Journal Home page : www.jeb.co.in ★ E-mail : editor@jeb.co.in

JEB
Journal of Environmental Biology

ISSN: 0254-8704
CODEN: JEBIDP

Modelling system dynamics and phytoplankton diversity at Ranchi lake using the carbon and nutrient mass balance equations

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Publication Info

Paper received:
10 July 2012

Revised received:
12 May 2013

Accepted:
19 August 2013

Abstract

Modelling system dynamics in a hyper-eutrophic lake is quite complex especially with a constant influx of detergents and sewage material which continually changes the state variables and interferes with the assessment of the chemical rhythm occurring in polluted conditions as compared to unpolluted systems. In this paper, a carbon and nutrient mass balance model for predicting system dynamics in a complex environment was studied. Studies were conducted at Ranchi lake to understand the altered environmental dynamics in hyper-eutrophic conditions, and its impact on the plankton community. The lake was monitored regularly for five years (2007 – 2011) and the data collected on the carbon flux, nitrates, phosphates and silicates was used to design a mass balance model for evaluating and predicting the system. The model was then used to correlate the chemical rhythm with that of the phytoplankton dynamics and diversity. Nitrates and phosphates were not limiting (mean nitrate and phosphate concentrations were 1.74 and 0.83 mgl-1 respectively). Free carbon dioxide was found to control the system and, interacting with other parameters determined the diversity and dynamics of the plankton community. N/P ratio determined which group of phytoplankton dominated the community, above 5 it favoured the growth of chlorophyceae while below 5 cyanobacteria dominates. TOC/TIC ratio determined the abundance. The overall system was controlled by the availability of free carbon dioxide which served as a limiting factor.

Key words

Eutrophication, Modeling, Nutrient dynamics, Plankton, System dynamics

Introduction

Cultural eutrophication or eutrophication due to human activity has become a global problem for aquatic systems due to the influx of a variety of substances such as detergents, sewage material, fertilizers and urban runoff washed into the system from upland drainage and serves as a stressor leading to changes in niche dimensions, thermodynamic equilibrium and eco-exergy. A change in niche dimensions creates stress for organisms adapted to unpolluted conditions. Stress leads to change in the community composition so that the best fitted, and tolerant of the changed conditions now take over the community.

The word eutrophy is generally taken to mean "nutrient rich". Natural eutrophication of lakes is a slow process involving geologic time scale. The process has been greatly accelerated by cultural eutrophication. The cultural (man-made) eutrophication of freshwater ecosystems is one of the most prevalent environmental problems, responsible for water quality degradation on a worldwide scale (Vezjak *et al.*, 1998; Biggs, 2000; Pierzynski *et al.* 2000; Wetzel, 2006). Cultural eutrophication relates to the rapidly increasing amount of phosphorus and nitrogen, normally present at relatively low concentrations in natural waters. Of the two, phosphorus is considered to be the major cause of eutrophication, as it is a growth limiting factor for algae in freshwaters. At present, however, these are not limiting in most freshwater ecosystems due to their influx from a variety of sources.

Classical modelling approaches, for addressing lake eutrophication are based mostly on Vollenweider's (1975), and Dilon and Riglers (1974) steady-state, and input–output or mass balance equations. Conventionally, the parameters used to evaluate eutrophication and to construct models include nitrates, phosphates, carbon and chlorophyll (OCED, 1982; Ryding and Rast, 1989; Cooke et al. 1993; Nurnberg, 1996; Correll, 1999; and Wetzel, 2001). Recent eutrophication models have been given by Zhang *et al*. (2004) and Arhonditsis and Brett (2005). In this paper we present a data oriented, mass balance model to explain the diversity and dynamics of the phytoplankton in a non limiting environment with respect to nitrates and phosphates.

Ranchi lake (Fig. 1) is an eutrophic lake that has been experiencing stress due to human activities for the last two decades. It has an area of about 0.157km^2, a mean depth of about 6 m and is one of the oldest water bodies in the city. Unfortunately, the lake has been experiencing tremendous stress due to wide range of anthropogenic activities and the receipt of a diverse range of inputs (especially detergents through washing clothes, animals, automobiles and sewage materials) such, that the water has become unfit for any reasonable use.

The phytoplankton community at Ranchi lake has about 31 species encompassing five classes. The mean annual percentage of various classes of phytoplankters in a descending order is as follows: Cyanobacteria (38%) > Bacillariophyceae (27) > Chlorophyceae (22%) > Chrysophyceae (9%) > and Euglenophyceae (4%). Among these, the Cyanobacteria and Bacillariophyceae form the dominant members in these eutrophic waters indicating organic pollution (Fig. 2).

Plankton species composition and abundance are functions of interactions with environmental conditions including salinity, temperature, light, nutrients, turbulence and water depth in addition to grazing, competition and disease. In general, the

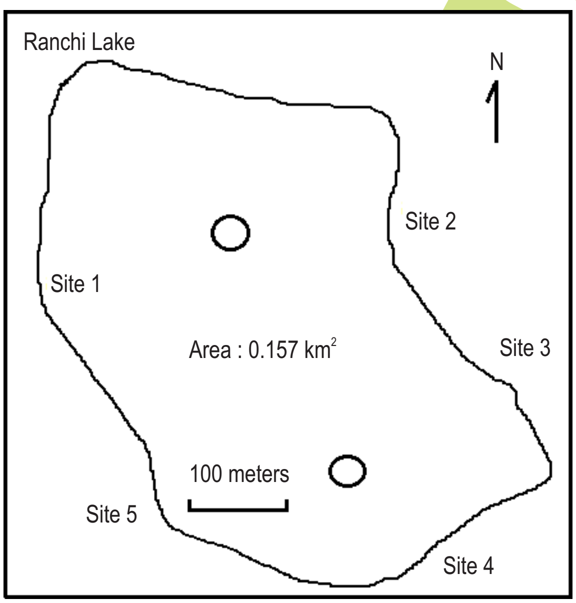

Fig. 1 : Ranchi lake and the sites of sample collection

phytoplankton shows two peaks or blooms in coordination with the overturns and availability of nutrients (mainly nitrates and phosphates) as proposed by Hutchinson (1967), Reynolds (1984, 1990, 1997) and Lewis (1987).

Reports of annual planktonic rhythm and peak concentration for Indian fresh waters have been given by Das (1957, 1959) and Michael (1968). In general, a bimodal peak (spring peak and monsoon peak) occurs in February – March and July-August respectively coinciding with peak nutrient availability. The spring peak is usually greater than the monsoon peak. However small scale departures usually occur due to specific changes. Michael (1968) reported a single but prolonged peak, lasting from January to April. Similarly, Mukherjee *et al*. (1993, 1995) in their studies on a polluted pond reported a single peak of phytoplankton (other than cyanobacteria) from February to April while the cyanobacteria exhibited two peaks: one in June and the other in October-November.

