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Development of a Sample Multiattribute and Multireservoir System for Testing Operational Models

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Abstract: Reservoir systems are built to deliver multiple functions, such as water supply, energy production, flood control, recreation, and fisheries protection in a safe, economic, and efficient manner. This paper presents a sample three-reservoir system with comprehensive physical and hydrologic characteristics. The sample reservoir system considers energy production, water supply, and recreational and flood-control objectives. The results from the operation of this paper's reservoir system under four different scenarios show that this system's characteristics and structure conform well with actual reservoir operational processes. The reliabilities associated with meeting reservoir-operation objectives were calculated for the sample reservoir system for the four operational scenarios, ranging from independent reservoir operation with single objectives to integrated reservoir operation with multiple objectives. The results show acceptable ranges of reliability for the three objectives considered under each operational scenario. The sample reservoir system can be used to test a wide range of optimization models that are commonly used in reservoir operation. **DOI: 10.1061/(ASCE)IR.1943-4774.0000908.** *© 2015 American Society of Civil Engineers.*

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Introduction

Many simulation and optimization techniques have been developed and applied in all aspects of water resources systems, such as reservoir operation (Fallah-Mehdipour et al. 2012a), hydrology (Orouji et al. 2013), project management (Fallah-Mehdipour et al. 2012b), cultivation rules (Fallah-Mehdipour et al. 2013), pumping scheduling (Bozorg Haddad et al. 2011), hydraulic structures (Bozorg Haddad et al. 2010), water distribution networks (Seifollahi-Aghmiuni et al. 2013), operation of aquifer systems (Bozorg Haddad and Mariño 2011), site selection of infrastructures (Karimi-Hosseini et al. 2011), and algorithmic developments (Shokri et al. 2013). Various simulation and optimization models have been developed for effective design and operation of water resources systems. Simulation models such as HEC-3 (Hydrologic Engineering Center 1971), HEC-5 (Hydrologic Engineering Center 1979), MODSIM (Labadie et al. 1986), WASP (Kuczera and Diment 1988), RiverWare (Zagona et al. 2001), REALM (Perera et al. 2005), and others are designed to achieve efficiency objectives defined by users using computer-based algorithms. Most simulation models rely on optimization methods that range from simple mathematical procedures such as graphical methods to more complex evolutionary and metaheuristic algorithms such as the genetic algorithm (GA) (Holland 1975), particle swarm optimization (PSO) (Kennedy and Eberhart 1998), firefly algorithm (FA) (Abshouri et al. 2011), and bat algorithm (BA) (Koffka and Ashok 2012).

The performance of water resources simulation and optimization models must be tested with realistic systems. The lack of integrated sample reservoir systems hinders the comprehensive assessment of water resources optimization models. This work presents a multireservoir sample system suitable for testing simulation and optimization of water resources models. The sample system has been designed considering multiple traits of water resources management. Single- and multiobjective nonlinear and evolutionary optimization methods are applied to the proposed sample multireservoir system to test their performances under different scenarios.

At the same time, water resources systems differ among themselves, and it is likely that a test system may not represent all possible systems adequately.

Structure of the Sample Multireservoir System

The developed sample three-reservoir system is shown in Fig. 1. The triangles, circles, and squares shown in this figure represent reservoirs, different users, and powerhouses, respectively. Three reservoirs with three powerhouses and three types of users (agricultural, municipal, and industry) are included in the developed sample system. Reservoirs 2 and 3 are connected gravitationally to Reservoir 1, and Reservoir 1 can be connected to Reservoirs 2 and 3 by pumping (if necessary). Each user can be supplied directly by each reservoir or by the outflow from each powerhouse (or considering a combination of these resources). The supply lines to the first (agricultural), second (municipal), and third (industrial) users are shown in Fig. 1. Each supply line has return flow capabilities shown as lines that issue from the user nodes and terminate on the river at various locations in the system. The return flows of users served by Reservoirs 2 and 3 are the inflows to Reservoir 1, and the return flows of users served by Reservoir 1 are released

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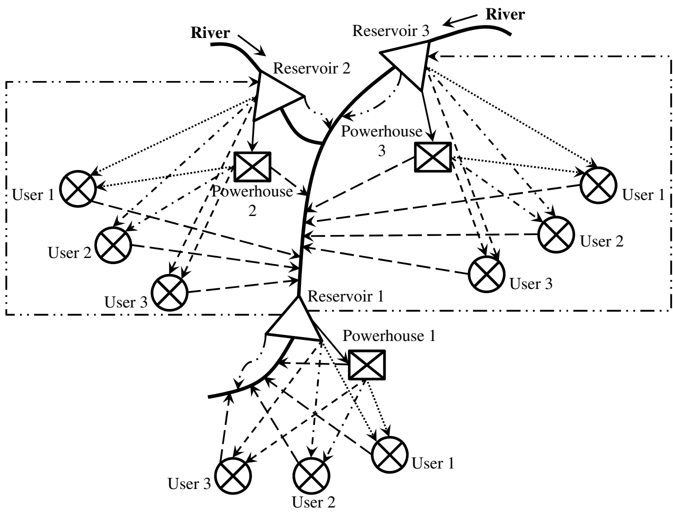

Fig. 1. Schematic of the sample reservoir system

Table 1. Constant Parameters and Characteristics of Reservoirs in the Sample System

Parameter	Reservoirs number		
	1	2	3
$S^{\min}$ (10^6 m^3)	300	150	400
$S^{\max}$ (10^6 m^3)	3,000	2,500	3,000
S^a (10^6 m^3)	2,700	2,350	2,600
H^{dam} (m)	120	100	150
SF (10^6 m^3)	750	1,500	1,700
Se (10^6 m^3)	290	140	390
I (%)	1	4	2
Elevation of reservoir above mean sea level (m)	700	750	800

Note: H^{dam} = height of dam; I = water leakage and seepage percentage from each reservoir lake; Se = long-term sediment input volume to each reservoir; SF = design flood volume; S^a = active storage equals the difference between $S^{\min}$ and $S^{\max}$ in each reservoir; $S^{\min}$ and $S^{\max}$ = minimum and maximum water storage volume, respectively.

downstream of this reservoir. One powerhouse has been assigned to each reservoir, which generates electric power by means of penstock releases. The outflow of each powerhouse can be an inflow to each reservoir. In the sample system, the outflows of Powerhouses 2 and 3 flow to Reservoir 1. The outflow of Powerhouse 1 is released to the river downstream of Reservoir 1. The powerhouses' flows are not connected to each other.

The sample three-reservoir system's management requires integrated and comprehensive modeling, simulation, and optimization. All pertinent system characteristics have been designed in an integrated manner, and their interactions are captured by the system connectivity. In addition, the management of the three-reservoir system considers a comprehensive database. The hydraulic and hydrologic characteristics of the sample system shown in Fig. 1 are presented in the following sections. This study considers three general objectives to be met by the sample three-reservoir system: hydropower generation, water supply (agricultural, municipal, and industrial), and recreation and flood control.

Material and Methods

The data for reservoir management correspond temporally to a monthly operational time step commonly used in reservoir planning and management. Reservoir, users, and powerhouse data are presented in the following sections.

Reservoir Data

Reservoirs 2 and 3 are in parallel, and each is in series with Reservoir 1. Each reservoir has specific characteristics and parameters used in its operation and management, regardless of the reservoir system connectivity.

