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Simulation model of phosphorus dynamics of an eutrophic impoundment – East Calcutta Wetlands, a Ramsar site in India

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ABSTRACT

The East Calcutta Wetlands is one of the largest wastewater-fed aquaculture in the world. It is the aggregation of salt marshes, salt meadows and wastewater-fed ponds that receive wastewater from various small and large scale industries and urban settlements. The available nutrient supports the grazing food chain of the wetland ecosystem and agriculture around it. Eutrophication is caused by the imbalance between nutrient load and utilization by the autotrophs in the system. In this wetland, there has been a gradual decrease in the fish production for the last few decades. The physical and chemical conditions of the system are deteriorating continuously. Therefore, modelling of the system is felt to be the need of the hour to mitigate the problem of eutrophication and identify the important parameters that govern the system dynamics.

Here, a dynamic model is constructed to study the phosphorus dynamics of the system. The five state variable includes; inorganic phosphorus (orthophosphate), phytoplankton, zooplankton, organic phosphorus and sediment. Important processes, like mineralization, uptake, grazing, predation, settling, resuspension and sorption are considered in the model. Field data are collected over two years and incorporated in the model as graph time function. Sensitivity analysis is performed and the model is calibrated using first set data followed by the validation process. Results indicate that the wetland is in hypereutrophic condition. The model result shows that the inorganic phosphorus of the system is mainly controlled by desorption of phosphorus from the sediments and mineralization during the premonsoon. The settling of organic phosphorus and adsorption of inorganic phosphorus are major regulating processes in the postmonsoon. In monsoon, resuspension process has important role in governing the phosphorus dynamics of the wetland. Moreover, allochthonous input of phosphorus is dominant over autochthonous input and controls the system dynamics. The input rate of inorganic phosphorus from outside is the system sensitive parameter. The paper discusses the present condition of the East Calcutta Wetlands and outlines some of the important management strategies that can be applied to alleviate the eutrophication problem of the wetland ecosystem.

1. Introduction

The East Calcutta Wetlands (ECW) is the biggest urban wetland ecosystem in India, which is the aggregation of 286 wastewater fed ponds that produce nearly 10,915 metric tonnes of fish annually (Chatterjee et al., 2006). This wetland has become a sink for the untreated wastewater from municipal sewage and various small and large scale industries adjoining the area. Since independence of India, there has been gradual decrease in the size of fishing area from 81 km^2 to 51 km^2 due to human infiltration. Despite its reduction in the size of aquatic bodies, the wetland still produces around 11.4% of total annual supply of fishes for India. For the last few decades, gradual decrease in the fish production is noted along with the deterioration of physical and chemical condition (Mukhopadyay et al., 2007). This massive production of fish is contributed by the nutrient–phytoplankton–zooplankton (*NPZ*) system of the wetland. Moreover, the *NPZ* system is controlled by the external input and the internal dynamics. Therefore, modelling

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of the system is needed to identify the important parameters that govern the system dynamics.

Among the major nutritional and structural components like carbon, hydrogen, nitrogen and sulphur, phosphorus is the least abundant and a common limiting component of biological productivity (Wetzel, 2001). The field observation indicates that the nitrogen: phosphorus ratio (by weight) in phytoplankton is 11:1 in the ECW. This ratio is higher than the Redfield ratio 7:1 (N:P) (Wetzel, 2001). This shows that the impoundment is phosphorus limited. In the present work, phosphorus is considered as currency of the model. The most significant form of inorganic phosphorus is orthophosphate ($PO_4{}^{3-}$), which is taken up by phytoplankton followed by zooplankton (Wetzel, 2001).

The empirical models are simple and effective method of analyzing the eutrophication process. Dillon and Rigler (1974a) used linear regression method to determine the average summer chlorophyll-*a* concentration from the total phosphorus concentration at spring.

Nyholm (1978) developed a simulation model for phytoplankton growth and nutrient cycling in twelve different eutrophic shallow lakes in Denmark. Studies on shallow lakes and different processes include resuspension, diffusion (Reddy et al., 1996; Vymazal, 2007; Holmroos et al., 2009), internal nutrient load (Sondergaard et al., 2003; Ruley and Rusch, 2004; Fisher et al., 2005), effect of important factors like temperature, pH (Jensen and Andersen, 1992).

Models became complicated by gradual addition of trophic levels to describe the transfer of carbon in the food chains and the productivity at all trophic levels in aquatic systems. Di Toro et al. (1975) developed a *NPZ* simulation model of the western basin of Lake Erie. The model is focused on the effects of nutrient (nitrogen and two forms of phosphorus, organic phosphorus and orthophosphate) loading on the seasonal dynamics of phytoplankton and zooplankton biomass. Scavia et al. (1976) presented an ecological model on Lake Ontario plankton community using various forms of phosphorus. The model includes various processes and relationships involved in *NPZ* dynamics in the epilimnion and hypolimnion region of the lake. Janse et al. (1992) developed a mathematical model of phosphorus cycle in the Lake Loosdrecht of The Netherlands. Their model comprises three algal groups, zooplankton, fish, detritus, zoobenthos, sediment detritus and some inorganic phosphorus fractions. Similar approaches are advanced by Ray et al. (2001) and Mandal et al. (2012b).

