MODELLING AND SIMULATION OF PHYTOPLANKTON, NUTRIENTS AND DISSOLVED OXYGEN CONCENTRATIONS IN CHILIKA LAGOON

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ABSTRACT

Chilika Lagoon ($19^0 28$'N and $19^0 54$'N and $85^0 06$'E and $85^0 36$'E) is the largest brackish water lagoon with estuarine character. The present study is aimed at studying the seasonal variability of plankton in Chilika through a four-compartment ecological model. This model is solved for different sectors of the lagoon. Numerical experiments with different parameters showed that the main parameter affecting the phytoplankton population is the growth rate, which is expressed as a product of functions of terms affecting the growth of phytoplankton i.e., temperature, light and nutrients. The relative importance of all these individual factors was examined through numerical experiments. It was found that time of phytoplankton bloom was more dependent upon the parameter values within the growth rate term. The model results have been validated against the data and were found to be in good agreement.

INTRODUCTION

Coastal lagoons are highly productive and ideal system for aquaculture projects. In their ideal state, lagoons accumulate most anthropogenic / man-made pollutants and are liable to become eutrophic. Limiting eutrophication processes and their effects is essential for limiting the economic damage to aquaculture and tourism industries. Models need to be constructed which can help making strategies to control the eutrophication.

This paper describes the modelling of plankton dynamics in Chilika Lagoon ($19^0 28$'N and $19^0 54$'N and $85^0 06$'E and $85^0 36$'E) on the Orissa coast, India (Figure 1). Chilika is one of the unique ecospheres in the world. It is the largest brackish water lagoon with estuarine character. On account of its rich biodiversity and socio – economic importance, it was designated as a 'Ramsar site'- a wetland of international importance in 1981. Interest in detailed analysis of the circulation, biotic and abiotic factors affecting the lagoon and its limnology is due to the opening of the new mouth on 23 September 2000 to resolve the threat to its environment from various factors – Eutrophication, weed proliferation, siltation, industrial pollution and depletion of bioresources (CHANDRAMOHAN and NAYAK, 1994). Though there have been various taxonomic studies as well as detailed accounts of the distribution and seasonal abundance of algal forms in Chilika (RATH and ADHIKARY, 2005; ADHIKARY and SAHU, 1992), very little work is done in terms of modelling the circulation or biological production in the lagoon.

In the next section a brief description of the analysis area is presented. This is followed by the mathematical equations pertaining to our study domain. Finally, the results, based on several numerical experiments, are analysed and important conclusions are presented.

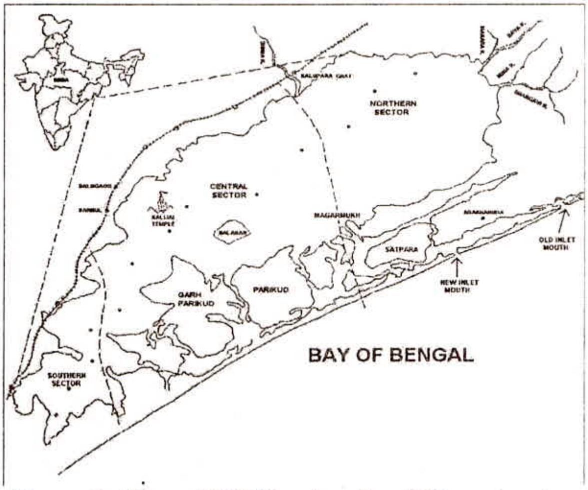

Figure 1: Map of Chilika showing different sectors

DESCRIPTION OF STUDY AREA

The water-spread area of the Chilika Lagoon varies between 1165 to 906 sq km during the monsoon and summer respectively (SIDDIQI and RAO, 1995). A significant part of the fresh water and silt input to the lagoon comes from river Mahanadi and its distributaries (MOHANTY *et al.*, 1996).

Based on the physical and dynamical characteristics of the lagoon, the lagoon is divided into four sectors (Figure 1). The northern sector receives discharge of the floodwaters from the rivers. The southern sector is relatively smaller and does not show much seasonal variation in any of the hydrographic parameters. The central sector has features intermediate of the other sectors. The lagoon is separated from the Bay of Bengal by a sand bar 60 km in length. The width of this inlet is about 1.5 km. A distinct salinity gradient exists along the lagoon due to the influx of fresh water during monsoon and the inflow of seawater through the outer channel. Opening of the new mouth has significantly changed the lagoon environment (CHILKA, 2001). The new inlet mouth is also situated in the northeastern end of the lagoon and the distance between the old and the new inlet mouths is around 17 km along the coastline (Figure 1).

