Title
Multiobjective Optimal Operation of Gated Spillways

Journal
Journal of Irrigation and Drainage Engineering, 143(2)

ISSN
0733-9437

Authors
Amirkhani, Masoud
Bozorg-Haddad, Omid
Azarnivand, Ali
et al.

Publication Date
2017-02-01

DOI
10.1061/(asce)ir.1943-4774.0001132

Peer reviewed

Multiobjective Optimal Operation of Gated Spillways

Masoud Amirkhani[1]; Omid Bozorg-Haddad[2]; Ali Azarnivand[3]; and Hugo A. Loáiciga, F.ASCE[4]

Abstract: This paper develops an optimal, multistage operation of gated spillways for the Karkheh Reservoir, Iran. In each stage of the proposed method, the opening of the gates is proportional to the water level of the reservoir. Two novelties are introduced in this work. The first one is consideration of the absence of a spillway or the existence of blocked spillway gates as two operation scenarios. The second novelty is attributed to using improvement of dam safety as an objective function rather than a constraint of the optimization problem. A genetic algorithm (GA) was implemented for determining the optimal opening of gates to minimize downstream damages. The nondominated sorting genetic algorithm-II (NSGA-II) was applied to optimize the two objectives of minimizing downstream damages and reducing the probability of dam overtopping. This paper's results reveal that increasing the number of stages of gate opening improved the value of the objective functions. On the other hand, the lack of spillways or blocked spillways increases the risk of dam overtopping for long return periods. **DOI: 10.1061/(ASCE)IR.1943-4774.0001132.** *© 2016 American Society of Civil Engineers.*

Author keywords: Gated spillway; Flood management; Multistage operation; Single-objective optimization; Multiobjective optimization.

Introduction

Flood management strategies are typically categorized into structurally oriented and nonstructurally oriented groups. The nonstructurally oriented flood-management procedures such as flood warning systems emphasize mitigation of flood damages while the structurally based actions are rooted in alleviation or control of flood impacts through proper design, operation, and implementation of hydraulic structures. The structural practices are possible through storage, diversion, and other actions that consider economic and environmental aspects. In this regard, reservoirs are effective in controlling high flows. Nowadays, gated spillways are used to provide a mechanism for increasing reservoir storage, which increases hydropower generation when available. In addition, gated spillways are practical tools for managing and controlling flood damages downstream from reservoirs.

The operation of gated spillways is far from trivial. This is because of the challenge of accurately forecasting the actual flood flows (Hydrologic Engineering Center 1982; Linsley et al. 1982; Sakakima et al. 1992; Japan International Corporation Agency 1994; Southeast Queensland Water Corporation 2004).

Various procedures have been previously employed to optimally operate gated spillways. Ait Alla (1997) used fuse gates for the purposes of minimizing the cost of water loss, replacing the gates, the initial investment, and gate installation. Ahmad and Simonovic (2000) applied system dynamics to compare a gated spillway against an unregulated one regarding their impacts on the flood-management capacity. The results highlighted the environmental and economic benefits of constructing the spillways. Karaboga et al. (2004) developed a fuzzy-based approach to extract a real-time operational rule for the spillways of a dam in Turkey. Their proposed approach outperformed that of Kisi (1999), who applied deterministic releases for five critical depths. Salehi (2011) provided a comparative context for real-time reservoir operation policies based on the following considerations: (1) releases from spillways were considered as a percentage of the flood volume when the water level increased to the critical levels and (2) the operational policy was optimized by minimizing the downstream flood flows of the reservoir. Based on the results, the first approach bested the second one in alleviating the peak discharge and increasing the reservoir storage. Sordo-Ward et al. (2013) applied an integrated model including hydrological, rainfall, and structural models along with the Monte-Carlo method to simulate hydrological events in 21 regions in Spain.

Recent research has proven the benefits of optimization methods and algorithms applied to various water-resources problems (Ahmadi et al. 2014, 2015; Akbari-Alashti 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, 2015a, b; Farhangi et al. 2012; Fallah-Mehdipour 2013a, b, d, 2014; Jahandideh-Tehrani et al. 2015; Orouji et al. 2013, 2014a, b; Shokri et al. 2013, 2014; Soltanjalili et al. 2013), as well as flood management. An incremental dynamic programming program was employed by Acanal et al. (2000) to optimize the firm and secondary energies of hydroelectric generation for monthly periods in Turkey. Ngo et al. (2007) employed the shuffled complex evolution (SCE) algorithm to optimize flood control and hydropower generation for investigating the optimum release from a dam in Vietnam. Karaboga et al. (2008) used an operational method via a fuzzy-logic controller for optimal operation of spillway gates of a reservoir in Turkey during floods. The tabu search algorithm was applied to optimize rule base of a fuzzy-logic controller. Qin et al. (2010) applied a new approach called multiobjective cultured differential evolution (MOCDE) for reservoir flood-control operation (RFCO). In comparison to

[1]Dept. of Irrigation and Reclamation Engineering, Faculty of Agricultural Engineering and Technology, College of Agriculture and Natural Resources, Univ. of Tehran, Karaj, 3158777871 Tehran, Iran. E-mail: M.Amirkhani12@ut.ac.ir

[2]Professor, Dept. of Irrigation and Reclamation Engineering, Faculty of Agricultural Engineering and Technology, College of Agriculture and Natural Resources, Univ. of Tehran, Karaj, 3158777871 Tehran, Iran (corresponding author). E-mail: OBHaddad@ut.ac.ir

[3]Ph.D. Student, Dept. of Irrigation and Reclamation Engineering, Faculty of Agricultural Engineering and Technology, College of Agriculture and Natural Resources, Univ. of Tehran, Karaj, 3158777871 Tehran, Iran. E-mail: Azarnivand_ali@ut.ac.ir

[4]Professor, Dept. of Geography, Univ. of California, Santa Barbara, CA 93106-4060. E-mail: Hugo.Loaiciga@ucsb.edu

Note. This manuscript was submitted on March 10, 2016; approved on August 22, 2016; published online on October 10, 2016. Discussion period open until March 10, 2017; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, © ASCE, ISSN 0733-9437.

weighted and constrained methods, MOCDE performed efficiently for flood management in multiobjective problems. A decision-support system (DSS) was introduced by Nishioka et al. (2014) for RFCO in Japan. Woodward et al. (2014) introduced a decision-support system that joins a multiobjective optimization algorithm with a flood risk analysis model and an automated cost model. It optimizes the performance of the alleviation practices against conflicting criteria. Luo et al. (2015) applied multiobjective immune algorithm with preference-based selection (MOIA-PS) for reservoir flood-control operation. Their rainfall-runoff model, which was called the hydrological river basin environment assessment model (HRBEAM), employed a weekly forecasted rainfall as the input to calculate the operational policies. Jia et al. (2015) applied an integrated, multiobjective decomposition–coordination (DCDP) model for extracting optimal flood-control operational policies in a four-reservoir system by maximizing dam safety besides minimizing the downstream damages. Their proposed model can be coupled with optimization models that assist the analysts in searching for near-optimal solutions in large-scale systems. Chiang and Willems (2015) coupled a genetic algorithm (GA) with the model predictive control (MPC) technique to analyze a real-time flood-control method for the 12 gated weirs on the River Demer (Belgium).