The constant reservoir characteristics are listed in Table 1. The reservoir spill capacity is estimated based on the design flood that can be spilled from the reservoir with a reliable buffer depth under normal conditions. A design flood with a return period of 5,000 years is used for flood-control purposes in the three-reservoir system. Floods with return periods of 5,000 years have been used as the design flood of large dams by the Power Ministry of Iran. The design flood volume (SF) is specified as an unregulated inflow to each reservoir during the operational period.

Sediment carried by river flow from the upstream catchments is input into each reservoir. Water release gates are placed at an elevation higher than the long-term storage elevation of input sediments in the sample three-reservoir system. Therefore, sediment storage is not considered in the three-reservoir operation during its service life. The minimum storage ($S^{\min}$) of each sample reservoir exceeds the long-term sediment input volume (Se) to ensure that the input sediments are stored below $S^{\min}$, and the reservoir operation relies on actual volumes of stored water at all times. The volumes of seepage from the reservoirs are calculated based on the defined percentage of stored water (I) in the reservoir at different time steps during any year of operation.

The geometric characteristics of each reservoir are evaluated through storage [$S(10^6\ \mathrm{m}^3)$] and lake area [A (kilometers squared)] versus water elevation [H (meters)] shown in Eqs. (1)–(6) for different reservoirs in the sample system. Notice that, in these equations, the storage or lake area is zero when the water elevation is zero:

for Reservoir 1:

$$S_1(t) = 0.195H_1^2(t) + 3H_1(t)R^2 = 1 \tag{1}$$

$$A_1(t) = 0.0055H_1^2(t) + 0.5H_1(t)R^2 = 1 \tag{2}$$

for Reservoir 2:

$$S_2(t) = 0.195H_2^2(t) + 6.5H_2(t)R^2 = 1 \tag{3}$$

$$A_2(t) = 0.0155H_2^2(t) + 0.055H_2(t)R^2 = 1 \tag{4}$$

for Reservoir 3:

$$S_3(t) = 0.095H_3^2(t) + 6.5H_3(t)R^2 = 1 \tag{5}$$

$$A_3(t) = 0.0055H_3^2(t) + 0.055H_3(t)R^2 = 1 \tag{6}$$

where t = number of operational time steps in the three-reservoir system; $t = 1,2, \ldots, T$; subindices 1, 2, and 3 correspond to the characteristics of Reservoirs 1, 2, and 3, respectively; T = total number of operational time steps; and R^2 = coefficient of determination.

Sedimentation takes place gradually over time during reservoir operation. Therefore, applying Eqs. (1)–(6) can cause errors in system design and operation by not considering sedimentation

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Table 2. Data for Natural River Flow Q, Recreation and Flood Control Storage Threshold ST, Evaporation Ev, and Precipitation P for Different Reservoirs of the Sample System

Parameter	Reservoir number	Spring 1	Spring 2	Spring 3	Summer 4	Summer 5	Summer 6	Fall 7	Fall 8	Fall 9	Winter 10	Winter 11	Winter 12
$Q(10^6\ \mathrm{m}^3)$	1	760	680	400	240	160	120	80	120	240	280	360	560
	2	960	720	540	420	240	60	120	180	480	540	660	1,080
	3	850	1,030	630	450	280	110	170	230	290	460	570	630
$ST(10^6\ \mathrm{m}^3)$	1	1,950	2,030	2,310	2,470	2,550	2,590	2,630	2,590	2,470	2,430	2,350	2,150
	2	970	1,210	1,390	1,510	1,690	1,870	1,810	1,750	1,450	1,390	1,270	850
	3	1,080	900	1,300	1,480	1,650	1,820	1,760	1,700	1,640	1,470	1,360	1,300
Ev (mm)	1	60	70	80	110	140	100	60	50	30	20	30	50
	2	70	70	80	90	110	70	40	40	20	10	40	60
	3	60	60	70	90	80	70	50	40	5	5	20	50
P (mm)	1	40	30	10	0	0	0	40	50	70	70	80	60
	2	60	40	20	0	0	10	60	90	110	130	110	70
	3	60	30	20	0	0	10	50	70	90	100	90	80

effects. The effects of gradual sedimentation are considered by reformulating the storage-elevation and area-elevation equations. The reformulation was accomplished by means of the area increment method developed by the Management and Planning Organization of Iran (2011). The reformulated equations are as follows (where $t = 1,2, \ldots, T$):

for Reservoir 1:

$$A_1(t) = -2.682 \times 10^{-6} S_1^2(t) + 4.846 \times 10^{-2} S_1(t) R^2 = 0.999 \tag{7}$$

$$H_1(t) = -11.517 \times 10^{-6} S_1^2(t) + 6.628 \times 10^{-2} S_1(t) + 20 R^2 = 0.969 \tag{8}$$

for Reservoir 2:

$$A_2(t) = 4.128 \times 10^{-6} S_2^2(t) + 5.372 \times 10^{-2} S_2(t) R^2 = 0.999 \tag{9}$$

$$H_2(t) = -11.668 \times 10^{-6} S_2^2(t) + 6.404 \times 10^{-2} S_2(t) + 10 R^2 = 0.985 \tag{10}$$

for Reservoir 3:

$$A_3(t) = 2.284 \times 10^{-6} S_3^2(t) + 3.869 \times 10^{-2} S_3(t) R^2 = 0.999 \tag{11}$$

$$H_3(t) = -10.734 \times 10^{-6} S_3^2(t) + 7.214 \times 10^{-2} S_3(t) + 30 R^2 = 0.989 \tag{12}$$

The natural river flows (Q) are presented in Table 2 as unregulated inflows to each reservoir in each time step. The objective of recreation and flood-control is met by controlling storage volume in the reservoirs. Therefore, reservoir storage is adjusted so that there is enough capacity to store the design flood volume and allow recreational activities such as fishing, boating, etc. For this purpose, a threshold (ST) has been considered for storage volume of each reservoir, called *recreation and flood-control storage threshold*. Its values are listed in Table 2. Several meteorological factors such as evaporation and precipitation affect the water levels in reservoirs. Evaporation (Ev) and rainfall (P) data for the sample system are given in Table 2.

In addition to the dam wall, there are other components in each reservoir that make achieving the reservoir-system objectives possible. The stored water in each reservoir is transferred downstream through regulating gates to meet different objectives. Two similar regulating gates are dedicated to each objective in the sample reservoir system. Their pertinent data are presented in Tables 3 and 4. The minimum allowable release capacity for each gate is equal to zero. The excess storage in each reservoir is spilled (Sp) by spillway with capacity equal to $10^9\ \mathrm{m}^3/\mathrm{month}$ in each reservoir of the sample system.

