Ecological Indicators 91 (2018) 575–588

Contents lists available at ScienceDirect

Ecological Indicators

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

Short Note

Improving land-based total nitrogen load allocation using a variable response matrix-based simulation–optimization approach: A case study

Ying Su[a,b,c], Keqiang Li[a,b,*], Bo Yang[d], Shengkang Liang[a,b], Xiulin Wang[a], Xianwen Bao[e], Wensheng Jiang[c,e], Yanbin Li[a,b]

[a] Key Laboratory of Marine Chemistry Theory and Technology (Ocean University of China), Ministry of Education, Qingdao 266100, China
[b] Chemistry and Chemical Engineering Department, Ocean University of China, Qingdao 266100, China
[c] Environmental Science and Engineering Department, Ocean University of China, Qingdao 266100, China
[d] Oceanic and Atmospheric Sciences Department, Ocean University of China, Qingdao 266100, China
[e] Key Laboratory of Physical Oceanography (Ocean University of China), Ministry of Education, Qingdao 266100, China

A R T I C L E I N F O

Keywords:
Load allocation
Total nitrogen
Variable response matrix approach
Simulation–optimization
Coastal ocean

A B S T R A C T

Human activities have increased land-based pollutant loads, which have caused a significant variation in unit source concentration response matrices (USCRMs) of the coastal ocean. A variable response matrix approach (VRMA) for simulation–optimization load allocation is proposed and applied to solve the uncertainty caused by variations in USCRMs in calculating allocated load (AL). In contrast to the traditional fixed response matrix approach (FRMA), the USCRMs are iteratively updated by a simulation model using iterative solutions from an optimization model. The ALs of 48 main dischargers in Shandong Province, a typical coastal province in China, are calculated via the VRMA and FRMA. The water quality under each AL emission is simulated via a three-dimensional water quality simulation model. The advantages of applying the VRMA over the FRMA in waste load allocation are demonstrated by comparing the ALs and the correspondence between the simulated water quality and the water quality standards of the two methods. Results show that the VRMA can maintain better water quality than the FRMA when higher total nitrogen loads are allowed.

1. Introduction

Land-based pollution significantly contributes to water quality deterioration in estuarine, coastal, and bay regions (GESAMP, 1990). According to long-term data, the land-based total nitrogen (TN) load is identified as a key control indicator that is responsible for dissolved inorganic nitrogen (DIN) concentration variation in the coastal ocean of China (State Ocean Administration China, 2017; Zhang et al. 2017; Li et al. 2018). Effective pollutant load (PL) control programs, such as the total maximum daily load program in the United States, are necessary for water quality improvement and aquatic ecological restoration (Faulkner, 2008). Two complementary approaches, namely, technology- and water quality-based, can be adopted to establish the emission limits for pollution discharges (Ragas and Leuven, 1999). Owing to its fairness, efficiency, and rationality, water quality-based waste allocation control is strongly favored by the Environmental Protection Agency of the United States, over the technology-based control strategy (Lung, 2001). Since the 1960 s, water quality-based methods, such as mathematical programming (Deininger, 1965; Loucks et al., 1967), fuzzy optimization (Zimmermann, 1978; Burn and McBean, 1985; Lee and Wen, 1997; Ghosh and Mujumdar, 2010; Nikoo et al., 2013; Mahjouri and Abbasi, 2015), trial-and-error simulation (Boese, 2002; Culver et al., 2002), and water quality-based simulation–optimization (Jia and Culver, 2006; Deng et al., 2010; Zou et al., 2010; Han et al., 2011; Afshar and Masoumi, 2016), have been developed and widely used in water bodies worldwide. The results of different methods are considerably different in terms of uncertainty and reliability given the differences in the water quality and optimization models used and in the connections between two types of models (Liao et al., 2013).

The simulation–optimization method exploits the combined use of water quality simulation and optimization models. Optimization models maximize the total allocated load (AL), whereas water quality models ensure that water quality standards[1] (WQS) are satisfied (Saadatpour and Afshar, 2007). The simulation–optimization method clearly reveals the response of water quality to the ALs, which not only

* Corresponding author at: Key Laboratory of Marine Chemistry Theory and Technology (Ocean University of China), Ministry of Education, Qingdao 266100, China.
E-mail address: likeqiang@ouc.edu.cn (K. Li).

[1] According to National Seawater Quality Standard of People's Republic of China (Ministry of Environmental Protection of the People's Republic of China, 1997), seawater quality of DIN are categorized to five levels: level I ≤ 0.2 mg·L^{-1}, level II ≤ 0.3 mg·L^{-1}, level III ≤ 0.4 mg·L^{-1}, level IV ≤ 0.5 mg·L^{-1}, worth than level IV > 0.5 mg·L^{-1}.

https://doi.org/10.1016/j.ecolind.2018.04.014
Received 4 January 2018; Received in revised form 5 April 2018; Accepted 6 April 2018
Available online 24 April 2018
1470-160X/

reduce the uncertainty of AL calculation but also increase the efficiency (Ines et al., 2006; Singh, 2012). The method has been widely used in load allocations in ground waters (Gorelick, 1982), lakes (Su et al., 1992), river basins (Karamouz et al., 1992; Li, 1992; Jia and Culver, 2004; Mujumdar and Subbarao Vemula, 2004; Jia and Culver, 2006; Afshar and Masoumi, 2016), estuaries (Deng et al., 2010), and coastal ocean (Li et al., 1999; Han et al., 2011; Ding, 2012).