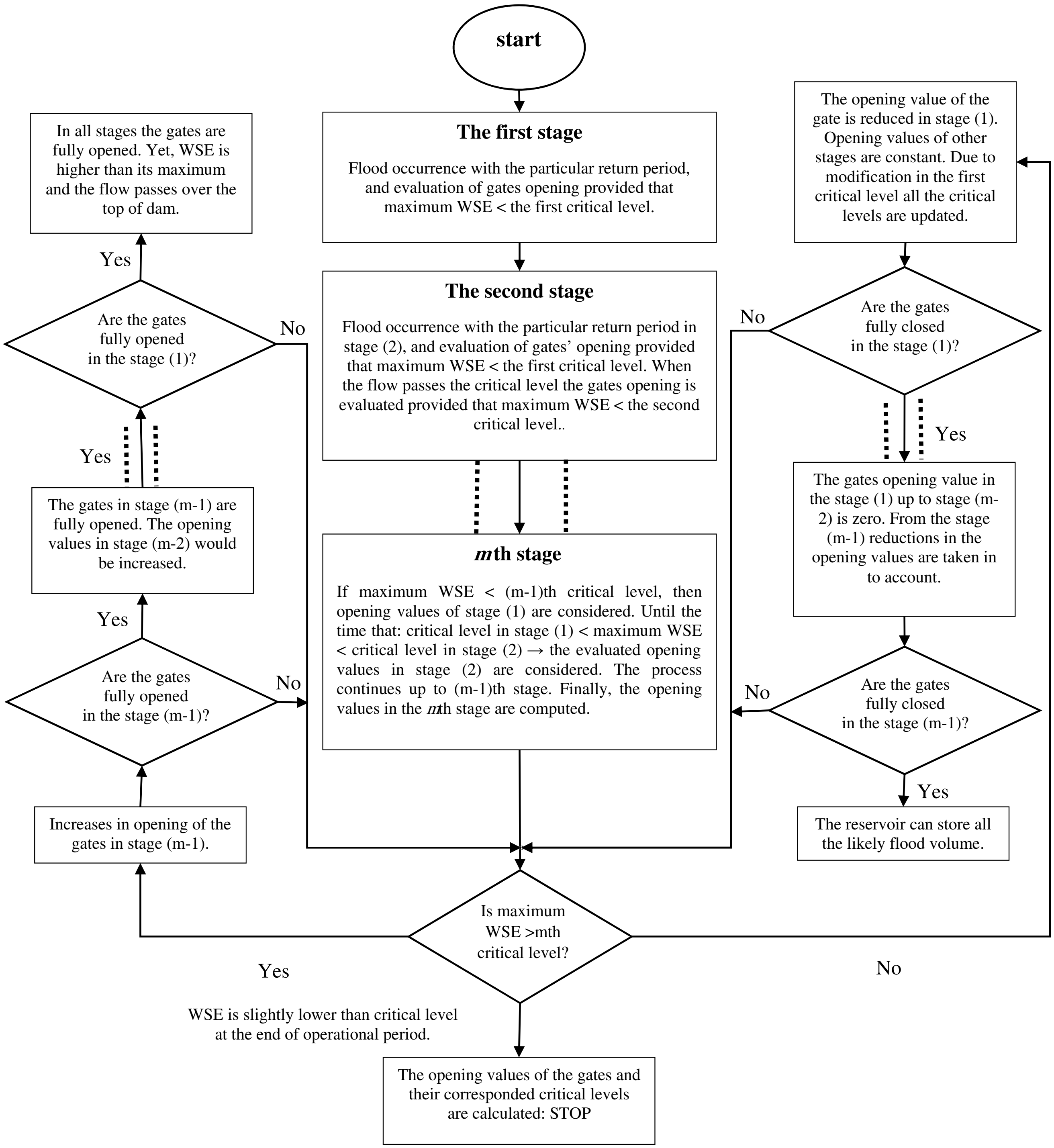

Fig. 1. Flowchart of the computational and operational process

Azarnivand and Malekian (2016) designed an interval-valued intuitionistic fuzzy multiattribute framework to prioritize structural and nonstructural measures for flood risk mitigation.

Haktanir et al. (2013) calculated operational rules for gated spillways of two dams in Turkey during floods. Their approach increased generation and reduced flood damages, and it did not require forecasting the flood hydrograph. Their approach assumes that each flood of a given return period occupies a specific fraction of the reservoir storage. The flood-retention storage of a dam was divided into 15 substorages whose surface elevations were calculated based on volume-elevation formulas and identified as critical levels. The maximum observed water surface elevations (WSEs) of floods of given return period were calculated. If maximum WSE values were less than the critical level, then the spillway gate-opening values were accepted. Otherwise, the gates' opening is increased until reaching the new first critical level. This process continues until the probable maximum flood (PMF) fills the entire reservoir storage. If the maximum WSE values were less than critical level at the end of the operational period, then it is concluded that the opening of the gates in the previous phase was more than what was needed. Therefore, the gates' opening is updated. On the other hand, if the maximum WSE values were greater than critical level at the end of the operational period then the gates' opening is increased. Fig. 1 depicts the gate-opening scheme employed by Haktanir et al. (2013), which was implemented in this paper and succeeded in safeguarding dam safety and hindering overtopping.

Afshar and Salehi (2011) reported a comparison between two different reservoir operational policies in Iran. The first policy accounted for the water level of the reservoir only. However, the second policy accounted for the water level of the reservoir and the timing of the peak reservoir inflow, which was gauged at an upstream hydrometric station. In the first policy the opening value of the gates increased with increasing WSE. The second policy, on the other hand, employed the first policy whenever the reservoir inflow was less than its peak value at the upstream gauging station. Otherwise, the remainder of the flood volume was forecasted and the forecast guided the gate opening. The second policy could store a larger volume of flood flow than did the first policy. In contrast to Haktanir et al. (2013), Afshar and Salehi (2011) employed critical levels and spillway releases as decision variables that could be optimized by suitable algorithms. This paper's approach was inspired by the method introduced by Afshar and Salehi (2011), which requires real-time operation of gated spillways. Such real-time operation reduces the peak reservoir outflow and increases storage. This work compares the performance of a reservoir system serving a flood-control function with and without spillway gates.

The Karkheh Reservoir in Iran was used as an example of flood control via spillway gates in this paper. The goals of reservoir operation were the minimization of downstream flood damages and the improvement of dam safety. Unlike previous studies that considered improvement of dam safety as the constraint of the optimization problem, the present study uses this pivotal factor as an objective which is a novelty. This work analyzed the effect of five different spillway operational scenarios including the absence of a spillway, blocked spillway gates, and three multistage schemes for operating spillway gates. Consideration of the absence of a spillway and blocked spillway gates is another novelty of the present study that has been ignored by former investigators of water-resources management. In multistage operations, there are multiple possible openings of the spillway gates. Increasing the number of opening scenarios promotes the accuracy of flood routing calculations; yet, it also raises the complexity of the computational process. Thus, it is vital to provide an effective, multiple-criteria framework for making robust decisions about the proposed scenarios for spillway gate openings. This paper's major objective is investigating the impacts of increasing the number of operational gate openings on the objective function of flood management.

Methods and Materials

Case Study

The Karkheh Dam is the largest embankment in Iran and the Middle East. The dam is in the northwestern province of Khuzestan, the closest city being Andimeshk to the east. It is 127 m high and has a reservoir capacity equal to 5.9 billion m^3. The Karkheh Dam and Reservoir are operated to irrigate 320,000 ha of land, produce 520 MW of hydroelectricity, and offer flood protection (Hydro-Iran 2015; Karkheh 2015). The Karkheh Dam features gated spillways to release high outflows including the probable maximum flood (PMF). The design parameters such as dam height, reservoir storage volume, type of dam, free board, irrigation and hydropower functions, and distance from residential areas were considered prior to and during construction of the dam. Dam crest elevation is 209 m higher than WSE. The slope of upstream side of the spillway crest is 1:1. The spillway has five middle columns that are 4 m wide. The spillway has six radial gates that control outflow. The height, width, radius, and weight of each gate are 18, 15, and 22 m, and 170 t, respectively.

The following equation estimates the outflow (Q_G) from an Ogee gated spillway:

$$Q_G = \frac{2}{3} C_G B_G \sqrt{2g} (H_I^{1.5} - H_{II}^{1.5}) \tag{1}$$

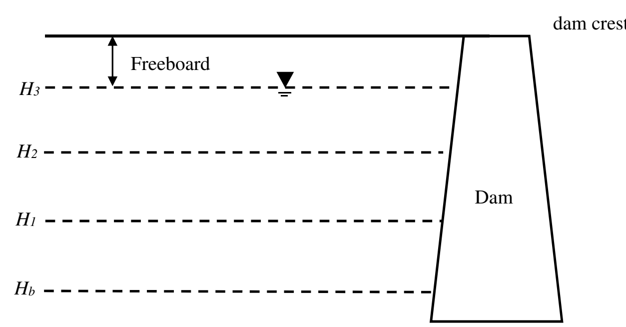

Fig. 2. Model scheme of critical levels for the second scenario

Table 1. Parameters of the GA

Parameter	Number/type
Population	200
Crossover rate	0.6
Crossover operator	Uniform crossover
Selection operator	Roulette wheel
Mutation rate	0.2

Table 2. Parameters of the NSGA-II

Parameter	Number/type
Population	200
Crossover rate	0.6
Crossover operator	Uniform crossover
Selection operator	Tournament
Mutation rate	0.2

Table 3. Critical Levels and Gate-Opening Values for OS3

Critical level	Elevation (m)	Opening value (m)
H_b	209.00	0.81
H_1	215.81	6.89
H_2	219.42	17.86
H_3	234.00	

Table 4. Critical Levels and Gate-Opening Values for OS4

Critical level	Elevation (m)	Opening value (m)
H_b	209.00	0.94
H_1	215.46	5.53
H_2	216.52	12.03
H_3	220.54	14.99
H_4	222.75	16.61
H_5	225.1	17.82
H_6	234.00	

Table 5. Critical Levels and Gate-Opening Values for OS5

Critical level	Elevation (m)	Opening value (m)
H_b	209.00	0.04
H_1	216.67	4.04
H_2	217.73	9.02
H_3	218.26	11.28
H_4	219.19	11.86
H_5	219.86	13.92
H_6	220.68	15.34
H_7	224.95	16.16
H_8	231.25	16.95
H_9	232.54	17.09
H_{10}	234.00	

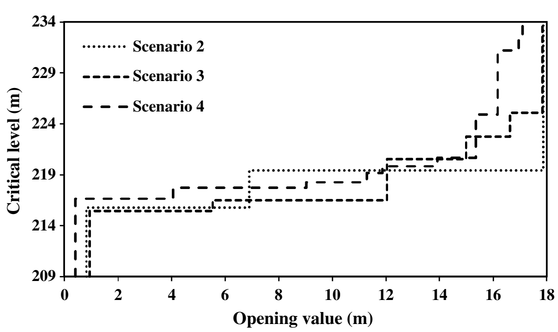

Fig. 3. Critical levels versus opening values of the gates in single-objective problem

where C_G = spillway discharge coefficient; B_G = effective spillway length; H_I = net head acting on the bottom of the orifice; and H_{II} = net head acting on the top of the orifice.

