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Research article

Optimal reservoir operation using multi-objective evolutionary algorithms for potential estuarine eutrophication control

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ABSTRACT

Increased nutrient loads and changed nutrient ratios in estuarine waters have enhanced the occurrence of eutrophication and harmful algae blooms. Most of these consequences are caused by the new proliferation of toxin-producing non-siliceous algae. In this study, we propose a multi-objective reservoir operation model based on 10-day time scale for estuarine eutrophication control to reduce the potential non-siliceous algae outbreak. This model takes the hydropower generation and social economy water requirement in reservoir into consideration, minimizing the ICEP (indicator of estuarine eutrophication potential) as an ecological objective. Three modern multi-objective evolutionary algorithms (MOEAs) are applied to solve the proposed reservoir operation model. The Three Gorges Reservoir and its operation effects on the Yangtze Estuary were chosen as a case study. The performances of these three algorithms were evaluated through a diagnostic assessment framework of modern MOEAs' abilities. The results showed that the multi-objective evolutionary algorithm based on decomposition with differential evolution operator (MOEA/D-DE) achieved the best performance for the operation model. It indicates that single implementation of hydrological management cannot make effective control of potential estuarine eutrophication, while combined in-estuary TP concentration control and reservoir optimal operation is a more realistic, crucial and effective strategy for controlling eutrophication potential of non-siliceous algae proliferation. Under optimized operation with controlled TP concentration and estuarine water withdrawal of 1470 m^3/s, ecological satiety rate for estuarine drinking water source increased to 77.78%, 88.89% and 83.33% for wet, normal and dry years, the corresponding values in practical operation were only 72.22%, 58.33% and 55.56%, respectively. The results suggest that these operations will not negatively affect the economic and social interests. Therefore, the proposed integrated management approaches can provide guidance for water managers to reach a stable trophic control of estuarine waters.

1. Introduction

Over the last several decades, eutrophication has raised widespread concern in environmental issues of estuaries, and has become increasingly serious as noxious algal blooms started to occur in estuaries and coastal areas (Lu et al., 2014; Strokal et al., 2014). Estuaries are important catchment areas and these regions generally receive large amounts of nutrients from rivers. With the rapid growth of economy, there have been significant increases in human activity, sewage discharge, population growth, use of agricultural chemical fertilizers, dam construction and poultry and livestock farming (Cao et al., 2014; Li et al., 2015a; Strokal et al., 2014). The effects of anthropogenic disturbances coupled with climate change lead to the receiving of high nutrient loadings and nutrient ratio changes in estuaries (Liu et al., 2016; Wu et al., 2017). Excessive nutrient loading in aquatic ecosystem may result in eutrophication, which is an enrichment of terrigenous nutrients (such as nitrogen and phosphorus), and increase the proliferation potential of phytoplankton.

The effects of estuarine eutrophication will exert the deterioration of water quality, the modification of aquatic food webs and the threats to aquatic ecosystem (Li et al., 2014; Zhou et al., 2017); therefore, studies on limiting estuarine eutrophication are increasingly crucial and urgent. Biological predation is an effective method to control eutrophication in coastal waters (Sturt et al., 2011). Changing the hydrodynamics of the system's nutrient loading has also been widely used to control a recurrent harmful algal bloom (Passy et al., 2016; Ralston et al., 2015). While these measures can only control algal growth passively with the help of invertebrate grazers or reducing nutrient loads, it is not clear that what extent that load reductions can impact the estuarine water quality. Given the nature of nutrient control schemes, it is

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wise to control nutrient compositions to limit eutrophication problems. Optimal reservoir operation models are useful tools which can be used to control water eutrophication by adjusting nutrient compositions.

New understanding of nutrient acquisition revealed that shifts in species composition (algae community transforms from siliceous algae species to toxin-producing non-siliceous algae species) have often occurred in the estuary and along the coast due to changes in nutrient ratios, mainly N:P or N:Si (Anderson et al., 2012; Glibert, 2017). This phenomenon is also happening at the Yangtze Estuary (Li et al., 2014). Jiang et al. (2014) declared that total nitrogen (TN) and total phosphorus (TP) loads entering the Yangtze Estuary are now significantly higher than they were decades ago due to anthropogenic emissions. However, dissolved silicon (DSi) load has been reduced due to dam construction especially the construction of the Three Gorges Dam (TGD) (Ran et al., 2013). These changes would result in a decrease of the ratios of Si:N and Si:P in the estuarine waters, further causing eutrophication and even harmful algae blooms (Liu et al., 2016). Li et al. (2014) revealed that the percentage of *Dinoflagellates* (non-siliceous algae) increased from less than 1% to over 25% in the Yangtze Estuary and the East China Sea (ECS) from 2002 to 2007, while diatoms decreased from 99% to 73% because of the increased N:P ratio and decreased Si:N. These results were consistent with investigations that major species in harmful algae blooms over the last decades shifted from diatoms (*Skeletonema* spp.) which do not produce algae toxins to toxin-producing non-siliceous algae (*Dinoflagellates*) in the ECS (Guo et al., 2014). It is reported that siliceous algal, mainly *Diatoms*, may induce harmful algal blooms in nutrient-rich waters, but its occurrence frequency is far below that of non-siliceous algae (Wang et al., 2013). Considering the above information, it is feasible to select non-siliceous algae as a specific indicator species to control eutrophication potential in estuarine water area.

