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# Multi-objective ecological reservoir operation based on water quality response models and improved genetic algorithm: A case study in Three Gorges Reservoir, China

Ming Hu[a,b], Guo H. Huang[b,*], Wei Sun[c,**], Yongping Li[b], Xiaowen Ding[b], Chunjiang An[c], Xiaofei Zhang[b], Ting Li[b]

[a] State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[b] MOE Key Laboratory of Regional Energy Systems Optimization, S-C Resources and Environmental Research Academy, North China Electric Power University, Beijing 102206, China
[c] Institute for Energy, Environment and Sustainable Communities, University of Regina, Regina, Saskatchewan, Canada S4S 7H9

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This study proposes a self-adaptive GA-aided multi-objective ecological reservoir operation model (SMEROM) and applies it to water quality management in the Xiangxi River near to the Three Gorges Reservoir, China. The SMEROM integrates statistical water quality models, multi-objective reservoir operations, and a self-adaptive GA within a general framework. Among them, the statistical water quality models of the Xiangxi River are formulated to deal with the relationships between reservoir operation and water quality, which are embedded in constraints of the SMEROM. The multiple objective functions, including maximizing hydropower generation, minimizing loss of flood control, minimizing rate of flood risk, maximizing the average remaining capacity of flood control and maximizing the benefit of shipping, are considered simultaneously to obtain comprehensive benefit among the environment, society and economy. The weighting method is employed to convert the multiple objectives to a single objective. To solve the complex SMEROM, an improved self-adaptive GA is employed through incorporating simulated binary crossover and self-adaptive mutation. To demonstrate the advantage of the developed SMEROM model, the solutions through ecological reservoir operation are compared with those through the traditional reservoir operation and the practical operation in 2011, in terms of water quality, reservoir operation and objective function values. The results show that most of benefit in the ecological operation is better than that in the traditional or practical operations except for the hydropower benefit and loss benefit of flood control. This is because flood control and environmental protection are reasonably considered in the ecological operation.



## 1. Introduction

Reservoirs are common elements of the cultural landscape worldwide, which have mostly been built by the damming of rivers (Krolová et al., 2012). Reservoir operation facilitates flood control, agriculture irrigation, hydropower generating, and shipping (Wang et al., 2006), which serves human by optimizing benefit through meeting societal demand but often ignoring environmental sustainability (Mukand et al., 2012). In fact, the damming results in significant changes to the river ecological environment. For example, water recreational activities cut down the space for aquatic organisms (Jiang et al., 2006a, 2006b; Rohdea et al., 2006); water transfer projects change the spatial and temporal pattern of regional water resources (Zeilhofer and Rubem, 2009;); and reservoirs aggravate the degradation of water quality and the spread of water-borne diseases (Mukand et al., 2011; Lu et al., 2012). Considering these changes, modern reservoir management demands a new paradigm, which integrates ecological components into its management decisions (Camdevyren et al., 2005; Suen and Eheart, 2006; Cabecinha et al., 2009; Chen et al., 2011).

Ecological reservoir operation involves complex decision making processes with multiple decision variables and objectives as well as considerable risk (Mehrdad et al., 2010). In nature, ecological reservoir operation is a multi-objective optimization problem (MOP). These objectives may be conflicting and incommensurable

* Corresponding author. Tel.: +1061773889; fax: +1061773885.
** Corresponding author.
*E-mail addresses:* huang@iseis.org (G.H. Huang), sunwei@iseis.org (W. Sun).

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while different groups of people or interests may be interacted (Chen et al., 2007). During the past decades, a variety of methods have been developed to solve the MOP (Mehrdad et al., 2010; Labadie, 2004). For example, Chen et al. (2007) proposed a diversified multi-objective Genetic Algorithm (GA) for optimizing reservoir rule curves. Chang et al. (2010) developed constrained genetic algorithms for optimizing multi-use reservoir operation. Wang et al. (2011) showed multi-tier interactive GAs for the optimization of long-term reservoir operation. Yin and Yang (2011) developed a coupled reservoir operation and water diversion model, which balanced human and environmental flow requirements. Mukand et al. (2011) studied a reservoir operation simulation to analyze the impact of hydropower system operation in alternative scenarios on energy production and natural flow regime in the La Nga river basin in Vietnam.

Although multiple objectives could be dealt with effectively, it is still necessary to incorporate the detrimental effects of reservoirs and the related environmental requirement within the reservoir operation framework. Some work illustrated the impact of reservoir operation on the water quality (Yandamuri et al., 2006; Hakimi-Asiabar et al., 2010; Castelletti et al., 2012). Most of the above methods dealt with the water quality problem by simulation models instead of statistical models (Camdevyren et al., 2005; Cabecinha et al., 2009; Li et al., 2011; Chen et al., 2011). Few studies directly relating water-quantity control measures to water quality have been found. The statistical model is a useful method to directly quantify the detrimental effects of reservoirs based on the relationships between reservoir operation and water quality responses. Various multivariable statistical approaches have been widely used to explore spatial and temporal variations, which are capable of obtaining relationship through reducing the dimensionality of datasets (Singh et al., 2005; Li et al., 2010a, 2010b, 2011). Thus, it is desired a statistical water quality response model should be embedded in water quality constraints within the reservoir operation management framework (Han et al., 2012).