The following subsections introduce the reservoir operation objectives, variables, and constraints of the optimization problem.

Optimization Problem

Objectives

The two objectives of the current study are optimized management of spillway gates for mitigating flood damages by minimizing the peak-outflow hydrograph (Z_1) and reducing the probability of reservoir outflow overtopping the dam. The peak-outflow hydrograph was evaluated with the Modified-Puls method. The formulas and concepts of this method are available in Strelkoff (1985). Reduction of the probability of dam overtopping can be achieved by reducing the WSE at the end of the operational period, and this was chosen as the second objective (Z_2). Minimization of the peak outflow is determined as follows:

$$\text{Min } Z_1 = \sum_{d=5}^{\text{PMF}} O\text{max}_d \times \text{Weight}_d \tag{2}$$

where $O\text{max}_d$ = maximum reservoir outflow with return period d (in years); and Weight_d = probability of flood occurrence.

Minimization of water surface elevation (WSE) is determined as follows:

$$\text{Min } Z_2 = \sum_{d=5}^{\text{PMF}} H\text{final}_d \tag{3}$$

where $H\text{final}_d$ = WSE after real-time optimal operation during flood occurrence with return period d.

Constraints

The constraints of the present optimization problem are as follows:

1. The opening value of the first critical level must be lower than the second one. The constraint for this purpose is

$$\begin{cases} \text{if } OG_i \leq OG_{i+1} \rightarrow Z_1 = Z_1 + 0 \\ \text{else} \rightarrow Z_1 = Z_1 + P \end{cases} \quad i = 1, 2, \ldots, m \tag{4}$$

where OG = opening value; i = counter of critical level; P = penalty function; and m = number of critical levels or number of stages in each scenario.

2. The WSE at time t should not be higher than the ultimate critical level. The ultimate critical level equals the dam crest elevation minus the freeboard. The constraint during the flooding period (T) for different return period d is

Table 6. Peak Discharge of Flood Hydrograph for Each Scenario (10^3 m^3/s)

	Return period (years)									
Scenario	10	20	50	100	200	500	1,000	2,000	10,000	PMF
Scenario 1	1.64	3.4	3.71	3.79	4.6	5.46	6.6	7.74	11.9	15.55
Scenario 2	0.57	3.08	3.32	3.92	4.42	6.03	6.95	7.97	12.07	15.57
Scenario 3	0.51	2.7	2.97	4.14	4.92	5.76	6.81	7.9	11.97	15.52
Scenario 4	0.27	2.45	2.61	4.58	5.22	6	7.09	8.13	11.89	14.95
Scenario 5	0.00	0.00	0.00	0.00	0.00	0.00	0.98	3.3	14.82	21.64

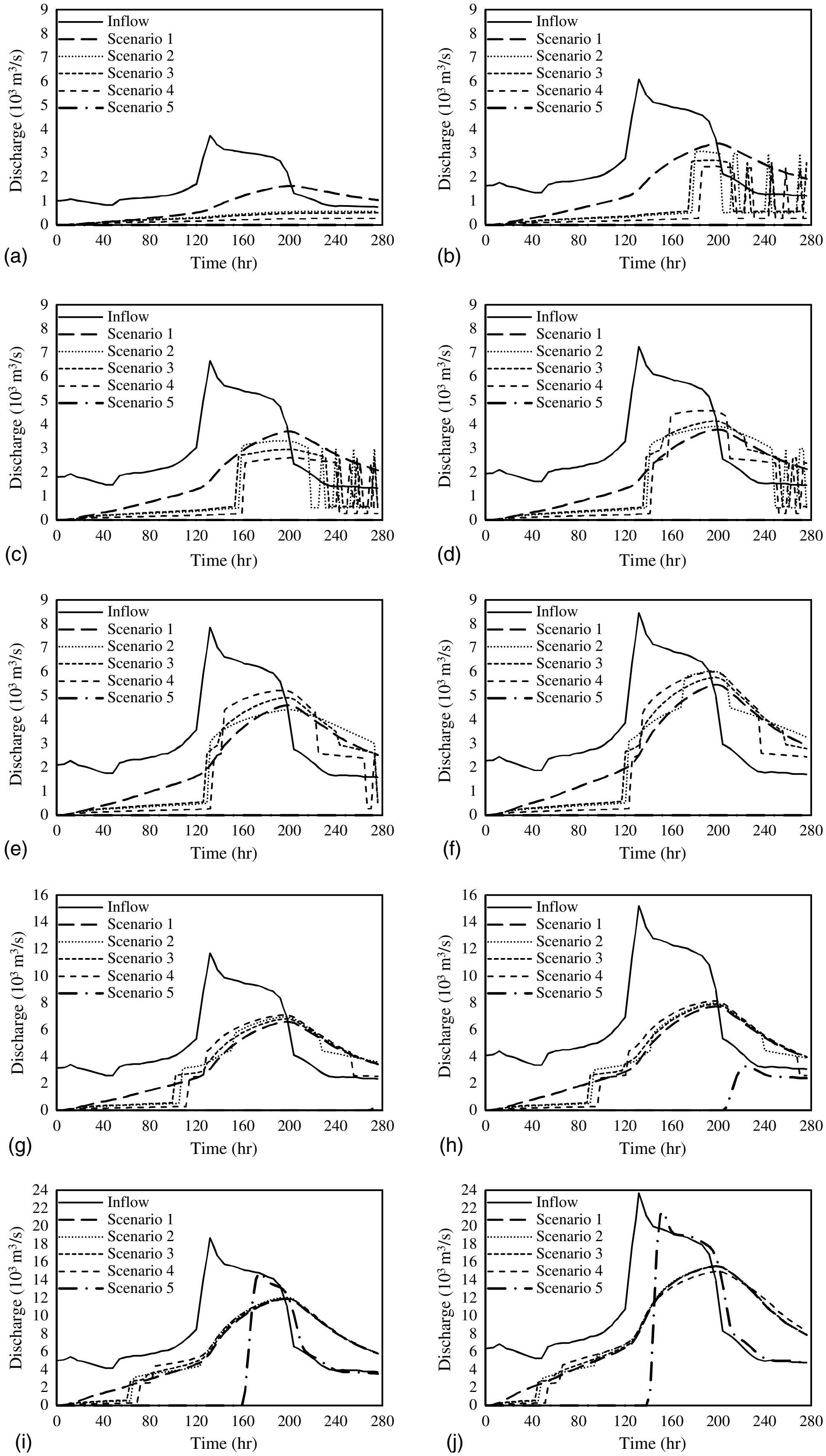

Fig. 4. Outflow flood hydrograph for various return periods (years): (a) 10; (b) 20; (c) 50; (d) 100; (e) 200; (f) 500; (g) 1,000; (h) 2,000; (i) 10,000; (j) PMF

