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Nutrient cycling in a simulated pond ecosystem

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Abstract: *Mathematical modeling of ecosystems requires a considerable amount of knowledge about the subsystems functioning within the broad framework and the various rate processes and transfer coefficients that control the dynamic aspects. A detailed analysis of the transfer rates and budget of inorganic carbon and nutrients in a simulated pond was conducted for assessment and comparison with aquatic bodies that undergo cultural eutrophication. In these systems the processes are complicated by a variety of inputs. Such inputs interfere with the assessment of lake background conditions and water quality. We used the compartmental model of biogeochemical cycling to calculate transfer rate of inorganic carbon and nutrients through various processes. The major external variables or forcing functions considered were light and temperature, while the state variables included the biotic and the abiotic compartments. The major processes studied were: photosynthesis, respiration and decomposition that play an important part in balancing the nutrient content of the system and maintain a dynamic equilibrium. The study illustrates how computational modeling studies are useful for analysis and management of systems for control and optimization of processes. The system shows a perfect cycling of carbon and the rate of withdrawal is equal to the return keeping the system in balance. About 0.284 m moles l^{-1} is withdrawn from the reservoir for primary production each day and returned back through respiration and decomposition. The concentration of nitrates and phosphates resonate in tune with the utilization of carbon and productivity.*

Key words: *System analysis, Carbon budget, Carbon speciation, Photosynthesis, Respiration, Decomposition, Phosphates, Nitrates*
PDF of full length paper is available with author ***(*bm_ebag@rediffmail.com.)***

Introduction

A common approach to ecosystem modeling has been to define such units in terms of a series of compartments: producers, consumers, and decomposers linked by equations describing the energy or material cycling (Bertalanffy, 1972; Beck, 1983; Odum, 1982; Beeby, 1993; Wirtz, 2000 ; Benz *et al.,* 2001; Kompare *et al*., 2001; Todorovski, 2003; Wilcock and Chapra, 2005; Atanosova *et al.* 2006). This took the form of energy flow diagrams and nutrient cycling models using reservoirs (nutrient pools) and transport pathways along which material and energy was transferred from one compartment to the other (Fig. 1) and maintained a dynamic equilibrium.

One of the most general definitions of a system were given by Bertalanffy (1972) and Beeby (1993). They define a system as a set of components interrelated between each other and with the environment. The components are connected with relations that usually represents exchange of matter, energy and information. The relations that influence the components are called input to the system and those which have influence on the environment are output from the system. Having this definition in mind we can conceptualize an aquatic system through the following groups of variables (Beck, 1983): (i) independent variables also called forcing or driving functions (such as light and temperature); (ii) dependent variables, also called state or endogenous variables (such as inorganic nitrogen, phosphates and carbon, dissolved oxygen, and biota); (iii) rate processes that quantify the flow of energy, materials or information moving between components (the rate of photosynthesis for instance, or the rate of phosphorus uptake) .

In this paper we describe the conceptual modeling of carbon and nutrient cycle in a simulated pond ecosystem and implications of the interaction between inorganic carbon, pH, light, temperature and nutrients. Results of this model can be used to assess background conditions of complex systems such as culturally eutrophicated waterbodies and polluted systems that undergo wide displacement from homeostatic conditions due to stress that develops form the influx of a wide variety of substances.

Materials and Methods

For our study we created a pond ecosystem within the college campus. Fig. 2 represents a satellite image of the same. The pond has an area of about 56 meter square. The biotic compartment included three sub compartments: (a) producers consisting chiefly of the submersed aquatic weed *Hydrilla verticillata*; (b) consumers, represented by the fish Tilapia (*Oreochromis mossambicus*) and (c) the decomposers.

The abiotic compartment was nutrient controlled. The initial concentration of nitrates, phosphates and inorganic carbon were set at 4.27 mg l^{-1}, 0.27 mg l^{-1} and 0.55 mmoles l^{-1} by adding measured amounts into the system, while the sulphate concentration of the system was found to be adequate (37.27 mg l^{-1}) and thus was not altered. The pond was left to mature for a year. By April 2006 the concentration of nitrates, phosphates and inorganic carbon were stabilized around 0.9 mg l^{-1}, 0.11 mg l^{-1} and 0.735 mmoles l^{-1} respectively.