Data for Water Users

There are agricultural ($l = 1$), municipal ($l = 2$), and industrial ($l = 3$) demands for each reservoir in the sample system. The monthly variations of agricultural and municipal demands are similar during the year, whereas the monthly change in industrial demand is approximately constant with seasonal variations. The information for each type of water user is listed in Table 5. The return flow percentages corresponding to each user are determined according to studies done by the Power Ministry of Iran

Table 3. Capacity of Different Intake Gates ($10^6\ \mathrm{m}^3/\mathrm{month}$) for Sample Reservoirs

Total capacity of two intake gates for	Supplying downstream users	Generating hydropower	Emergency water and sediment drain
Reservoir 1	980	1,520	2,500
Reservoir 2	980	600	1,040
Reservoir 3	980	600	1,020

Table 4. Elevation of Different Intake Gates (Meters) above Mean Sea Level for Sample Reservoirs

Elevation of intake gates for	Supplying downstream users Gate 1	Supplying downstream users Gate 2	Generating hydropower Gate 1	Generating hydropower Gate 2	Emergency water and sediment drain Gate 1	Emergency water and sediment drain Gate 2
Reservoir 1	718	735	760	780	715	720
Reservoir 2	768	775	790	810	755	759
Reservoir 3	828	855	880	905	825	830

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(Table 6). The return flow percentage measures how much of the water delivered to each user is returned to the system. The amount of return flow is allocated to surface waters or to groundwater through recharge wells, as shown in Table 6. The amounts of water returned to the surface resources are pertinent to consider in the sample system because its operation is based on surface water resources.

Powerhouse Data

Fig. 1 shows that there is a separate powerhouse for each reservoir in the sample system. Each powerhouse consists of several independent units with specific installed capacity [power production capacity (PPC)] for generating energy. Each powerhouse has two generators with similar characteristics and PPCs. Also, each powerhouse features a performance efficiency. Energy is generated according to the powerhouse's plant factor. The plant factor shows the percentage of time in different time steps of operation during which the powerhouse turbines generate energy with their installed capacity (PPC). Plant factors are determined so that each powerhouse generates energy equal to its installed capacity during at least 6 h per day. Powerhouses' data are presented in Table 7.

The discharge-stage (Qw-El) equation is another characteristic of powerhouses determined according to turbine characteristics. The water column height above the turbine axis is determined using the discharge-stage equation for each volume of water released from the reservoir to produce energy. The discharge-stage equations are as follows for each powerhouse (in Reservoirs 1, 2, and 3) for all operation periods ($t = 1,2, \ldots, T$):

$$El_1^{\text{down}}(t) = -5.5 \times 10^{-7}\left[\sum_{j=1}^{J} Qw_1(j,t)\right]^2 + 0.3 \times 10^{-3}\sum_{j=1}^{J} Qw_1(j,\ t) \quad (13)$$

$$El_2^{\text{down}}(t) = -3.3 \times 10^{-7}\left[\sum_{j=1}^{J} Qw_2(j,t)\right]^2 + 0.25 \times 10^{-2}\sum_{j=1}^{J} Qw_2(j,t) \quad (14)$$

$$El_3^{\text{down}}(t) = -2.2 \times 10^{-7}\left[\sum_{j=1}^{J} Qw_3(j,t)\right]^2 + 0.2 \times 10^{-2}\sum_{j=1}^{J} Qw_3(j,t) \quad (15)$$

where $Qw_1(j,\ t)$, $Qw_2(j,\ t)$, and $Qw_3(j,\ t)$ = regulated water release (cubic meters per second) from intake gate j of Reservoirs 1, 2, and 3, respectively, to produce hydropower energy in each powerhouse during time step t; $El_1^{\text{down}}(t)$, $El_2^{\text{down}}(t)$, and $El_3^{\text{down}}(t)$ = the height of regulated water released from each powerhouse (meters) during time step t in Reservoirs 1, 2, and 3, respectively; j = index for designating intake gates, $j = 1,2, \ldots, J$; and J = total number of intake gates for producing hydropower energy in each reservoir.

Operational Planning of the Sample Reservoir System

The operation of the sample system considers four scenarios. In Scenario 1, each reservoir is operated according to each objective independently from the operation of the other ones [single-reservoir–single-objective (SRSO) scenario]. In Scenario 2, each reservoir is operated considering all objectives simultaneously, but independently from the operation of the other reservoirs [single-reservoir–multiobjective (SRMO) scenario]. In Scenario 3, the integrated reservoir system is operated according to each objective separately [multireservoir–single-objective (MRSO) scenario], and Scenario 4 evaluates the integrated reservoir system considering all objectives [multireservoir–multiobjective (MRMO)].

Table 5. User Data for the Sample System (10^6 m^3)

Month number	Reservoir 1 $l=1$	Reservoir 1 $l=2$	Reservoir 1 $l=3$	Reservoir 2 $l=1$	Reservoir 2 $l=2$	Reservoir 2 $l=3$	Reservoir 3 $l=1$	Reservoir 3 $l=2$	Reservoir 3 $l=3$
Spring									
1	510	550	420	480	520	450	550	600	460
2	570	600	480	600	640	500	620	660	510
3	680	660	530	840	750	560	790	720	570
Summer									
4	740	720	640	840	760	560	850	780	570
5	800	720	580	780	700	620	850	780	630
6	630	550	530	720	580	610	730	600	570
Fall									
7	460	330	420	480	350	500	490	360	460
8	340	270	370	300	290	390	300	300	400
9	170	170	370	180	170	340	190	180	400
Winter									
10	170	160	320	180	170	280	180	180	340
11	230	270	270	240	350	340	180	300	340
12	400	500	370	360	520	450	370	540	450
Total annual	5,700	5,500	5,300	6,000	5,800	5,600	6,100	6,000	5,700

Table 7. Powerhouse Data for the Sample System

Parameter	Powerhouse number 1	2	3
Total capacity of powerhouse's units (10^6 W)	1,168	440	650
Efficiency (%)	90	90	96
Plant factor (%)	30	25	35
Elevation of turbine above mean sea level (m)	690	730	790
Elevation of downstream above sea level (m)	685	725	785

Table 6. Percentages of Users' Return Water in the Sample System

Parameter	Reservoir 1 $l=1$	Reservoir 1 $l=2$	Reservoir 1 $l=3$	Reservoir 2 $l=1$	Reservoir 2 $l=2$	Reservoir 2 $l=3$	Reservoir 3 $l=1$	Reservoir 3 $l=2$	Reservoir 3 $l=3$
Return water	25	70	60	20	65	70	30	60	65
Return water to surface resources	30	20	10	35	10	15	40	15	20
Return water to groundwater	70	80	90	65	90	85	60	85	80

The model of the sample reservoir system involves nonlinear characteristics such as the area, storage, elevation characteristics, power generation, flow release, etc. Therefore, nonlinear programming (NLP) is used to optimize reservoir system operation according to Scenarios 1 and 3, which are single objective. Operations for Scenarios 2 and 4, multiobjective scenarios, are solved using the nondominated sorting genetic algorithm II (NSGA-II). The NSGA-II is a random search method based on GA concepts, whose final result is a near optimum solution. The NSGA-II must be run multiple times when solving an optimization problem due to its random-search approach. Moreover, a set of nondominant near optimum solutions called Pareto boundary is obtained with NSGA-II, instead of one optimum solution. Thus, the final solution of each reservoir operation will be a global optimum solution in Scenarios 1 and 3, and it is expressed as a Pareto boundary under Scenarios 2 and 4.

