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Utilization of Carbon in NPZ Model of Hooghly Estuarine System, India

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Abstract

Hooghly estuary along with the luxurious mangroves of the Sundarbans is one of the important estuaries of India. A quite rich mangrove forest patch in association with the creeks is visible at Sagar Island, the largest island in the row. Degradation and leaching of litter provides nutrient for the growth and development of phytoplankton which in turn strengthens the grazing food chain from zooplankton to fish. Phytoplankton growth is influenced by solar radiation, nutrient and temperature. The model incorporates light acclimation by algae, self-shading, photosynthetic production and nutrient uptake. Water quality changes with seasons. The model uses the functional relations among the three state variables as observed in response to the changeable environment throughout the year there. The model is calibrated and validated taking carbon as the currency of the model. Dissolved inorganic carbon as nutrient, water temperature, surface solar irradiance, and salinity of upstream and downstream of the estuary are collected from the field. Model results indicate that the growth of zooplankton and phytoplankton are enhanced by increasing nutrient input in the system. The predicted temporal distribution and trends of plankton biomass, inorganic carbon is in general agreement with field observations. Sensitivity analysis has been done. The model captures the dynamics of plankton population, which serve as major food source for fish species of the estuary. This model could be predictive in search for the role of mangrove in estuary and its control on nutrient and plankton dynamics of this region which will be helpful in management aspect.

Keywords: Mangrove; Sensitivity analysis; STELLA; Validation

Introduction

Rate of carbon fixation by phytoplankton is one of the most important biological processes and this is affected by a number of physical parameters. In spite of its huge impact on the whole living world, description on this aspect as a part of total carbon concentration has been scarce in literature till 1980s. But last two decades a number of works have been done on this topic in different ecological environments and depicting CO_2 as limiting nutrient and also as a basic physiological autotrophic process. Since carbon dioxide (CO_2) is the major greenhouse gas emitted by human activities, it is necessary to assess its sources and sinks, simulating the complex dynamics of CO_2 flows involved in the carbon balance. Many researchers have studied the plankton dynamics along with nutrient fluctuation in different systems. They have proposed a number of nutrient (N)-phytoplankton (P)-zooplankton (Z), i.e., NPZ models. These models emphasized on different aspects of this dynamics. Simple NPZ model with simple equations [1] describing the nature of the system, gradually become complex model with incorporation of complexity at different level of the model. A ten compartment model by Fasham et al. [2], described the detailed equation for plankton dynamics. Dual currency is latest modification in *NPZ* models to understand the impacts of multinutrient on phytoplankton growth dynamics [3,4]. Edwards [5] studied the dynamics of two plankton population models to investigate the sensitivities of model complexity and introduced detritus to traditional NPZ models. Those models were aimed to study the dynamics (steady state and oscillations) of four state variables (NPZD) but lacked simulation using any particular set of data. Ray and Straskraba [6] constructed nutrient-phytoplankton-zooplankton-detritus-fish model of the Hooghly-Matla estuary and studied the dynamics of NPZD in the presence and absence of detritivorous fish in the system. They concluded that this group of fish had no impact on primary production but played a major role in the total fish production.

This work is done on the same Hooghly-Matla estuarine system and follows similar formulation of NPZ model as described in Ray and Straskraba [6] but excluding the fish compartment. Dynamic models are useful diagnosing the current state of the ecosystems, and for exploring how the system might respond to future changes in environmental factors.

This work describes the structure and dynamics of a nutrient, phytoplankton, and zooplankton model for the estuarine system near Sagar Island. The model tracks the flow of nutrient (inorganic carbon) from the bottom of the food web (phytoplankton) to zooplankton which includes copepods, cyclopods, rotifers, some fish larvae etc. Higher order predators in the system are not directly incorporated as state variables in the model. Field data of environmental factors as forcing functions are used to simulate this model. This work is the extension of the previous work [7] where a simulation dynamic model is constructed describing the role of litrerfall of the adjacent mangrove forest as a source of nutrient (carbon) supply in this estuarine system. The objectives of the present work are to know – (i) the dynamic behaviour of plankton throughout the year in relation to the nutrient supply, (ii) the dynamics of nutrient and plankton in relation with environmental factors.