Sea is a fairly complex hydrodynamic system. To obtain any realism in the biogeochemical results, the coupled model system should be based on an advanced three-dimensional (3D) physical model that can realistically represent the vertical exchanges (Skogen et al., 1995). The complexity of ocean models results in the deviation of the eigenvalue and response surface methods from the simulation models, while the large constraint sets that cause numerical difficulties and entail high computational costs render the embedding water quality models in optimization models unsuitable for connecting the simulation model with the optimization model (Pulido-Velázquez et al., 2006; Chiu et al., 2009). Thus, a unit source concentration response matrix (USCRM) (Gorelick and Remson, 1982) is used to replace the simulation model and link the optimization with the simulation (Louie et al., 1984). This approach is called response matrix approach (Gorelick, 1983).

The response matrix approach is based on two assumptions as follows: water quality is linearly related to the PLs, and the multi-discharger system conforms to the linear superposition principle (Gorelick and Remson, 1982). However, the water quality response to the PLs and the superposition of the multi-discharger system are nonlinear (Nikolaidis et al., 1998). The water quality predicted by the response matrix approach deviates from the underlying water quality simulation model.

The variable response matrix approach (VRMA) was first introduced by Carmichael and Strzepek (2000) to solve the nonlinear problem of waste load allocation. The USCRM is iteratively updated by the simulation model using iterative solutions from the optimization model until the optimization and previous solutions are identical (Carmichael and Strzepek, 2000). Although the VRMA is the most rational and practical approach for complicated water bodies, such as the coastal ocean, most of the published studies that used the response matrix approach preferred the fixed response matrix approach (FRMA), which treats the USCRM as a fixed matrix (Li et al., 1999; Han et al., 2011; Ding, 2012) and significantly overestimates the effectiveness of the selected AL (Carmichael and Strzepek, 2000). The applications of VRMA are constantly limited to ideal or small watersheds.

Thus, the VRMA and FRMA are applied in this study to solve a large-scale and complicated real-world problem for coastal system management. The study area, Shangdong Province, is the third largest coastal province in China. The sea area, which covers the Bohai and the Yellow Seas, under the jurisdiction of this province is comparative to its land area. The ALs of 48 main pollutant dischargers are calculated via the two methods. The water quality under the AL emission of each method is simulated via a 3D water quality model. This study is aimed at evaluating the performance of the VRMA and establishing the TN load management of Shandong based on the AL selected by the VRMA.

2. Study area

Shandong Province is a typical coastal province that is located on the northeast coast of China (Fig. 1), with 17 cities under its jurisdiction. The province covers 156,700 km^2 of land area and approximately 159,500 km^2 of sea area of the Bohai and the Yellow Seas. It also has 3024 km coastlines under its jurisdiction (Local Chronicles Office of Shandong Province, 2014).

Owing to the rapid economic development and population growth over the last 30 years, the total land-based PL of Shandong Province ranks first among the 31 provinces in China. The annual TN loads of all the pollution sources are estimated to be 55,321 tons, according to the First China Pollution Source Census (The First National Pollution Census Compilation Committee, 2011a). Approximately 90% of the pollution is discharged into the coastal ocean (Su et al. 2014), which has been causing serious water quality problems, especially for the DIN (Deng et al., 2017).

The government of Shandong Province has implemented the Total Pollutant Load Control program on ammonia nitrogen since 2011. The program is aimed at reducing ammonia emissions by 10% from 2011 to 2015. Management measures, such as industrial enterprises relocation, wastewater treatment facilities (WWTFs) upgrade, watershed restoration and coastline management (Zhang, 2007; Jiang et al., 2011; Li et al., 2018), have also been implemented since the mid-2000s. However, according to the Coastal Marine Environmental Quality Bulletin of China (Ministry of Environmental Protection of the People's Republic of China, 2017) and Marine Environmental Quality Bulletin of China (State Ocean Administration China, 2017), nitrogen pollution remains serious in the coastal ocean, especially in Laizhou Bay (Deng et al., 2017) and Jiaozhou Bay (Li et al., 2018). The algae bloom frequency and area have increased markedly since the 1990s (Zhang, et al., 2012).

A systematic and quantitative TN load reduction scheme would be helpful to the policymakers for determining the location, time and manner for implementing management measures to control pollution and satisfy water quality targets.

3. Methods

3.1. VRMA and FRMA

Load allocation aims to select an optimal pollution control system to maximize the total AL while maintaining the desirable and necessary water quality (Pearson, 1963). Thus, the calculation of ALs should search for the maximal PLs:

$$\sum_{i=1}^{I} AL_i = max \sum_{i=1}^{I} F_i, \tag{1}$$

while satisfying the WQS:

$$[C_j^{AL}] \leqslant [C_j^S], \tag{2}$$

where subscripts i and j are the identification numbers of the dischargers and checkpoints, respectively. I is the total number of dischargers. $[AL_i]$ is the optimal AL under a particular condition (coastlines and locations of the dischargers), $[F_i]$ is the PLs, $[C_j^{AL}]$ is the pollutant concentration under the emission of $[AL_i]$, and $[C_j^S]$ is the WQS.

To ensure the rationality of the ALs, the total AL should not exceed the environmental capacity of the receiving water body:

$$\sum_{i=1}^{I} AL_i \leqslant EC, \tag{3}$$

and should not be negative:

$$AL_i > 0, \tag{4}$$

where EC is the environmental capacity, which is obtained by the method proposed by Li and Wang (2013).

The response matrix approach is based on two assumptions. First, the water quality variation is linearly related to the PL. Thus, the concentration variation caused by the unit load is constant. The USCRM could be calculated by an arbitrarily selected "unit load" $[\overline{F_i}]$ (Gorelick and Remson, 1982):