Table - 1: Analysis of the photosynthetic activity based on the changes in concentration of different carbon species (23.11.05)

Time (hr)	pH	Alkalinity	Species of inorganic carbon (m moles l^{-1}) ΣC_t	H_2CO_3	HCO^{3-}	CO_3^{2-}
0630	7.94	0.6	0.6134	0.0159	0.5950	0.0025
0700	7.98		0.6117	0.0145	0.5945	0.0027
0730	8.05		0.6091	0.0123	0.5936	0.0032
0800	8.27		0.6021	0.0074	0.5895	0.0053
0830	8.56		0.5936	0.0037	0.5798	0.0101
0900	8.85		0.5827	0.0018	0.5618	0.0191
0930	9.04		0.5726	0.0011	0.5428	0.0286
1000	9.06		0.5713	0.0011	0.5404	0.0298
1030	9.12		0.5672	0.0009	0.5326	0.0337
1100	9.28		0.5542	0.0006	0.5072	0.0464
1130	9.35		0.5474	0.0005	0.4939	0.0531
1200	9.57		0.5214	0.0003	0.4422	0.0789
1230	9.53		0.5267	0.0003	0.4527	0.0736
1300	9.64		0.5116	0.0002	0.4228	0.0886
1330	9.68		0.5057	0.0002	0.4111	0.0945
1400	9.67		0.5072	0.0002	0.4141	0.9296
1430	9.79		0.4886	0.0001	0.3769	0.1115
1500	9.82		0.4837	0.0001	0.3671	0.1164
1530	9.86		0.4770	0.0001	0.3539	0.1230
1600	10.01		0.4514	0.0001	0.3027	0.1487
1630	9.74		0.4966	0.0002	0.3928	0.1036
Total			**- 0.1168**	**- 0.0157**	**- 0.2022**	**+ 0.1011**

$\Sigma C_t = H_2CO_3 + HCO^{3-} + CO_3^{2-} = -0.0157 - 0.2022 + 0.1011 = -0.1168$

Parameters such as light, temperature, pH, oxygen, inorganic carbon, nitrates, sulphates, phosphates, dissolved organic matter and BOD were monitored daily. Light intensities were measured using a lux meter while, temperature DO and pH were measured using a combined pH-DO meter supplied by Eutech instruments. Chemical analysis of phosphates, nitrates and sulphates was done using standard methods (APHA, 2005). Values for total inorganic carbon, free carbon dioxide, carbonates and bicarbonates were calculated using the basic dissociation equation for polyprotic acids (Christian, 1986) and a program developed by our group for this purpose (Mukherjee, 2002, 2007).

Table - 2: The carbon budget (m moles l^{-1} d^{-1}) of the simulated pond system at Ranchi

Total inorganic carbon	Withdrawal	Return	Balance
0.6134003	Photosynthesis 0.284	1. Respiration a. producers 0.15 b. consumers 0.02 2. Decomposition 0.034	negative - 0.08 balanced by diffusion
Total	**0.284**	**0.204**	

The pool of dead organic matter was estimated by measuring the organic content of the bottom mud and the dissolved and particulate organic matter present in the water. Respiration by hydrilla was measured using dark cylinders (Teal, 1957), while that of fishes was estimated using a respirometer. The rate of decomposition was estimated from BOD and verified by changes in carbon dioxide and oxygen concentration of cylinders pushed into the bottom mud. The diffusion of oxygen and carbon dioxide was measured by the method of Odum (1956), Odum and Hoskin (1958) and Chengxin *et al.* (2005).