The planktonic community rhythm at Ranchi lake shows a wide displacement from those occurring in natural unpolluted water bodies. There is no nutrient limitation and the lake is in constant bloom and shoots up thrice in January, May and December. The phytoplankton community is dominated by Cyanobacteria and Bacillariophyceae, with occasional spurts of Chlorophyceae.

In our study, encompassing five years: 2007-2011, we found the lake to be in constant bloom (3.24×10^5 cells per liter) and shoots up thrice (5×10^5 cells per liter), forming three peaks (Fig. 3): one in the months of January – February (P-1), second in the month of May (P- 2), and third in the month of November – December (P- 3). These are the periods when free carbon dioxide is available, and the pH is relatively low. The community resonates in tune with a chemical environment, characterized by high nitrates, phosphates, organic matter, alkalinity, pH, and with a high oxygen demand. We tried to analyze the system in this altered regime. The zooplankton population did not have any significant impact on the phytoplankton community being lower by a factor of 10^2. The fish community which, experiences anoxic conditions (about 2 mg l^{-1} during the night) is represented by a single tolerant species, *Tilapia mossambica*.

Four groups of zooplankton were found in Ranchi lake. The percentage of various classes of zooplankton in descending order is as follows: Rotifera (48%) > Copepoda (43%) > Branchiopoda (6%) > and Ostracoda (3%). Of these, the Rotifera and Copepoda form the dominant members. Rotifers are represented by five genera while, copepods have three. Two genera, Brachionus and Mesocyclops show maximum abundance during most part of the year.

Studies were therefore conducted on a eutrophic lake, Ranchi Lake, in order to assess the characteristics of the plankton community living in a high nutrient regime with altered niche

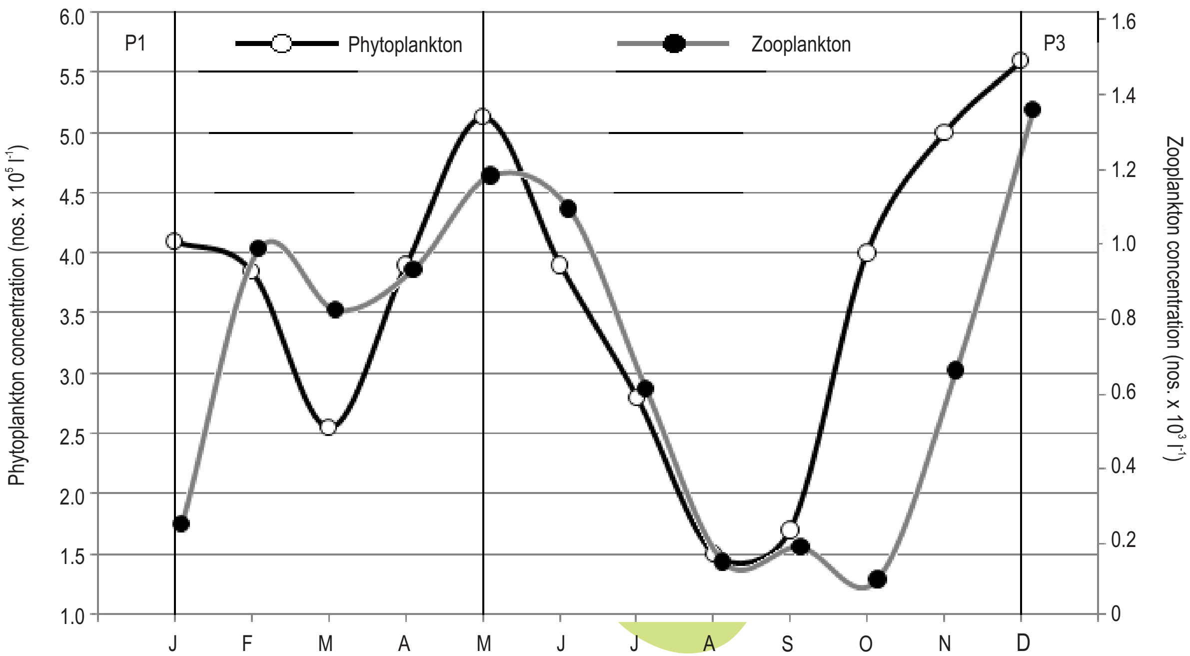

Fig. 2 : The three phytoplankton peaks during an annual cycle at Ranchi lake and the associated zooplankton peak. The zooplankton population are lower by a factor of 2

dimensions and present a model for predicting the altered nutrient dynamics and its impact on the diversity and dynamics of the plankton population.

Materials and Methods

Samples were collected twice each month from five stations (Fig. 1). Parameters such as light, temperature, pH, oxygen, inorganic carbon, nitrates, sulphates, phosphates, dissolved organic matter, DOM, BOD, and COD were monitored at regular monthly intervals. Chemical analysis of phosphates, nitrates, sulphates, BOD and COD was done using standard methods (APHA, 2006).The plankton samples were preserved in 5% neutralized formalin and Lugol's iodine after collection. Preserved samples (1 ml) were used for species identification and counting on a Sedgwick-Rafter cell at 45x and 100xmagnification.The mathematical model developed by Mukherjee *et al.,* (2002) has been used to predict the altered nutrient dynamics of Ranchi lake.

Results and Discussion

Carbon cycle is usually not included in detail in eutrophication models (Jorgensen, 2010), although some work in this direction has been done by Kuentzel (1969) and King (1970). Here, we developed a model that takes into account the nutrient processes that are dependent to an extent on the carbon cycle. This approach has wide ranging implications in the general development of eutrophication models.

From the data obtained, a box model involving mass balance of various constituents and rate processes we developed (Fig. 4). The inorganic pool at Ranchi lake contained 81.59 mg l^{-1} of inorganic carbon, 0.83 mg l^{-1} of phosphates, and 1.737 mg l^{-1} of nitrates forming the nutrient base of the phytoplankton.

One of the major considerations was the carbon cycle of the system. The major reservoir of inorganic carbon was free and bound carbon present in the system. The major uptake from the reservoir was due to fixation of carbon dioxide to organic carbon through the process of photosynthesis by the phytoplankton, while the major return pathway was through respiration and decomposition. These changes did not alter alkalinity.