The sample system is simulated based on the standard operation policy (SOP). The following equations describe the simulation and modeling of a single reservoir based on SOP (for times $t = 1,2, \ldots, T$):

Water balance in a reservoir:

$$S(t+1) = S(t) + Q(t) + Q'(t) + Se(t) + SF(t) - \text{Loss}(t) - I(t) - Sp(t) - \sum_{v=1}^{V} \sum_{j=j(1)}^{J(v)} Rw(j, v, t) - \sum_{l=1}^{C} \sum_{j=j'(1)}^{J'(V')} Rw'(j, l, t) \tag{16}$$

where $S(t)$ and $S(t+1)$ = reservoir storage volumes at the beginning of time steps t and $t+1$, respectively; $Q'(t)$ = hypothetical regulated inflow to the reservoir during time step t; $\text{Loss}(t)$ = losses volume caused by evaporation and precipitation in the reservoir lake during time step t; $Rw(j, v, t)$ = regulated release from different intake gate j for supplying the objective v (hydropower generation and recreation and flood control) during time step t; $Rw'(j, l, t)$ = regulated release from different intake gates j for supplying downstream demands l during time step t; v = number of objectives considered in reservoir operation (except supplying user demands); V = total number of objectives for reservoir operation (except supplying user demands); $j(1)$ = number of the first intake gate in a reservoir for supplying objective v (except supplying user demands); $J(v)$ = total number of intake gates used to supply objective v (except supplying user demands); C = total number of user nodes downstream of a reservoir; $j'(1)$ = number of the first intake gate in a reservoir for supplying objective V' (supplying user demands); and $J'(V')$ = total number of intake gates used for supplying user demands.

Net loss by evaporation minus precipitation:

$$\text{Loss}(t) = \left[\frac{A(t) + A(t+1)}{2}\right][Ev(t) - P(t)] \tag{17}$$

$$A(t) = f[S(t)\, ,\, h^{\text{up}}(t)] \tag{18}$$

$$A(t+1) = f[S(t+1)\, ,\, h^{\text{up}}(t+1)] \tag{19}$$

where $A(t)$ and $A(t+1)$ = lake areas at the beginning of time steps t and $t+1$, respectively [calculated with Eqs. (18) and (19)]; $f[\ ]$ = area, storage, and elevation function for the reservoir; and $h^{\text{up}}(t)$ and $h^{\text{up}}(t+1)$ = water heights stored in the reservoir lake at the beginning of time steps t and $t+1$, respectively.

Release for supplying downstream demands:

$$\sum_{j=j'(1)}^{J'(V')} Rw'(j, l, t)|_{l=l'} = \begin{cases} De(l,\, t)|_{l=l'} & 0 < De(l,\, t)|_{l=l'} < Z(t) \\ Z(t) & 0 \le Z(t) \le De(l,\, t)|_{l=l'} \\ 0 & 0 > Z(t) \end{cases} \tag{20}$$

where $l' = 1, 2, 3$, the numbers designating user types; $De(l,\, t)$ = demand of user l during time step t; and $Z(t)$ = existing storage volume in a reservoir for calculating $Rw(j, v, t)$ and $Rw'(j, l, t)$ based on the SOP during time step t.

Generating a power equivalent to the PPC of a powerhouse during all of the operation time steps is desirable in the reservoir operation. If the SOP is used for determining the hydropower release, calculating the required water volume for generating a power equal to the PPC of a powerhouse becomes necessary. For this purpose, Eq. (21) is used, where γ = the specific weight of water ($9,810\ \text{kg/m}^3$); η = the efficiency of powerhouses; $\Delta H(t)$ = the difference between the upstream and downstream water heights across turbines in each powerhouse during time step t [Eq. (22)]; $PF(t)$ = the plant factor of a powerhouse during time step t; and $h^{\text{down}}(t)$ = the downstream water height in the powerhouse's turbine during time step t:

$$\text{PPC} = \frac{\gamma\eta DePw(t)\Delta H(t)}{PF(t)} \rightarrow DePw(t) = \frac{PF(t)\text{PPC}}{\gamma\eta\Delta H(t)} \tag{21}$$

$$\Delta H(t) = \left[\frac{h^{\text{up}}(t) + h^{\text{up}}(t+1)}{2}\right] - h^{\text{down}}(t) \tag{22}$$

$$h^{\text{down}}(t) = f''[Rw(j, V'', t)]j = j(1), j(2), \ldots, J(V'') \tag{23}$$

It is worth noting that electricity is generated in each powerhouse only when $\Delta H(t)$ is nonnegative. The parameter $h^{\text{down}}(t)$ is calculated based on $Rw(j, V'', t)$ using Eq. (23), where $f''[\ ]$ = the Qw-El equation for the powerhouse of each reservoir; V'' = the number of objectives corresponding to the hydropower generation in each reservoir, and $J(V'')$ = the number of the last intake gate used for generating hydropower.

Release for power generating equal to the PPC is based on the SOP:

$$\sum_{j=j(1)}^{J(V'')} Rw(j, V'', t) = \begin{cases} DePw(t) & DePw(t) < Z(t) \\ Z(t) & Z(t) \le DePw(t) \end{cases} \tag{24}$$

Release for recreation and flood control is based on the SOP:

$$\sum_{j=j(1)}^{J(V''')} Rw(j,\ V''',\ t) = \begin{cases} Z(t) - ST(t) & ST(t) < Z(t) \\ 0 & Z(t) \le ST(t) \end{cases} \tag{25}$$

where V''' = the number of the objective corresponding to recreation and flood control in each reservoir. After calculating the input and output factors for each reservoir, its storage and spill volumes are calculated with Eqs. (16) and (26), respectively:

$$Sp(t) = \begin{cases} Z(t) - S^{\max} & S^{\max} < Z(t) \\ 0 & Z(t) \le S^{\max} \end{cases} \tag{26}$$

Constraint on reservoir storage volume:

$$0 \leq S^{\min} \leq S(t) \leq S^{\max} \tag{27}$$

The reservoir storage volume includes the active storage and the stored sediments in the reservoir that must satisfy the previous inequality during all time steps of operation. Also, each intake gate is either a pipe or an adjustable gate with a specific capacity.

Constraint on release volume for supplying demands:

$$0 \leq Rw'^{\min}(j,l) \leq Rw'(j,l,t) \leq Rw'^{\max}(j,l)$$
$$l = 1,2,\ldots,C; \qquad j = j'(1), j'(2), \ldots, J'(V') \tag{28}$$

Constraint on release volume for supplying other objectives (except supplying user demands):

$$0 \leq Rw^{\min}(j,v) \leq Rw(j,v,t) \leq Rw^{\max}(j,v)$$
$$v = 1,2,\ldots,V; \qquad j = j(1), j(2), \ldots, J(v) \tag{29}$$

In these inequalities, $Rw'^{\min}(j,l)$ and $Rw'^{\max}(j,l)$ = minimum and maximum water releases from outlet j in each reservoir considering the supply to user demand l, respectively; and $Rw^{\min}(j,v)$ and $Rw^{\max}(j,v)$ = minimum and maximum water releases from the outlet j in each reservoir with objective v (except supplying user demands), respectively. The spillway is an important structure that must be reliable and efficiently operated.

Constraint on reservoir spill:

$$0 \leq Sp^{\min} \leq Sp(t) \leq Sp^{\max} \tag{30}$$

where $Sp^{\min}$ and $Sp^{\max}$ = minimum and maximum allowable spill from each reservoir, respectively.

