Ecological Modelling 372 (2018) 1–11

Contents lists available at ScienceDirect

Ecological Modelling

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

Using the EFDC model to evaluate the risks of eutrophication in an urban constructed pond from different water supply strategies

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ARTICLE INFO

Keywords:
EFDC
Eutrophication risk
Water supply strategy
Scenario analysis
Urban constructed pond

ABSTRACT

Managers of urban lakes are faced with the challenge of finding a balance between saving water resources and preventing eutrophication. One way to address both of these issues is to use the unconventional water source s such as stormwater and reclaimed water to maintain the water supply in urban constructed ponds. We validated and calibrated the Environmental Fluid Dynamics Code and then evaluated the risks of eutrophication from various water supply scenarios, such as different proportions of stormwater (SW), reclaimed water (RW), and tap water (TW). We found that the different types of water influenced the nutrient or Chl*a* levels in the constructed ponds, but that there was little difference between different hydrological years. The range of the trophic state index in the study pond increased from 5.55% to 68.17% in the urban ponds as the proportion of RW increased from 0% to 100%. Stormwater collection strategies had a clear effect on the trophic state of TW-fed ponds but not of RW-fed ponds. Using an index that integrated the eutrophication risks, eutrophication state, and economic costs, we found that the optimal water supply strategy was to collect treated SW and use TW to replenish the water supply.

1. Introduction

Eutrophication is a common problem in urban ponds (Smith and Schindler (2009)). It has various negative effects, causes the color, taste, transparency, and odor of pond water to change, reduces the pond biodiversity, and also results in super-saturation and deficits of oxygen in the surface water and bottom water layers, respectively (Ellwood et al., 2009; Grochowska et al., 2014; Dunalska et al., 2015). In water-scarce areas, the risks of eutrophication in urban lakes or ponds can be very high because there is insufficient water to dilute the non-point source pollutants and nutrients in the lake or pond (Wang et al., 2014; Chen et al., 2016b; Gao et al., 2014). Water managers in water-scarce areas therefore have to ensure there is enough water of suitable quality in urban lakes and ponds to prevent eutrophication.

Reclaimed water (RW) can contribute to sustainable and effective water resource management in water- scarce areas such as Beijing and California (Zhou et al., 2017; Marks, 2006). However, we know that, when RW is introduced to aquatic systems, the bacterial communities shift because of changes to their habitat (Vaquersunyer et al., 2016) and biogeochemical cycling of nutrients is altered (Wakelin et al., 2008; Wang et al., 2016). Where RW with high levels of organic matter and nutrients is introduced to aquatic systems (Beaulieu et al., 2013; Martí et al. (2009); Ribot et al., 2017), primary production may decrease (Vaquersunyer et al., 2016), and the phytoplankton species composition may be altered, with consequences for the chlorophyll a (Chl*a*) concentrations (Kraus et al., 2017). Various factors, including sewage outflows, season will determine the influence of RW (Rodríguezcastillo et al., 2017; Yang et al., 2016). While numerous studies have reported how RW influences receiving water systems, there is a lack of information about how RW can be used to avoid or reduce the risks of eutrophication.

Stormwater (SW) can also be used to replenish urban lakes; however, SW may contain nutrients at high concentrations (Hobbie et al., 2017), which may contribute to degradation of the water quality of the receiving system, and may result in harmful cyanobacterial blooms and high levels of microcystin toxins (Wu et al., 2016). Studies have shown that, because of the ‘first flush’ phenomenon, the initial 30% of the runoff volume can contain between 40% and 70% of the nutrient load for the entire event (Gunaratne et al., 2017; Bach et al., 2010). Nutrients should therefore be removed before SW is used to supplement the water supply in urban ponds (Glaister et al., 2017). In the event that the supply of SW is not sufficient for a given pond, it will have to be mixed with other types of water. Further, because the nutrients contents in SW generally vary widely (Bratieres et al., 2008), we need to

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https://doi.org/10.1016/j.ecolmodel.2018.01.020
Received 24 August 2017; Received in revised form 20 January 2018; Accepted 29 January 2018

determine how inputs of treated SW might influence the trophic state of constructed urban ponds.

Studies have shown that the trophic state of a lake or pond can be improved by ensuring a sufficient water supply or by implementing water diversion measures (Li et al., 2013; Sirunda and Mazvimavi, 2014; Zeng et al., 2015). The water quality in the lake may change depending on the source of the water supply (Hu et al., 2010) and the hydro-dynamic condition s in the lake (Gibbins et al., 2010). There are numerous examples of how regulatory measures have been optimized to control eutrophication, such as the Yangtze Estuary (Wang et al., 2013), Baiyangdian Lake (Chong et al., 2010), Cheng-Ching Lake (Kuo et al., 2008), and in brackish tidal ponds (Cui and Chui, 2017). However, while these regulation strategies have been widely used in natural lakes, there are few reports of how regulation measures have been optimized for constructed ponds that receive artificial water supplies.

Mathematical models can be used to predict the water quality and responses of algae to variations in external nutrient loadings and have been frequently used to find optimal solutions for various water quality problems (Chen et al., 2016b; Wu and Xu, 2011). Simulation system s such as the Environmental Fluid Dynamics Code (EFDC) can be used to forecast the fate of water quality variables and quantify the trophic status under various conditions, while the optimization systems can be used to identify the optimal water transfer strategies from a range of alternative scenarios (Dai et al., 2016; Zeng et al., 2015).