Materials and Methods

Description of study area

Sundarbans, vast lash green mangroves with distinctive faunal diversity, is located along the coastal line of Bay of Bengal, where the Ganges meets the sea (Figure 1). A wide variety of fishes harbour in the whole estuarine area and so the livelihood of the local people is mainly dependent on this ecosystem. The Sundarbans, a unique bioclimatic zone, is expanded over the borders of two countries- India and Bangladesh. A number of rivers, creeks and canals perforate the areas like a network [6,8]. Hooghly estuary, a meso-macrotidal estuary shows a wide mixing zone extending from Diamond Harbor to the mouth of the

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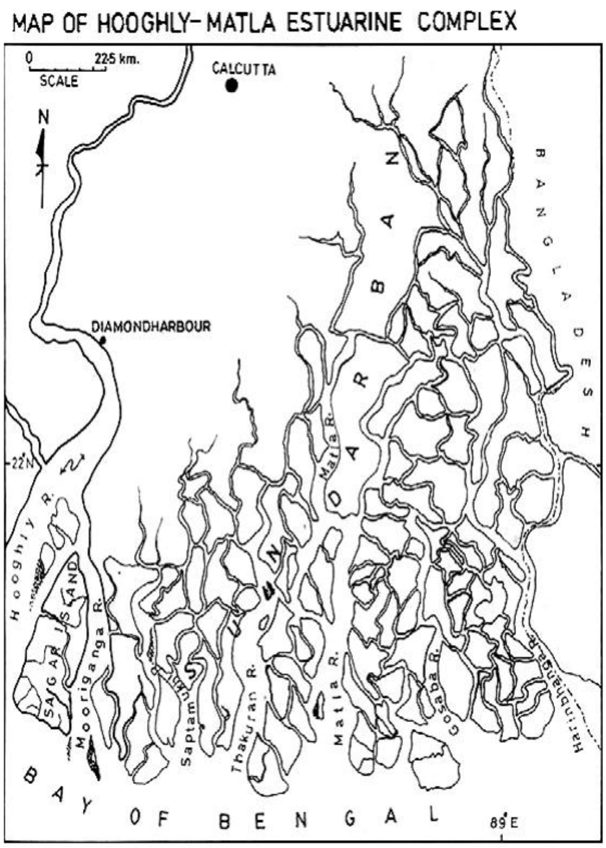

Figure 1: Study site - Hooghly Matla estuarine system.

river [9]. Sagar Island, the largest deltaic island in this estuarine complex, lying between 21°56′–21°88′ N and 88°08′–88°16′ E is located in the western sector of the estuary. The island is about 144.9 km^2 in area, and is surrounded by the river Hooghly on the north and northwest and the river Mooriganga on the east [10]. South western wind controls the monsoon here. During premonsoon when the river run off is low, temperature remains high and salinity is also very high. With the arrival of the monsoon nutrient and suspended matters are increasing.

This region is under the wet tropical climatic zone, with pronounced seasonal climatic changes. The seasons can be divided into pre-monsoon (March–June) with average high temperature ranging from 27–46°C and minimum rainfall; monsoon (July–October), when about 80% of annual rainfall occurs, and post-monsoon (November–February), with cold weather (average 23°C) and negligible rainfall. The monsoon season is generally dominated by southwest winds. The average humidity is about 80% and more or less uniform throughout the year. *Avicennia marina* (grey mangrove) is the dominant species among the halophytes of Sagar Island. *Avicenna alba*, *Porteresia coarctata*, *Excoecaria agallocha*, *Ceriops decandra*, *Acanthus ilicifolius* and *Derris trifoliate* are also present [11].

Experiments

Samples are collected from the creeks of Sagar Island. Some experimental and survey works are done over two years in the field to collect data for water temperature, water pH, dissolved inorganic carbon (DIC), water temperature, salinity, etc.

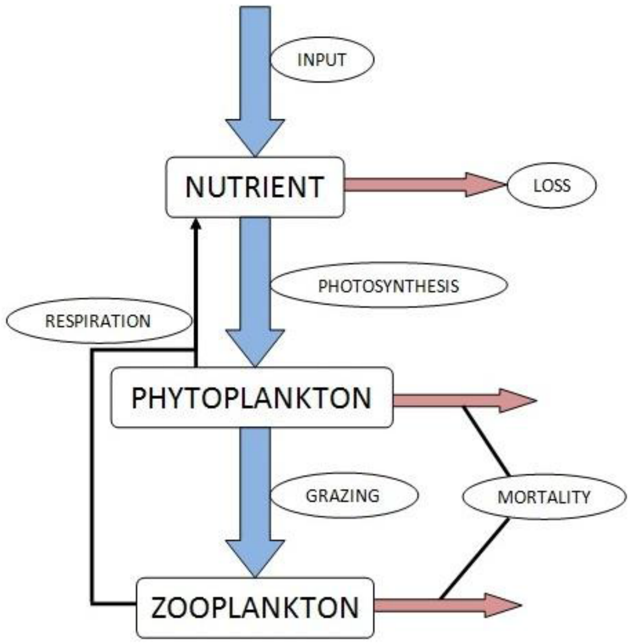

Figure 2 : Conceptual diagram of NPZ model.

