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Identification of optimal water transfer schemes for restoration of a eutrophic lake: An integrated simulation-optimization method

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ABSTRACT

This research developed an integrated simulation-optimization method (ISOM). This model incorporated eutrophication modeling, water resource allocation and trophic status assessment within a general modeling framework. In ISOM, the simulation effort [i.e. environmental fluid dynamics code (EFDC)] was used to forecast the concentration of water quality variables to evaluate the lake trophic status under various conditions, while the optimization studies were used to identify the optimal water transfer strategies from a number of alternatives. To solve the model, a surrogate-based genetic algorithm (GA) was proposed in which the support vector regression (SVR) was used to create a set of easy-to-use and rapid-response surrogates for identifying the functional relationships between water transfer and lake trophic status. By replacing the EFDC and the corresponding trophic state index (TSI) equations with the surrogates, the computation efficiency could be improved. The developed ISOM was applied to the inter-basin water transfer management of the Niulanjiang-Dianchi Water Transfer Project (NDWTP) to support the eutrophication restoration of Lake Dianchi. Optimal water transfer schemes for three different remediation durations were generated from the model. The results demonstrated that NDWTP could exert a positive influence on the ecology and environment of Lake Dianchi, and that the trophic level for the Lake Dianchi could be effectively mitigated through the adoption of optimal water transfer schemes.

1. Introduction

Water quality degradation has become ubiquitous in many freshwater bodies across the world, such as reservoirs and lakes (Misra et al., 2011; Ni and Wang, 2015). Many complex and irreversible consequences are associated with such a process. Among them, the frequent occurrence of eutrophication is of increasing concern due to its adverse effects upon aquatic ecosystems, drinking water supplies, and human health. Among numerous efforts to mitigate the impacts of eutrophication, water transfer is an effective short-term remedy method by diluting the polluted water with large amounts of fresh water. It was widely used in many reservoirs and lakes, such as Green Lake and Moses Lake in the USA (Oglesby, 1968; Welch, 1981), and several lakes in China (e.g., Dianchi, Taihu, and Chaohu) (Hu et al., 2008; Xie et al., 2009; Zhao et al., 2012a). However, such a process is fraught with complexities due to the nonlinear response of water quality to nutrient loading, the trade-offs among the flow allocation of water transferred, the eco-environmental water requirements of rivers and the trophic status of the lake. For example, a variety of complexities are associated with practical water transfer practices due to the combination of local hydrological cycles and physical and biochemical processes of water contaminants, as well as interactions between two locations of water transfer. This calls for an integrated tool that can effectively reflect or tackle the hydrological cycles, water contaminant reduction processes, and interactive mechanisms between various watersheds. The identification of optimal water transfer schemes is thus highly desired for achieving multiple targets, such as the minimization of water transfer cost, the improvement of the aquatic ecological environment of rivers, and the alleviation of lake water quality deterioration. This may lead to many challenges for decision makers and managers of water transfer projects. Therefore, it is necessary to propose an integrated approach by incorporating a eutrophication modeling system, water resource

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allocation and trophic status assessment within a general modeling framework.

Recently, many eutrophication models, such as WASP, CE-QUAL-W2 and EFDC were applied to water environment management (He et al., 2011; Li et al., 2013; Wang et al., 2015). Among them, the environmental fluid dynamics code (EFDC) is a comprehensive one-, two-, or three-dimensional model capable of simulating water circulation, temperature dynamics, and advanced eutrophication processes involving nutrients, phytoplankton, macrophytes, and predation/grazing processes (Hamrick and Mills, 2000). It integrates the hydrodynamic and eutrophication modules, and can provide insights into the relationship between nutrients and eutrophication for a specific water body. Recently, EFDC has been applied for simulation and decision support analysis of many surface water bodies such as lakes, reservoirs, bays, wetlands and estuaries (Anderson, 2010; Guo and Jia, 2012; Jin et al., 2007; Sinha et al., 2013; Zhao et al., 2013). These works revealed that EFDC could provide high-resolution simulation of eutrophication phenomena, quantify the lake's response to external loading and evaluate the effectiveness of restoration efforts (such as water transfer projects). However, it is computationally expensive, especially when a large number of runs are required for conducting further analysis.