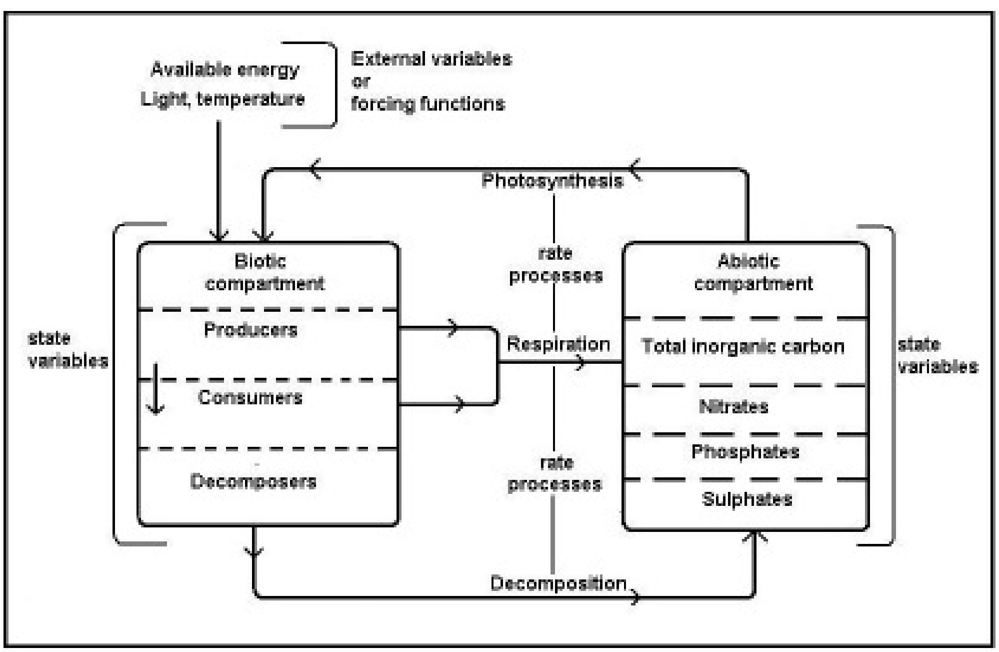

Fig. 1: The compartmental model of an aquatic ecosystem showing nutrient pools and transport pathways

Fig. 2: Figure showing the simulated system within the college premises

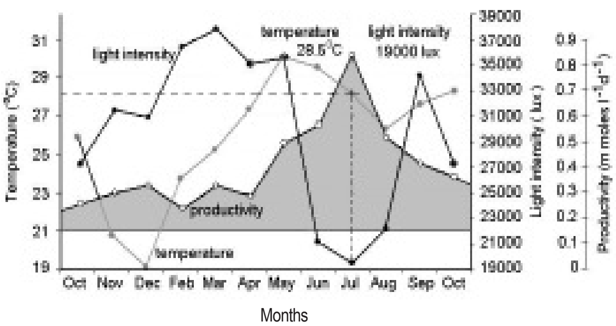

Fig. 3: Average water temperature and light intensity during an annual cycle in the simulated pond

Results and Discussion

Light and temperature: Light intensities showed enormous variations with seasons. Fig. 3 shows the average water temperature and light intensity recorded during an annual cycle. Maximum average light intensity was found in March while, the minimum in June, July and August representing the onset of the rainy season. Temperature was maximum in May (30.11ºC) and minimum in December (19.15ºC).

The optimum temperature for photosynthesis in *Hydrilla* is 36.5°C and require the least irradiance to reach half-maximal photosynthetic rate (Van *et al.* 1976). Light saturation of photosynthesis in these macrophytes occurs at 600- 700 µ moles $m^{-2}sec^{-1}$. In our