The reservoir storage volume changes during a year and causes the stored water elevation to be variable. The capacity of intake gates in reservoirs of the sample system is constant and larger than the required demand volume needed to meet each objective downstream of the reservoirs. Water releases from each gate occur only when the stored water level is above the elevation of that gate. Therefore, the maximum release from each reservoir depends on the stored water elevation at each time step. One of the important assumptions in the SOP policy is carryover in the system—that is, the storage volume of the reservoir system at the beginning of the operation period is equal to the storage volume at the end of this period. In this manner, the system operation pattern would be sustainable, and can be repeatedly used during the useful life of the reservoir system.

The modeling and simulation equations for the three-reservoir system were solved with *Lingo13.0* when using Scenarios 1 and 3. The optimization problems corresponding to Scenarios 2 and 4 were solved with the NSGA-II toolbar of *MATLAB2012b*. The results obtained under each scenario are presented in following section.

Results and Discussion

Scenario 1: SRSO Optimization

Reservoirs 2 and 3 are operated in parallel, and their return flows for each objective are calculated. It is seen in Fig. 1 that the outflows from Reservoirs 2 and 3, such as spill, the water release for hydropower generation, the return flows from each user, and water releases for flood control, enter into Reservoir 1. These outflows are added to the natural river inflow of Reservoir 1. There are 13 decision variables in each objective assessment, including releases at each time step and the reservoir storage volume at the beginning of the operation period.

Hydropower Generation under Scenario 1

The objective function of the optimization problem for each reservoir is the maximization of the reliability (minimization of the relative deficit) of the hydropower generation:

$$\text{Maximize } F_i = 1 - \sum_{t=1}^{12} \frac{\text{Def}_i(t)}{\text{PPC}_i} \qquad i = 1,2,3 \tag{31}$$

$$\text{Def}_i(t) = \text{PPC}_i - PT_i(t) \qquad i = 1,2,3 \; t = 1,2,\ldots,12 \tag{32}$$

where i = index for the reservoirs, F_i = optimization objective function in reservoir i, $\text{Def}_i(t)$ = existing hydropower deficits (10^6 W) during time step t in reservoir i, and $PT_i(t)$ = generated power in the powerhouse of reservoir i during time step $t(10^6\ W)$. Because each powerhouse can generate a power equivalent to its installed capacity [$\text{PPC}_i \geq PT_i(t)$], Eq. (32) is always nonnegative. Fig. 2 shows the variations of the calculated decision and state variables in Scenario 1 for generating power.

It is seen in Fig. 2(a) that most deficits occur in the summer and at the beginning of the fall, and there is no deficit in other time steps during the year. This is because of the low volume of the natural river flow during deficit time steps at each reservoir. In fact, Fig. 2(a) shows that deficits occur in time steps in which the stored water volume in each reservoir is less than the required water volume for generating the hydropower energy, and the reservoir cannot release water for this purpose. Also, the variations of the storage volume in all reservoirs of the sample system [Fig. 2(b)] are in the allowable range (between the $S^{\min}$ and $S^{\max}$). The maximal deficit of generated power (approximately 174×10^6 W) occurs in Reservoir 1 [Fig. 2(c)]. The objective function's value for each reservoir is presented in Table 8, which shows at least 84% reliability of generating the possible maximum power in the powerhouses of all sample reservoirs.

Supplying User Demands under Scenario 1

The objective function of the optimization problem for each reservoir is defined in this scenario as the maximization of the reliability (minimization of the relative deficit) of supplying different user demands:

$$\text{Maximize } F_i = 1 - \frac{\sum_{t=1}^{12} \text{Def}_i(t)}{\sum_{t=1}^{12} De_i(l,t)} \qquad i = 1,2,3 \; l = 1,2,3 \tag{33}$$

$$\text{Def}_i(t) = De_i(l,t) - \sum_{j=1}^{J'} Rw'_i(j,l,t) \quad i = 1,2,3$$
$$l = 1,2,3 \; t = 1,2,\ldots,12 \tag{34}$$

The released volume is never larger than the required demand of different users when the SOP is used as the operation policy in the sample reservoirs, and the value of Eq. (34) is nonnegative. The variations of water releases to supply different users are shown in Fig. 3.

Fig. 3 shows that the natural river flow reduction during summer and at the beginning of fall constrains the amount of water available for release. Although all of the stored water in the reservoirs is released to supply different user demands in these time steps (the stored volume in the reservoir becomes equal to the minimum allowable storage), there are supply deficits, nevertheless.

Fig. 3(c) shows that the ability to supply industrial demand (approximately 100%) exceeds the levels of supply for other users

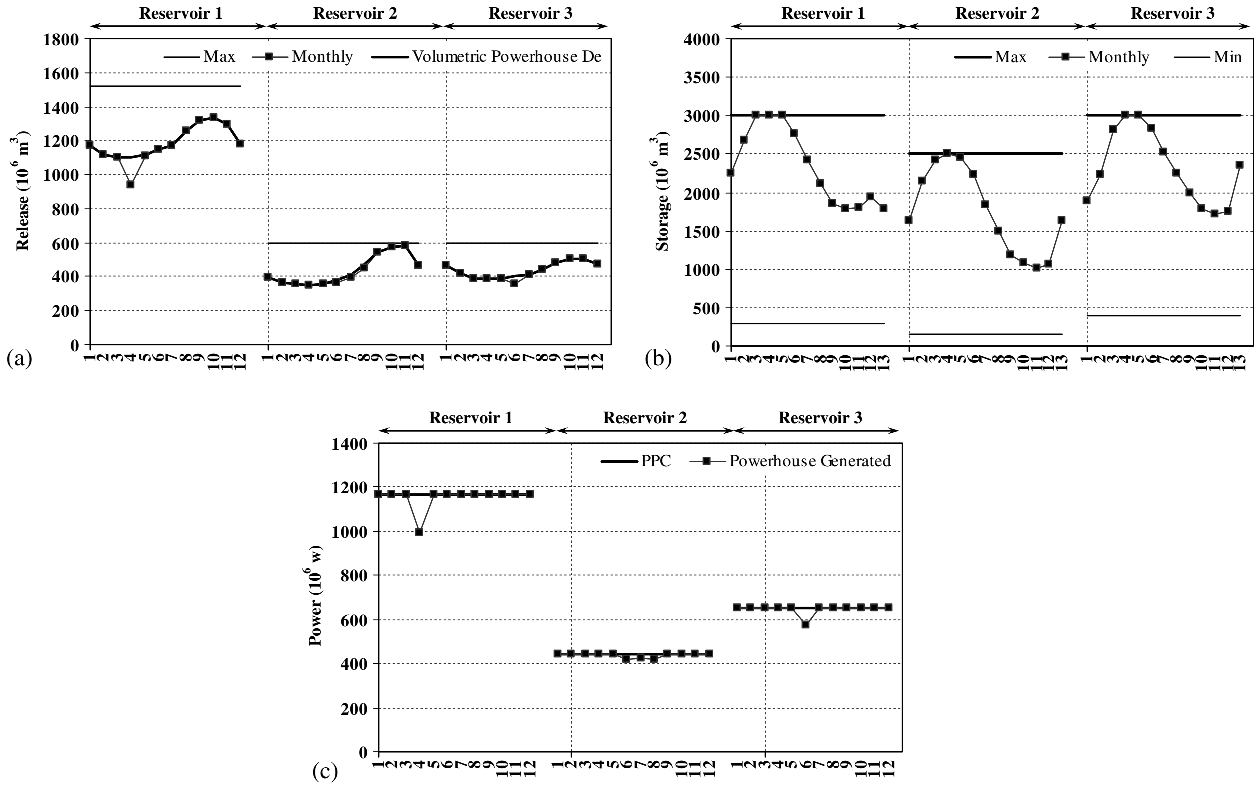

Fig. 2. Monthly variations of the (a) water release from different reservoirs; (b) reservoir storage volume; (c) generated power in different powerhouses, under scenario 1 considering the hydropower generation objective

in all reservoirs during the operation period. This is because the demand of water for industry is smaller than that of agricultural and municipal users. Monthly variations of release and reservoir storage are also in the allowable range for all reservoirs. The objective functions' values for reservoirs are presented in Table 8, which shows at least 87% reliability of supplying various demands by all sample reservoirs.

