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Multiobjective Reservoir Operation for Water Quality Optimization

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Abstract: Total dissolved solids (TDS) may enter reservoirs at high concentrations during flooding events. The release of TDS from reservoirs depends on water quality stratification within them. This paper presents an approach for the optimal operation of a reservoir with two objectives: (1) the minimization of TDS in reservoir releases, and (2) the minimization of the temperature difference between inflow to the reservoir and released water from the reservoir. The Karaj reservoir in Iran is operated to optimize these two objectives. The reservoir has two water outlets with an elevation difference equal to 40 m. Water quality and 2D hydrodynamic modeling is carried out with the model CE-QUAL-W2, which is coupled with the nondominated sorting genetic algorithm-II (NSGA-II) to produce a simulation-optimization method. The simulation-optimization method is applied to the Karaj reservoir operation under four scenarios (seasons). The paper's results indicate enhanced reservoir operation with two-outlet releases compared with one-outlet releases. Specifically, the TDS in reservoir releases and the temperature difference between inflow into and released water from the reservoir achieved with two-outlet operation are 11.81 and 4.02% lower than those achieved with single-outlet operation, respectively. **DOI: 10.1061/(ASCE)IR.1943-4774.0001105.** *© 2016 American Society of Civil Engineers.*

Author keywords: Reservoir operation; Multiobjective optimization; Total dissolved solids (TDS); CE-QUAL-W2; Thermal stratification; Karaj reservoir.

Introduction

Temperature is one of the most significant characteristics of aquatic environments (Brown et al. 2004; Begon et al. 2006; Clarke 2006; Desonie 2009). The Atlantic salmon, for example, can tolerate temperatures between 16 and 22°C before hatching, and the weight of the fish decreases with increasing temperature (Ojanguren et al. 1999). The largest species of catfish depends on temperature and dissolved oxygen (DO) in water, such that a temperature of 27.18°C is optimal for the growth of this species (Buentello et al. 2000). Thus, variations of water temperature endanger the life cycle of many native species. Lessard and Hayes (2003) compared temperature variations of ten rivers in Michigan, and showed that increasing water temperature by 5°C decreased brook species during the summer. Temperature regulates directly or indirectly the life cycle of several fish species and many other aquatic organisms.

Reservoirs impound river water and change its temperature. Preece and Jones (2002) showed that the Keepit reservoir caused temperature variations in the Namoi river and adversely impacted fish species. Elçi (2008) studied the effects of thermal stratification in the Tahtali reservoir in Turkey, and established that air temperature, wind speed, and humidity affected the thermal stratification in the reservoir and impacted its water quality. Hester and Doyle (2011) addressed the effects of human factors on water temperature. The results showed that reservoirs can increase river-water temperature up to 10°C. Fish are particularly sensitive to temperature variations in aquatic ecosystems. Another characteristic of river-water quality that is impacted by reservoirs is the concentration of total dissolved solids (TDS). TDS concentrations rise during flooding events. Etemad-Shahidi et al. (2009) modeled the total maximum daily load (TMDL) of TDS in the Karkheh reservoir, which features the largest dam in Iran with a capacity of more than 5 billion m^3 and which serves agricultural and municipal supply functions. They used a calibrated CE-QUAL-W2 model for reservoir water quality simulation. Their model results demonstrated that a 50% reduction of the TDS load is required for a 40% reduction of TDS at the reservoir outlet. Rangel-Peraza et al. (2012) analyzed dynamics of water temperature, dissolved oxygen, and total dissolved solids concentrations in the Aguamilpa reservoir in Mexico considering horizontal and water column variations. They used CE-QUAL-W2 to simulate the temporal TDS variations calibrated with data gathered every 2 months from June 2008 to June 2009. Their results showed that reservoir TDS stratification was seasonal, occurring during the rainy season and especially in the lowest reservoir zones. The CE-QUAL-W2 model provided comprehensive results of the temporal behavior of the water quality variables studied during the modeling period.