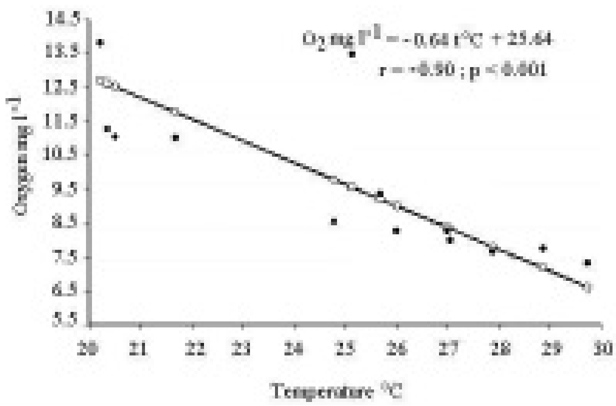

Fig. 4: Correlation graph of oxygen versus temperature in the simulated pond

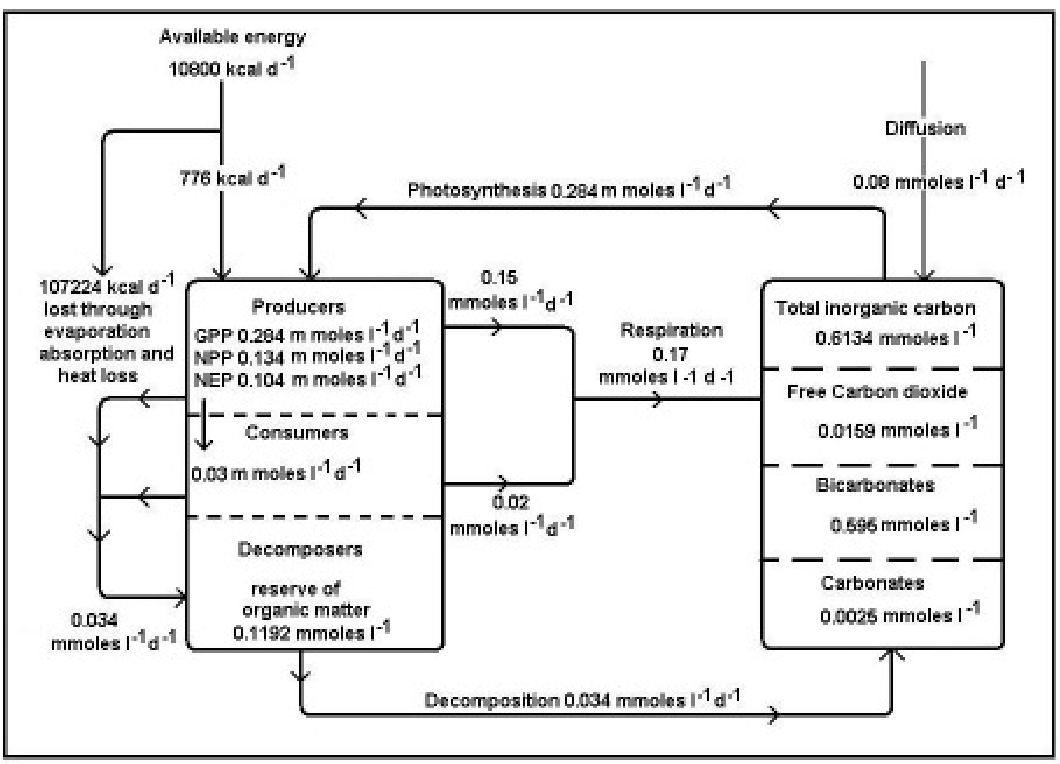

Fig. 5: The carbon cycle of the simulated system depicting pools and transfer rates of inorganic carbon

