vollenweider (1976) (Eq. 8).

230   Initial number given to start up the process of random numbers generation.

240   Creates virtual water bodies, which are used as future inputs in the simulation model.

250   A file named MISDATOS.TXT is opened.

260   55.88% of the generated virtual water bodies are delivered to a block identified as INTER (line 350). The remaining 44.12% are delivered to a block identified as EUTRO (line 280), which corresponds to the percentage of the eutrophic water bodies in the Table 1.

280   Based on the values on Table II, the random numbers generator 1 assigns to the eutrophic water bodies a normal distributed mean depth of 2.15 m and a standard deviation of 0.52m.

290   Based on the values on Table 2, the random numbers generator 2 assigns to the eutrophic water bodies a normal distributed mean depth of 2.71m and a standard deviation of 1.30m.

300   Based on the values in Table 2, the random numbers generator 3 assigns to the eutrophic water bodies, a normal distributed mean depth of 1.95m and a standard deviation of 1.64m.

310   The random numbers generator 4 assigns to the eutrophic water bodies, a normal distributed mean total phosphorus concentration with mean and standard deviation defined on lines 120 and 170, respectively.

320   The code 3 is assigned to all simulated eutrophic water bodies.

330   If Ks>0 (that is, the inequality (9) is satisfied), the eutrophic water body will go to next block (line 340), otherwise will be deliver to the SALE block (line 540).

340   The water body is unconditionally transferred directly to the block labeled REGIS (line 510).

350   All transactions arriving at INTER (55.88% of the generated transactions), randomly sends 52.63% of the leveled transactions to the OLIGO location. This fraction corresponds to 55.88×0.5263 = 29.41% of all oligotrophic water bodies described on Table 1. The remainder generated water bodies (55.88%-29.41% = 26.47%) are transferred to the MESO location, which corresponds to mesotrophic lakes described on Table 1.

360-430   Instructions are repeated in similar way to the lines 280 to 340, but the data now correspond to mesotrophic water bodies.

450-500   Instructions are repeated in similar way to the lines 280 to 330, but the data now correspond to oligotrophic water bodies.

510   A chain of text is written on the file with the generated values of TP', as is the code of the water body classification (1, 2 or 3). If an error occurs, the active water body is sent to the block leveled as SALE.

520   The active water body closes the text file.

530   As Ks>0, the active oligotrophic lake is 'removed' from the simulation and its statistic is not taken into account.

540   As Ks≤0, the eutrophic lake closes the text file and its statistic is taken into account.

550   As Ks≤0, the active eutrophic lake is 'removed' from the simulation.

560   As Ks≤0, the mesotrophic lake closes the text file and its statistic is taken into account.

570   As Ks≤0, the active mesotrophic lake is 'removed' from the simulation.

580   As Ks≤0, the oligotrophic lake closes the text file and its statistic is taken into account.

590   As Ks≤0, the active oligotrophic lake is 'removed' from the simulation and its statistics is discarded.

600   The logic sequence of the previous blocks is repeated ten thousand times.

iting algal growth, because N usually is massively in excess of algal requirements. This is not true in Latin America, where nitrogenous material in fresh waters is much less abundant (Lewis, 2002). In many lakes of this region the relative N to P availability approximates that required for a balanced algal growth and, in some of them, shortage of N limits growth. Water managers aiming to control eutrophication in Latin America lakes are advised to use the OECD predictive equations with utmost caution.

Conclusions and Recommendations

Due to shortage of available trophic data in the Latin American region, a GPSS simulation technique is proposed for determining the trophic status of warm tropical lakes and reservoirs. This technique was applied to obtain a more realistic image of the trophic state of these water bodies and to predict it. The stochastic GPSS simulation models have some advantages when compared to the classical deterministic models: while the sampling of a water body permits to analyze just one picture of the film, simulation permits to have a wider vision of the reality. The simulation models are easier to understand and visualize than the pure analytical methods. They add more realism to the analysis because they introduce variability to the parameters describing the water body and they are cheaper to use because they require less information, time and money to be developed. Simulation models like this can incorporate mathematical descriptions of physical, chemical and biological processes in lakes and reservoirs. If properly designed, these models can assist with management decisions that require considering alternative scenarios. The present study should encourage the practical uses of discrete event simulation in the area of ecological modeling and analysis.

Although this procedure provides a solution to the problem of determining the boundary values for trophic categories, its main disadvantage is its difficult application by managers and technicians having limited simulation modeling knowledge. The strength of this method is that it is strongly supported by the probabilistic distributions of the predictive variables of the water bodies in each trophic state and its effect in the variability of the dependent variable, which permits a better understanding of the trophic states of warm tropical lakes and reservoirs.

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ESTIMACIÓN DE LOS ESTADOS TRÓFICOS EN LAGOS Y EMBALSES CÁLIDOS TROPICALES EN LATINOAMÉRICA USANDO SIMULACIÓN GPSS

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RESUMEN

En este trabajo se propone un modelo de simulación estocástica para determinar los límites de los estados tróficos en lagos y embalses cálidos tropicales en Latinoamérica, basada en una correlación estadística y en técnicas de MonteCarlo. El modelo se desarrolló en el lenguaje de simulación discreto GPSS y fue calibrado con un conjunto de variables de estado de 27 lagos y presas de América Latina monitoreados por el Centro Panamericano de Ingeniería Sanitaria (CEPIS). A fin de garantizar una mejor estabilidad en el comportamiento probabilístico de la variable dependiente a partir de las distribuciones muestrales de las variables predictivas, se generaron 10000 cuerpos de agua de los diferentes estados tróficos y se produjo un índice de estado trófico basado en la concentración del fósforo total. Sobre la base de los resultados obtenidos se concluye que la metodología es apropiada para estimar los límites entre los estados tróficos de lagos y embalses y produce resultados similares a los obtenidos por otras metodologías.

ESTIMAÇÃO DOS ESTADOS TRÓFICOS EM LAGOS E REPRESAS CÁLIDOS TROPICAIS NA AMÉRICA LATINA USANDO SIMULAÇÃO GPSS

Mario A. Ortiz-Jiménez, José de Anda e Ulrich Maniak

RESUMO

Neste trabalho se propõe um modelo de simulação estocástica para determinar os limites dos estados tróficos em lagos e represas cálidos tropicais em Latino América, baseada em uma correlação estatística e em técnicas de MonteCarlo. O modelo se desenvolveu na linguagem de simulação discreta GPSS e foi calibrado com um conjunto de variáveis de estado de 27 lagos e represas de América Latina monitorizada pelo Centro Panamericano de Engenharia Sanitária (CEPIS). Com o fim de garantir uma melhor estabilidade no comportamento probabilístico da variável dependente a partir das distribuições amostrais das variáveis preditivas, foram gerados 10.000 corpos de água dos diferentes estados tróficos e se produziu um índice de estado trófico baseado na concentração do fósforo total. Sobre a base dos resultados obtidos se conclui que a metodologia é apropriada para estimar os limites entre os estados tróficos de lagos e represas e produz resultados similares aos obtidos por outras metodologias.