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Research papers

Developing a comprehensive framework for eutrophication management in off-stream artificial lakes

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ABSTRACT

In this paper, a comprehensive and interdisciplinary framework for management of eutrophication in off-stream artificial lakes in semi-arid and arid regions is proposed. Identification of the lake's water resources system components and stakeholders, simulation of Phosphorus (P) export from upstream watershed, simulation of the lake water quality as well as simulation of water demands and supply, development of management scenarios for the lake and selecting the best scenario using social choice methods (i.e. discrete and fuzzy Borda counts) are the four main parts of the framework. The proposed framework is applied on Chitgar Artificial Lake (ChAL), the largest intra-urban artificial lake in Tehran which has been constructed in 2010–2013 for recreational purposes. The Load Apportionment Model (LAM) is used for the simulation of P loads from the point and non-point (diffusive) sources and the LakeMab model is used for the simulation of P dynamics in the lake. The management scenarios contain optimized rule curves for water intake/outtake blended with P management plans (i.e. removal of point sources of P load in the upstream watershed, construction of a hydroponic bio-filter or an advanced water treatment plant beside the lake for reduction of external loading of P and recycling lake water, alum treatment of lake sediments for controlling the internal loading of P as well as construction of a dry detention basin). The most preferred scenarios selected by the discrete Borda count are the low-cost alum treatment and dry detention basin, while the most preferred scenario according to fuzzy Borda count, which considers the uncertainty of model inputs, is the costly water treatment plant. In all preferred scenarios, water intake is conducted from flood flows in order to avoid conflict with downstream agricultural demands. In addition to decentralized decision making and stakeholders' participation, the proposed framework promotes the integration of the technical aspects such as the role of internal loading in lake eutrophication and separation of flood and non-flood flows in the off-stream lakes' systems.

1. Introduction

Population growth combined with an increase in living standards is heightening the pressure on quantity and quality of freshwater resources and the consequential problems are intensified under a lack of sound management. In addition to relatively large changes that damming imposes on down-streamflow, the artificial lakes are also subject to serious pollutions. Hence, artificial lake system planning and management is of crucial importance (Zhang et al., 2017). Eutrophication is one of the main issues in both natural and artificial lakes. Lake eutrophication, by nature, refers to the process of lake aging, in which lake is gradually filled with the sediment inflow and the accumulation of dead flora and fauna in the bottom (Rast et al., 1996). The increased entry of nutrients into the water bodies due to human activities accelerates the growth of algae and aquatic plants which is referred to as cultural eutrophication (Smith et al., 2006). Nitrogen (N) and phosphorus (P) are long considered to be the most important limiting nutrients for the growth of phytoplankton (Blomqvist et al., 2004; Hecky and Kilham, 1988). The dominant paradigm in freshwater limnology is that P limits phytoplankton growth and though some scientists questioned this paradigm (Lewis and Wurtsbaugh, 2008), it is widely accepted that reducing P is the most feasible approach to oligotrophication (Schindler, 2012; Smith and Schindler, 2009).

Methods of management and restoration of eutrophication in lakes are well reviewed and categorized in the literature (Cooke et al., 2005; Hickey and Gibbs, 2009; Le et al., 2010; Lürling et al., 2016; Zamparas and Zacharias, 2014). Eutrophication is spotted as a wicked (complex) problem that there is not a single or even a fixed number of methods for resolving it (Thornton et al., 2013). Reddy et al. (2018) has thoroughly investigated the interactions and trade-offs of eutrophication – as a

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result of the high amount of fertilizers used in the food sector – with the water and energy sector and highlighted the need for using holistic decision making approaches toward sustainable development. The first step for improving lake water quality is to reduce the excessive external loading of nutrients, but since lakes trap and recycle substances, a second step for manipulating internal recycling processes might be required (Cooke et al., 2005).

There have been many efforts to link lake water quality models to watershed models to evaluate the response of lakes to different Best Management Practices (BMPs) in watershed through scenario analysis (Karamouz et al., 2015; Mateus et al., 2014; Morales-Marín et al., 2017; Motew et al., 2017; White et al., 2010; Yazdi and Moridi, 2017). Searching for the optimal set of BMPs employing simulation-optimization methods is another field of study in eutrophication management (Huang et al., 2012; Karamouz et al., 2010; Kuo et al., 2008). However, due to land ownership issues, the final applicable decision may deviate from optimal solution (Hsieh et al., 2010). Hydrologic manipulations for eutrophication management, i.e. dilution, flushing and hypolimnetic water withdrawal require large amounts of low nutrient water (Cooke et al., 2005). Modeling the response of lakes to water transfer plans has recently received paramount scrutiny (Dai et al., 2016; Huang et al., 2016; Li et al., 2011; Liu et al., 2014b; Zhang et al., 2016; Zou et al., 2014). Apart from whether water transfer improves the lake water quality, conflicts among stakeholders may rise and the above-mentioned researchers do not appropriately address the impacts of water transfer plans on both water donor and receiving basins.