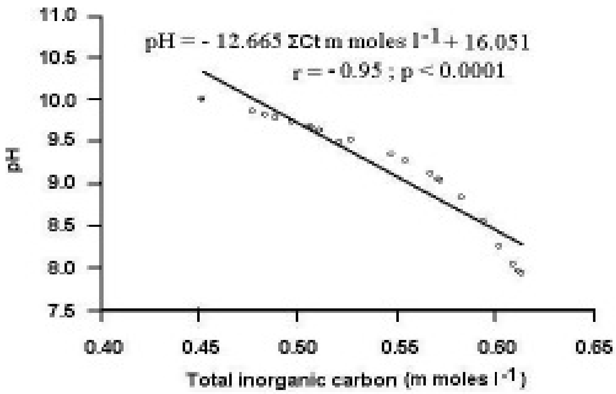

Fig. 6: Correlation between pH and total inorganic carbon in the simulated pond

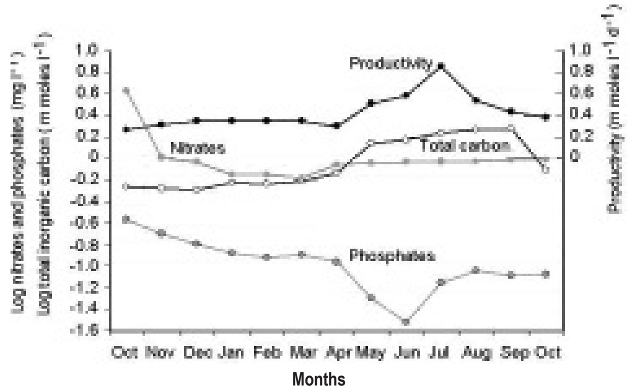

Fig. 8: Changes in nutrients with productivity in the simulated pond

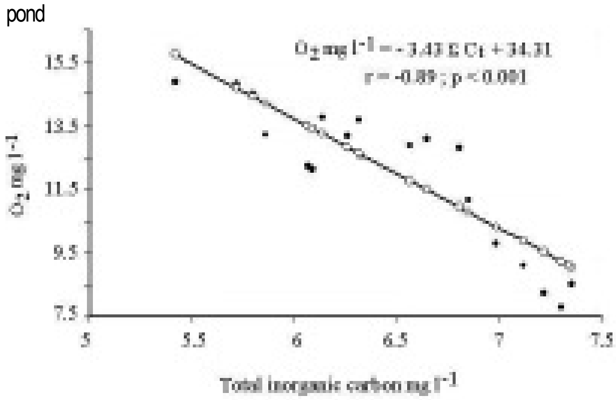

Fig. 7: Correlation between total inorganic carbon and oxygen in the simulated pond

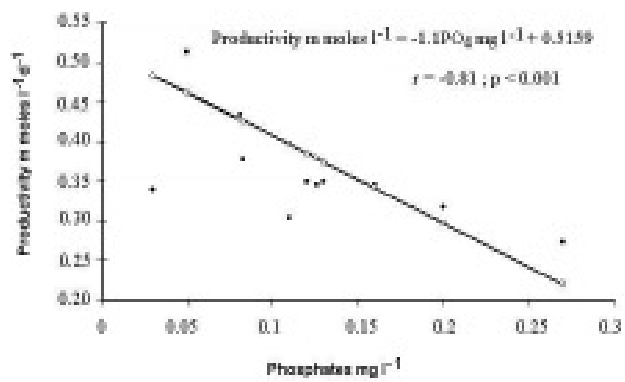

Fig. 9: Correlation between phosphates and productivity in the simulated pond

studies we found that a combination of temperatures around 28.5ºC and light intensities of about 19000 (400 μ moles $m^{-2}sec^{-1}$) was optimum for primary productivity by *Hydrilla*.

Temperature and oxygen: Oxygen has an inverse relationship with temperature. Oxygen sharply increases with the decrease in temperature in November and decreases rapidly with the onset of higher temperatures in March. The correlation between temperature and oxygen (Fig. 4) in our simulated pond can be represented by the following equation:

O_2 mg l^{-1} = - 0.64 t°C + 25.64 (r = - 0.90 ; p < 0.001) Eq.1

In fact the diurnal cycle is predominantly controlled by the metabolic rhythm of the biota. Since the oxygen saturation increases to 200 percent by the end of the day, diffusion plays an important part in controlling the oxygen concentration of the system. The diffusion coefficient in the pond was found to be about 0.19 g m^{-2} hr^{-1}. Similar oxygen saturation has been reported by Van *et al*. (1976) for *Hydrilla* mats. They found that most of the photosynthetic activity occurred in the morning when free CO_2 was highest and solar radiation lowest. The low light requirement of *Hydrilla* provides a competitive advantage in comparison to other submersed aquatic plants.

Total inorganic carbon: The major reservoir of inorganic carbon is the free and bound carbon present in the aquatic system (Fig. 5). The major uptake from the reservoir is due to the fixation of carbon dioxide to organic carbon through the process of photosynthesis by the producers. This organic carbon then moves through the food chain via the consumers and then to the decomposers. The other components have been left out to simplify the process. The major return pathway to the reservoir is via the respiratory process taking place in the producers and consumers, and decomposition of organic matter by the decomposers.