When the water quality response model is incorporated in a MOP model, its solution would become more difficult (Yeh and Becker, 1982; Chen et al., 2007). With development of intelligent computation, evolutionary algorithms become very efficient in dealing with MOP due to their population-based nature (Cai et al., 2001; Huang et al., 2002; Kerachian and Karamouz, 2007; Tripathi and Pal, 2007; Chaves and Chang, 2008; Chen and Chang, 2009). In recent years, multi-objective evolutionary algorithms have been applied in reservoir operation problems (Janga Reddy and Nagesh Kumar, 2006, 2007; Hakimi-Asiabar et al., 2008; Chang, 2008; Han et al., 2012). It is shown that real-coded GAs are more suitable for large dimensional search spaces than binary-coded GAs, since they are more consistent and accurate, and they generate faster convergence (Kancev et al., 2011). The weighting method was employed to translate multiple objectives to a single objective, which was obtained from the weighted sum of the original multiple objectives (Chen et al., 2007). In order to improve the efficiency of GA, the self-adaptive characteristic was incorporated in the real-coded GA by using special mutation operators and crossover operators, such as simulated binary crossover (SBX), which create offspring statistically located in proportion to the difference of the parents in the searching space (Deb and Beyer, 1999; Su and Chiang, 2004; Subbaraj et al., 2011). Although the conventional GA has been improved in various aspects, few GA was designed to solve a MOP for ecological reservoir operation.

Therefore, the objective of this study is to develop a self-adaptive GA-aided multi-objective ecological reservoir operation model (SMEROM) and apply it to water quality management in the Xiangxi River (XXR) near to the Three Gorges Reservoir (TGR) in China, which is the largest and most representative hydropower project all over the world. The SMEROM will directly incorporate statistical models in constraints to reflect the relationships between reservoir operation and water quality; it possesses the excellent attributes of self-adaptive evolutionary algorithms for solving the corresponding complicated MOP; and it will help decision-makers evaluate alternative operating rules efficiently. The optimized solutions through the ecological reservoir operation will be compared with those through the traditional and the practical operation in 2011.

## 2. Methodology

### 2.1. Framework

A multi-objective ecological reservoir operation problem can be described as finding a vector of decision variables that satisfies the constraints of environment and optimizes a vector function of economic interest whose elements represent the objective functions. These functions result from the mathematical description of performance criteria, and in most cases are in conflict with each other (Chen et al., 2007). To deal with the problem, the developed SMEROM consists of: (1) establishing a statistical water quality model by using multiple linear regression in order to find the response dependence of water quality on reservoir operation, which is embedded in water quality constraints related to total nitrogen concentrations (TN), total phosphorus concentrations (TP) and the density of algal cell (DA) in Xiangxi river (the river is the largest tributary in the Hubei portion of TGR); (2) developing a multi-objective ecological reservoir operation model for predicting the different function value under various constraints in order to maximize the overall benefit of reservoir operation; (3) improving the traditional genetic algorithm by self-adaptive crossover operators and self-adaptive mutation operators, real-coded and weighting method; (4) integrating the statistical water quality model and self-adaptive GA to the SMEROM framework. The components of the SMEROM model are described in detail in the following sections.

### 2.2. The statistical water quality model of XXR

Many factors affect the water quality of reservoir, such as pollution sources, temperature, physico-chemical properties of the water mass as well as interactions among these physical, chemical and biological components of the system. To improve water quality, a response model between water quality and reservoir operation has been established to deal with the water quality problems caused by reservoir. Pearson correlation analysis is conducted between reservoir operation and water quality index, respectively. The multiple linear regression analysis is conducted between reservoir operation and three water quality indexes (TN, TP and DA) in the Xiangxi River. The three regression equations between reservoir operation and water quality indexes are constructed respectively as follows:

$$\mathrm{DA}(Y) = a_1 + b_1x_1 + b_2x_2 + b_3x_3 + e_1 \tag{1a}$$

$$\mathrm{TN}(Y) = a_2 + c_1x_1 + c_2x_2 + c_3x_3 + e_2 \tag{1b}$$

$$\mathrm{TP}(Y) = a_3 + d_1x_1 + d_2x_2 + d_3x_3 + e_3 \tag{1c}$$

where $a_k$ is a constant term; $b_k$, $c_k$ and $d_k$ are the regression coefficients; $x_k$ is the value related to reservoir operation ( water release, water head and inflow) and $e_k$ is the error term of the model.