Although single-objective optimization techniques have been widely used in different fields of the study of water resource problems (Ahmadi et al. 2014; Ashofteh et al. 2013a, b, 2015a, b, c; Beygi et al. 2014; Bolouri-Yazdeli et al. 2014; Bozorg-Haddad et al. 2013, 2014, 2015b; Fallah-Mehdipour 2013a, b;

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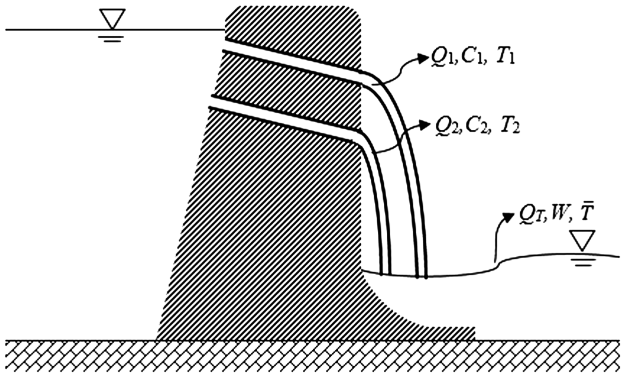

Fig. 1. Released discharge, temperature of water, and concentration of released contaminant from each outlet or layer

Orouji et al. 2013, 2014; Shokri et al. 2013, 2014; Soltanjalili et al. 2013), multiobjective optimization has had limited applications in such problems. Multiobjective optimization methods are appropriate tools to determine a trade-off between temperature variations and the effects of decreasing water quality in reservoirs. The calculated points of a Pareto frontier using the nondominated sorting genetic algorithm-II (NSGA-II) represent a set of decision alternatives whereby each alternative represents a choice by the decision maker as to which values of the decision variables to implement. Kim and Heo (2006) applied the NSGA-II to multireservoir system optimization in the Han river basin in Korea. They proposed a method for identifying the best solutions among the nondominated ones by analyzing the relation between the objective function values and the decision variables. Chang and Chang (2009) employed NSGA-II to examine the operations of a multireservoir system in

Fig. 2. Areas of municipal and agricultural water demands

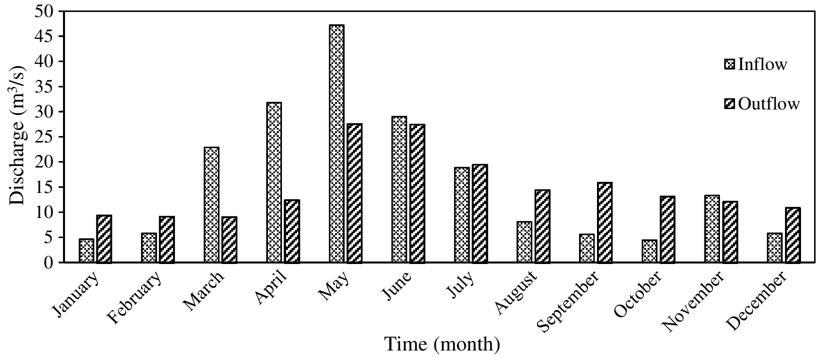

Fig. 3. Volumes of inflow to and outflow from the Karaj reservoir during the period of study

Table 1. Characteristics of the Karaj Reservoir

Characteristic	Type or number
Number of spillways	2
Bottom of the spillways (elevation above sea level, m)	1,757
Crest of the spillways (elevation above sea level, m)	1,765
Number of sediment gates	1
Number of outlet gates	3
Lower outlet (elevation above sea level, m)	1,660
Upper outlet (elevation above sea level, m)	1,700

Taiwan. They developed a daily operational simulation model to guide the releases of the reservoir system and to calculate the shortage indexes (SIs) of the reservoirs over a long-term simulation period.