Plankton are collected from surface water using a plankton net during high tide, and preserved with Lugol's iodine solution (phytoplankton) or buffered formaldehyde (zooplankton). For quantitative analysis of phytoplankton, wet and dry weights are measured and phytoplankton carbon content is calculated following the literature [12]. For zooplankton carbon, the Sedgewick Rafter counting method is employed to obtain the number of organisms and the corresponding carbon content is estimated following standard method [13].

Description of model

To observe the dynamics of *NPZ* throughout the year, STELLA 6.0 computer software (High Performance System Inc.) is used to construct a 3-state variable model (Figure 2). The model is integrated by using fourth-order Runge–Kutta method with a time step of 1 day. Carbon (mgC/l) is considered as currency in the model. Dissolved inorganic carbon (D_{IC}) in estuary is contributed by various sources and converted to other forms of carbon [7]. In the creeks of Sagar Island, input of D_{IC} to the system (I_{np}) is through various sources like diffusion of CO_2 at air-water interface, conversion from Soil Inorganic Carbon and Soil Organic Carbon to D_{IC} loss of nutrient, respiration of plankton (R_p and R_z). D_{IC} is converted to other forms of carbon (C_p) depending on pH of water. Phytoplankton uptake D_{IC} during photosynthesis (U). D_{IC} is removed from the system during tidal flash (L_1). Dynamics of D_{IC} is stated in equation 1.

$$\frac{dD_{IC}}{dt} = I_{np} + R_P + R_Z - U - C_P - L_1 \quad (1)$$

$$I_{np} = I_{npDIC} \quad (1.1)$$

$$C_P = r_{CP} \quad (1.2)$$

$$R_P = P \times r_{phy} \quad (1.3)$$

$$R_Z = Z \times r_{zoo} \quad (1.4)$$

$$U = P_{psyn} \times P \times D_{IC} / \left(D_{IC} + k_{DIC}\right) \tag{1.5}$$

$$L_1 = D_{IC} \times l_{rt1} \tag{1.6}$$

Uptake of D_{IC} by phytoplankton during photosynthesis is described in equation 1.5. Nutrient uptake by algae is generally described by a Michaelis-Menten (Type II) equation with the half- saturation constant serving affinity of phytoplankton for a particular nutrient [14]. Dynamics of phytoplankton in the estuary is balanced by uptake of D_{IC} during photosynthesis(U), grazing by zooplankton (G), respiration (R_p), natural mortality (M_p) and settling (S) and loss from the system (L_2) (Eq 2).

$$\frac{dP}{dt} = U - G - R_p - M_p - S - L_2 \tag{2}$$

$$G = D \times P \times Z \times g_{rt} / \left(P + k_Z\right) \tag{2.1}$$

$$D = 1/f \tag{2.2}$$

$$f = 1 - \left(S_r / S_e\right) \tag{2.3}$$

$$M_P = P \times m_{rP} \tag{2.4}$$

$$S = P \times s_{rt} \tag{2.5}$$

$$L_2 = P \times l_{rt2} \tag{2.6}$$

Michaelis–Menten kinetics is followed for grazing of zooplankton on phytoplankton (G). Phytoplankton (P), zooplankton (Z), and half saturation constant for phytoplankton grazing by zooplankton (K_z) are included in the grazing equation. G is also dependent on dilution (D) and grazing rate of zooplankton (g_{rt}) (Eq. 2.1). Because estuary is a transition zone of river and sea, there is always fluctuation of salinity throughout the year, which is because of dilution or mixing of water. D is calculated, equations (2.2) and (2.3), following [15], where f is the dilution factor, S_r is salinity of upstream, and S_e is salinity of downstream.

$$\frac{dZ}{dt} = G - P_r - E_x - R_Z - M_Z - L_3 \tag{3}$$

$$P_r = Z \times p_{rZ} \tag{3.1}$$

$$E_x = Z \times r_{ex} \tag{3.2}$$

$$M_Z = Z \times m_{rZ} \tag{3.3}$$

$$L_3 = Z \times l_{rt3} \tag{3.4}$$

Besides grazing, the abundance of zooplankton is also dependent on respiration (Rz), loss because of fish predation (P_r), and mortality (M_z), excretion (E_x) and loss from the system during tidal flush (L_3) (equation 3). All the parameter values and the initial values of the state variables are listed in Tables 1-3.

Sensitivity analysis

All the parameters are considered for sensitivity analysis which is the fundamental step before calibration. Sensitivity analysis attempts to provide a measure of the sensitivity of either parameters, or forcing functions, or submodels to the state variables of greatest interest in the model. Sensitivity analysis is performed using the following formula: S=(dx/x)/(dp/p) (Jorgensen, 1994), where S=sensitivity, x=state variable (here, DIC, P and Z), p=parameter, dx and dp are change of values of state variables, parameters and forcing functions respectively. Those parameters, which are almost impossible to calculate from field are calibrated using a range of values (minimum to maximum) collected from literature first and further the appropriate value for that parameter for this estuary are determined according to the best fit of the value during the model run by using standard calibration procedure [16].