Carbonic acid is a polyprotic that is, it has more than one ionizable proton, and the distribution of the different species is a function of the pH. It is thus possible to calculate the fraction of the total inorganic carbon (ΣCt) that exists in a given form under a specific pH and alkalinity. The changes in pH show a good correlation (Eq. 2) with changes in total inorganic carbon (Fig. 6).

pH = - 12.665 ΣCt (m moles l^{-1}) + 16.051 (r = - 0.95; p < 0.0001) ....Eq. 2

Table 1 represents the changes in total and the different forms of inorganic carbon during a photosynthetic period. The values were calculated by a program developed by us for the purpose. Initially the bicarbonate ions increase as photosynthesis proceeds but, when free carbon dioxide becomes exhausted, the bicarbonate ion breaks down into carbonates and free carbon dioxide to maintain photosynthesis.

$2HCO_3^- \rightarrow CO_2 + CO_3^{2-} + H_2O$ .....Eq. 3

The use of HCO_3^- is a carbon-concentrating mechanism, and often coupled to a C4 metabolism, as has been reported for *Hydrilla verticillata* (Holaday and Bowes, 1980; Reiskind *et al*., 1997).

We are now ready to construct a carbon cycle model for our simulated aquatic system (Fig. 5). In the abiotic compartment the total inorganic carbon was 0.6134 m moles per liter, the average phosphate concentration was 0.12 mg l^{-1} and the average nitrate concentration recorded was 1.102 mg l^{-1}. This served as the nutrient base for the macrophytes (*Hydrilla*).

The available energy was 10800 kcal per day of which 7.2 percent (776 kcal) was utilized for photosynthesis and subsequent production of organic matter. About 0.284 m moles per liter of inorganic carbon was drawn from the abiotic reservoir. This represents gross primary production. Of the total gross production about 53 percent (0.15 m moles per day) was returned back by the primary producers into the reservoir through respiration, retaining about 0.134 as net primary production. Of the total net production about 0.03 m moles were taken up by the consumers and the net ecological production retained in the producer compartment was 0.104 m moles per liter per day.

Of the total carbon taken up by the consumers, about 0.02 m moles of inorganic carbon was returned back to the reservoir through respiration retaining about 0.01m moles of carbon per day in this compartment. Tilapia feeds on a wide variety of potential food including plankton, organic detritus and aquatic weeds (Lasher, 1967; Mallin, 1985; Whetstone, 2002; Malcolm and Baird, 2000). About 10-15 percent of the primary production is converted into fish tissue (Beveridge, 1984) and the fresh fish carbon content is about 10 percent of the body weight. In our studies we found the transfer of primary productivity to be close to 10 percent while, the respiratory loss to be about 67 percent.

In the decomposer compartment the available dead organic matter was about 0.1192 m moles of which 0.034 m moles was returned daily to the inorganic reservoir through decomposition and in order to maintain the rate , the transfer of dead organic matter from the producer and consumer compartment was of the same value. Table 2 represents the budget of inorganic carbon of the simulated system. There is a negative balance of about 0.08 m moles per liter per day representing utilization for the growth of the producers and consumers. This can be accounted as follows: the retention in the producer compartment is 0.104 m moles while that in the consumer compartment is about 0.01 m moles. So, the total retention is equal to 0.114 (0.104 + 0.01) m moles. Of this about 0.034 m moles is transferred to the decomposer compartment therefore the net retention is 0.08 (0.114-0.034) m moles. Since the total inorganic carbon remains close to the original value next day, this deficit is balanced by diffusion. So the system serves as a sink for carbon dioxide, absorbing the same from the atmosphere.