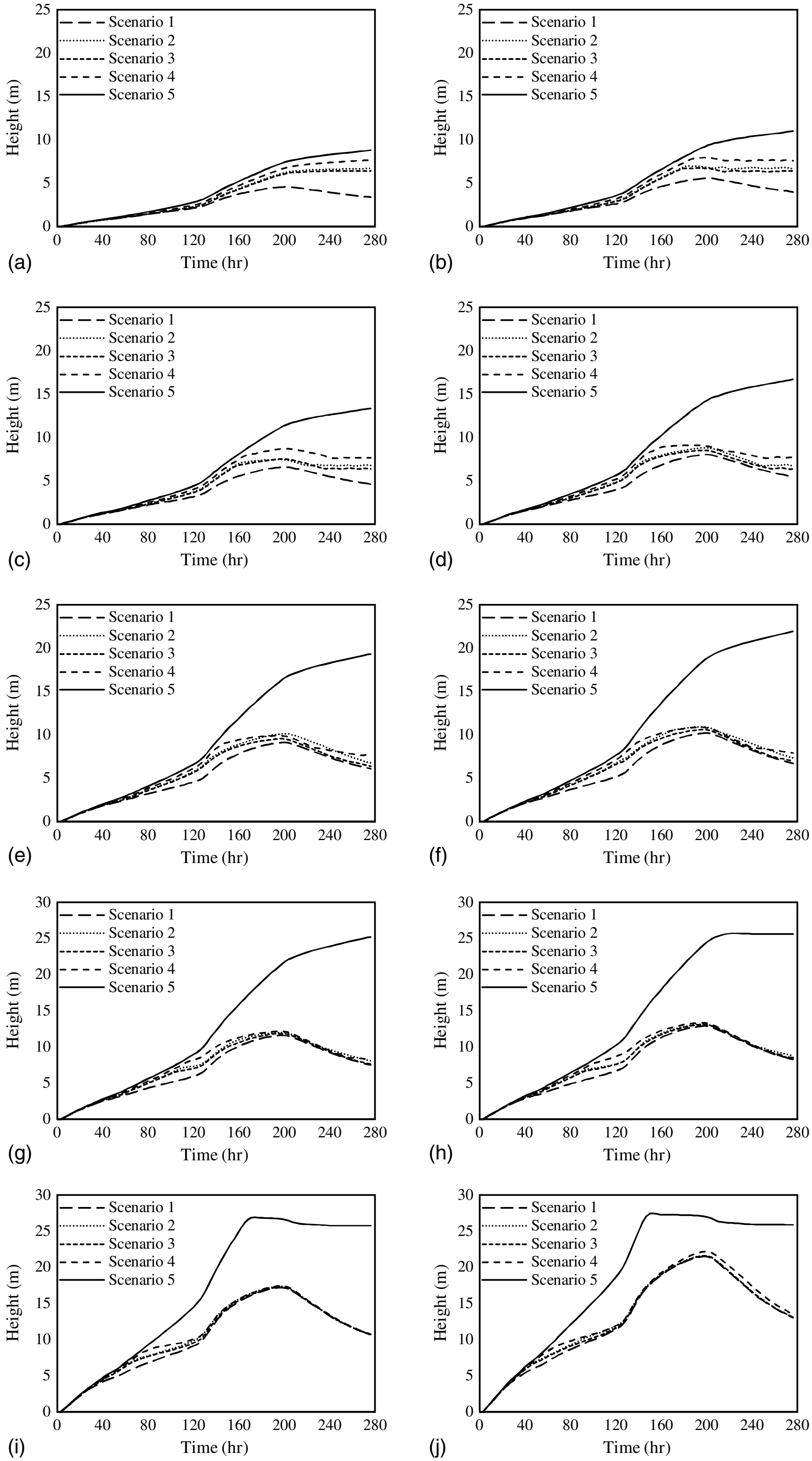

Fig. 5. Elevation of the flood hydrograph for various return periods (years): (a) 10; (b) 20; (c) 50; (d) 100; (e) 200; (f) 500; (g) 1,000; (h) 2,000; (i) 10,000; (j) PMF

$$\begin{cases} \text{if } H_t^d \leq H_{\text{Max}} \rightarrow Z_2 = Z_2 + 0 \\ \text{else} \rightarrow Z_2 = Z_2 + P \end{cases} \quad t = t_1, t_2, \ldots, Td = 5, 10, \ldots, \text{PMF} \tag{5}$$

where H_t^d = WSE in the moment of t and H_{Max} = maximum WSE.

Multiobjective Optimization

Such features as crowding distance, binary tournament selection, and elitist nondominated sorting constitute the computational components of the nondominated sorting genetic algorithm-II (NSGA-II) method. After initialization of the population of solutions, the decision variables as well as objective functions are evaluated step by step. The main steps of the (NSGA-II) method are as follows:

1. Ranking of the population after extracting the first Pareto front to assign levels to the nondominated fronts;
2. Removing the solutions with higher ranks/levels;
3. Evaluating the average distance of its two neighboring solutions (crowding distance);
4. Using binary tournament selection operator among two randomly chosen solutions from the population to choose a solution with lower rank and greater crowding distance is selected;
5. Generating the children population by repeating the selection operator and using the crossover and mutation operators;
6. Using nondominated sorting for the combination of parent and children populations; and
7. Constructing a new parent population based on the optimal solutions of each generation.

Supplementary information is presented in Deb et al. (2001). *MATLAB* was used to implement the NSGA-II for simulation and optimization using the aforementioned equations. The crossover rate, mutation rate, population size, and number of generations of the NSGA-II were determined by trial and error.

Operational Scenarios

The five following operational scenarios (OSs) were considered:

- OS1: Free operation without gated spillways;
- OS2: Three-stage operation of gated spillways. The opening values of the gates are evaluated on the basis of critical water levels. The optimization problem of this scenario has five decision variables, of which three variables describe the opening of the gates while the two remaining variables are assigned to the critical levels. According to Fig. 2, the water levels H_1 and H_2 are evaluated with respect to the initial and normal WSE (H_b) and maximum WSE (H_3);
- OS3: Six-stage operation of gated spillways. Six variables describe the opening of the gates while the five remaining variables are assigned to the critical levels;
- OS4: Ten-stage operation of gated spillways. Ten variables describe the opening of the gates while the nine remaining variables are assigned to the critical levels; and

Table 7. Water Level at the End of Operational Period for Each Scenario (m)

	Return period (years)									
Scenario	10	20	50	100	200	500	1,000	2,000	10,000	PMF
Scenario 1	3.36	3.96	4.57	5.4	6.03	6.66	7.42	8.15	10.51	12.87
Scenario 2	6.72	6.7	6.72	6.66	6.74	7.23	7.94	8.67	10.55	12.91
Scenario 3	6.45	6.4	6.37	6.44	6.4	6.91	7.48	8.19	10.53	12.9
Scenario 4	7.69	7.63	7.67	7.62	7.68	7.88	8.27	8.53	10.58	13.3
Scenario 5	8.82	11.05	13.41	16.78	19.41	22.04	25.00	25.00	25.00	25.00

Table 8. Maximum Changes in the Outflow Hydrograph for Each Scenario (10^3 m^3/s)

	Return period (years)									
Scenarios	10	20	50	100	200	500	1,000	2,000	10,000	PMF
Scenario 1	0.07	0.1	0.13	0.18	0.22	0.27	0.33	0.39	0.61	0.85
Scenario 2	0.01	2.52	2.56	2.6	2.56	2.57	2.57	2.48	2.59	2.5
Scenario 3	0.01	2.07	2.08	2.06	2.03	2.09	2.02	2.05	2.09	2.04
Scenario 4	0.01	2.14	2.12	2.15	2.16	2.13	2.16	2.12	2.18	2.14
Scenario 5	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.88	4.88	8.13

Table 9. Overflow Volume for Each Scenario (10^3 m^3)

	Return period (years)									
Scenario	10	20	50	100	200	500	1,000	2,000	10,000	PMF
Scenario 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Scenario 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Scenario 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Scenario 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Scenario 5	0.00	0.00	0.00	0.00	0.00	0.00	0.01	39.99	199.74	657.87