State Variables		Value	Unit	Reference
DIC	Dissolved Inorganic Carbon pool	225	mgC/l	Field survey
P	Phytoplankton	0.39	mgC/l	Field survey
Z	Zooplankton	0.48	mgC/l	Field survey

Table 1: Description, initial values, units and references of the state variables of the model.

Graph Time Functions		Value	Unit	Reference
l_{npDIC}	Conversion rate of DIC to DBC	Graph	dimensionless	Field survey
S_e	Conversion rate of DIC to DCO_2	Graph	dimensionless	[17]
S_r	Conversion rate of DBC to DCO_2	Graph	dimensionless	[17]

Table 2: Description, values, units and references of the graph time functions of the model.

Model calibration and validation

Calibration is done by adjusting selected parameters in the model to obtain a best fit between the model calculations and the field data collected during first year of study period. Validation of the model is performed using data collected during second year of study period. The monthly average values of the state variables of first year and second year are used for calibration and validation of the model respectively. The model is simulated for the period of 365 days.

Results

Model result indicates that the state variable DIC is sensitive to $p_{psyn,}$ r_{tCP} and l_{rt1} (Table 4). If r_{CP} is increased and decreased 10% then DIC is increased or decreased by 4.5% and 4.8%, respectively. If l_{rt1} is changed (increase and decrease) by 10%, DIC values change by about 5%. If P_{psyn} is increased and decreased by 10% DIC increases 1.6% and 3.6%, respectively. Few forcing functions (g_{rt}, k_Z, r_{ex} and p_{rZ}) which are not sensitive at 1% level show little sensitivity when forcing functions are changed at 10% level. But the values are low, always below 0.5%. The variation of DIC throughout the year ranges between 140–320 mg/l. Field observations show DIC concentrations are higher in premonsoon (210–320 mg/l) and lower in monsoon (140–183 mg/l). Chi-square value for observed and simulated results of DIC shows that the discrepancy is not significant. Phytoplankton dynamics is directly proportional and highly sensitive to P_{syn}, r_{CP}, k_{DIC}, l_{rt1}, g_{rt}. The range of the state variable P throughout the year is very narrow. The value is lowest in monsoon due to the facts that during monsoon water column remains turbid and light penetration is lowered and also availability of DIC is lowered, so, growth of phytoplankton is diminished. Cyanophyta, Green algae, Euglenophyta, Dinophyta, Bacillariophyta, and Pinnate are different groups comprising of phytoplankton population. It is reported that not all these groups are encountered at a time rather representative genus of these groups appears at different seasons throughout the year [9,17]. In post monsoon (November to February), the phytoplankton growth is enhanced by favorable environmental conditions like less turbid water, sufficient

	Forcing Functions	Value	Unit	Reference
P_{psyn}	Photosynthesis rate	1.0002	day^{-1}	Calibrated
k_{DIC}	Half saturation constant for nutrient uptake by phytoplankton	0.05	day^{-1}	[12]
r_{CP}	Rate of conversion of DIC to other forms of carbon	0.43	day^{-1}	Calibrated
m_{rP}	Mortality rate of phytoplankton	0.234	day^{-1}	[12]
r_{phy}	Respiratory rate of phytoplankton	0.024	day^{-1}	[12]
l_{rt1}	Loss rate of nutrient	0.49	day^{-1}	Ray, 2008
s_{rt}	Settling rate of phytoplankton	0.15	day^{-1}	[12]
l_{rt2}	Loss rate of phytoplankton	0.156	day^{-1}	Roy et al., 2012
r_{ex}	Excretion rate of zooplankton	0.01	day^{-1}	[12]
r_{Zoo}	Respiratory rate of zooplankton	0.025	day^{-1}	[12]
g_{rt}	Growth rate of zooplankton	0.6	day^{-1}	[12]
k_Z	Half saturation constant for phytoplankton grazing by zooplankton	0.02	day^{-1}	[12]
p_{rZ}	Rate of predation by fish	0.22	day^{-1}	Ray et al., 2002
m_{rZ}	Mortality rate of zooplankton	0.15	day^{-1}	[12]
l_{rt3}	Loss rate of zooplankton	0.18	day^{-1}	Roy et al., 2012

Table 3: Description, values, units and references of the forcing functions of the model.