Decision making in the presence of different stakeholders with various interests, almost unavoidably, prompt conflicts. In order to resolve and manage conflicts, group decision making theory is often employed, in which the decision makers, as a group, select a choice among available ones. This choice is not attributed to any individual and it is the whole group's decision. Based on the nature of decision problem and the behavior of decision makers, various solution methodologies such as Multi-Criteria Decision Making (MCDM), social choice and game theory can be selected. MCDM approaches assume full cooperation among a few decision makers/criteria and that a supreme and impartial power/criterion specifies the final decision from a set of Pareto-optimal solutions (Madani and Lund, 2011; Srdjevic, 2007). For decision-making problems with partial cooperative decision makers, social choice methods are supposed to help to avert the poor outcomes of fully non-cooperative behavior (Madani et al., 2014).

Complexities of the eutrophication management stem from the fact that stakeholders in the upstream region may have to adapt to new practices and they may resist changing, also the in-lake management practices and different outflow patterns will change flow regime in downstream which also affect stakeholders. By considering a combination of upstream, in-lake and downstream issues, some researchers have tried to solve the problems of artificial lakes with MCDM approaches. Liu et al. (2014a) developed a methodology for simultaneously maximizing economic benefits of water allocation, minimizing the water shortages and maximizing waste load allocation in a complex river-reservoir region of China. Masoumi et al. (2016) linked a water quality model (CE-QUAL-W2) with an optimization algorithm in Karkheh river-reservoir system in order to minimize water deficit in the downstream and maximize the Total P (TP) load allocation. However, reaching such high levels of cooperation – as assumed by aforementioned researchers – in the real world can be an ambitious goal due to divergent interests and conflicting objectives of different stakeholders involved in decision-making process.

Given that water withdrawals and water quality are not necessarily conflicting targets (Efstratiadis and Hadjibiros, 2011), some level of cooperation can be expected to exist among water users and environmentalists to reach an agreeable management plan. Social choice methods aim to reach a collective choice by ranking the alternatives regarding each criterion. The limited applications of social choice methods in water resources management have been well reviewed in recent publications (Alizadeh et al., 2017; de Almeida-Filho et al., 2017; Ghodsi et al., 2016; Mahjouri and Abbasi, 2015; Zolfagharipoor and Ahmadi, 2016). Silva et al. (2010) developed a group decision making model by collective alternative ranking using PROMETHEE II method to combine the rankings conducted by water users (industry and agriculture), public sector and civil society to reach the whole group decision regarding eutrophication management in a watershed. Even though uncertainty analysis is overlooked, the model provides a tool for promoting decentralized decision making. Estalaki et al. (2016) proposed 15 combinations of water supply and water quality management plans for Chitgar Artificial Lake as an urban lake. Employing SWMM model to predict lake inflow water quality and Vollenweider static model for lake response to different water management plans, they used Evidential Reasoning as an MCDM and Fuzzy Borda count as a social choice method to select the best available lake water management scenario considering a group of stakeholders. Although the proposed methods were able to prevent conflicts among stakeholders, none of the plans fully prevented the eutrophication of the lake.

The main aim of this paper is to provide a comprehensive framework for the management of quality and quantity of water in artificial lakes considering the utilities and constraints of the stakeholders. The proposed methodology is employed to define and rank a set of 16 management scenarios for the Chitgar Artificial Lake (ChAL) in Tehran considering the main existing uncertainties in the river-lake model. In this framework, the interactions of the upstream region as the source of pollution to the lake, and the downstream region as the impacted area by the construction of the artificial lake are taken into account.

In the remainder of the paper, first, the proposed methodology is discussed in detail. Then, the components of Chitgar Artificial Lake system and its stakeholders are described. In the next section, the results of simulation models, scenario developments and selecting the most preferred scenario is presented. In the last section concluding remarks are provided.

2. Methodology

A flowchart for the proposed framework is shown in Fig. 1. In the following sections, main components of the proposed framework are discussed.

2.1. Identification of the system

Identification of the system is a process which gives a clear explanation of the system to be used in the next steps and includes identification and clustering of stakeholders as well as their viewpoints. Defining the objectives and boundaries of the system are the main outputs of system identification.

2.1.1. Identification of the system components

This step is about data and information gathering and an initial assessment to define the purpose and boundaries of the system. Necessary information needs to be collected and be provided to stakeholders in order to help them to understand the system and properly identify their priorities at this stage. As it can be seen in Fig. 1, identification of components can be conducted at various levels. The selection of the level of identifications highly depends on the anticipated depth of identification and is limited by time and budget. Conducting the first level is mandatory but more thorough investigations are discretionary. The aim of the first layer is to form an initial overall view of water resources and consumptions as well as the pollutions. This provides the stakeholders with basic information to use as the starting point to find a common ground. The aim of the second layer is to establish a basis for delving deeper into the issue by separating the surface and ground water resources, various consumptions as well as point and diffusive sources of pollutions. The third layer provides thorough and detailed information for specialist identification of system