However, with the entry of detergents, sewage and other materials there was a change in the inorganic carbon, alkalinity and nutrients. In order to differentiate between the natural metabolic processes and the influx of inorganic carbon, an equation that could account for both was formulated based on the basic chemical principles which is as follows:

$$\frac{d\Sigma C_t}{d[H^+]} = \frac{AK_1([H^+]^2+4K_2[H^+]+K_1K_2)}{(K_1[H^+]+2K_1K_2)^2} + \frac{[H^+]^2+K_1[H^+]+K_1K_2}{(K_1[H^+]+2K_1K_2)^2} \times \frac{dA}{d[H^+]} \quad \text{Eq. 1}$$

Photosynthesis and Respiration Addition and deposition

The phytoplankton transduces the available light energy (432 kcal m^{-2} d^{-1}) and maintained a productivity rate of 9.84 mg C l^{-1} d^{-1} with a photosynthetic efficiency of 0.3 % and was close to the respiration rate of 9.78 mg C l^{-1} d^{-1} (Fig. 4). The phytoplankton population dominated by cyanobacteria (*Gloeocapsa, Microcystis, Spirulina*) increased utilizing the abundant supply of inorganic carbon, however there was a dearth of free carbon dioxide so that the phytoplankton could use bound carbon. Photosynthesis did not change alkalinity because any change is buffered by the bicarbonates and carbonates. However, addition of detergents or deposition of calcium did change alkalinity. Since, the total carbon depends on alkalinity, there was a good correlation ($r = 0.9411$; $p > 0.001$) between the two variables represented below :

$$\Delta Ct \text{ m moles } l^{-1} = 1.2872 \text{ TA meq } l^{-1} - 2.0524 \; (r=0.9411; p>0.001) \quad \text{Eq. 2}$$

The phytoplankton transduced the available light energy (432 kcal m^{-2} d^{-1}) and maintained a productivity rate of 9.84 mg C l^{-1} d^{-1} with a photosynthetic efficiency of 0.3 % and was close to the respiration rate of 9.78 mg C l^{-1} d^{-1} (Fig. 4). The phytoplankton population dominated by cyanobacteria (*Gloeocapsa, Microcystis, Spirulina*) increased by utilizing the abundant supply of inorganic carbon, however there was a dearth of free carbon dioxide so that the phytoplankton had to use bound carbon. Photosynthesis did not change alkalinity because any change is buffered by the bicarbonates and carbonates. However, addition of detergents or deposition of calcium did change alkalinity. With a high load of phytoplankton and consequent high photosynthesis, free carbon dioxide decreased rapidly so that by 1100-1200 hours free carbon dioxide is exhausted. Only moderate amount of free carbon dioxide was present during the months of January, June, August and December. Thus, the phytoplankton community had to depend on the bound carbon which provided carbon dioxide as follows:

$$2HCO_3^- = H_2O + CO_2 + CO_3^{2-} \quad \text{Eq. 3}$$

$$CO_3^{2-} + H_2O = CO_2 + 2OH^- \quad \text{Eq. 4}$$

The availability of carbon dioxide for photosynthesis was now limited by the rate at which bicarbonate ions dissociated to give free carbon dioxide according to the equilibrium kinetics discussed by Mukherjee (2007, 2008). The most widespread mechanism to increase carbon dioxide availability was the ability to use HCO_3 ions in photosynthesis or alternatively itself may also be actively taken up (Lara *et al.,* 2002).

Thus, with the utilization of carbon dioxide, initially bicarbonates were utilized which increased the carbonate concentration. When the bicarbonate concentration decreased, carbonates were utilized and the hydroxyl ion concentration increased (Fig. 5). Photosynthesis increased the pH, while respiration decreased it.

At Ranchi lake, the pH and alkalinity (Table 1) was very high due to discharge of detergents which contain large amount of sodium carbonate as fillers. The entry of sodium carbonate further decreased the free carbon dioxide concentration due to formation of bicarbonates:

$$Na_2CO_3 + CO_2 + H_2O = 2NaHCO_3 \quad \text{Eq. 5}$$

Using equation 1, changes in inorganic carbon due to photosynthesis and respiration, and those due to entry of detergents and other materials could be differentiated. The cyanobacteria are better able to function at lower levels of carbon dioxide and are able to tolerate high temperatures (Novak and Brune, 1976) consequently they have an advantage in such waters and form the dominant component of the community. Utilization of carbon draws upon the carbon reserve so; there was a negative correlation between photosynthesis and total inorganic carbon ($r = -0.76$; $p > 0.05$):

$$\text{Phytoplankton (nos.} \times 10^5 \, l^{-1}) = -0.7941 \Delta Ct \text{ m moles } l^{-1} + 5.4158 \quad \text{Eq.6}$$

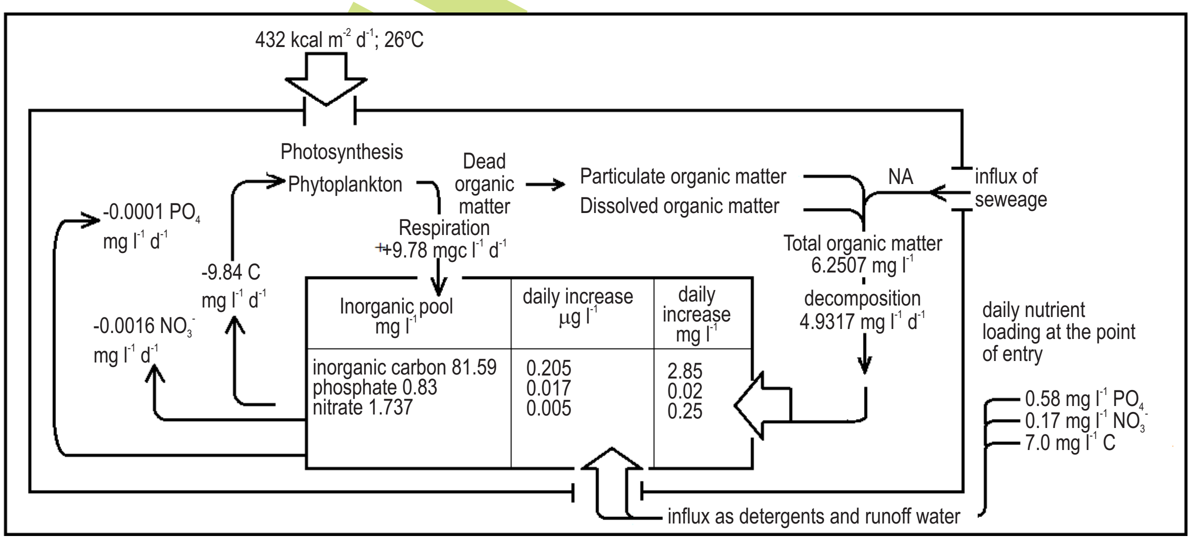

Fig. 3 : The system model of Ranchi lake showing state variables, rate processes and influx