MATHEMATICAL FORMULATION

In our earlier paper JAYARAMAN *et al.*, (2005), we modeled the dynamics and salinity distribution of Chilika and validated the model with the available observations. In the present paper, a purely ecological model was developed for simulating the annual plankton dynamics for Chilika. This model is a four-compartment model and consists of a system of rate equations for nutrients (nitrate and phosphate), phytoplankton and dissolved oxygen. The basic general equation that gives the time evolution of a chemical or biological quantity is

$$\frac{dB_i}{dt} = S_i + D_i \qquad i=1,..,4 \qquad (1)$$

where, B_i represents the concentration of the i^{th} chemical or biological species, S_i is the source term and D_i is the decay and biochemical interaction term for the i^{th} species. The source term S_i represents the quantity of B_i introduced in the system by external sources like river runoffs, coastal industrial wastes etc. The decay term D_i is defined for each variable B_i by a function depending upon the concentration of some other variables B_j as well as B_i itself.

The specific governing equations for the four variables considered in this study namely Phytoplankton (P), Nitrate (N), Phosphate (PH) and Dissolved Oxygen (DO) are:

$$\frac{dP}{dt} = (\mu - d_p - m)P \qquad (2)$$

$$\frac{dN}{dt} = \frac{N_S}{D} - A_N P \qquad (3)$$

$$\frac{dPH}{dt} = \frac{PH_S}{D} - A_{PH} P \qquad (4)$$

$$\frac{dO}{dt} = 0.0267(\mu - r)P \times CCHL - BOD + \frac{K_r}{D}(O_S - O) \qquad (5)$$

where, μ (day^{-1}) is the growth rate, d_p (day^{-1}) is the loss rate due to grazing and natural mortality etc., m (day^{-1}) is the metabolic loss rate of phytoplankton. N_S (µg/l) and PH_S (µg/l) are the sources (external) of nitrate and phosphate respectively, D (m), the depth and A_N (µgN/µgP/day) and A_{PH} (µgPH/µgP/day) are the uptake rate of nitrate and phosphate respectively. r (day^{-1}) represents the respiratory losses from phytoplankton, CCHL is the carbon to chlorophyll ratio (µgC/µgChl-a), BOD (mg/l/day) the biological oxygen demand, K_r (m/day) the reaeration rate for oxygen from the atmosphere and O_S (mg/l) the saturation oxygen concentration.

GROWTH AND LOSS OF PHYTOPLANKTON µ

The growth rate is assumed to be mainly governed by water temperature, light intensity and nutrient availability and is given by:

$$\mu = \mu_0 \, G_T(T) \, G_I \, G_N(N,PH) \qquad (6)$$

where $G_T(T)$, G_I and $G_N(N,PH)$ are dimensionless growth limiting factors for temperature, light and nutrient respectively.

Optimal growth rate for a phytoplankton community generally follows an exponential curve with temperature. The function $G_T(T)$ is given by

$$G_T(T) = (1.066)^{(T-T_0)} \tag{7}$$

where T (^{0}C) is the water temperature and T_0(^{0}C) is the reference water temperature.

According to Liebig's Law of minimum growth rate of plants depends only on the nutrient in shortest supply (i.e., the limiting nutrient). In the model the nutrient limiting factor G_N is given by

$$G_N(N,PH) = \min\left[G_N(N), G_N(PH)\right] \tag{8}$$

For Nitrate the formulation is given as follows:

$$G_N(N) = \frac{N}{K_N + N} \tag{9}$$

$$A_N = \mu\, Q_N \tag{10}$$

where K_N (μg/l) is the half saturation coefficient for nitrate uptake, and Q_N (μgN/μgP) is the ratio of nitrate to phytoplankton biomass (cell quota). For phosphate the formulations are same as for nitrate with phosphate (PH) replacing nitrate (N). Nitrate and Phosphate concentrations are affected by the phytoplankton uptake and regeneration from different sources.