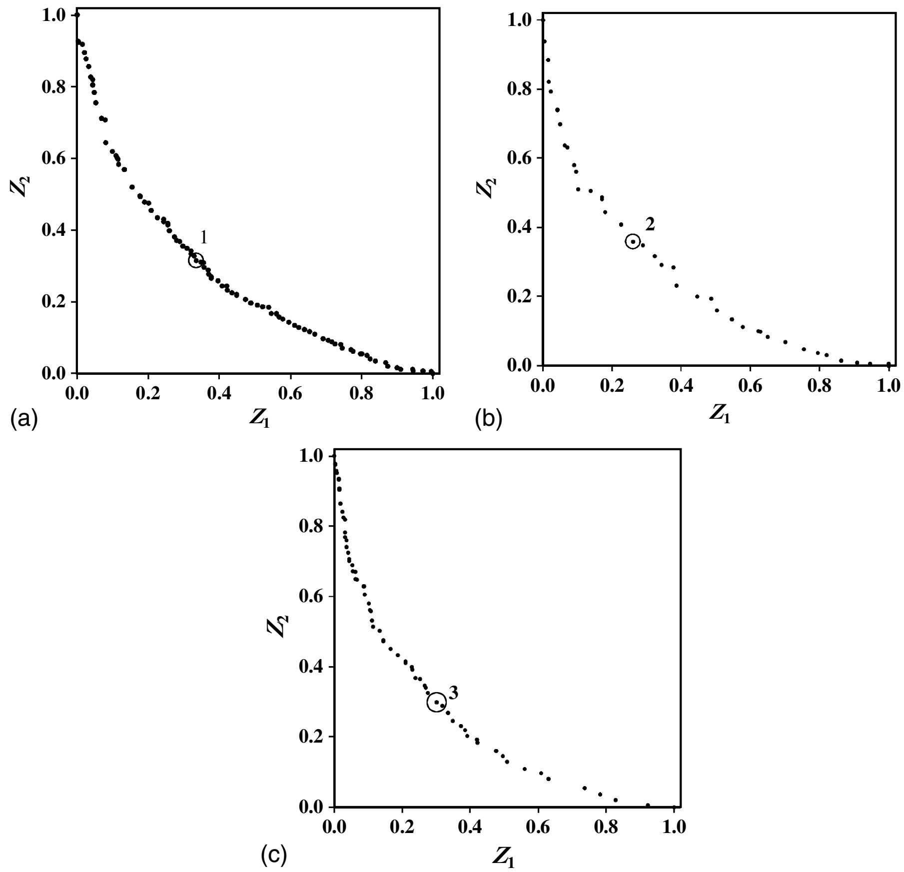

Fig. 6. Pareto solutions for (a) OS2; (b) OS3; (c) OS4

- OS5: Blocked (closed) gated spillways. Owing to natural disasters, technical problems, and improper operation, it is likely for the spillways to be blocked (closed). This increases the probability of dam overtopping.

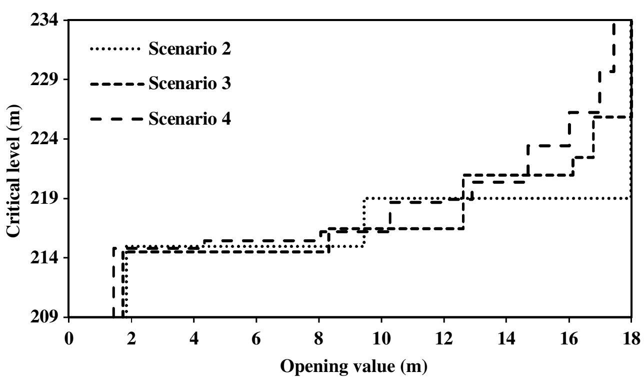

Fig. 7. Critical levels versus gate-opening values in multiobjective problem

Evaluation Criteria

The following evaluation criteria (EC) were used to assess the performance of the various gate-opening schemes:

- EC1: Peak reservoir outflow;
- EC2: Reservoir storage;
- EC3: Maximum change in the outflow hydrograph; and
- EC4: Volume of dam overtopping, which is employed to assess the efficiency of OS5, only.

Conflict Resolution

For each multistage scenario (OS2, OS3, and OS4) the opening values of the gates were compared based of their effectiveness of satisfying the Objective Z_1. Thereafter, the assessment was based on satisfaction of the Objectives Z_1 and Z_2. The results were compared with those for OS1 and OS5, which did not involve multistate gate operation. The present section is divided into two subsections, one applying single-objective optimization with the genetic algorithm (GA) and multiobjective optimization with the nondominated sorting genetic algorithm-II (NSGA-II). Tables 1 and 2 list the parameters of the GA and the NSGA-II. The convergence of

Table 10. Peak Discharge of the Flood Hydrograph for Each Scenario (10^3 m^3/s)

	Return period (years)									
Scenario	10	20	50	100	200	500	1,000	2,000	10,000	PMF
Scenario 1	1.64	3.4	3.71	3.79	4.6	5.46	6.6	7.74	11.9	15.55
Scenario 2	0.97	2.58	3.2	3.97	4.78	5.64	6.71	7.81	11.94	15.55
Scenario 3	0.92	2.43	3.18	3.94	4.75	5.59	6.68	7.8	11.93	15.56
Scenario 4	0.8	2.2	3.13	4.02	4.83	5.65	6.74	7.84	11.97	15.58
Scenario 5	0.00	0.00	0.00	0.00	0.00	0.00	0.98	3.3	14.82	21.64

J. Irrig. Drain Eng., 2017, 143(2): 04016078

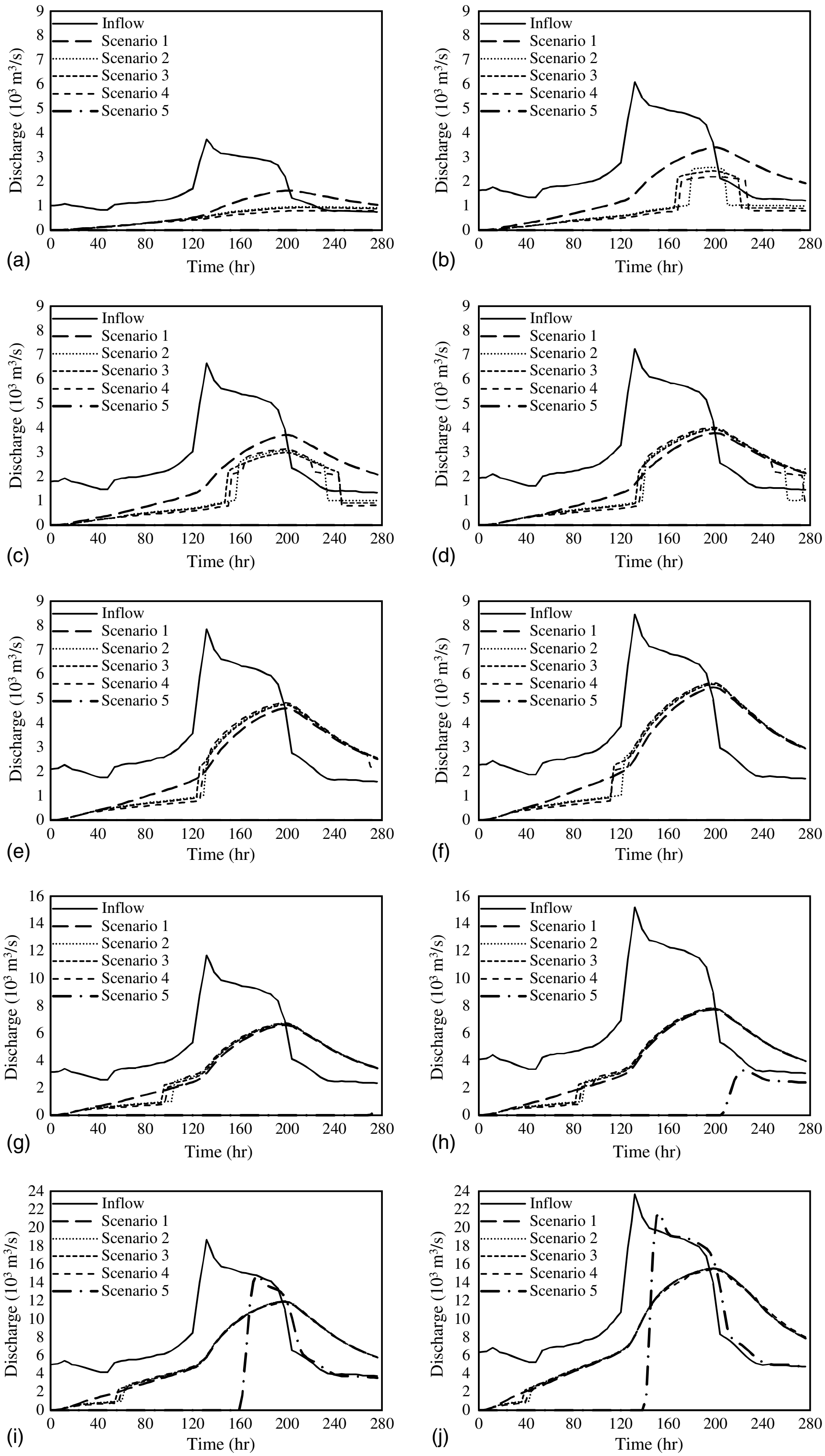

Fig. 8. Outflow flood hydrograph for various return periods (years): (a) 10; (b) 20; (c) 50; (d) 100; (e) 200; (f) 500; (g) 1,000; (h) 2,000; (i) 10,000; (j) PMF

the objective function after 30 iterations was chosen as the termination criterion.

The two objective functions Z_1 and Z_2 were normalized (in the range of [0, 1]) with the following formula:

$$nZ_j = \frac{Z_j - Z_j^{\min}}{Z_j^{\max} - Z_j^{\min}} \qquad j = 1, 2 \tag{6}$$

where nZ_j = normalized value of the jth objective function; Z_j = value of the jth objective function; $Z_j^{\max}$ = maximum value of the jth objective function; and $Z_j^{\min}$ = minimum value of the jth objective function.