In the cited publications optimal operation includes single and multiobjective models. Yet, coupled CE-QUAL-W2 simulation and optimization algorithm has been applied only to single-objective optimization of reservoir operation. This study considers the TDS concentration in reservoir releases and the temperature difference between reservoir inflow and released water from reservoirs as objectives that are optimized by linking CE-QUAL-W2 simulation with NSGA-II optimization to determine the best alternatives for reservoir operation.

Methodology

Water Quality Simulation Model

CE-QUAL-W2 is a water quality and hydrodynamic model that simulates water quality conditions of rivers, estuaries, lakes, reservoirs, and river basin systems. This model is based on eutrophication processes that involve temperature, nutrient, algae, dissolved oxygen, organic matter, and sediment relations (Cole and Wells 2006). CE-QUAL-W2 calculates water surface elevations, velocities, and temperatures. Effects of salinity or TDS on density and, thus, hydrodynamics, are included only if they are simulated in the water-quality module. CE-QUAL-W2 is modular, allowing constituents to be added as additional subroutines, such as

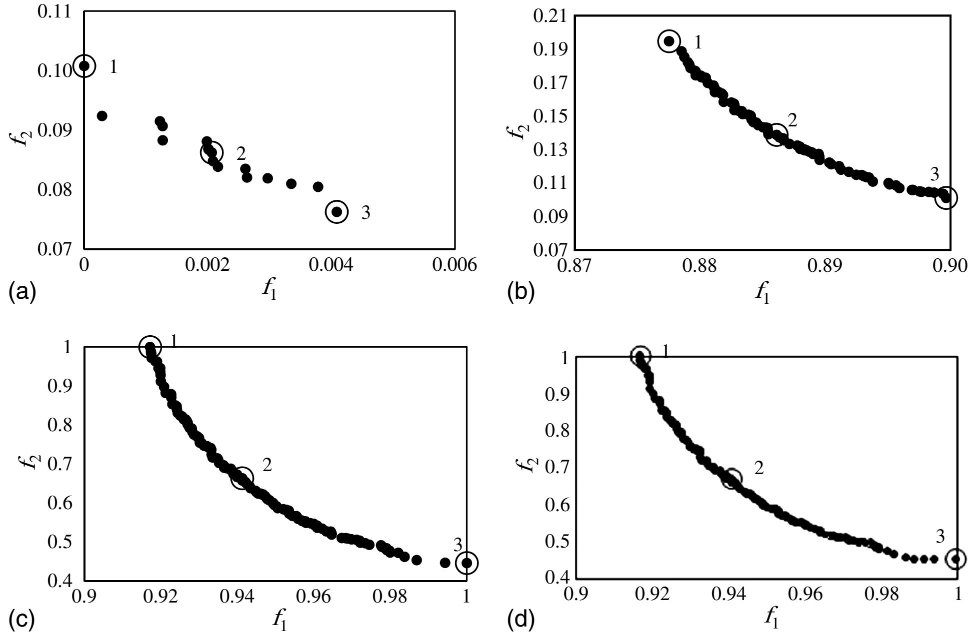

Fig. 4. Optimal frontiers for (a) the first scenario; (b) the second scenario; (c) the third scenario; (d) the fourth scenario

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Table 2. Percentage of the Total Release that Flows through Each Outlet Corresponding to Different Points on the Pareto Frontiers

		Release percentage	
Scenario	Pareto points	1,660 MASL	1,700 MASL
1	1	20.41	79.59
	2	19.96	80.04
	3	19.62	80.37
2	1	36.52	63.48
	2	33.08	66.92
	3	31.21	68.79
3	1	38.39	61.61
	2	30.98	69.02
	3	25.37	74.63
4	1	37.98	62.02
	2	34.30	69.70
	3	31.19	68.81

Note: Points 1 and 2 are the extremes of the Pareto frontiers; Point 2 is a middle point in the Pareto frontier (Fig. 4).