McGovern (2006) used one dimensional lake water quality model that includes three phytoplankton groups, zooplankton and phosphorus in Lake Washington and observed that the eutrophication of lake was due to the upload of phosphorus in the wastewater received by this system.

Wetlands have been comprehensively investigated for the treatment of wastewater and improvement of ecological environment (Costanza et al., 1997; Wang and Mitsch, 2000; Malmaeus and Hakanson, 2004; Ruley and Rusch, 2004; Carvalho et al., 2009; Zeng and Chen, 2009; Chen et al., 2010, 2012; Feng et al., 2011; Xu et al., 2011, 2013; Zeng et al., 2012; Chen, 2013). Previous research works on ECW includes studies of heavy metals (Chatterjee et al., 2006, 2007; Aich et al., 2011), wetland plants (Chatterjee et al., 2010, 2011), zooplankton diversity analysis (Mukhopadyay et al., 2007; Sarbajna et al., 2009). Studies on this wetland by the authors are based on experimental works and empirical studies on physical and chemical characteristics of water, plankton and fish dynamics. However, the interactions among the biological components, internal and external processes that govern this system are remained unexplained. The present work focuses on the development of model based on the studies related to ECW and other literatures (Mukhopadhyay et al., 2000; Wang and Mitsch, 2000; Chattopadhyay et al., 2004; Ruley and Rusch, 2004; Malmaeus and Hakanson, 2004; Pradhan et al., 2008; Sarbajna et al., 2009; Roy Goswami, 2013). The five state variables considered in construction of the model are based on the available field data of ECW. The study investigates how the simple model with five state variables adequately simulates the phosphorus and plankton dynamics of ECW in response to the authochthonous and allochthonous input of phosphorus. The model includes; inorganic phosphorus or orthophosphate (P), phytoplankton (P_{hy}), zooplankton (Z_{oo}), organic phosphorus (O_P) and sediment (S_{ed}) as state variables. The O_P pool consists of particulate organic phosphorus (P_{OP}) or detritus and dissolved organic phosphorus (D_{OP}). Important processes, like mineralization, uptake, grazing, predation, settling, resuspension and sorption are considered in the model. The sorption process includes both the adsorption and desorption of P from the sediment pool. The main objectives of this research work are

(i) To determine the sensitive parameters that governs the phosphorus dynamics of ECW.
(ii) What are the major factors responsible for eutrophication in this wetland?
(iii) How the authochthonous and allochthonous input of phosphorus along with the environmental factors influence the plankton dynamics.
(iv) What changes this *NPZ* system will have in near future if the situation of nutrient loading changes and what will be its impact on fish production.

The detailed description of the model is provided in separate section below.

2. Methods

2.1. Study area

The East Calcutta Wetlands (ECW), a Ramsar site, located in Kolkata, South 24 Parganas district, West Bengal in India receives industrial run off from at least 6000 small and large scale industries, and Kolkata metropolitan city wastewater throughout the year. The wastewater flows through web of canals and enters into the fishponds in ECW and is utilized for pisciculture by the local farmers. There are three types of pond in the ECW; nursery pond, rearing pond and stocking pond. The stocking ponds bear fishes of all sizes and are the largest among all. A stocking pond of a mean area of 13.3 ha located at Chowbaga (22°31′58.7″ N and 88°25′00.92″ E) is selected for study. There exists no significant variation among stocking ponds because all of them receive wastewater from the same source. The impoundment is sourced from the Dry Weather Flow (DWF) channel which carries untreated municipal and industrial effluents of the city of Kolkata. The stocking pond has a wastewater inlet point, located at the south eastern corner of the pond and also an outlet point near north-east corner through which the excess pond water is discharged (Fig. 1).

2.2. Sampling and measurement

Four sampling sites (Site 1, Site 2, Site 3 and Site 4) are selected for the collection of data. Samples are collected four times every month from the sampling sites from March 2010 to February 2012 and the mean results are used for quantitative analysis. Physico-chemical conditions such as water temperature and surface solar irradiance are measured using Mettler Checkmate 90 Toledo and LUTRON-LX 101, respectively. Total phosphorus is determined following acid per sulphate ($K_2S_2O_8$) digestion method. Inorganic phosphate, orthophosphate ($PO_4{}^{3-}$) of water is analyzed on the spot titrimetrically using E. Merck (Germany) field