PRODUCTION AND CONSUMPTION OF DO

Oxygen deficient, i.e., below saturation, waters are replenished via atmospheric reaeration. The reaeration rate coefficient is a function of the average water velocity, depth and temperature. Reaeration coefficient is calculated as a function of velocity (v) and depth based on the formula:

$$K_r = 5.439\, v^{(0.67)}\, D^{(-1.85)} \tag{11}$$

Saturation oxygen concentration O_S is calculated as a function of temperature (T (^{0}C)) and salinity (S (ppt)) by using the formula:

$$\begin{aligned} O_s = {} & 1.43\left(10.291 - 0.2809\,T + 0.006009\,T^2 - 0.0000632\,T^3\right) \\ & - 0.607\,S\left(0.1161 - 0.003922\,T + 0.000063\,T^2\right) \end{aligned} \tag{12}$$

INITIAL CONDITIONS

Initial values for phytoplankton, nitrate, phosphate and DO concentrations were taken from observed data (ADHIKARY and SAHU, 1992). Based on the assumption that phytoplankton growth is mainly nutrient and light limited, this model was solved for different sectors in Chilika, as these sectors have different sediment nutrient concentrations and depths, which in turn affect the penetration of light along the water column hence affecting the light limited growth rate of the phytoplankton. The results obtained from the numerical simulation of this model are discussed under Results and Discussion.

RESULTS AND DISCUSSION

The model described above is used to simulate the annual concentration of phytoplankton, nitrate, phosphate and dissolved oxygen in Chilika Lagoon. The time step used in the numerical integration of the model is 15 minutes. The numerical results validate the observations with the parameter set given in table 1. The results for the phytoplankton concentration in all the three sectors are given in figures 2, 3 and 4 along with the observed values for 1992 (ADHIKARY and SAHU, 1992). The model results are discussed as follows:

Table 1. Parameters used in the model

Parameter	Definition	Northern Sector	Central Sector	Southern Sector
D (m) (Jayaraman *et al.*, 2005)	Depth	0.3 – 1.6	1.5 – 2.8	1.5 – 3.25
T (^{0}C) (Rath and Adhikary, 2005)	Temperature	27	27.5	27
μ_0 (day^{-1})	Maximum growth rate	2	2	2
T_0 (^{0}C)	Reference temperature	20	20	20
G_I	Light limited growth rate	0.85	0.73	0.45
K_N (μg/l)	Half saturation for nitrate uptake	8.2	4.5	9.9
K_{PH} (μg/l)	Half saturation for phosphate uptake	5.5	2.3	5
d_P (day^{-1})	Loss of phytoplankton (Grazing, natural mortality)	0.3	0.3	0.05
M (day^{-1})	Metabolic loss rate	0.05	0.08	0.05
N_S (μg/l) (Rath and Adhikary, 2005)	Nitrate source	0.99	0.4	0.6
PH_S (μg/l) (Rath and Adhikary, 2005)	Phosphate source	0.7	0.3	0.2
Q_N (μgN/μgP)	Cell quota (Nitrate : P biomass)	10	10	10
Q_{PH} (μgPH/μgP)	Cell quota (Phosphate : P biomass)	1.2	1.2	1.2
r (day^{-1})	Phytoplankton respiration	0.001	0.001	0.001
BOD (mg/l/day)	Biological Oxygen Demand	0.26	0.1	0.1
CCHL (μgC/μgChl-a) (WASP 6 model)	Carbon – Chlorophyll ratio	150	150	150
v (m/sec) (Jayaraman *et al.*, 2005)	Average water velocity	0.10	0.08	0.05
S (ppt)	Salinity	0.2 – 1.3	4.6 – 9.2	8.0 – 11.2

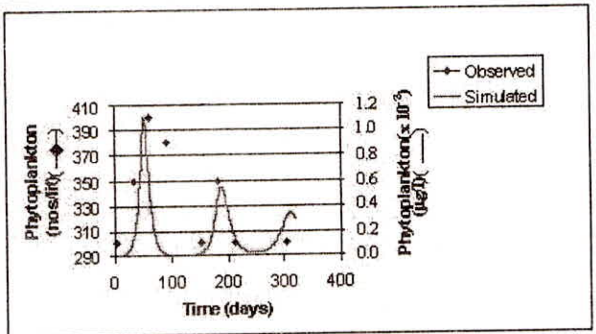

Figure 2: Observed and Simulated Annual Phytoplankton Concentration in Northern Sector