NSGA-II in *MATLAB*. The main CE-QUAL-W2 equations are as follows:

horizontal momentum equations

$$\frac{\partial UB}{\partial t}+\frac{\partial UUB}{\partial x}+\frac{\partial WUB}{\partial z} = gB\sin\alpha + g\cos\alpha B\frac{\partial \eta}{\partial x} - \frac{g\cos\alpha B}{\rho}\int_{\eta}^{z}\frac{\partial \rho}{\partial x}dz + \frac{1}{\rho}\frac{\partial B\tau_{xx}}{\partial x} + \frac{1}{\rho}\frac{\partial B\tau_{xz}}{\partial z} + qBU_x \quad (1)$$

vertical momentum equation

continuity equation

$$0 = g\cos\alpha - \frac{1}{\rho}\frac{\partial P}{\partial z} \quad (2)$$

$$\frac{\partial UB}{\partial x}+\frac{\partial WB}{\partial z} = qB \quad (3)$$

state equation

$$\rho = f(T_w, \phi_{\text{TDS}}, \phi_{ss}) \quad (4)$$

hydrostatic equation

$$B_\eta\frac{\partial \eta}{\partial t} = \frac{\partial}{\partial x}\int_{\eta}^{h} UBdz - \int_{\eta}^{h} qBdz \quad (5)$$

contaminant continuity equation

$$\frac{\partial B\phi}{\partial t}+\frac{\partial UB\phi}{\partial x}+\frac{\partial WB\phi}{\partial z}-\frac{\partial(BD_x\frac{\partial\phi}{\partial x})}{\partial x}-\frac{\partial(BD_z\frac{\partial\phi}{\partial z})}{\partial z} = q_\phi B + S_\phi B \quad (6)$$

where η = water elevation (m); W and U = average velocity along longitudinal and vertical axes (m/s), respectively; B = width of the water-control volume (m); τ = stresses on xx and xz planes (N/m^2); α = slope of the river bed river (m/m); q = infiltration into the water-control volume (m^3/s); T_w = water temperature (°C); ϕ = contaminant concentration, which in this study represents TDS in Eq. (4); D_x and D_z = diffusion coefficient of heat and pollution along the longitudinal and vertical directions, respectively; q_ϕ = water input (infiltration) or output (seepage); B_η = width at the surface (m); and S_ϕ = input or output of contaminant by other sources (m^3/s).

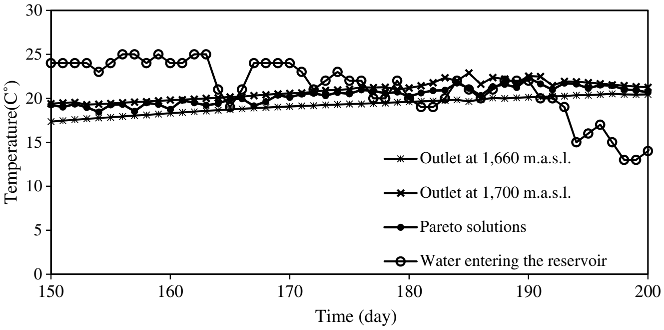

Fig. 5. Time series of the temperatures of inflow to and outflow from the Karaj reservoir during days 150–200; the Pareto solutions are also graphed

Objective Functions

The minimization of TDS in released water is the first objective and the minimization of the water temperature difference between inflow into a reservoir and released water from a reservoir is the second objective. The average temperature of the released water is the average of the water temperatures in different reservoir layers

$$\bar{T} = \frac{m_1T_1 + m_2T_2}{m_1 + m_2} = \frac{Q_1T_1 + Q_2T_2}{Q_1 + Q_2} \quad (7)$$

where $\bar{T}$ = average temperature of the released water (°C); T = temperature of water from each layer (°C); m = mass of released water from layers 1 and 2 (mg/L); Q = released discharge from each layer (m^3/s); and Q_T = total released discharge (m^3/s). There are two layers of water and each has one outlet in the application of this study (Fig. 1).