Divergent interests of stakeholders and policymakers plus the existence of multiple objectives in water-resources management projects introduce complexity in this type of problem (Azarnivand et al. 2015). In the context of nondominated sorting or Pareto optimality, there is no single optimal solution capable of accomplishing all the optimization objectives simultaneously. Therefore, it is vital to find the tradeoff solutions in the Pareto sense. These solutions feature the two following characteristics: (1) none of the decision makers would accept a deal in which the utility function is lower than the decision maker's minimum desirable utility and (2) there is no best solution for all the decision makers. A simple conflict resolution technique was herein employed to find the shortest distance to a Pareto solution as follows:

$$M = \sqrt{(U_1 - y_1)^2 + (U_2 - y_2)^2} \qquad \text{Best point} = \min M \tag{7}$$

where U_1 = best value of the first objective function; U_2 = best value of the second objective function; y_1 = value of the first objective function at the yth point expressing a set of decision variables; and y_2 = value of the second objective function at the yth point expressing a set of decision variables.

Results and Discussion

Results of Single-Objective Optimization

Tables 3–5 list the GA-driven, optimized decision variables of Z_1 for OS2, OS3, and OS4. The most striking result emerging from the Table 3 is the considerable difference between gate-opening values corresponding to the optimal levels. There is a sudden increase in the outflow from the spillways when the outflow exceeded the second critical level (H_2), when the opening value of the gate rose from 6.89 to 17.86. The values of the decision variables for OS3 and OS4 are presented in Tables 4 and 5, respectively. Fig. 3 compares the opening values of the gates according to their critical levels. The results regarding the comparison of the proposed scenarios on the basis of the considered evaluation criteria (EC) are summarized as follows:

For EC1, it is seen in Table 6 that the increase in the return period raises the peak outflow. Due to the fact that floods with shorter return periods have higher frequency of occurrence, mitigation of these floods must be a priority. In this regard, OS4 could mitigate the peak outflow for short-term floods better than the other scenarios. Fig. 4 depicts the outflow hydrograph of each scenario. The fluctuations observed in some scenarios are explained by realizing that once the flood flow reaches a critical level, the gate opening increases. Yet, this action can reduce the WSE close to the critical level, which could lead to reducing the gate opening. In the fourth scenario, the peak flow of 10-year flood in comparison to the first, second, and third scenario was 13.6, 3, and 2.4% reduced, respectively. This trend reduced by increase of return periods. OS3 reduced the peak flows; expect the 100- and 200-year floods, which increased the peak, respectively, by 2.2 and 5%.

For EC2, owing to the fact that the objective function Z_1 does not consider safety of the dam, a maximized value of EC2 is desirable. Yet, overflow by dam overtopping must be taken into account. According to Fig. 5 and Table 7 the OS4 and OS5 were the best and the worst scenarios, respectively. OS3 and OS4 showed an approximately similar performance. The largest difference was observed for the return period of 50 years, in which water level of OS2 was 35% more than OS3.

For EC3, according to Table 8, the best and the worst performance belonged to OS1 and OS5, respectively. Among the multistage scenarios, OS3 and OS4 outperformed OS2. This shows that a large number of stages produce an improved satisfaction of the EC3 than would otherwise occur.

In terms of EC4, in the OS1, the gates are open. Furthermore, a constraint of the optimization problem does not allow overtopping in OS2, OS3, and OS4. Hence, EC4 was only employed to assess the efficiency of OS5 (Table 9).

Water-resources management problems are inherently multiobjective. Hence, the current study expands the works of He et al. (2014) and Chiang and Willems (2015) by including more than one objective function. The next subsection presents the outcomes of the multiobjective assessment.

Results of the Multiobjective Optimization

Similar to single-objective problem, the optimal values of the decision variables were computed for each scenario. Based on Eq. (7), a compromised Pareto solution was obtained for each scenario (Fig. 6). Then, similar to single-objective problem, the optimal values of the decision variables were computed for each scenario. Fig. 7 demonstrates critical levels and gate-opening values for three multistage scenarios. The results regarding comparison of the proposed scenarios on the basis of utilized EC are as follows.

For EC1, according to Table 10, the increase in return period raises the peak outflow. Based on Fig. 8, OS4 outdid others in mitigating the peak outflows for such return periods as 10, 20, and 50 years. Yet, this scenario could not outperform others for longer-term return periods. The scenarios that successfully mitigate peak flow with short-term return periods increase the reservoir storage and lower the WSE. As a result of large storage, the peak flow would be increased for long-term return periods.

Table 11. Water Level at the End of the Operational Period for Each Scenario (m)

Scenario	Return period (years)									
	10	20	50	100	200	500	1,000	2,000	10,000	PMF
Scenario 1	3.36	3.96	4.57	5.40	6.03	6.66	7.42	8.15	10.51	12.87
Scenario 2	4.95	5.68	5.81	5.95	6.09	6.71	7.46	8.17	10.52	12.88
Scenario 3	5.10	5.27	5.44	5.46	6.08	6.70	7.45	8.16	10.52	12.87
Scenario 4	5.56	5.76	5.77	5.83	6.20	6.71	7.46	8.17	10.54	13.02
Scenario 5	8.82	11.05	13.41	16.78	19.41	22.04	25.00	25.00	25.00	25.00

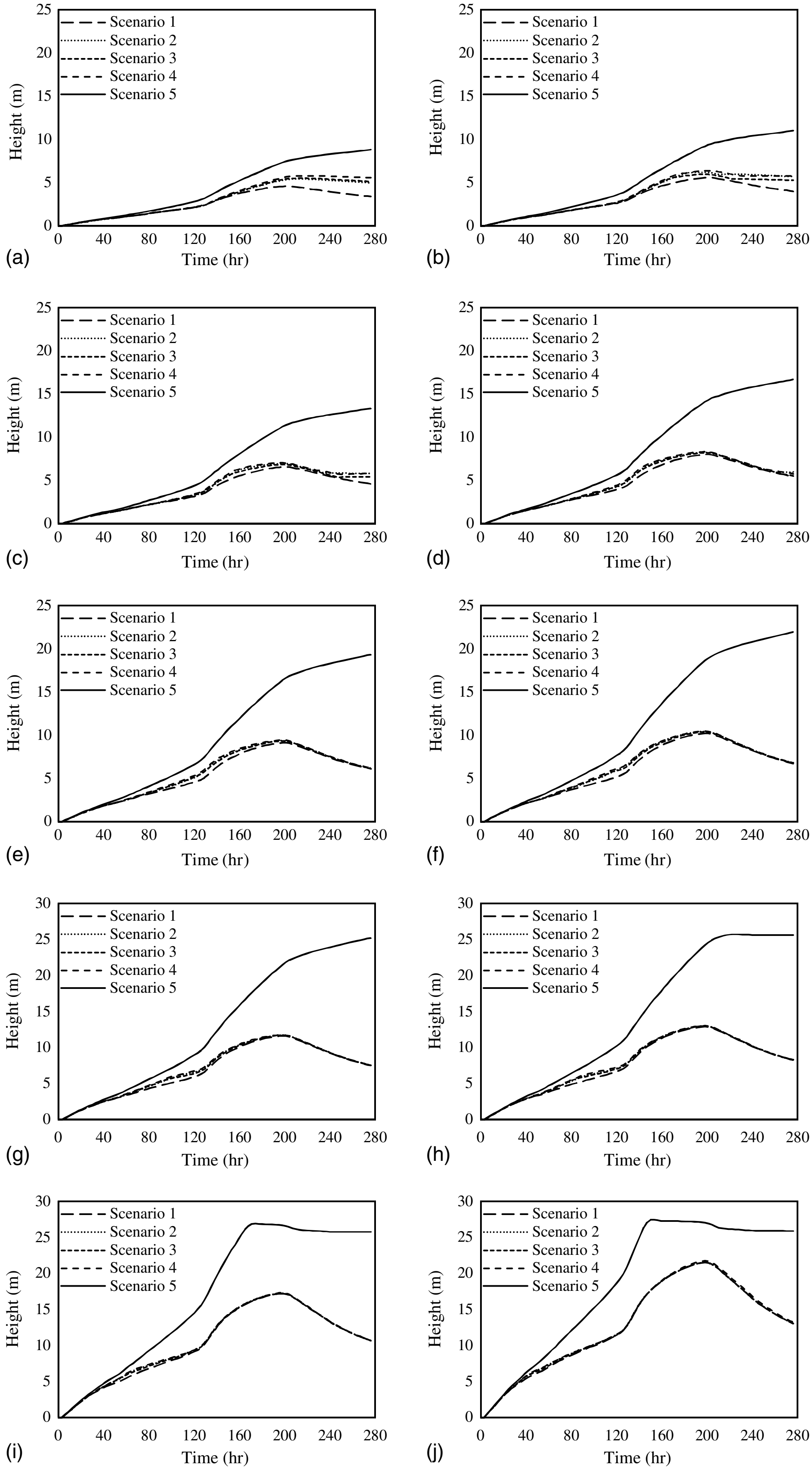

Fig. 9. Elevation of the flood hydrograph for various return periods (years): (a) 10; (b) 20; (c) 50; (d) 100; (e) 200; (f) 500; (g) 1,000; (h) 2,000; (i) 10,000; (j) PMF