Thus our simulated pond system shows a perfect cycling of carbon and the rate processes are such that they keep the inorganic carbon reservoir in equilibrium. A similar result was found in a simulated aquarium (Mukherjee *et al.* 2007) although the transfer rates were slower in comparison. The pattern of gross production, net production and respiration (0.142; 0.067; 0.075 moles m^{-2} d^{-1}) is comparable to values obtained by Szyper and Ebeling (1993). Kelly *et al.* (1984) in their studies in acidified experimental lakes found the decomposition rate to be about 6.185 m moles m^{-2} d^{-1}. In our system the rate of decomposition was found to be relatively high, about 17 m moles m^{-2} d^{-1} in predominantly alkaline conditions.

The increase in oxygen shows a good correlation (Eq. 15: $r = -0.899$: $p < 0.001$) with the decrease in total inorganic carbon due to photosynthesis (Fig. 7).

$$O_2 \text{ mg } l^{-1} = -3.43\ \Sigma Ct \text{ (mg } l^{-1}) + 34.39 \quad \text{.....Eq. 4}$$

The diffusion coefficient calculated by the method of Odum (1956) was found to be 0.19 g m^{-2} hr^{-1}.

Cycling of nitrates and phosphates: In our study we found that the initial growth of the macrophytes was controlled both by nitrates and phosphates. In fact when the macrophytes were establishing themselves, there was a sharp decrease in the nitrates (Fig. 8) but then equilibrium was established between the rate of input and output so that the nitrates fluctuated at a mean level. The later part of the growth and productivity was greatly influenced by the phosphate concentration and Fig. 9 shows a good correlation (Eq. 10: $r = -0.81$; $p < 0.001$) between the increase in productivity and the decrease in the phosphate concentration of the system.

$$\text{Productivity (m moles } l^{-1}) = -1.1\ PO_4\text{-P mg } l^{-1} + 0.5159 \quad \text{....Eq. 5}$$

The cycling of phosphorus is relatively fast to maintain a mean phosphate level of 0.11 mg l^{-1} in the reservoir compartment. Sulphates did not have a major effect and the concentration varied around 40 mg l^{-1}.

The average C:N:P ratio was found to be 170: 11: 1. The ratio increased considerably during the period of maximum primary production, decreasing again with the decrease in productivity. Such decreases as a function of decrease in light availability and low temperatures have been reported by Armitage *et al.* (2005); Iqbal *et al.* (2005).

Thus our simulated system system shows a perfect cycling of carbon and the rate of withdrawal is equal to the return keeping the system in balance. About 0.284 m moles l^{-1} is withdrawn from the reservoir for primary production each day and returned back through respiration and decomposition. The concentration of nitrates and phosphates resonate in tune with productivity.

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References

APHA: Standard methods for examination of water and wastewater, 21st Edn., Washington, DC (2005).

Armitage, A.R., T.A. Frankovich,, K.L. Heck Jr. and J.W. Fourqurean:. Experimental nutrient enrichment causes complex changes in seagrass, microalgae, and macroalgae community structure in Florida Bay. *Estuaries*, **28**, 422-434 (2005).

Atanosova, N., L. Todorovski, S. Dzeroski and B. Kompare: Constructing a library of domain knowledge for automated modelling of aquatic ecosystems. *Ecol. Model*., **194**, 14-36 (2006)

Beeby, A.: Applying Ecology. Chapman and Hall, London (1993).

Beck, M.: A Procedure for Modeling. *In*: Mathematical modeling of water wuality: Streams, lakes and reservoirs (*Ed.*: G. Orlob). John Wiley and Sons, Chichester. p. 42 (1983)

Bertalanffy, L.: The history and starts of general system theory. *In*: Trends in general systems theory (*Ed.*: G.J. Klir). John Wiley Sons Inc., New York (1972).

Benz, J., R. Hoch and T. Legovic: ECOBAS – Modelling and documentation. *Ecol. Model*., **138**, 3-15 (2001).

Chengxin, F.A.N., H.U. Weiping, P.W. Ford, C.Yuwei, Q.U. Wenchuan and Z. Lu: Carbon dioxide partial pressures and carbon fluxes of air-water interface in Taihu lake, China. *Chin. J. Oceanol. Limnol*., **23**, 29-38 (2005).

Christian, G.D.: Analytical chemistry. John Wiley and Sons, New York (1986).

