Ecological Modelling 368 (2018) 111–120

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Mathematical modelling for phytoplankton distribution in Sundarbans Estuarine System, India

Tanaya Das[a,b,*], Saranya Chakraborti[a,b], Joydeep Mukherjee[b], Goutam Kumar Sen[a]

[a] School of Oceanographic Studies, Jadavpur University, Kolkata 700032, West Bengal, India
[b] School of Environmental Studies, Jadavpur University, Kolkata 700032, West Bengal, India

ARTICLE INFO

Article history:
Received 2 August 2017
Received in revised form
17 November 2017
Accepted 18 November 2017

Keywords:
Phytoplankton
Nutrient
Estuary
Ecosystem model
Sundarbans

ABSTRACT

Mathematical modeling is an important tool to study planktonic ecosystem dynamics and various mechanisms involved in its interaction with hydrological regime. The difficulty arises when describing plankton dynamics under wide range of estuarine environmental conditions due to inadequate knowledge to interpret the mechanism to which the environmental nature of a given situation force the model condition towards the observation and the extent to which the details of the model implementations do. We present a model of the phytoplankton dynamics and nitrogen cycling in the estuarine environment of Sundarbans. We have tested the sensitivity of each model parameter in turn by running the model to a steady-state within a certain range of value satisfying the trend of phytoplankton and nutrient distribution. In this way, it is possible to determine which parameters had the most influence on which variables and the possible mechanism underlying the ecological processes in estuarine environment. The model exhibits stable behavior for the state variables over the tidal cycle and follows the trend of phytoplankton and nutrient distribution along the river channel. This exercise will obviously set a background to have some knowledge of the tuning of the ecological model to the parameter values.

1. Introduction

Estuarine waters are one of the fluvial-dynamic ecological system which undergo through a continuous changes due to the physical processes of coastal water (e.g. diffusion, stratification) and as well as due to the inherent biological processes (e.g. nutrient uptake, physiological changes, growth rate) which are instrumental in producing spatial variation of planktonic distribution (Bonachela et al., 2011). Hence models of planktonic processes have gaining much interest of researchers in order to understand the functions of different part of estuarine ecosystem. Such works are needed to assess the health of the marine life and environment conditions of the estuaries in changing climate scenario and to locate the potential marine economic zones.

Several researchers have attempted to explain the growth of phytoplankton in different environmental conditions. Oceanic plankton distribution is related to the physical features like eddies and fronts (Biktashev and Brindley, 2004; Abraham, 1998; Flier and Davis, 1993; McGillicuddy and Robinson, 1997; Martin and Richards, 2001; Oschlies and Garcon, 1988). Changes in temperature and nutrient availability induced by seasonal changes such as, variation in thermocline depth and strength are considered to be responsible to the rapid and massive phytoplankton bloom in rivers, lakes and oceans. The effect on inflows on phytoplankton population is an interesting problem to study how the magnitude and the timings of inflows influence the physical features and nutrient availability by altering hydrology that affect phytoplankton growth and productivity. Moreover, seasonal forcing also acts as the controlling factor on phytoplankton population that lives in natural systems in a periodically varying environment and population interactions. Since phytoplankton have the capacity to acclimate to changes in environmental conditions by altering their chemical composition in response to environmental variability, physical aspects of nutrient uptake and the change in plankton dynamics in physical limitations in response to limited nutrient condition have been the focus of intense study in changing hydrological regime. Temperature, availability of light in addition to nutrients regulates the phytoplankton photo-physiology (Steele, 1978; Bainbridge, 1957; Venrick, 1990; Mukhopadhyay and Bhattacharya, 2006; Jang and Allen, 2015; Bonachela et al., 2011).

To date a large number of model formulations have made to express the nutrient and plankton dynamics in a wide variety of marine environment i.e., ocean, lake, estuary etc. Among them

* Corresponding author at: School of Environmental Studies, Jadavpur University, Kolkata 700032, West Bengal, India.
E-mail address: tanaya16.das@gmail.com (T. Das).

https://doi.org/10.1016/j.ecolmodel.2017.11.020
0304-3800/

Michaelis-Menten Kinetics was one of the remarkable pioneer attempts to describe the influence of ambient nutrient concentration (external and internal) on nitrogen uptake rate by algal cells (Caperon, 1967; Dugdale, 1967; Droop, 1973; Burmaster, 1979). A number of models tended to concentrate on interaction among nutrients, phytoplankton and zooplankton and the flows of materials among these components of ecosystem. Effects of light limitation, temperature, zooplankton grazing, role of bacteria, protozoans and dissolved organic matter and toxic elements on planktonic system are extensively explored (Pace et al., 1984; Fasham, 1985; Moloney et al., 1986; Williams and Druffel, 1988). But these models have not put much light on the variability of plankton dynamics in seasonal cycle in the ambient of explicit physical processes as addressed by Evans and Parslow (1985) using a simple model of plankton and nutrient dynamics in a seasonally varying mixed layer. Here, the role of physical mixing on seasonal recurrence of spring bloom formation is well explained. A simple model of planktonic ecosystem was developed by Fasham et al. (1990) (hence called FDM model) to describe the ecosystem of Sargasso Sea, near Bermuda in which temporal changes in the thermocline depth plays a major role in ecosystem. Later Haney and Jackson (1996) modified this model with changes in algal growth rate formulations to combine the effects light and nutrient limitation.