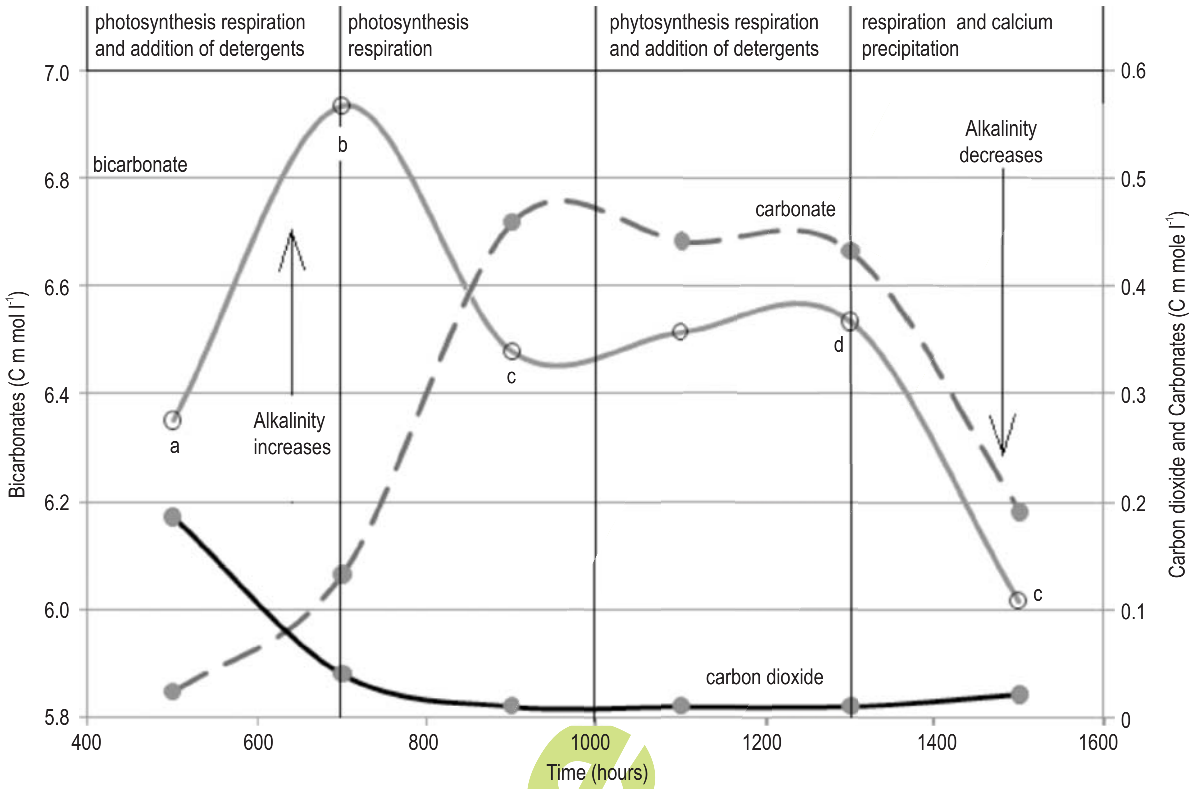

Fig. 4 : The diel fluctuation in the various forms of carbon due to photosynthesis, respiration, addition in the form of detergents, and calcium precipitation

Table 1 : Showing the mean chemical environment of Ranchi lake (2007-2011)

Parameters	Concentration
pH	8.39
Temperature (°C)	26.0
Turbidity (NTU)	120
Oxygen (mg l^{-1})	10.08 (daytime) 2.0 (night time)
Alkalinity (meq l^{-1})	7.39
Total inorganic carbon (m moles l^{-1})	7.46
Phosphate (mg l^{-1})	0.83
Nitrate (mg l^{-1})	1.74
Sulphate (mg l^{-1})	153.0
Silica (mg l^{-1})	5.45
Chloride (mg l^{-1})	184.8
BOD_5 (mg l^{-1})	37.84
COD (mg l^{-1})	152.0
DOM (mg l^{-1})	5.76
Conductivity (μ mhos)	1300
Chlorophyll (μg l^{-1})	>80

BOD = Biological oxygen demand, COD = Chemical oxygen demand; DOM : Dissolved organic matter

At Ranchi lake, the rate of respiration was roughly equal to the rate of production so that the carbon dioxide released at night rejuvenated carbonate-bicarbonate system while that released through decomposition provided free carbon dioxide required to initiate photosynthesis next day.

Phytoplankton convert inorganic carbon into organic carbon. When phytoplanktons die, they contribute towards the dead organic matter of the system. The dead organic matter can be resolved into two components: dissolved organic matter (DOM) and particulate organic matter (POM), and the two constitute total organic matter (TOM). The mean concentration of total organic matter was about 6.2507mg l^{-1}. Additional organic matter entered the system in the form of sewage material, increasing BOD, COD and DOM.

Decomposition of organic matter release nutrients thus as the concentration of total organic matter decreased, nutrient concentration increased, indicating a negative correlation between the two variables:

ΔNF mg l^{-1} = - 0.3921Δ TOM mg l^{-1}+0.1904 (r=-0.71; p>0.05) Eq.7

Organic carbon constitutes about 58 % of the total organic matter so as organic matter increases; organic carbon also increases (Fig. 6). When oxidative decomposition processes reached to completion, the end-products were carbon dioxide and water, as shown below :

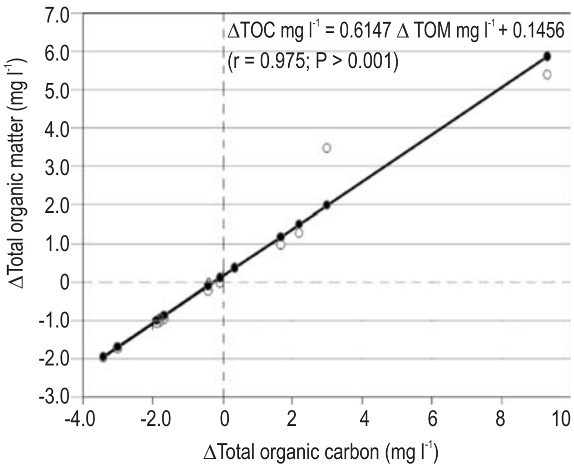

Fig. 5 : Correlation between the flux of total organic matter and total organic carbon at Ranchi lake

$$(CH_2O) + O_2 \rightarrow CO_2 + H_2O \qquad \text{Eq. 8}$$

Decomposition of organic matter releases free carbon dioxide. The mean rate of decomposition of organic matter at Ranchi lake was about 4.9317 mg l^{-1}. This decomposition involved about 2.85 mg C l^{-1} and lead to the formation of about 10 mg l^{-1} of carbon dioxide per day and provide for the initial start of photosynthesis before the use of bound carbon. There was a fine balance between inorganic and organic carbon within the system as inorganic carbon increased, organic carbon decreased and vice-versa so, a negative correlation existed, as represented below :

TOC mg l^{-1} = -0.136 TIC mmoles l^{-1} + 3.357(r=-0.73; p>0.01) Eq. 9

Thus, as organic matter decreased through decomposition, inorganic carbon was released and the phytoplankton used this inorganic carbon for their growth. The phytoplankton thus showed a negative correlation (Fig. 7) with total organic matter.