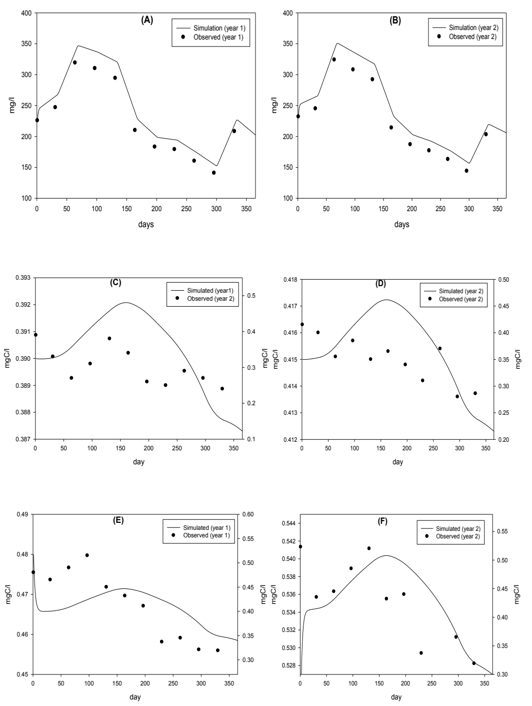

Figure 3: . (A) Result of calibration of DIC; (B) Result of validation of DIC (C) Result of calibration of Phytoplankton; (D) Result of validation of Phytoplankton; (E) Result of calibration of Zooplankton; (F) Result of validation of DIC.

surface solar irradiance, and adequate nutrient availability in the estuary [18]. Zooplankton population mainly consists of cyclopod, rotifers and copepods. Seasonal variation does not show very distinct in their abundance throughout the period of study. In premonsoon (March to June), zooplankton biomass reaches its highest value in April (0.515 mgC/l) whereas their population decreases during monsoon (July to October) and reaches its lowest value in October (0.319 mgC/l). Chi-square value for observed and simulated results of Z is 0.20 (p<0.05). Zooplankton dynamics is highly sensitive to r_{CP}, l_{rt3}, k_{DIC}, m_{rZ}, P_{psyn} and p_{rZ}. In premonsoon, the zooplankton in the estuary is very high which in turn also reduces the phytoplankton population (Figure 3).

Equilibrium solutions and stability of the model

(i) The first equilibrium of the system is Nutrient only equilibrium point $E_1^*(D_{IC_1}^*, 0, 0)$, where $I_{npDIC} > r_{cp}$ and when the rate of dissolved inorganic carbon (D_{IC}) in estuary (I_{npDIC}) is more than the D_{IC} conversion

Forcing Functions	DIC	Phytoplankton	Zooplankton
r_{cP}	0.338	0.138	0.175
l_{rt1}	0.043	0.209	0.148
P_{syn}	-0.796	1.030	0.946
r_{phy}	0.000	0.000	0.000
k_{DIC}	0.000	0.002	0.006
r_{zoo}	0.000	0.000	0.005
l_{rt2}	0.000	0.000	0.000
s_{rt}	0.000	0.000	0.000
m_{rP}	0.000	0.000	0.000
g_{rt}	0.000	0.750	0.294
k_z	0.000	0.000	0.000
r_{ex}	0.000	0.000	0.002
p_{rZ}	0.000	0.156	0.394
m_{rz}	0.000	0.215	0.068
l_{rt3}	0.000	0.116	0.078

Table 4: Result of sensitivity analysis.

to other forms of carbon (Cp) ($I_{npDIC} > r_{cp}$), then this equilibrium point is feasible and in this situation if the per-capita phytoplankton mortality rate due to different causes ($r_{phy} + m_{rp} + s_{rt} + l_{rt2}$) is higher than its per-capita growth $\left(\frac{P_{pshy}D^*_{IC_1}}{k_{DIC} + D^*_{IC_1}}\right)$ i.e. $\frac{P_{pshy}D^*_{IC_1}}{k_{DIC} + D^*_{IC_1}} < r_{phy} + m_{rp} + s_{rt} + l_{rt2}$, then system settles down to Nutrient only steady state (E_1^*) (Appendix A). It is quite obvious that, if phytoplankton's mortality due to different causes is higher than its growth rate, then with increasing time, phytoplankton naturally goes to extinction and zooplankton automatically suffers and is also eliminated. The input rate of dissolved inorganic carbon in estuary is more than its conversion to the other forms of carbon hence; D_{IC} is increased unless the condition is changed.