Total contaminant mass of TDS is calculated with the following equation:

$$W = Q_1C_1 + Q_2C_2 \quad (8)$$

where W = total released contaminant (g/s) and C = concentration of released contaminant from each outlet or layer (mg/L) (Fig. 1).

The objective functions are represented in Eqs. (9) and (10), as follows:

minimization of TDS in released water

$$\min f_1 = \sum_{i=1}^{n} W_i \quad (9)$$

minimization of difference in water temperature

$$\min f_2 = \sum_{i=1}^{n} (T_{\text{in}} - \bar{T})_i^2 \quad (10)$$

where i = time index; n = maximum number of time steps; and T_{in} = inflow water temperature to reservoir.

The objective functions are normalized between 0 and 1 as follows:

$$nf_i = \frac{f_i - f_i^{\min}}{f_i^{\max} - f_i^{\min}} \quad (11)$$

where nf_i = ith normalized objective functions; $f_i = f_1, f_2$; $f_i^{\max}$ = maximum value of the objective function; and $fi^{\min}$ = minimum value of the objective function.

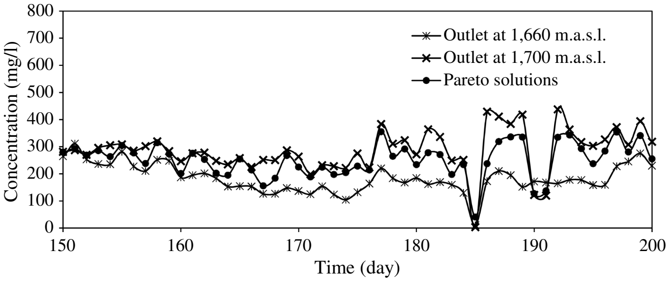

Fig. 6. Time series of released TDS concentration from the reservoir outlets during days 150–200; the Pareto solutions are also graphed

This method rescales all the objective functions values between 0 and 1, where a larger value (closer to 1) of f_1 and f_2 means a larger amount of TDS in released water and a larger difference between inflow and released water temperature, respectively. The optimization results decrease in quality as the objective functions approach 1.

Scenario Introduction

Four different scenarios are considered based on season for TDS and temperature analyses: (1) spring, (2) summer, (3) autumn, and (4) winter.

Case Study

The Karaj reservoir is one of the oldest water reservoirs in Iran, located on the Karaj river in Alborz province; it supplies municipal and agricultural sector demands as its primary objective and hydropower energy as its secondary objective (Fig. 2). Fig. 3 shows the volumes of water inflow to and outflow from the Karaj reservoir during the period of study. The baseline concentration of TDS in the river inflow to the Karaj reservoir is 50 mg/L.

The reservoir has two water outlets at different elevations: (1) a lower outlet at 1,660 meters above sea level (MASL), which is the main outlet, and (2) an upper outlet at 1,700 MASL, which is located at the hydropower station. The results of reservoir operation considering the two outlets are compared to the calculated results with one outlet at 1,660 MASL. Bozorg-Haddad et al. (2015a) simulated the fluctuation in reservoir water quality caused by the sudden entry of a biological load in the Karaj reservoir using CE-QUAL-W2 software. The CE-QUAL-W2 model can be coupled with multiobjective optimization algorithms such as NSGA-II. The CE-QUAL-W2-NSGA-II coupled model calculates the optimal (best) alternatives (Pareto frontier) for water-quality management in reservoirs.