Sundarbans Estuarine System (21.25°–22.5° N and 88.25°–89.5° E), situated in the eastern coastal state of West Bengal, is India's largest monsoonal, macro-tidal delta-front estuarine system. It comprises the southernmost part of the Indian portion of the Ganga-Brahmaputra delta bordering the Bay of Bengal. This estuary has gained considerable impetus as an interesting study area on phytoplankton dynamics. Twice-daily mixing of the estuarine waters by the tidal phenomenon (Chatterjee et al., 2013) causes changes in water level, salinity and nutrient and such wide range of environmental conditions which have an important impact on the characteristics of phytoplankton distribution in rivers of Sundarbans. River discharge, stratification of water column, grazing pressure by zooplankton, nutrients and light availability are the main controlling factors in growth of phytoplankton. A number of comprehensive studies have conducted to diagnose the current state of ecosystem in Hoogly-Matla estuarine system for exploring the possible impact of future changes in environmental factors on the ecosystem. The impact of mangroves on nutrients and plankton dynamics, temperature dependent growth rate of phytoplankton in saline environment and implication of body sizes plankton for total system dynamics in optimization of exergy are critically analyzed (Roy et al., 2016; Mandal et al., 2012; Ray et al., 2001; Joyita et al., 2015)

On these developments we have taken a simple but realistic phytoplankton-nutrient distribution model (Fasham et al., 1990; Haney and Jackson, 1996) as a tool to determine the controlling forcing parameters of plankton and nutrient dynamics in rivers of Sundarbans estuary. The organization of the paper is as follows. Section 2 gives a brief overview on physical and environmental conditions of the study area. Section 3 provides the description of the base model along with the parameters and significance. Parameter sensitivity analysis and stability test are included in this section. Section 4 analyzes the behavior of plankton and nutrient dynamics with the help of sensitivity analysis, stability conditions and model output. Section 5 deals with the salient features and significance of the work in the concluding part.

2. Study area

The principal estuaries of the Sundarbans Estuarine System (SES), India, are: the Saptamukhi, Thakuran, Matla, Bidya, Gomdi, Gosaba, Gona, Harinbhanga and Raimangal. All these north-south flowing estuaries are lying east of the Hoogly River. A wide range of tidal variations in different environmental and estuarine conditions of these estuaries are reported by Chatterjee et al. (2013). According to this report and an extensive hydrological survey of the southern stretch of the river Saptamukhi during 1961–1963 (Jha et al., 1999) have noted that Saptamukhi East Gulley (SEG), the stronger branch of Saptamukhi, carries a major portion of the inflow from the bay. Tide induced daily mixing of the estuarine waters cause changes in hydrological and physico-chemical characteristics of the estuary which makes the eastern part of river Saptamukhi an ideal estuary to study the dynamic interaction of estuarine hydrology with the ecosystem of the estuary.

In this paper we have chosen the River Jagaddal, an easterly branch of the SEG, flowing parallel to the SEG straight to the Bay of Bengal as our study area to model the phytoplankton and nutrient distribution along the river Jagaddal. Goutam et al. (2015) discussed about the nature of nonlinearity (role of bottom drag coefficient), mixing characteristics, variation of water level, tidal current and estuarine current along the river Jagaddal based on the observations in equinoctial spring phase (18–21 March) of 2011, on the three stations on this river: Indrapur, Dhanchi and Ramganga and numerical simulation of hydrological parameters (water level, tidal current, estuarine current, bottom drag coefficient, gradient Richardson number etc.). Since an initial overview on tidal hydrodynamics of flow regime is available in this river, so it is a straight approach to undertake a comprehensive study on variation of ecological parameters (phytoplankton, nutrients etc.) in the influence of tidal action on this river.

A number of studies have conducted in different seasons to understand the variation of physico-chemical parameters (salinity, nutrients, phytoplankton) in the eastern part of river Saptamukhi, as well as on the principal estuaries of Sundarbans (Chaudhuri et al., 2012; Mitra et al., 2014; Mitra et al., 2009; Raha et al., 2012). To model the variation of phytoplankton and nutrient concentration along the river Jaggaddal, we have considered these available references to get an idea about the nature of phytoplankton and nutrient variation on this river in monsoon and identify the controlling parameters to understand the interaction of hydrological and ecological processes.

3. Methodology

3.1. Model structure and equations

To model the phytoplankton and nutrient dynamics along the estuarine channel of river Jagaddal (Fig. 1), coupling of physics and biology is essential for simulation of phytoplankton and nutrient distribution. Evans and Parslow (1985) explored a 1D (vertical) model in which the plankton were affected by shoaling and deepening of the mixed layer where the effect of shallowing or deepening of mixed layer on the volumetric concentration of a state-variable in mixed layer remains unchanged. In this study we have taken this model to induce the hydrodynamics of estuarine river in a simplified form in phytoplankton and nutrient dynamics. For a mixed layer of depth M, the rate of change of mixed layer depth is

$$h^{+}(t) = \frac{dM}{dt} \tag{1}$$

Now the mixing process rate is fast compared to the growth rate of the organisms (Robinson et al., 1979). Following these features we make the basic assumption that in the shallow estuarine channel of Jagaddal river, the vertical water column can be considered biologically homogeneous. With mixing rate m, the rate of change of mixed layer provides the physically driven rate to change the