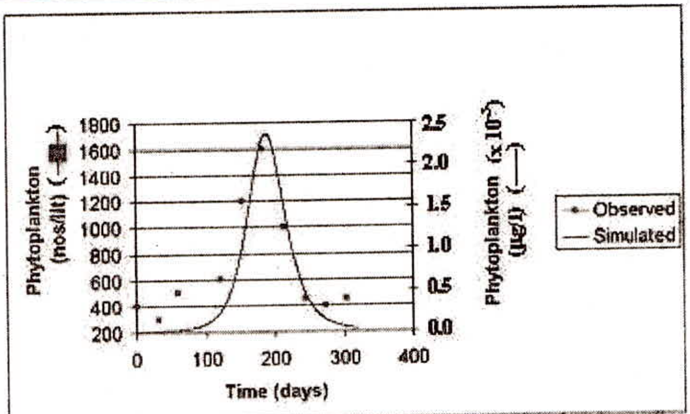

Figure 3: Observed and Simulated Annual Phytoplankton ation in Central Sector

Numerical experiments were performed to examine the relative importance of different parameters involved in the model equations (1 – 12). It was found that μ i.e., the growth rate of phytoplankton was the most effective parameter. Since μ is given as a product of different terms (equation no 6), an individual discussion about the relative importance of each of the terms is required. The first term is the temperature limited growth rate, it was observed that any decrease in temperature leads to a decrease in the phytoplankton growth and delays the time of bloom. With the light limited growth rate G_I, as expected the phytoplankton growth is seen to increase with the increase in G_I. The range of the numerical values of G_I for the stability of the solution in the Northern and Central sector is 0.7 to 0.9 d^{-1} whereas for Southern sector it is $0.3 - 0.5\ d^{-1}$. If we go below the ranges specified above the phytoplankton population does not show any bloom and tend to die after some time. Decrease in the value of G_I beyond the above specified range also delays the time of phytoplankton bloom.

There are two parameters involved in the nutrient limited growth rate $G_N(N,P)$ i.e., the half saturation coefficients K_N and K_{PH}. As it is expected from the equations (8) and (9) increase in the half saturations will lead to a decrease in the phytoplankton population. It was also observed that the changes in K_{PH} were more effective in changing the phytoplankton concentration rather than K_N. The reason for this comes from the definition of $G_N(N,P)$ (equation (7)) and the fact that Phosphate concentration is always low as compared to nitrate concentration. Hence phosphate, rather than nitrate, will act as the controlling nutrient for phytoplankton population. Increase in half saturation coefficients lead to a delay in the outbreak of phytoplankton bloom.

Another controlling factor for phytoplankton is the respiration rate r (d^{-1}). Since respiration rate is a sink for phytoplankton therefore any increase in r will lead to a decrease in phytoplankton population. The range for r in the Northern and Central sectors is 0.2 – 0.4 d^{-1} whereas in the Southern sector it is 0.1 – 0.15 d^{-1}. Increase in the value of r beyond the specified range leads to a delay in the bloom.

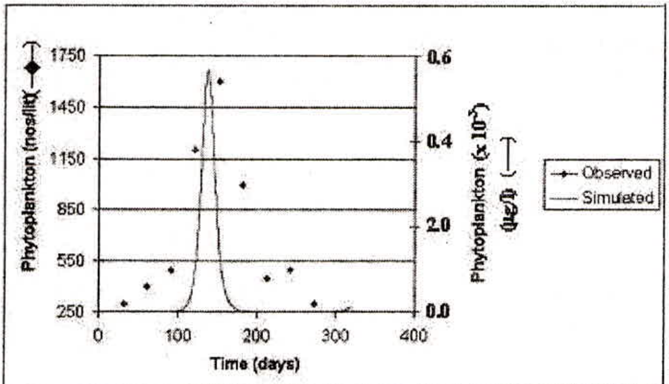

Figure 4: Observed and Simulated Annual Phytoplankton Concentration in Southern Sector

For DO concentration the most effective parameter is BOD. Since BOD acts as a sink for DO therefore any increase in BOD will lead to a decrease in DO concentrations. Changes in DO concentration do not show any effect on phytoplankton concentration. However changes in phytoplankton concentration do have effect on DO. For example, any increase in the growth rate will result in an increase in phytoplankton and therefore an increase in DO concentration as well. This change in DO due to changes in phytoplankton concentration is not very significant.

The major peaks of phytoplankton (representing blooms) in all the sectors of Chilika, as seen in the data (figures 2, 3 and 4, ADHIKARY and SAHU, 1992), have been well reproduced by the model. However, the model fails to validate the smaller peaks of phytoplankton particularly in the central sector (small peak in April – May and November – December) and southern sector (small peak in April – May and September – October).

CONCLUSIONS

It has been found that the main parameter affecting the entire system is the phytoplankton growth term. Out of the different terms in the growth rate term, changes in light limited growth rate and nutrient limited growth rate are the controlling factors for phytoplankton population. Changes in temperature only affect the time of occurrence of the bloom. For DO concentration the only factor that has a major contribution in BOD. DO levels show changes along with the phytoplankton concentrations since photosynthetic activity of the phytoplankton results in the release of oxygen but these changes are not very significant. The results have been validated against the observed values for 1992 (ADHIKARY and SAHU, 1992) and were found to be in good agreement. However, for the model calibration more data, say three to four years, will be required.

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