Results and Discussions

The Karaj reservoir characteristics—e.g., the geometry of the reservoir model, the hydrological and metrological data, and the type and concentration of contaminants—constitute the input data sets to CE-QUAL-W2. Table 1 shows values of the Karaj reservoir characteristics. Four seasonal scenarios for water quality were considered and compared using CE-QUAL-W2 as the simulation model and NSGA-II as the optimization model. The values of the parameters for population size, generation, crossover probability, and mutation probability for NSGA-II are 200, 500, 0.8, and 0.09, respectively. Fig. 4 depicts the Pareto frontiers for the four scenarios calculated with the coupled CE-QUAL-W2 and NSGA-II model. The points 1, 2, and 3 shown in each scenario are the first endpoint, the midpoint, and the second endpoint on the Pareto frontiers, respectively. The concave upward shape of the Pareto frontiers implies a trade-off between the two objective functions: as one increases, the other decreases.

Table 3. Calculated Objectives for the Four Scenarios Corresponding to the First Endpoint, the Middle Point, and the Second Endpoint on the Pareto Frontiers

Scenario	Pareto frontier points	Objective functions	Outlet at 1,660 m.a.s.l.	Outlet at 1,700 m.a.s.l.	Percentage improvement of the objective function: relative to using one outlet for reservoir releases
1	1	f_1	0.105	0.101	4.18
		f_2	0.001	0.001	14.77
	2	f_1	0.090	0.086	4.27
		f_2	0.002	0.002	13.31
	3	f_1	0.079	0.076	4.36
		f_2	0.005	0.004	13.24
2	1	f_1	0.204	0.195	4.45
		f_2	0.997	0.878	13.50
	2	f_1	0.145	0.139	4.61
		f_2	0.999	0.886	12.72
	3	f_1	0.106	0.101	5.33
		f_2	1.004	0.900	11.50
3	1	f_1	0.295	0.285	3.39
		f_2	1.006	0.751	34.00
	2	f_1	0.111	0.107	3.60
		f_2	1.027	0.778	32.05
	3	f_1	0.002	0.002	3.71
		f_2	0.996	0.718	38.69
4	1	f_1	1.000	0.926	7.96
		f_2	0.999	0.875	14.12
	2	f_1	0.721	0.663	8.79
		f_2	1.000	0.868	15.22
	3	f_1	0.486	0.446	9.04
		f_2	1.000	0.868	15.20

Note: The objective function f_1 is measured in g/m^3 of TDS; the objective function f_2 is measured in °C squared.

Table 2 lists the percentage of the total release that flows through each outlet for different points on the Pareto frontiers. These percentages show that the higher-elevation outlet (with elevation of 1,700 m) has a more pronounced effect regulating water quality in the Karaj reservoir than the lower-elevation outlet.

Fig. 5 portrays the temperature of inflow to and released water from the Karaj reservoir, as well as the Pareto solutions during days 150–200. It is evident that deeper water released through the lower-elevation outlet is cooler than water released through the higher-elevation outlet. Fig. 6 depicts the TDS concentrations in water released through the two outlets, as well as the Pareto solutions, during days 150–200. Table 3 lists the values of the calculated objective functions corresponding to the four scenarios at the first endpoint, the middle point, and the second endpoint on the Pareto frontier. Table 3 also shows the improvement of the objective functions achieved with two reservoir outlets compared with the values of the objective functions achieved with one outlet.

Concluding Remarks

Optimal multiobjective seasonal operation of a reservoir system with TDS input was addressed. This was accomplished with coupled CE-QUAL-W2 and NSGA-II models. The existence of two reservoir outlets improved the two objectives compared to reservoir operation with lower outlet. The released mass of TDS and the temperature difference between inflow to and released water from the reservoir decreased by 11.81 and 4.02% compared to reservoir operation with the lower outlet during days 150–200 of simulation and optimization, respectively. Thus, the existence of more than one outlet in the reservoir improves its operation, especially when there is high TDS concentration. Reservoir managers can achieve minimal TDS in released water and minimal difference between the inflow and outflow temperatures. Moreover, the CE-QUAL-W2 and NSGA-II coupled model is recommended to calculation reservoir operation policies for water quality and quantity.

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