Nutrient enrichment is the major factor inducing eutrophication. The normal concentration of nitrates, phosphates and sulphates in freshwaters were 0.1-1.0 mg l^{-1}, 0.003-0.1mg l^{-1} and 5-30 mg l^{-1} (Wetzel, 2001). Ranchi lake experienced a daily influx of phosphates, nitrates and sulphates in the form of detergents, oil and sewage.

Phosphate often considered as a limiting factor (Hutchinson, 1967), was high at Ranchi lake. Its concentration varied from about 0.16 – 1.51 mg l^{-1}. The concentration was lowest in the month of February and started increasing with the entry of detergents and reached maximum in the month of July (when the process was accelerated by the drainage from surrounding areas). The concentration showed a dip in the month of September and increased again in October. The concentration

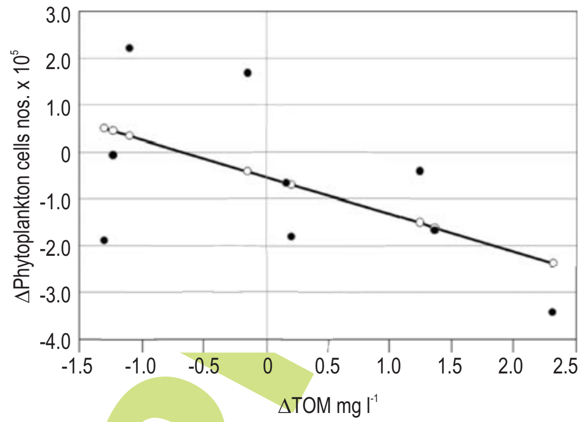

Fig. 6 : Correlation between the change in the phytoplankton concentration and change in total organic matter. The decomposition of organic matter releases nutrients which triggers the growth of phytoplankton

then decreased continuously till December (Fig. 8).

Nitrate concentration was also relatively high at Ranchi lake. Similar to phosphate nitrate was maximum during July and August but in contrast was maximum during January and April. The lowest concentration are in May, June, October and November. Nitrate and phosphates, along with carbon are three main nutrients controlling the productivity of an ecosystem and under unpolluted conditions, controls the development of the community and its rhythm. At Ranchi lake, the process was complicated due to influx of nutrients due to anthropogenic activity, so it was very difficult to differentiate between the fluctuation due to metabolic activities of the community and those due to anthropogenic activity, as expected in culturally eutrophicated lakes.

At Ranchi lake, nitrates and phosphates were relatively high (Table 1) so, they did not serve as limiting factors, but the phytoplankton used the same to maintain a high population level. There is no direct correlation between nitrates and phosphates concentration and phytoplankton abundance. However, when the two were combined in the form of a nutrient factor (NF) and analyzed with multiple regressions, the phytoplankton showed a good positive correlation with increase in the combined nutrient concentration (Fig. 9) and can be represented as follows:

Phytoplankton (nos. l^{-1}) = 4.943 – 1.602 nitrate + 0.078 phosphate

Eq.10

Where, 1.602 nitrate + 0.078 phosphate = Nutrient factor

However, nitrates and phosphates, as parameters, showed a negative correlation between each other in an annual cycle.

Table 2 : General trophic classification of lakes and the status of Ranchi lake

Parameter	Total phosphorus (µg l^{-1})	Total nitrogen (µg l^{-1})	Chlorophyll a (µg l^{-1})	Secchi transparency (m)
Trophic state				
Oligotrophic	8	661	4.2	9.9
Mesotrophic	26.7	753	16.1	4.2
Eutrophic	84.4	1875	42.6	2.45
Hyper-eutrophic	100	>1900	>125	0.50
Ranchi lake	830	1800	48	0.70

Compiled from: Vollenweider, 1979; OCED, 1982; and Nurnberg, 1996

The daily utilization of phosphates and nitrates were of the order 0.0001 and 0.0016 mg l^{-1} d^{-1} respectively. Daily nutrient input was by two process: nutrient loading at the point of entry was about 0.58 mg l^{-1} of phosphates and 0.17 mg l^{-1} of nitrates that increased these nutrients by 0.017 and 0.05 µg l^{-1} respectively; the other source was decomposition of organic matter which increased the phosphates and nitrates by 0.02 and 0.25 mg l^{-1} respectively. Thus, these nutrients increased daily while the amount of free inorganic carbon decreased.

Part of the particulate dead organic matter settles to the bottom of the lake and a part remains in the dissolved form. Both the forms increased the organic load of the system which was further aggravated by anthropogenic inputs in various forms. Consequently, it is imperative that this would increase the biological and chemical oxygen demand of the system. Since, the composition of organic matter was quite complex and so was the decomposition process, therefore a direct correlation between COD-DOM, and BOD-DOM was not found. However, multiple regressions showed a good positive correlation (Fig. 10) between COD, BOD and DOM. In contrast, there was a direct positive correlation between BOD and COD at Ranchi lake. This implied that BOD in the present case was not only regulated by the dead organic matter from the planktonic population alone but was complicated due to POM, entry of organic sewage as well as organic chemicals entering the system.

With this basic nutrient budget, a system dynamics model (Fig. 11) that could explain the displacement of phytoplankton community from the usual pattern in a non-limiting environment with respect to nitrates and phosphates but limiting in relation to free inorganic carbon was developed.