One concern regarding computational efficiency has motivated researchers to seek advanced methods for alleviating the huge computational efforts (Dai et al., 2014). One solution approach is to create effective surrogates to replace the complex EFDC simulation system. Aly and Peralta (1999) employed a first-order approximation to replace simulation models, thus formulating a linear optimization problem. However, because such linear formulations were incapable of reflecting the complex nonlinear relationships, further studies on exploring surrogates with high approximation accuracy were developed. For instance, Huang et al. (2003) developed an integrated simulation–optimization approach using a dual-response surface method for solving relevant problems in a simpler and quicker manner. Lall et al. (2006) utilized a locally weighted polynomial regression surrogate to approximate the arbitrary nonlinear relationship between inputs and outputs. He et al. (2008) used an artificial neural network to link the time-consuming fuzzy simulation process with an optimization model. Dai et al. (2014) advanced a simulation-aided nonlinear programming model, where a surrogate-based solution approach based on support vector regression (SVR) was proposed. These research efforts indicated that the surrogates could not only improve computational efficiency but also execute the simulation and optimization processes without introducing significant errors. Among these surrogates, SVR was regarded as one of the desired candidates for universal regression purposes (Thissen et al., 2004). Compared to artificial neural networks, SVR has the advantage of producing a global optimization model that is capable of efficiently dealing with high-dimensional input vectors. Moreover, it can adhere to the principle of structural risk minimization seeking to minimize the upper bound of the generalization error, rather than to minimize the training error (Dai et al., 2011).

At the same time, many methods were developed to support the management of inter-basin water transfer, water resource allocation and lake trophic status assessment (Carlson, 1977; Hu et al., 2014; Song et al., 2016; Xu et al., 2011; Zhang et al., 2015). For example, Carlson (1977) presented the trophic state index (TSI) to conduct a trophic classification of lakes. Khan (1982) presented a nonlinear programming model for managing irrigated agriculture with varying quality of water. Misirli and Yazicigil (1997) demonstrated the usefulness of mixed integer programming in groundwater remediation system designs that required installation of interception wells. Maqsood et al. (2005) developed an inexact linear optimization model for the planning of water resources systems. When undertaking economic and environmental assessment of water transfer strategies, Karamouz et al. (2007) emphasized the necessity of inter-basin water transfer. Based on a hybrid two-stage genetic algorithm (GA) optimization model, Afshar et al. (2009) designed a nonlinear, non-convex, and large scale semi-distributed, cyclic reservoir system in an irrigable area.Chen and Chang (2010) emphasized the use of a multiple-objective programming approach to address the water resources redistribution problems between two neighboring water systems (i.e., the Tseng-Wen and Kao-Ping River Basins, South Taiwan). Based on the monitoring data, Xu et al. (2011) provided the eutrophication gradients of 29 Chinese lakes and 29 Italian lakes through a trophic status assessment approach. Jafarzadegan et al. (2013) proposed a dynamic programming model for optimal operation of inter-basin water transfer systems by conjunctive adoption of surface water resources in a water donor basin and groundwater resources in a water receiving basin.

Although many simulation and optimization modeling efforts have been undertaken for dealing with issues of water quality response, water resource allocation and water transfer management, several shortcomings need to be remedied. One major shortcoming of these studies is that no inherent linkages exist among the simulation and optimization systems. This has led to several problems. First, in terms of the simulation modeling, the studies focused on analysis and evaluation of lake trophic status without the implementation of best management practices for eutrophication mitigation actions. At the same time, those studies focusing on optimization of water resource allocation could not evaluate the effectiveness of the generated decision alternatives within a real-time context. Moreover, such simulation and optimization efforts were scarcely connected with lake-basin management actions and thus could not successfully reflect trade-offs among flow allocation of water transferred, the eco-environmental water requirements of rivers and the corresponding trophic status of lakes. Decision makers or managers thus could not adjust their strategies to maintain a balance between water transfer cost and eutrophication restoration.

Therefore, the objective of this research is to develop an integrated simulation-optimization method (ISOM). The simulation system (i.e., EFDC) will be employed to forecast the fate of water quality variables for quantifying the trophic status under various conditions, while the optimization system is adopted to identify the optimal water transfer strategies from a number of alternatives. Due to the difficulty in searching for the optimal solutions of ISOM, an indirect search approach will be proposed. In the approach, a large quantity of results from the complex EFDC simulation system will be replaced by a rapid-response SVR simulator, and subsequently the optimal solutions will be identified via GA. The objective entails the following tasks: (i) carrying out the EFDC simulation system for generating a number of statistical samples, (ii) using SVR to establish a set of surrogates to provide a bridge between water transfer schemes and the associated trophic status, (iii) advancing a nonlinear optimization method by incorporating the surrogates into the optimization framework, and (iv) applying the ISOM to an inter-basin water transfer management system in the Lake Dianchi basin for demonstration.

2. Methods and materials

The proposed ISOM contains three modules: simulation and trophic status assessment, statistical inference, and optimization. First, simulation (i.e., through EFDC) and trophic state index will be performed to predict the water pollution of lake bodies and the resulting trophic levels, respectively. Subsequently, numerical experiments will be conducted to select and identify statistical samples comprising explanatory and response variables