Table 12. Maximum Changes in Outflow Hydrograph for Each Scenario (10^3 m^3/s)

Scenario	Return period (years)									
	10	20	50	100	200	500	1,000	2,000	10,000	PMF
Scenario 1	0.07	0.10	0.13	0.18	0.22	0.27	0.33	0.39	0.61	0.85
Scenario 2	0.03	1.46	1.54	1.59	1.54	1.53	1.47	1.44	1.58	1.57
Scenario 3	0.03	1.25	1.30	1.31	1.28	1.32	1.29	1.32	1.35	1.31
Scenario 4	0.02	1.23	1.29	1.34	1.31	1.25	1.27	1.29	1.32	1.30
Scenario 5	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.88	4.88	8.13

For EC2, Table 11 lists the WSE for each scenario at the end of operational period. The decision variables of OS2, OS3, and OS4 were optimized to reduce the WSE at the end of the operational period in order to accomplish the second objective. Based on Fig. 9, the results of OS2, OS3, and OS4 are similar to those of OS1. Water storage of OS4 for return periods of 10, 20, 50, and 100 years is, respectively, 4.6, 4.9, 3.3, and 3.7% more than OS3. This result is in line with proper application of the optimization process because in the shorter return period, water storing occurs while in the longer return period, the water level should be reduced to improve safety.

In terms of EC3, a large value of this criterion would be harmful to spillways and could lead to significant damages downstream. Comparison of Tables 8 and 12 reveals that the multiobjective framework outdid the single-objective one in reducing large changes in the outflow hydrograph.

EC4 was evaluated for OS5 only; therefore, the results of multiobjective optimization are identical to those of single-objective optimization. These results demonstrate that blocked (closed) spillways increase the risk of overtopping occurrence for long-term return periods.

Continuous changes of the gates' openings are needed to provide a constant discharge due to the fact that the water level of reservoir during flood occurrences experiences continuous fluctuations. This complicates gate management for operators. Small errors by the operators might cause significant damage. This work's approach to gate operation introduces a multistage operational system that simplifies reservoir operation.

The NSGA-II can handle complex mathematical issues of multiobjective problems such as those with nonlinearity, high dimensionality, discreteness, and nonconvexity. Previous studies on multiobjective water-resources problems have demonstrated that classical optimization methods such as linear programming (LP), nonlinear programming (NLP), dynamic programming (DP), and stochastic dynamic programming (SDP) are beset by the curse of dimensionality in solving large-scale problems. Furthermore, they cannot determine optimal solutions in complex discrete or nonlinear problems (Deb 2001).

Concluding Remarks

Multiobjective and single-objective contexts were employed to achieve optimal operation of spillway gates for five scenarios with different return periods. Given that the shorter return period represents the higher frequency of occurrence, the short-term return period must be given careful consideration. The obtained results show that among the single-objective scenarios, the fourth one with 10 stages of gate opening proved superior to the others. OS4 outperformed others in reducing the peak outflow with a short-term return period and increased the outflow elevation at the end of the operational period more than the other scenarios, which resulted in storing large volume of water in the reservoir. In line with EC3, it was found that OS2, OS3, and OS4 approximately performed in a similar manner. The OS5 results indicate that the lack of spillways led to dam overtopping for return periods 1,000, 2,000, and 10,000 years and the PMF. Therefore, EC4 was considered as a separated objective to reduce the likelihood of overtopping.

Mitigation of the peak flood flow is associated with increases in volume storage, in which case the probability of overtopping occurrence would be increased consequently. Therefore, consideration of these two conflicting objectives in a problem led to a multiobjective framework. The multiobjective optimization results were calculated with a conflict-resolution technique. OS1, OS2, OS3, and OS4 performed similarly in satisfying the second objective, something not achieved by OS5. The performance of OS2, OS3, and OS4 was similar to that of OS1 for long-term return-period floods. Taking all EC into consideration, the highest priority belonged to OS4. Despite the single-objective approach, the results of OS2 and OS3 were similar to that from OS4. A limitation with the OS4 was its time-consuming and complex computational process for multistage spillway gate operations. Future research will focus on the merits of the proposed methodology for spillway gate operation because of its practicality and the robustness of its results thus far observed.

References

Acanal, N., Yurtal, R., and Haktanir, T. (2000). "Multi-stage flood routing for gated reservoirs and conjunctive optimization of hydroelectricity income with flood losses." *Hydrol. Sci. J.*, 45(5), 675–688.

Afshar, A., and Salehi, A. (2011). "Gated spillways operation rules considering water surface elevation and flood peak: Application to Karkheh Dam." *World Environmental and Water Resources Congress: Bearing Knowledge for Sustainability*, Environmental and Water Resources Institute of ASCE, Reston, VA, 3007–3015.

Ahmad, S., and Simonovic, S. P. (2000). "System dynamics modeling of reservoir operations for flood management." *J. Comput. Civ. Eng.*, 10.1061/(ASCE)0887-3801(2000)14:3(190), 190–198.

Ahmadi, M., Bozorg-Haddad, O., and Loáiciga, H. A. (2015). "Adaptive reservoir operation rules under climatic change." *Water Resour. Manage.*, 29(4), 1247–1266.

Ahmadi, M., Bozorg-Haddad, O., and Mariño, M. A. (2014). "Extraction of flexible multi-objective real-time reservoir operation rules." *Water Resour. Manage.*, 28(1), 131–147.

Ait Alla, A. (1997). "Achieving economies through innovative spillway design." *J. Hydropower Dams*, 4(2), 146–149.

Akbari-Alashti, H., Bozorg-Haddad, O., Fallah-Mehdipour, E., and Mariño, M. A. (2014). "Multi-reservoir real-time operation rules: A new genetic programming approach." *Proc. Institution Civ. Eng. Water Manage.*, 167(10), 561–576.

Ashofteh, P. S., Bozorg-Haddad, O., and Loáiciga, H. A. (2015a). "Evaluation of climatic-change impacts on multi-objective reservoir operation with multiobjective genetic programming." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000540, 04015030.

Ashofteh, P. S., Bozorg-Haddad, O., and Mariño, M. A. (2013a). "Climate change impact on reservoir performance indices in agricultural water supply." *J. Irrig. Drain. Eng.*, 10.1061/(ASCE)IR.1943-4774.0000496, 85–97.

Ashofteh, P.-S., Bozorg-Haddad, O., Akbari-Alashti, H., and Mariño, M. A. (2015b). "Determination of irrigation allocation policy under climate change by genetic programming." *J. Irrig. Drain. Eng.*, 10.1061/(ASCE)IR.1943-4774.0000807, 04014059.

Ashofteh, P.-S., Bozorg-Haddad, O., and Mariño, M. A. (2013b). "Scenario assessment of streamflow simulation and its transition probability in future periods under climate change." *Water Resour. Manage.*, 27(1), 255–274.

Ashofteh, P.-S., Bozorg-Haddad, O., and Mariño, M. A. (2015c). "Risk analysis of water demand for agricultural crops under climate change." *J. Hydrol. Eng.*, 10.1061/(ASCE)HE.1943-5584.0001053, 04014060.

Azarnivand, A, and Malekian, A. (2016). "Analysis of flood risk management strategies based on a group decision making process via interval-valued intuitionistic fuzzy numbers." *Water Resour. Manage.*, 30(6), 1903–1921.

Azarnivand, A., Hashemi-Madani, F. S., and Banihabib, M. E. (2015). "Extended fuzzy analytic hierarchy process approach in water and environmental management (case study: Lake Urmia Basin, Iran)." *Environ. Earth Sci.*, 73(1), 13–26.

Beygi, S., Bozorg-Haddad, O., Fallah-Mehdipour, E., and Mariño, M. A. (2014). "Bargaining models for optimal design of water distribution networks." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000324, 92–99.

Bolouri-Yazdeli, Y., Bozorg-Haddad, O., Fallah-Mehdipour, E., and Mariño, M. A. (2014). "Evaluation of real-time operation rules in reservoir systems operation." *Water Resour. Manage.*, 28(3), 715–729.