The idea was to explain the behaviour using basic correlation equation for state variables and metabolic activities and then to combine those equations for a holistic view of the

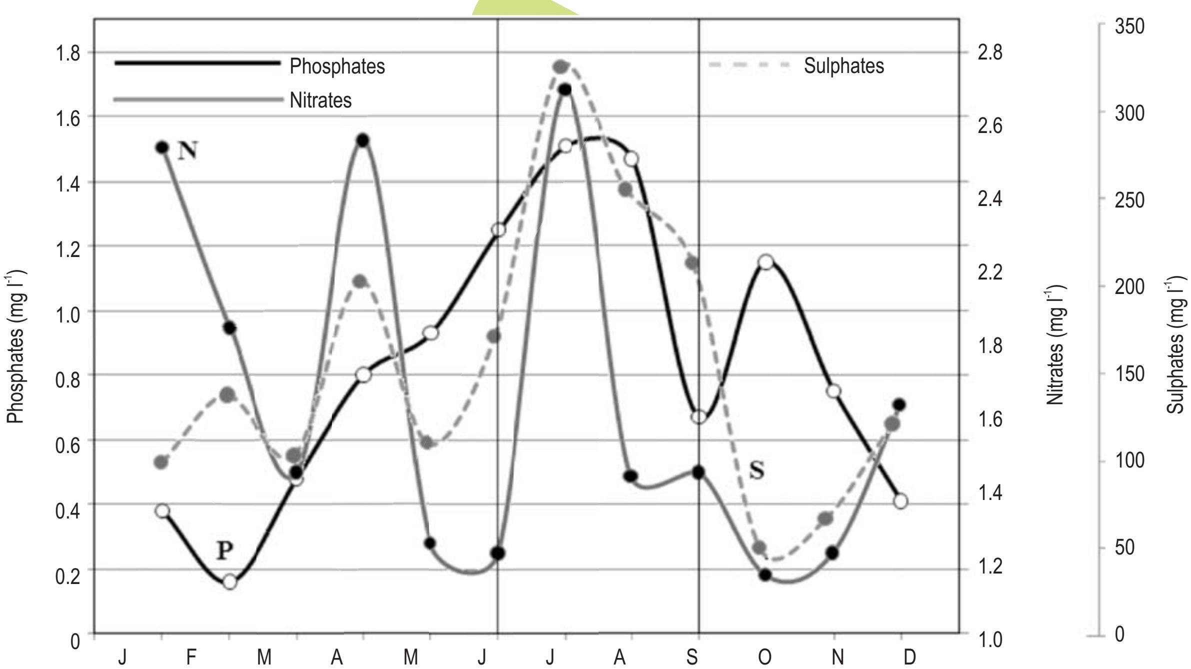

Fig. 7 : Annual fluctuation in the concentration of nitrates, phosphates and sulphates at Ranchi lake

system. One of the findings was a fine correlation ($r = -0.8601$; $p > 0.0001$) of the phytoplankton abundance with TOC/TIC ratio (Fig. 12) as given below :

$$\Delta \text{Phytoplankton}(\text{nos.} \times 10^5) = -4.8126 \Delta \log \text{TOC/TIC} + 0.4160 \quad \text{Eq.11}$$

In the next step, relationship using the stepwise system analysis and the basic functional relationships was derived. The phytoplankton population maintained a constant bloom using nutrients such as nitrates and phosphates, which were non-limiting:

$$\Delta \text{Phytoplankton (nos.} \times 10^5 \text{ cells per liter)} = \Delta \text{NF (mg l}^{-1}\text{)} - 0.3645 \ (r = 0.80) \quad \text{Eq.12}$$

Nitrate and phosphate concentration depended on the decomposition of organic matter as represented below :

$$\Delta \text{NF(mg l}^{-1}\text{)} = -0.3921 \Delta \text{TOM (mg l}^{-1}\text{)} + 0.1904 \ (r = -0.71) \quad \text{Eq.13}$$

The total organic matter contained organic carbon; from the data collected relation between the flux of total organic matter and total carbon is given as follows:

$$\Delta \text{TOM (mg l}^{-1}\text{)} = 1.6268 \Delta \text{TOC (mg l}^{-1}\text{)} - 0.2369 \ (r = 0.975) \quad \text{Eq.14}$$

Decomposition of organic carbon released inorganic carbon that added to the total inorganic carbon of the system:

$$\Delta \text{TOC (mg l}^{-1}\text{)} = -1.660 \Delta \text{TIC (mmoles l}^{-1}\text{)} - 0.7072 \ (r = -0.774) \quad \text{Eq.15}$$

The total inorganic carbon in turn controlled the TOC/TIC ratio as represented below :

$$\Delta \text{TIC (mmoles l}^{-1}\text{)} = -2.7607 \Delta \log \text{TOC/TIC} + 0.2744 \ (r = -0.8130) \quad \text{Eq.16}$$

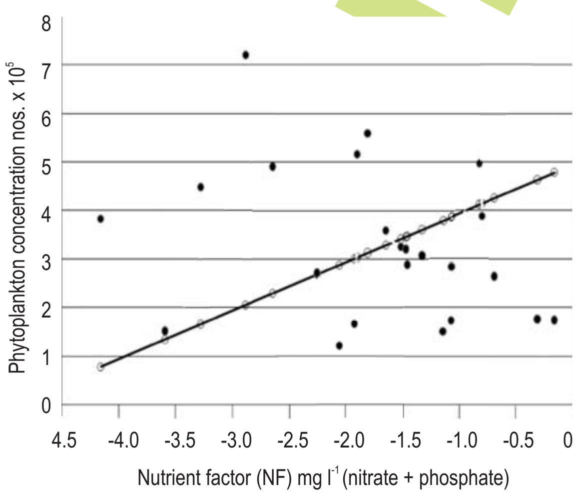

Fig. 8 : Positive correlation between nutrient factors and growth of phytoplankton at Ranchi lake

On combining equation 23-27, in order to build a final model so that the model could predict the changes in the phytoplankton concentration of the lake based on the chemical rhythm of the system:

$$\Delta \text{Phyto (nos.} \times 10^5 \text{ cells per liter)} = -2.1139 \Delta \log \text{TOC/TIC} + 0.6663 \quad \text{Eq.17}$$

Equation 28 shows changes in the phytoplankton community based on the dynamics discussed stepwise in the box model, and the rate processes mentioned in the system dynamics model. Fig. 13 shows the actual fluctuation (a); and the prediction (b) from equation 28. A close correlation between the two, validated the stepwise consideration of the dynamics of the system in this study.

We addressed the question how to model the diversity and dynamics of the phytoplankton population in a eutrophic environment and what are the determinants that control the system? This was a part of our effort to model the system and study the changes that occur in the system for planning management strategies.

Eutrophication model provided a good representation of system dynamics and factors controlling the phytoplankton rhythm. A unique feature of the model was its stability in the face of a constant stress that the lake was subjected to. In contrast to models provided by Zhang *et al.*(2004) and Arhonditsis and Brett (2005), the present model was relatively simple but provided a good explanation of the system dynamics in the face of continued stress.