(ii) The second equilibrium point of the system is *zooplankton free equilibrium point* $E_2^*(D^*_{IC_2}, P_2^*, 0)$,

where $D^*_{IC_2} = \frac{k_{DIC}\left(r_{phy} + m_{rp} + s_{rt} + l_{rt2}\right)}{P_{psyn} - \left(r_{phy} + m_{rp} + s_{rt} + l_{rt2}\right)}$ and

$P_2^* = \frac{r_{cp} + l_{rt1}D^*_{IC_2} - I_{npDIC}}{r_{phy} - \frac{P_{psyn}D^*_{IC_2}}{k_{DIC} + D^*_{IC_2}}}$. This equilibrium point is feasible if $I_{npDIC} < r_{cp} + l_{rt1}D^*_{IC_2}$ and either $P_{psyn} > max\{\theta_1, \theta_2\}$ or $\theta_1 < P_{psyn} < \theta_2$, where $\theta_1 = r_{phy} + m_{rp} + s_{rt} + l_{rt2}$ and

$\theta_2 = \frac{r_{phy} + m_{rp} + s_{rt} + l_{rt2} + \frac{k_{DIC}\left(r_{phy} + m_{rp} + s_{rt} + l_{rt2}\right)}{r_{phy}k_{DIC}}}{1 - \frac{k_{DIC}\left(r_{phy} + m_{rp} + s_{rt} + l_{rt2}\right)}{r_{phy}k_{DIC}}}$. Under this circumstances if the loss rate of zooplankton due to all causes ($p_{rz} + r_{ex} + r_{zoo} + m_{rz} + l_{rt3}$) is more than its growth rate $\left(\frac{g_{rt}P_2^*}{f\left(k_z + \bar{P}\right)}\right)$ i.e. $\frac{g_{rt}P_2^*}{f\left(k_z + \bar{P}\right)} < p_{rz} + r_{ex} + r_{zoo} + m_{rz} + l_{rt3}$ and loss rate of phytoplankton by all means except zooplankton consumption ($r_{phy} + m_{rp} + s_{rt} + l_{rt2}$) is more than its growth rate $\left(\frac{P_{pshy}D^*_{IC_2}}{k_{DIC} + D^*_{IC_2}}\right)$ i.e. $\frac{P_{pshy}D^*_{IC_2}}{k_{DIC} + D^*_{IC_2}} < r_{phy} + m_{rp} + s_{rt} + l_{rt2}$, the system shows zooplankton free equilibrium (Appendix A). By remaining the condition fixed, the stability of zooplankton free equilibrium point

$E_2^*(D^*_{IC_2}, P_2^*, 0)$ describes that the loss rate of zooplankton is higher than its growth rate; the zooplankton is eliminated from the system. In the absence of zooplankton, D_{IC} and phytoplankton shows equilibrium state, initially in that condition phytoplankton increases but up to its carrying capacity and perhaps equilibrium point stays around carrying capacity. But when zooplankton is present in the system, the whole system also shows equilibrium state and here it might in the equilibrium point lies between the carrying capacity of phytoplankton.

(iii) The third and most important equilibrium is the coexistence equilibrium point $E^*\left(D^*_{IC}, P^*, Z^*\right)$,

where $P^* = \frac{fk_z}{g_{rt} - \left(p_{rz} + r_{ex} + r_{zoo} + m_{rz} + l_{rt3}\right)f}$,

$Z^* = \frac{I_{npDIC} - r_{cp} - l_{rt1}D^*_{IC} - \left(m_{rp} + s_{rt} + l_{rt2}\right)P^*}{p_{rz} + r_{ex} + m_{rz} + l_{rt3}}$ and D^*_{IC} is the unique positive root of

$$\left(\frac{P_{psyn}D_{IC}}{k_{DIC} + D_{IC}} - r_{phy} - m_{rp} - s_{rt} - l_{rt2}\right)\frac{f(k_z + P^*)}{g_{rt}} - \frac{1}{r_{zoo}}\left(\frac{P_{psyn}D_{IC}P^*}{k_{DIC} + D_{IC}} + r_{cp} + l_{rt1}D_{IC} - r_{phy}P^* - I_{npDIC}\right) = 0.$$

This equilibrium point is locally asymptotically stable if $\phi_i > 0(i = 1,2)$ and $\phi_1\phi_2 - \phi_3 > 0$ (Appendix A). Figures of equilibrium point are depicted in Figure 4.

Discussion

Anthropogenic activities and ongoing climate change are posing stress to the coastal environment affecting the ecology of phytoplankton which is responsible for about 15% of global oceanic production. Fluctuations in river flow, stratification of the water column, grazing pressure by zooplankton, nutrient dynamics, and light availability control the phytoplankton bloom in shallow estuaries [9]. This estuary is highly disturbed due to nutrient load from river discharge which result from economic growth in areas of reclaimed from mangrove forest [19].