Bozorg-Haddad, O., Ashofteh, P.-S., Ali-Hamzeh, M., and Mariño, M. A. (2015a). "Investigation of reservoir qualitative behavior resulting from biological pollutant sudden entry." *J. Irrig. Drain. Eng.*, 10.1061/(ASCE)IR.1943-4774.0000865, 04015003.

Bozorg-Haddad, O., Ashofteh, P.-S., and Mariño, M. A. (2015b). "Levee's layout and design optimization in protection of flood areas." *J. Irrig. Drain. Eng.*, 10.1061/(ASCE)IR.1943-4774.0000864, 04015004.

Bozorg-Haddad, O., Ashofteh, P.-S., Rasoulzadeh-Gharibdousti, S., and Mariño, M. A. (2014). "Optimization model for design-operation of pumped-storage and hydropower systems." *J. Energy Eng.*, 10.1061/(ASCE)EY.1943-7897.0000169, 04013016.

Bozorg-Haddad, O., Rezapour Tabari, M. M., Fallah-Mehdipour, E., and Mariño, M. A. (2013). "Groundwater model calibration by meta-heuristic algorithms." *Water Resour. Manage.*, 27(7), 2515–2529.

Chiang, P. K., and Willems, P. (2015). "Combine evolutionary optimization with model predictive control in real-time flood control of a river system." *Water Resour. Manage.*, 29(8), 2527–2542.

Deb, K. (2001). *Multi-objective optimization using evolutionary algorithms*, Wiley, New York.

Fallah-Mehdipour, E., Bozorg-Haddad, O., and Mariño, M. A. (2013a). "Extraction of optimal operation rules in aquifer-dam system: A genetic programming approach." *J. Irrig. Drain. Eng.*, 10.1061/(ASCE)IR.1943-4774.0000628, 872–879.

Fallah-Mehdipour, E., Bozorg-Haddad, O., and Mariño, M. A. (2013b). "Prediction and simulation of monthly groundwater levels by genetic programming." *J. Hydro-Environ. Res.*, 7(4), 253–260.

Fallah-Mehdipour, E., Bozorg-Haddad, O., and Mariño, M. A. (2014). "Genetic programming in groundwater modeling." *J. Hydrol. Eng.*, 10.1061/(ASCE)HE.1943-5584.0000987, 04014031.

Fallah-Mehdipour, E., Bozorg-Haddad, O., Orouji, H., and Mariño, M. A. (2013d). "Application of genetic programming in stage hydrograph routing of open channels." *Water Resour. Manage.*, 27(9), 3261–3272.

Farhangi, M., Bozorg-Haddad, O., and Mariño, M. A. (2012). "Evaluation of simulation and optimization models for WRP with performance indices." *Proc. Inst. Civ. Eng. Water Manage.*, 165(5), 265–276.

Haktanir, T., Citakoglu, H., and Acanal, N. (2013). "Fifteen-stage operation of gated spillways for flood routing management through artificial reservoirs." *Hydrol. Sci. J.*, 58(5), 1013–1031.

HEC (Hydrologic Engineering Center). (1982). "Generalized real-time flood control system model." U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA.

He, Y., Xu, Q., Yang, S., and Liao, L. (2014). "Reservoir flood control operation based on chaotic particle swarm optimization algorithm." *Appl. Math. Modell.*, 38(17), 4480–4492.

Hydro-Iran. (2015). "Hydroelectric power plants in Iran." ⟨http://www.industcards.com/hydro-iran.htm⟩ (Feb. 19, 2015).

Jahandideh-Tehrani, M., Bozorg-Haddad, O., and Mariño, M. A. (2015). "Hydropower reservoir management under climate change: The Karoon reservoir system." *Water Resour. Manage.*, 29(3), 749–770.

Japan International Corporation Agency. (1994). *Feasibility study on flood control, forecasting and warning system for Seyhan River basin*, Vol. 1, Nippon Koei, Tokyo, 3–39.

Jia, B., Zhong, P. A., Wan, X., Xu, B., and Chen, J. (2015). "Decomposition-coordination model of reservoir group and flood storage basin for real-time flood control operation." *Hydrol. Res.*, 46(1), 11–25.

Karaboga, D., Bagis, A., and Haktanir, T. (2004). "Fuzzy logic based operation of spillway gates of reservoirs during floods." *J. Hydrol. Eng.*, 10.1061/(ASCE)1084-0699(2004)9:6(544), 544–549.

Karaboga, D., Bagis, A., and Haktanir, T. (2008). "Controlling spillway gates of dams by using fuzzy logic controller with optimum rule number." *Appl. Software Comput.*, 8(1), 232–238

Karkheh. (2015). "Karkheh dam & powerhouse." ⟨http://mahdas.com/karkheh-dam-powerhouse/⟩ (Jun. 12, 2015).

Kisi, Ö. (1999). "Optimum ten stage overflow operating model for dams having gated spillway." Ph.D. dissertation, Erciyes Univ., Kayseri, Turkey.

Linsley, R. K., Kohler, M. A., and Paulhus, J. L. H. (1982). *Hydrology for engineers*, McGraw-Hill, New York, 508.

Luo, J., Chen, C., and Xie, J. (2015). "Multi-objective immune algorithm with preference-based selection for reservoir flood control operation." *Water Resour. Manage.*, 29(5), 1447–1466.

MATLAB 7.11.0 [Computer software]. MathWorks, Natick, MA.

Ngo, L. L., Madsen, H., and Rosbjerg, D. (2007). "Simulation and optimization modelling approach for operation of the HoaBinh Reservoir." *J. Hydrol.*, 336(3), 269–281.

Nishioka, Y., Nohara, D., Hori, T., and Sato, Y. (2014). "Decision support for flood control operation of a multi-purpose reservoir considering operational one-week ensemble forecast of precipitation." *11th Int. Conf. on Hydroinformatics, HIC 2014*, International Association of Hydro-Environment Engineering and Research (IAHR), Netherlands, 429–436.

Orouji, H., Bozorg-Haddad, O., Fallah-Mehdipour, E., and Mariño, M. A. (2013). "Modeling of water quality parameters using data-driven models." *J. Environ. Eng.*, 10.1061/(ASCE)EE.1943-7870.0000706, 947–957.

Orouji, H., Bozorg-Haddad, O., Fallah-Mehdipour, E., and Mariño, M. A. (2014a). "Extraction of decision alternatives in project management: Application of hybrid PSO-SFLA." *J. Manage. Eng.*, 10.1061/(ASCE)ME.1943-5479.0000186, 50–59.

Orouji, H., Bozorg-Haddad, O., Fallah-Mehdipour, E., and Mariño, M. A. (2014b). "Flood routing in branched river by genetic programming." *Proc. Inst. Civ. Eng. Water Manage.*, 167(2), 115–123.

Qin, H., Zhou, J., Lu, Y., Li, Y., and Zhang, Y. (2010). "Multi-objective cultured differential evolution for generating optimal trade-offs in reservoir flood control operation." *Water Resour. Manage.*, 24(11), 2611–2632.

Sakakima, S., Kojiri, T., and Itoh, K. (1992). "Real-time reservoir operation with neural nets concept." *Proc., 7th Int. Conf. on Applications of Artificial Intelligence in Engineering, AIENG/92*, Computational Mechanics Publications, Southampton, U.K., 501–514.

Salehi, A. (2011). "Comparison and two operation rules for gated spillways: Application to Karkheh Dam." *World Environmental and Water Resources Congress*, Environmental and Water Resources Institute of ASCE, Reston, VA, 2468–2477.

Shokri, A., Bozorg-Haddad, O., and Mariño, M. A. (2013). "Reservoir operation for simultaneously meeting water demand and sediment flushing: A stochastic dynamic programming approach with two uncertainties." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000244, 277–289.

Shokri, A., Bozorg-Haddad, O., and Mariño, M. A. (2014). "Multi-objective quantity-quality reservoir operation in sudden pollution." *Water Resour. Manage.*, 28(2), 567–586.

Soltanjalili, M., Bozorg-Haddad, O., and Mariño, M. A. (2013). "Operating water distribution networks during water shortage conditions using hedging and intermittent water supply concepts." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000315, 644–659.

Sordo-Ward, A., Garrote, L., Bejarano, M. D., and Castillo, L. G. (2013). "Extreme flood abatement in large dams with gate-controlled spillways." *J. Hydrol.*, 498, 113–123.

Southeast Queensland Water Corporation. (2004). "Manual of operational procedures for flood mitigation for Wivenhoe Dam and Somerset Dam." Brisbane, QLD, Australia.

Strelkoff, T. (1985). "Modified-Puls routing in Chuquatonchee Creek." *No. HEC-RR-23*, Hydrologic Engineering Center (HEC), Davis, CA.

Woodward, M., Gouldby, B., Kapelan, Z., and Hames, D. (2014). "Multi-objective optimization for improved management of flood risk." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000295, 201–215.