The phytoplankton community at Ranchi showed a complete departure from normal conditions. High nutrient concentration maintained a high population, in the range of 3.7×10^5 cell units l^{-1}. The study showed dominance of two major

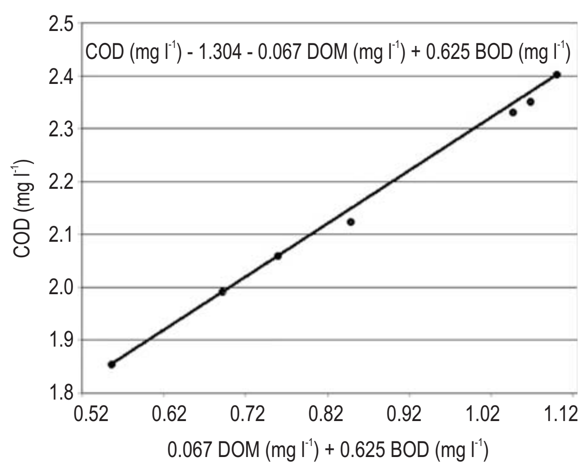

Fig. 9 : Multiple correlations between COD, DOM and BOD. There is a complex relationship between the three due to the influx of inorganic and organic matter into the system

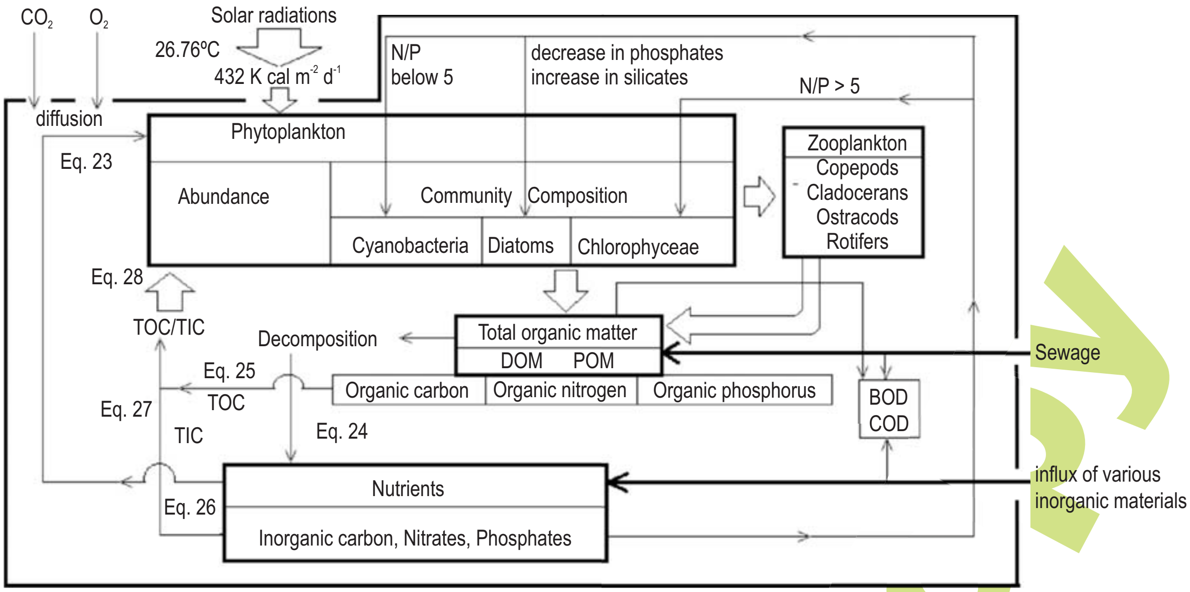

Fig. 10 : Showing a flowchart of the system dynamic model and the use of correlation equations at definite points

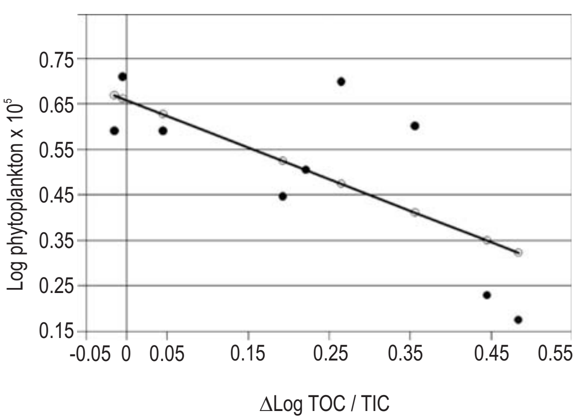

Fig. 11 : Correlation between the phytoplankton concentration and the TOC/TIC ratio. The ratio controls the abundance of phytoplankton at Ranchi lake

groups: Cyanobacteria and Bacillariophyceae. January peak was dominated by Bacillariophyceae while, the peak in May and December was dominated by Cyanobacteria. The major species of Cyanobacteria were *Gloeocapsa punctata* and *Microcystis flos aquae* and that of Bacillariophyceae included *Nitzschia palea* and *Navicula radiosa*, respectively.

Cyanophycean bloom is primarily warm water phenomenon and the range for optimum growth was 28.8-30.5°C, especially in organically polluted waters. At Ranchi lake however, Cyanobacteria showed dominance, starting from April and continued till December even at low temperature in the range of 22.4 – 26ºC. Only in January, at 22.3ºC, low BOD, COD and DOM; with low phosphate and high nitrate concentration and with an N/P ratio of 5.5, Chlorophyceae reached moderately high level. At other times, the three groups: Chlorophyceae, Chrysophyceae and Euglenophyceae remained at low to moderate levels.

An increase in the nutrient factor initiates the growth of the phytoplankton. Shortage of nitrogen and phosphorus generally limits the productivity of freshwater systems, due both to its immobilization in the biota and the insolubility of the compounds. If phosphorus alone is increased the cyanobacteria which are capable of fixing nitrogen, generally dominate the phytoplankton community. Indeed we can predict the dominance of different types of algae from the balance between nitrogen and phosphorus. Berthon *et al.* (1996) states, that the threshold level of N/P ratio for algae is greater than 7. When, the ratio falls below 5 the green algae collapse giving way to the cyanobacteria. At Ranchi Lake the N/P ratio remains above 5 from January to March, throughout rest of the year it remains below 5. Thus from January to March we have a moderate abundance of chlorophyceae, chrysophyceae, bacillariophyceae, and euglenophyceae but, throughout the rest of the year cyanobacteria dominates when the N/P ratio is below 4 (Fig. 14). Thus the N/P ratio is such that it favours the growth of cyanobacteria.