Holaday A.S. and G. Bowes G: C4 acid metabolism and dark CO_2 fixation in a submersed aquatic macrophyte (*Hydrilla verticillata*). *Plant Physiol*., **65**, 331-335 (1980).

Iqbal, M.Z., E.J. Brown and M.E. Clayton: Distribution of phosphorus in a biologically restricted lake in Iowa, USA. *J. Hydrol.,* **20**, 1-18 (2005).

Kelly, C.A., J.W.M. Rudd, A. Furtani and D.W. Schindler: Effects of lake acidification on organic matter decomposition in sediments. *Limnol. Oceanogr*., **29**, 687-694 (1984).

Kompare, B., L. Todorovski and S. D¡zerovski: Modelling and prediction of phytoplankton growth with equation discovery: Case study-LakeGlumsø, Denmark. *Verh. Int.Verein. Limnol*., **27**, 3626-3631 (2001)

Lasher, C. W., Jr.: *Tilapia mossambica* as a fish for aquatic weed control. *Prog. Fish Cult*., **29**, 48-50 (1967).

Malcolm, B. and D. Baird: Diet, Feeding and physiology. *In*: Tilapias: Biology and exploitation (*Eds.*: B. Malcolm and M.A. Brendan). Dordrecht: Kluwer Academic Publishers. pp. 59-87 (2000).

Mallin, M.A.: The feeding ecology of the blue tilapia (*T. aurea*) in a North Carolina reservoir. *Proc. Conf. Int. Symp. on App. Lake and Watershed Manage*., **5**, 323-326 (1985).

Mukherjee, B., P.N. Pandey and S.N. Singh: Mathematical modeling and system analysis of inorganic carbon in the aquatic environment. *Ecol. Model*., **152**, 129-143 (2002).

Mukherjee, B., D. Mukherjee, A. Prasad, A. and M. Nivedita: The transfer rates of inorganic carbon and budgetary analysis in a simulated aquatic system. *Ecol. Model*., **204**, 279-288 (2007).

Odum, H.T.: Primary production in flowing waters. *Limnol. Oceanogr*., **1**, 102-117 (1956).

Odum, H.T. and C.M. Hoskin: Comparative studies on the metabolism of marine waters. *Publ. Mar. Sci., Univ. Texas*, **5**, 16-46 (1958).

Odum, H.T.: Systems Ecology. John Wiley and Sons, New York (1982).

Reiskind, J.B., T.V. Madsen, L.C. Van Ginkel and G. Bowes: Evidence that inducible C-4-type photosynthesis is a chloroplastic CO_2-concentrating mechanism in Hydrilla, a submersed monocot. *Plant Cell Environ*., **20**, 211-220 (1997).

Szyper, J.P. and J.M. Ebeling: Photosynthesis and community respiration at three depths during a period of stable phytoplankton stock in a eutrophic brackish water culture pond. *Mar. Ecol. Prog. Ser*., **94**, 229-238 (1993).

Teal, J.M.: Community metabolism in a temperate cold spring. *Ecol. Monogr*., **27**, 283-302 (1957).

Todorovski, L.: Using Domain Knowledge for Automated Modeling of Dynamic Systems with Equation Discovery: Fakulteta zara'eunalni¡stvo in informatiko. University of Ljubljana, Ljubljana, Slovenia (2003).

Van, T.K., W.T. Haller and G. Bowes: Comparison of the photosynthetic characteristic of three submersed aquatic plants. *Plant Physiol*., **58**, 761-768 (1976).

Whetstone, J.M.: Demonstration of aquatic weed control by tilapia in South Carolina Ponds. *Proc. Aquatic Plant Manage. Soc., Inc*., **42**, 29-35 (2002).

Wilcock, R.J. and S.C. Chapra: Diel changes of inorganic chemistry in a macrophyte-dominated, softwater stream. *Mar. Freshwater Res*., **56**, 1165-1174 (2005).

Wirtz, K.W.: Second order up-scaling theory and an exercise with a complex photosynthesis model. *Ecol. Model*., **126**, 59-71 (2000).