Recreation and Flood Control under Scenario 1

The objective function of the optimization problem for each reservoir i has been defined as the maximization of the reliability (minimization of the deviation from the threshold storage) of recreation and flood control:

$$\text{Maximize } F_i = 1 - \sum_{t=1}^{12} \text{Def}_i(t) \qquad i = 1,2,3 \tag{35}$$

$$\text{Def}_i(t) = \begin{cases} \frac{S_i(t) - ST_i(t)}{S_i(t)} & S_i(t) \geq ST_i(t) \\ \frac{ST_i(t) - S_i(t)}{ST_i(t)} & S_i(t) < ST_i(t) \end{cases} \qquad i = 1,2,3 \; t = 1,2,\ldots,12 \tag{36}$$

Table 8. Value of the Objective Function for Different Reservoirs under Scenario 1 (Percentage)

Reliability of	Reservoir number 1	2	3
Generating hydropower	84.8	86.4	88.6
Supplying agricultural demand	87.4	91.8	90.6
Supplying municipal demand	87.5	95.8	92.7
Supplying industrial demand	98.4	98.5	97.2
Recreation and flood control	100.0	98.9	100.0

where $\text{Def}_i(t)$ = the rate of deviation from the threshold storage of flood control during time step t for the reservoir i. Eq. (36) does not account for reservoir storage to accommodate the probable flood in each time step t. Instead, reservoir storage volume must be controlled at the threshold storage to provide for the probable flood volume in each time step and ensure an adequate level of water for recreation activities. The monthly variations of water release to control the flood and the storage in the sample reservoirs are presented in Fig. 4.

Fig. 4 shows that the variations of water release and reservoir storage are in the allowable range in all of the sample reservoirs. The water release is reduced by decreasing the natural river flow [Fig. 4(a)]. Also, the reservoirs' storages do not violate the threshold storage in most time steps [Fig. 4(b)]. The objective function's value for each reservoir is presented in Table 8, which shows at least 99% reliability of recreation and flood control services for all sample reservoirs.

Scenario 2: SRMO Optimization

Each reservoir is operated separately, and all of the objectives are considered simultaneously under Scenario 2. To provide a realistic condition in evaluating the performance of Reservoir 1, Reservoirs 2 and 3 are operated in parallel first, and their spills and return flows for each objective are calculated. The total inflow to Reservoir 1 is the sum of the natural river inflow and the inflows from the upstream reservoirs. Several objective functions are defined under this scenario ($i = 1,2,3$ denotes the reservoir number):

$$\text{Maximize } F_{\text{Power}} = \frac{\sum_{t=1}^{12} PT_i(t)}{12 \times \text{PPC}_i} \tag{37}$$

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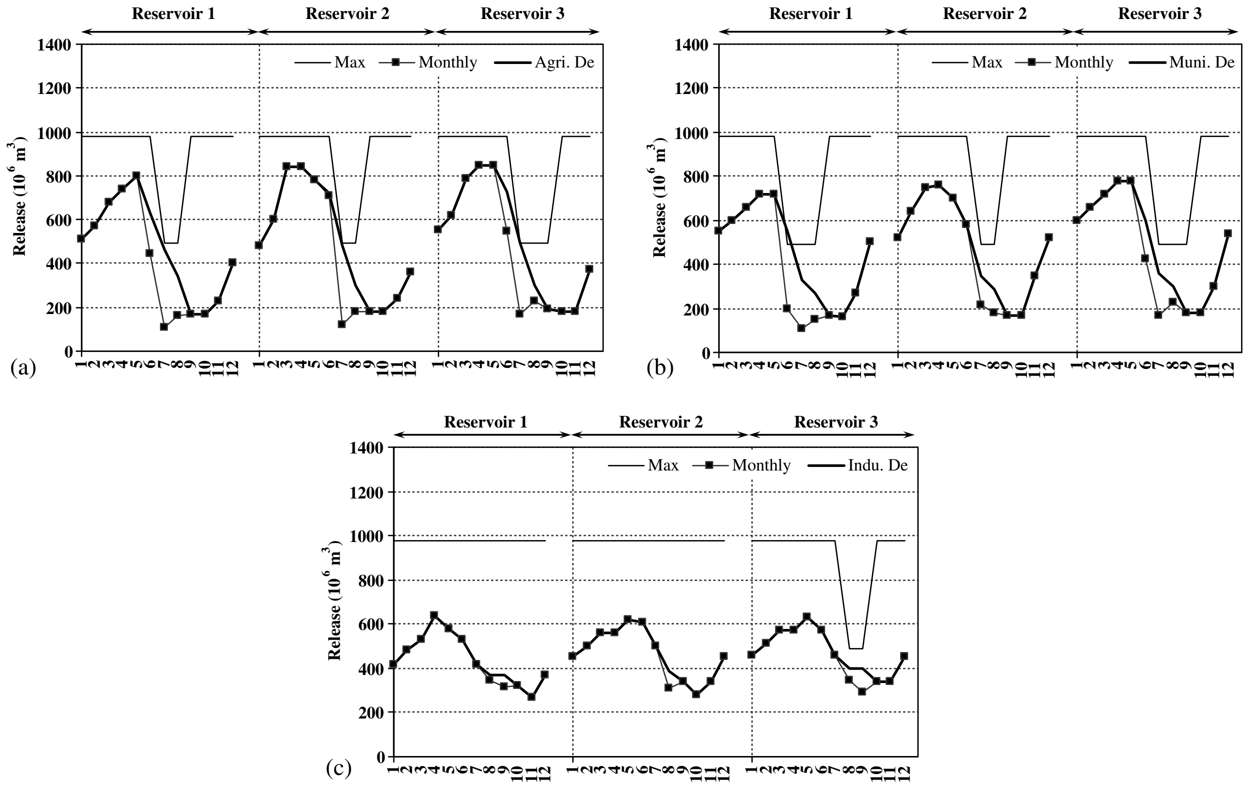

Fig. 3. Monthly variations of water release to meet the (a) agricultural; (b) municipal; (c) industrial demands, under scenario 1