Based on nutrient stoichiometry theory, several authors (Conley et al., 1989; Redfield et al., 1963; Rousseau et al., 2002) proposed that the nutrient requirements of the diatom growth in the molar C:N:P:Si ratios is 106:16:1:20 in coastal waters which is called the Redfield ratios. The essence of the Redfield ratios showed that excess N and P supply with respect to Si, compared to the requirements of diatom propagation, caused estuarine eutrophication problems (Billen and Garnier, 2007; Garnier et al., 2010). Consequently, a new synthetic indicator of coastal eutrophication potential (ICEP) was proposed to estimate the potential for new production of non-siliceous algae on the basis of riverine external inputs of N, P and Si (Billen and Garnier, 2007). The ICEP representing the potential impact of the riverine fluxes on estuarine eutrophic state has been applied to many coastal waters, and verified effectively assessing the eutrophication potential for most of the drainage basins (Garnier et al., 2010; Wang et al., 2013). The N:P ratio increased from 18.5 to 35, whereas the Si:N ratio decreased from 3.8 to 0.85 from 1959 to 2002 in the Changjiang plume water (Wang, 2006). Moreover, silicate concentration is decreasing continuously with the construction of large dams on the River (Liu et al., 2016). As a consequence, the limiting nutrient is excessive over silica in the Redfield ratios, which can lead non-siliceous algae to grow abundantly. The TGD has changed the Yangtze River runoff with man-made regulation, which has significant impact on nutrients input to the estuary and marine ecosystem (Gong et al., 2006). The shift in nutrient composition induced by the TGD is expected to result in greater P limitation in the Yangtze Estuary and coastal waters (Liu et al., 2016). Therefore, the ICEP can be an available optimization objective to guide discharge regulation to reduce the potential proliferation of non-siliceous algae.

Management objectives of most reservoirs usually include maximizing hydropower generation, minimizing water shortages, as well as meeting downstream flow requirements, such as water supplies, navigation, flood control, the environment and recreation. Achievements of the optimal decision-making process from reservoir operation are multi-objective optimization problems (MOPs). Traditional MOPs are usually solved by transforming it to a single objective optimization problem based on the weight sum approach (Chen et al., 2007). In multi-objective optimization there are various conflicting and incommensurable objectives, thus their optimal solutions cannot be solved by a single objective function summed by the given weights. Recently, a variety of multi-objective evolutionary algorithms (MOEAs) have been proposed to find Pareto optimal solutions simultaneously for MOPs (Li et al., 2015b; Trivedi et al., 2017). Although many MOEAs have been used for the water resources planning and management as well as pollution controls, such as non-dominated sorting genetic algorithm II (NSGA II) for water resources allocation (Ye et al., 2018), Strength Pareto Evolutionary Algorithm (SPEA) for controlling environmental impacts of non-point source pollution (Muleta and Nicklow, 2015), brog MOEA, epsilon-MOEA, NSGAII, epsilon-NSGAII and generalized differential evolution 3 (GDE3) for the environmental economics Lake Problem (Ward et al., 2015), it is difficult to implement these algorithms to obtain the Pareto optimal sets for large-scale multi-objective reservoir operation because of curse of dimensionality (Zhang et al., 2017) and high computational cost (Chu et al., 2015). Improved non-dominated sorting genetic algorithm III based on elimination operator (NSGA-III-EO) is a recent optimization algorithm that was introduced by Bi and Wang (2017). It can significantly keep diversity and convergence of population. Multi-objective evolutionary algorithm based on decomposition (MOEA/D) is one of the most efficient MOEA first using decomposition strategy and has gained popularity in solving optimization problems (Reed et al., 2013). MOEA/D-DE is an improved version of MOEA/D integrating differential evolution operator and has ability of dealing MOPs with complicated Pareto set shapes (Li and Zhang, 2009). NSGA-III-EO, MOEA/D and MOEA/D-DE are three modern representative algorithms based on decomposition and dominance, which can transform the MOP into a number of single-objective optimization subproblems and then solve them in one single run. This is very effective to reduce time consumption and promote population diversity in finding Pareto optimal sets for MOPs. In this study, these three excellent MOEAs were selected to analyze the developed reservoir operation problems. A practical problem is how to choose a suitable algorithm to ensure that algorithm can provide efficient, effective and reliable reservoir management tradeoffs. This study address this issue by implementing a comprehensive diagnostic assessment framework (Hadka et al., 2012; Reed et al., 2013) to evaluate the performance of each of the three MOEAs.

This study develops a multi-objective reservoir operation model, through the optimal operation of the reservoir to reduce the estuarine eutrophication potential. Then three different dominance- and decomposition-based MOEAs were adapted to solve the operation model, and their performances were compared and discussed. Ten-day inflow data in selected three typical hydrological years and operation schedule for China's Three Gorges Reservoir (TGR) were analyzed as a case study. Proposed ecological satiety rate indicator and objective function values under practical operation results and two optimized operation results were discussed. The combined multi-objective optimization operation model and TP concentration controlling strategy, as well as the most optimized MOEA can help water managers control eutrophication in estuarine waters more efficiently.

2. Material and methods

2.1. Study area and data

2.1.1. The Yangtze River

The Yangtze River, with 6397 km in total length and 1.8 million km^2 in drainage basin area, is the longest river in China and the third longest river in the world. It has a freshwater discharge of 924.8 billion m^3 per year and a sediment load of 0.5 billion tons per year into the ECS (Liu et al., 2016). The Yichang hydrologic station located in Hubei Province is the control point and the outlet of the Yangtze River upstream.

The Three Gorges Dam in the Yangtze River is located 44 km