In this study, we used the EFDC model to analyze 25 different water supply scenarios for an urban pond in Tianjin. We then evaluated how the nutrient and Chla levels and trophic state responded to these different water supply scenarios, which included whether SW was collected and various mixing ratios of RW. The specific objectives of the study were to (1) identify how different SW collection and treatment strategies impacted on the trophic state of an urban pond, (2) verify whether it was feasible to use RW as the main source of extra water, and (3) find the optimal water supply strategy that would both prevent eutrophication and minimize economic costs.

2. Materials and methods

2.1. Study area

The study pond (Fig. 1), was in the center of Tianjin Cultural Park (TCP) in the Hexi District of Tianjin. The pond has landscape and recreational functions. It covers an area of 92,500 m^2 and has a storage capacity of 160,000 m^3. Deeper in the east than in the west, the pond has an average depth of 3.04 m. The pond catchment is a multi-function commercial area that mainly comprises buildings, green spaces, and roads. The study area received 576 mm of rainfall during 2015. The pond has five inlets and two outlets. The pond water is circulated continuously at a circulation rate of 400 m^3/h by pumping water from two outlets and then reintroducing it into the pond through two inlets. Stormwater from the surrounding catchment is pre-treated in a wetland and then is discharged into the pond via two inlets. To maintain the water level during spring, TW and RW are added to the pond through one outlet at a supply rate of 800 m^3/d for a period of 80 days. To date, the constructed pond has been replenished with collected SW and TW.

2.2. Model description

The EFDC is a comprehensive three-dimensional numerical model that was developed at the Virginia Institute of Marine Science (Hamrick, 1992). It is a general-purpose model for simulating biogeochemical processes in surface water systems and has been widely used to evaluate the risks of eutrophication in lakes or ponds (Chen et al., 2016a; Wu and Xu (2011)); Zeng et al., 2015). The governing mass-balance equation is based on the conservation of mass and can be expressed as follows (Tech, 2007):

$$\partial_t C + \partial_x(uC) + \partial_y(vC) + \partial_z(wC) = \partial_x(K_x\partial_x C) + \partial_y(K_y\partial_y C) + \partial_z(K_z\partial_z C) + S_C$$

where C is the concentration of the water quality state variable; u, v and w are the velocity components in the x, y and z directions, respectively; K_x, K_y and K_z are the turbulent diffusivities in the x, y and z directions, respectively; and S_C is the internal and external sources and sinks per unit volume.

Algae dynamics, such as growth (production), basal metabolism, predation, and settling, are included in the conservation equation, and are described with the following kinetic equation (He et al., 2011):

$$\frac{\partial B_x}{\partial t} = (P_x - BM_x - PR_x)B_x + \frac{\partial}{\partial Z}(WS_x B_x) + \frac{WB_x}{V}$$

where B_x is the algal biomass of algal group x (g Cm^{-3}), (x = 1, 2, or 3; where 1 represents cyanobacteria, 2 represents diatoms, 3 represents green algae); t is time(days); P_x is the production rate of algal group x (day^{-1}); BM_x is the basal metabolism rate of algal group x (day^{-1}); PR_x is the predation rate of algal group x (day^{-1}); WS_x is the positive settling velocity of algal group x (m day^{-1}); WB_x represents the external loads of algal group x (g C day^{-1}), and V is the cell volume (m^3).

To facilitate comparisons, we calculated the Chl*a* concentrations by dividing the computed biomass by the carbon-to-chlorophyll ratio (Bunch et al., 2000; Zeng et al., 2015).

The eutrophication module in the EFDC model solves mass balance equations for 21 state variables in the water column, which include 3 algal groups; various components of the carbon, nitrogen, phosphorus, and silica cycles; dissolved oxygen dynamics, and fecal coliform bacteria. The interactions among those variables, the atmosphere, and sediment are illustrated in Fig. 2, which shows that the whole eutrophication process comprises physical, chemical, and biochemical reactions. In Fig. 2, each box represents a state variable and the symbol ‘ = ’ denotes a sediment phase. The arrows represent kinetic interactions among the state variables (Wu and Xu (2011)).

2.3. Model configuration

2.3.1. Grid generation and bathymetry processing

Cartesian grids were used to represent the geometry of the study pond at a spatial resolution of 9.5 × 12 m. The water quality model was set by allocating 738 active grids in the horizontal plane and one layer in the vertical direction. The boundary and the corresponding topography of the constructed pond are shown in Fig. 3.

2.3.2. Initial conditions and boundary conditions

In this study, the initial conditions included the water surface elevation, water temperature and water quality state, represented by concentrations of water quality variables. The starting time was March 12, 2015 (Julian data 0) and the calibration period was from 12 March 2015 to 20 November 2015, which was the unfrozen period of the pond. The initial elevation of the pond water surface was 3.04 m and was uniform. The initial water temperature was set as 10 °C in all the grids to reflect the homologous water temperature in the pond during spring. Information about the initial water quality was obtained from the field monitoring in the pond during March 2015.

We need information about the lateral and surface boundary conditions to drive the water dynamics. The lateral boundary conditions include the daily inflow, outflow rates, daily water temperature, and fortnightly nutrients loadings. We obtained meteorological data from China's Meteorological Scientific Data Sharing Service Network (http://www.escience.gov.cn). The flow rates were monitored at each inlet or outlet of the pond with a flow-meter during the calibration period. Water samples were collected monthly from March to May, the dry season, and fortnightly from May to September, the rainy season, from the inlets and outlets of the pond. We used the flow rates and the results from analysis of these samples to calculate the loads of the water