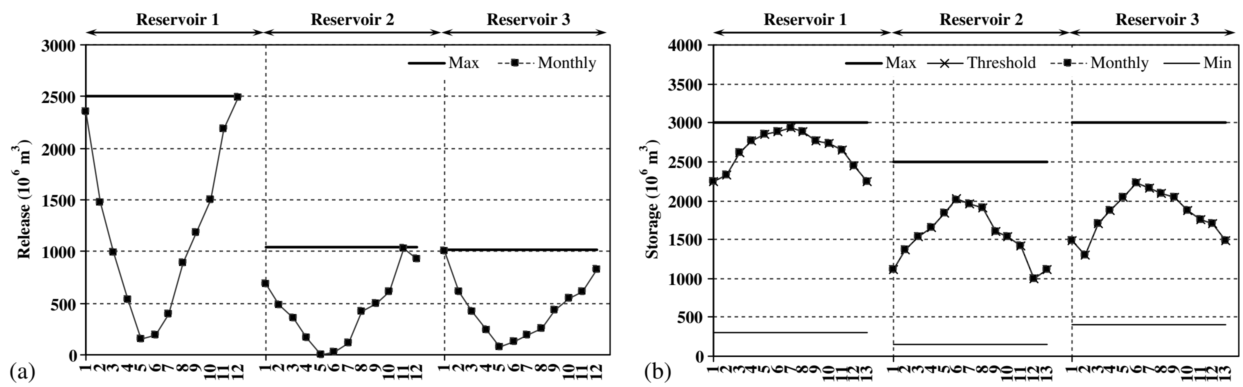

Fig. 4. Monthly variations of the (a) water release from different reservoirs; (b) reservoir storage volume, under scenario 1 considering the recreation and flood control objective

$$\text{Maximize } F_{\text{Demand}} = \frac{1}{3}\sum_{l=1}^{3}\sum_{t=1}^{12}\frac{\sum_{j=1}^{J'} Rw_i'(j,l,t)}{De_i(l,t)} \tag{38}$$

$$\text{Minimize } F_{\text{Flood}} = \frac{\sum_{t=1}^{12}|S_i(t) - ST_i(t)|}{\sum_{t=1}^{12} ST_i(t)} \tag{39}$$

where F_{Power}, F_{Demand}, and F_{Flood} = the optimization objective function of hydropower generation (maximization), supplying different user demands (maximization), and recreation and flood control (minimization), respectively. The previous formulations maximize the service reliabilities. The optimization is performed with three objectives [Eqs. (37)–(39)] and three types of decision variables including hydropower releases, releases to supply downstream demands, and the reservoir storages at the beginning of the operation period for each sample reservoir. The simulation model is based on the SOP considering five types of releases for generating hydropower energy; supplying agricultural, municipal, and industrial demands; and providing recreation and flood control. Because the optimization problem is multiobjective, determining the priority of various objectives at different time steps in each reservoir is important. The priorities chosen in decreasing order of importance are generating hydropower, supplying downstream demands, and providing recreation and flood control in the sample system. The priorities assigned in decreasing order of importance for meeting downstream demands are municipal, agricultural, and industrial water. In each reservoir, the hydropower release is allocated first in each time step according to the installed capacity of each powerhouse. The quantity and quality of outflow water from the powerhouse do not change in comparison with its input water.

This outflow water is used to meet downstream demands according to assigned priorities. If the downstream demands are not completely met after the allocation of powerhouses' outflows to them, the deficit is satisfied with the water stored in reservoirs after hydropower releases. Finally, the release to meet the recreation and flood control objective is determined according to the remaining water stored in each reservoir and the threshold volume for recreation and flood control.

The multiobjective optimization problem was solved using the NSGA-II with 5,000 iterations (generations), 350 members, and 25 decision variables for each reservoir. This model was run several times, and the final set of nondominant solutions obtained as the result of several runs is considered as the final Pareto solution for each reservoir (Fig. 5). Each non-dominant solution contains a monthly series of considered variables (types of releases, generated power of powerhouses, storage volume of reservoirs, etc.) in each year of reservoir operation and management. There are different monthly series for each variable corresponding to each nondominant solution. Because the presentation of all of these series is impossible given the space limitations, the maximum, average, and minimum of obtained values for each variable are displayed in Fig. 6.

Fig. 6 shows that all of the objectives are met satisfactorily, and the Pareto solution for each reservoir has an appropriate distribution in objective space. Based on the average values of different variables at each time step shown in Fig. 6, in months when the natural river flow decreases (end of spring and in summer), approximately 50% of the municipal demand is met under the best conditions, and no water is allocated to the agricultural and industrial users. Sufficient water in the reservoirs system at the end of fall and during winter permits supplying 100% of the municipal and agricultural demands, and at least 50% of the industrial demand [Figs. 6(a–c)].

To meet the recreation and flood control objective, water is stored in the reservoirs (without any release for this purpose) during the operation period [Fig. 6(d)]. The reservoir storage decreases at time steps when the natural river flow increases (end of fall and beginning of spring) to produce hydropower and supply downstream demands according to their assigned priorities. Recreation and flood control exhibit the lowest reliability of service (that is, the percentage of time the target service is met) because this objective is assigned the lowest priority. Other objectives are desirably achieved (even with 100% reliability in some cases).