Rasanen (2006) report from their studies on Ten Finnish Lakes that the abundance of diatom genera such as *Nitzschia*, *Navicula* and *Fragilaria* occur in lakes with high nutrient concentration, specially phosphates and the abundance of diatoms at Ranchi lake is in conformity to the above observation. Schelske (1971), states that diatom growth is dependent on supplies of available silica, which tends to decrease with phosphorus enrichment. At Ranchi lake the concentration of

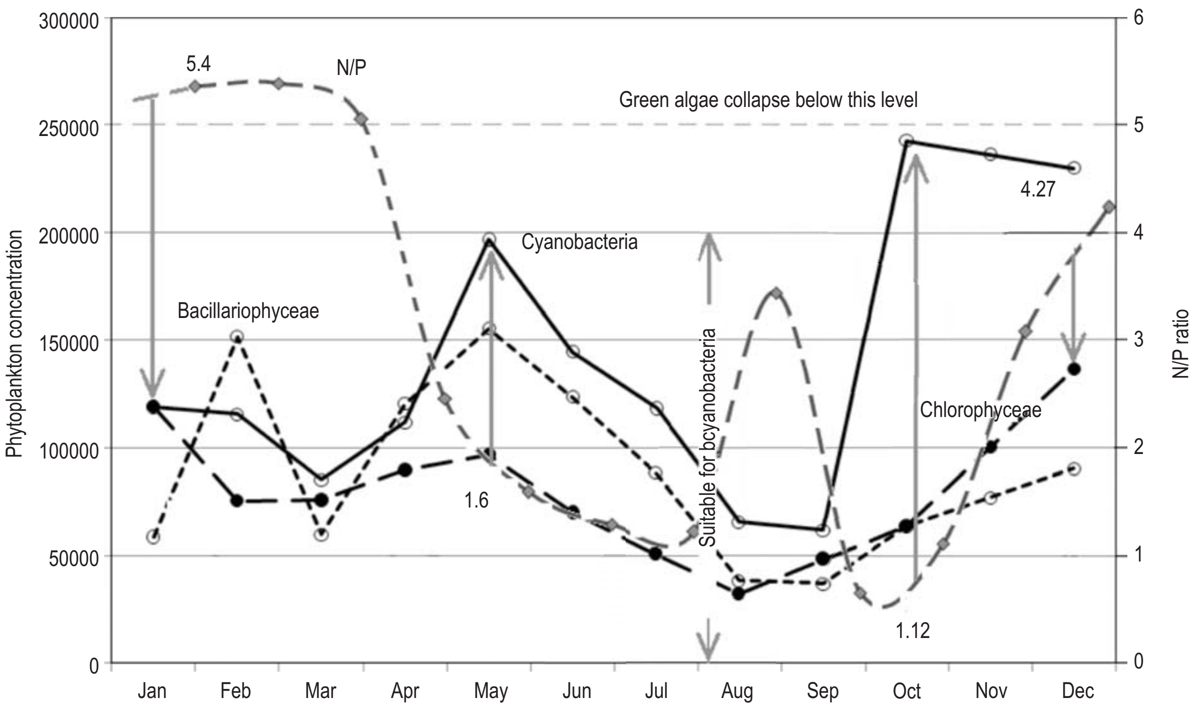

Fig. 12 : Showing the flux in the N/P ratio and changes in the various groups of phytoplankton during an annual cycle

silicates is relatively high (5.29 mg l^{-1}) and the diatoms show a high abundance from January to March when the phosphate concentration is relatively low (0.34 mg l^{-1}).

Murphy (1976) has demonstrated that during the cyanobacterian blooms, population growth of other algae can be strongly suppressed due to secretion of toxins. These toxins along with the altered niche conditions completely change the plankton community composition of the lake.

King (1970) has discussed the succession of green algae followed by the mid-summer bloom of blue greens. According to Novak and Brune (1985) the green algae grow rapidly between 21 - 27°C, while above and below this temperature growth decreases. With the advent of summer (30 - 35°C) the green algae decline and as the excess algae fall to the bottom, the bacterial activity increases. The net effect is oxygen depletion in the lower layers and low carbon dioxide in the upper layers. This sets the stage for the growth of the cyanobacteria because they can function at lower levels of carbon dioxide and are able to tolerate high temperatures. Thus in the absence of competitors they show a massive bloom.

Kuentzel (1969), states that one of the key factors in non-limiting conditions is a bacterial bloom before the algal bloom in order to provide enough free carbon dioxide to support the phenomenon. This is also supported by the studies of King (1970). Surely the freshwater lake system at Ranchi has more than sufficient organic matter for decomposition by the bacterial population and release of free carbon dioxide. At Ranchi lake decomposition of organic matter releases free carbon dioxide. The DOM shows a good negative correlation with free carbon dioxide. At Ranchi lake the free carbon dioxide concentration shoots up during January, May and December (consequently the pH decreases: 7.0 - 8.5) that triggers the growth of the phytoplankton. There is a good negative correlation between free carbon dioxide and phytoplankton implying that as the phytoplankton population increases, the free carbon dioxide decreases. Therefore, in these waters free carbon dioxide may be considered as a limiting factor.

With a high concentration of nitrates, phosphates and chlorophyll, Ranchi lake can be classified as hyper-eutrophic (Table 3) with free carbon dioxide as the limiting factor that controls the lake metabolism and community structure. Thus, a data based process oriented model was presented here to take into account the chemical and biological interactions.

Acknowledgment

Acknowledgments are due to the University Grants Commission, New Delhi for financial support through UGC major project no. project No. F. 38-180/2009(SR) entitled "Impact of cultural eutrophication on the plankton diversity and dynamics in freshwaters of Ranchi".

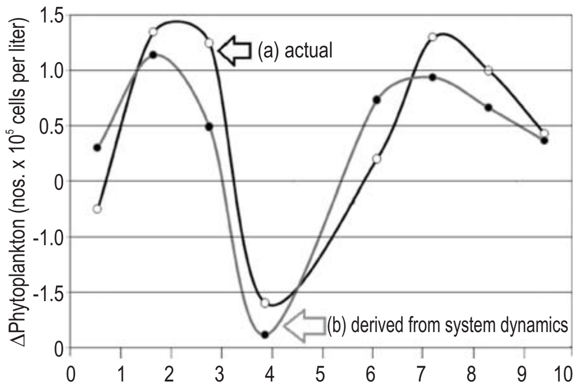

Fig. 13 : The actual and predicted flux of phytoplankton based on actual our model output

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