Anthropogenic nutrient input from the Hooghly–Matla estuary to the creeks of Sagar Island varies between 0.257 mg/l and 0.390 mg/l annually [19]. Apart from anthropogenic input of nutrient, the biomass of phytoplankton and zooplankton are directly related to litter production of the adjacent mangrove forest [17]. Salinity plays as an important factor determining zooplankton dynamics in Hooghly–Matla estuary [20]. Gradation of salinity along the estuarine area is dependent on the dilution factor which is a function of mixing fresh water from river and the saline water from sea. The salinity drops down where it meets river and its value increases along the stretch toward the sea. Salinity-dependent dilution is calculated following the method of [15]. In the monsoon months, salinity decreases considerably (2.04–5.16 ppt) because of heavy rains and higher fresh water input. This pattern is also shown by Biswas et al. [9]. As a result, only those species which are able to withstand lower salinity condition can establish themselves in the creeks [20]. During monsoon the river experiences a huge amount of fresh water input carrying significant amount of nutrient load. But at that time due to turbidity light penetration is lower causing poorer productivity and growth of plankton. The

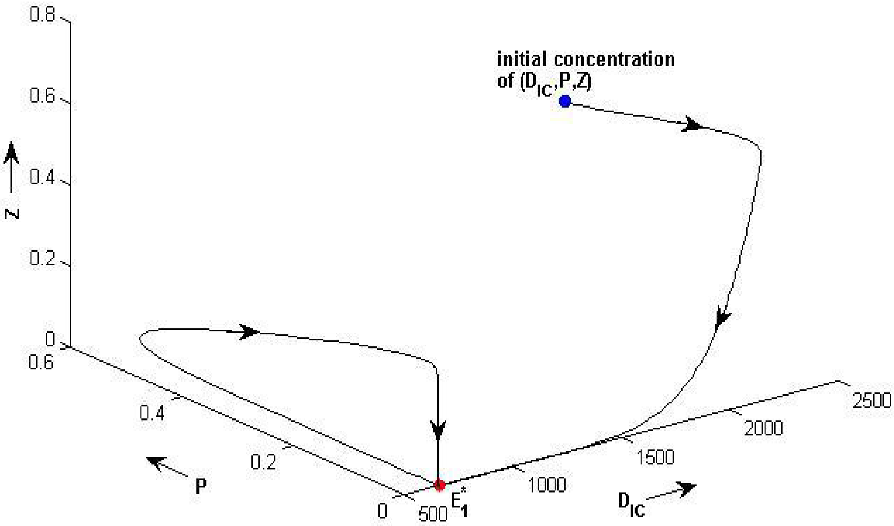

Figure 4: A. Phase space diagram of system (Eq.1, Eq.2, Eq.3). This figure shows that with any initial concentration of (D_{IC}, P, Z) which is denoted by blue bullet, system converges to Nutrient only equilibrium point E_1^* (D_{IC}^*,0,0) which is indicated by red bullet. Parameter are: r_{phy}=0.24; r_{zoo}=0.25; P_psyn=2.; k_DIC=1.5; r_cp=0.43; l_rt1=0.09; g_rt=0.6; k_z=0.02; m_rp=0.03; l_rt2=0.01; p_rz=0.22; r_ex=0.01; m_rz=0.15; l_rt3=0.01; I=60; s_e=3.32; s_r=1.64.

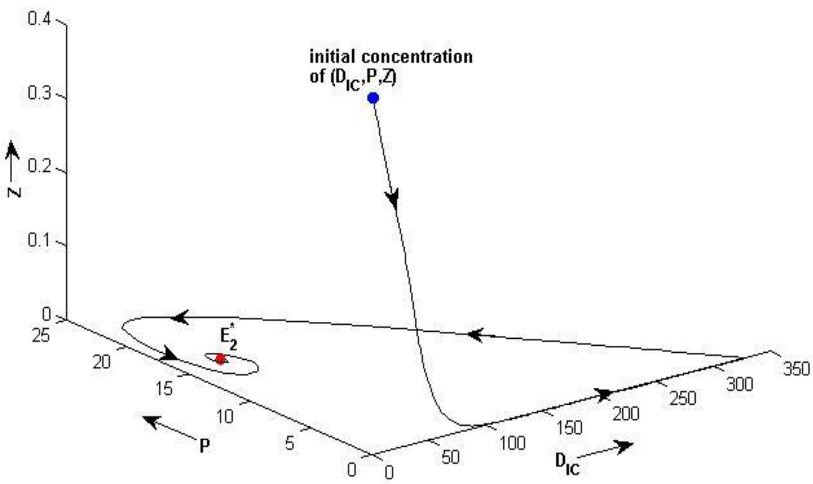

Figure 4: B. Phase space diagram of system (Eq.1, Eq.2, Eq.3). This figure shows that with any initial concentration of (D_{IC}, P, Z) which is denoted by blue bullet, system converges to Zooplankton free equilibrium point E_2^* ($D_{IC_2}^*$, P_2^*, 0) which is indicated by red bullet. Parameter are: r_{phy}=0.24; r_{zoo}=0.25; P_psyn=2.; k_DIC=1.5; r_cp=0.43; l_rt1=0.09; g_rt=0.6; k_z=0.02; m_rp=0.03; l_rt2=0.01; p_rz=0.22; r_ex=0.01; m_rz=1.15; l_rt3=0.1; I=30; s_e=3.32; s_r=1.64.

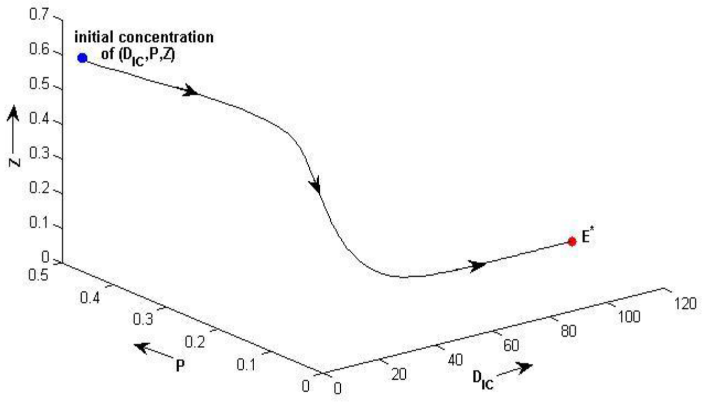

Figure 4: C. Phase space diagram of system (Eq.1, Eq.2, Eq.3). This figure shows that with any initial concentration of (D_{IC}, P, Z) which is denoted by blue bullet, system converges to coexistence equilibrium point E_2^* ($D_{IC_2}^*, P_2^*, 0$) which is indicated by red bullet. Parameter are: r_{phy}=1.24; r_{zoo}=0.25; P_psyn=2; k_DIC=1.5; r_cp=0.43; l_rt1=0.09; g_rt=0.6; k_z=0.1; m_rp=0.03; l_rt2=0.01; p_rz=0.22; r_ex=0.01; m_rz=0.05; l_rt3=0.1; I=10; s_e=3.32; s_r=1.64.

highest primary production is observed during premonsoon when nutrient availability is good and also light penetration is the most in the water column. It differs from the Godavari estuary where primary production in the system is mainly controlled by light availability in the water column than nutrients [21]. As the freshwater input is decreased and the transparency is increased due to reduction in suspended solids, phytoplankton bloom is developed. Similar result is also obtained in the study of phytoplankton over two decades in this estuary by Biswas et al. [9]. During post monsoon, sufficient nutrient encourages plankton growth. Besides, during monsoon, the area remains inundated with water which creates anoxic conditions beneath the water column and releases CO_2. Photosynthetic rate of marine algae as function of inorganic carbon concentration using Michelis Menten equation has been discussed by Caperon and Smith [22]. Similar equations are used in models [23, 24].

Phytoplankton biomass is lower in monsoon than pre and post monsoon. Therefore, rainfall is a factor determining plankton dynamics. Similar trend is also evident from previous studies [9]. Higher primary productivity is observed during the summer season, because of high population density of phytoplankton. As the salinity and other hydrological parameters are in stable condition during summer the phytoplankton production remain high. Perumal et al. [18] proposed that this higher density could also be due to neritic element domination, higher salinity and surface water temperature, clear water conditions besides availability of nutrients. The recorded low primary productivity could be related to the wash of the phytoplankton to the neritic region by the monsoonal flood besides reduction of salinity, which could have affected the phytoplankton population [25-27]. During monsoon, high amount of allochthonous input is very high as river runoff in the estuary. This input causes high turbidity in the estuarine water which retards phytoplankton growth. The observed low zooplankton productivity during monsoon might be due to the non-availability of food, low temperature and low salinity. The disturbances of the food web and minimum production of plankton during the monsoon season have been observed in many Indian estuaries [28,29]. Owing to the inflow of freshwater during the monsoon, the salinity of the water column decreases. The low salinity would drastically affect the plankton abundance [30]. In the present investigation, increase or decrease of salinity in the water column exerts either a direct or an indirect effect in the appearance or disappearance of some forms and replacement by others. This phenomenon is introduced in the model as salinity based grazing equation of zooplankton.

Conclusion

To avoid the mathematical complexity of the model, only essential parameters are dealt with in this model. After successful calibration and validation, the model seems to be realistic. This region is very important for the production of commercially important fisheries. Productivity is dependent on nutrient availability in the creeks of the Hooghly–Matla estuarine system. This model is able to predict the present status of plankton dynamics, which serve as major food resource for herbivorous and carnivorous fish species.

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Conflict of Interest

The authors have no conflict of interest whatsoever.

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