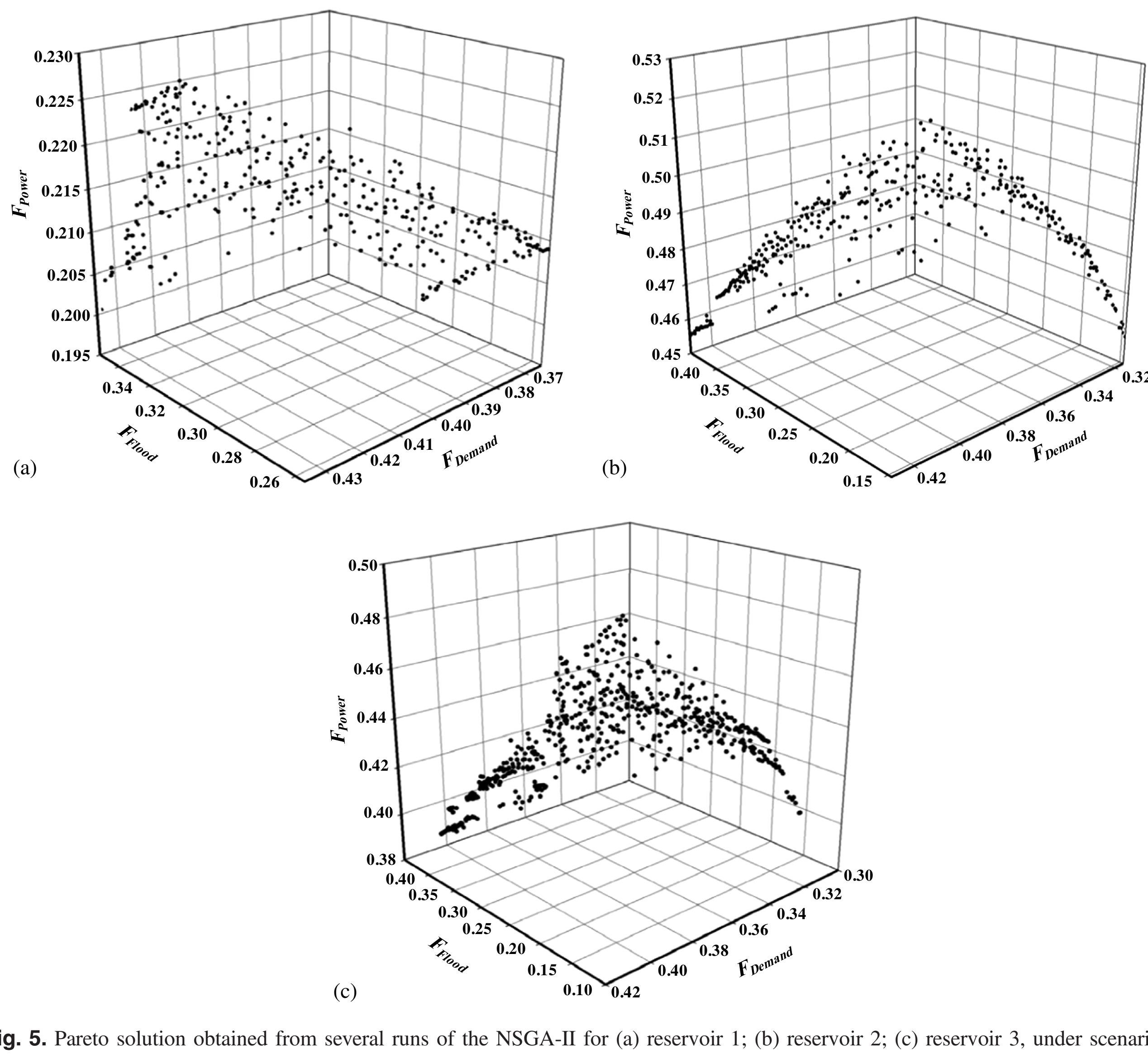

Fig. 5. Pareto solution obtained from several runs of the NSGA-II for (a) reservoir 1; (b) reservoir 2; (c) reservoir 3, under scenario 2

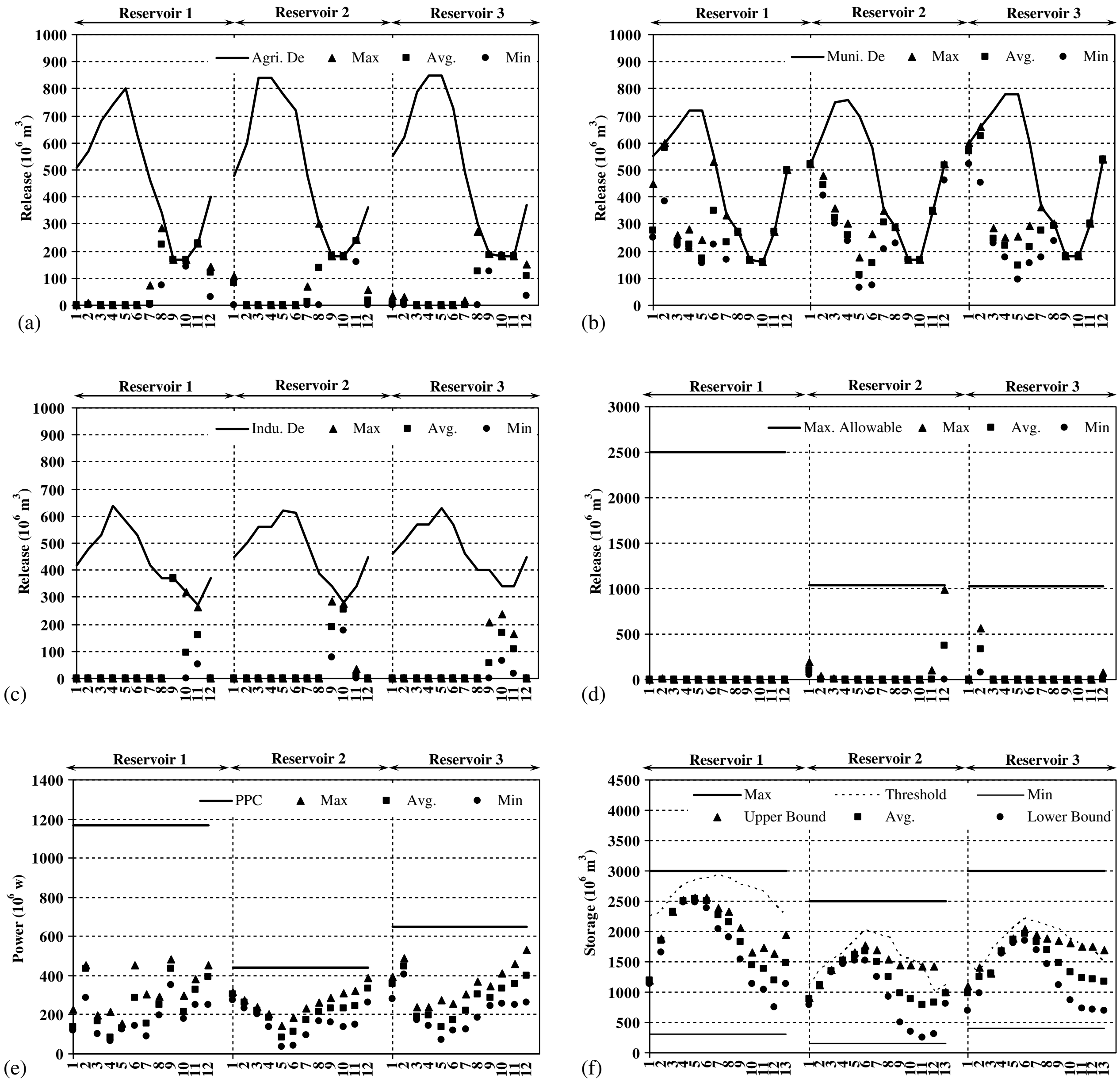

Fig. 6. Monthly variations of the (a) agricultural demands and releases; (b) municipal demands and releases; (c) industrial demands and releases; (d) releases of supplying recreation and flood control; (e) generated powers; (f) reservoir storages, under scenario 2

When the natural river flow decreases (during summer and the beginning of fall), reliability of meeting different objectives decreases because of water shortage. The reliability of hydropower generation is marginally adequate in the sample reservoirs [Fig. 6(e)] despite having the highest priority among objectives. The water allocated to each powerhouse is used to meet downstream demands after generating power, helping reduce deficits in water supply for users. However, it is not possible to reduce hydropower deficits with other components of the sample system. For this reason the volume of release for different objectives is determined in the optimization model so that a reasonable balance of meeting all of the objectives in the reservoirs is achieved. This explains the low reliability of hydropower generation in several operational time steps. The maximum deficit of generated power is approximately $1,104 \times 10^6$ W in Reservoir 1 [Fig. 6(e)]. Also, the variations of reservoir storage are in the allowable range for all reservoirs [Fig. 6(f)].

Scenario 3: MRSO Optimization

All of the reservoirs are operated jointly while considering each objective function separately in this scenario. Reservoirs 2 and 3 are operated in parallel, and these two reservoirs are operated in series with Reservoir 1.

Hydropower Generation under Scenario 3

The objective function in this case is the maximization of the relative generated power (maximization of the reliability):

$$\text{Maximize } F = \frac{1}{3}\sum_{i=1}^{3}\frac{\sum_{t=1}^{12} PT_i(t)}{12 \times \text{PPC}_i} \tag{40}$$

Because the generated power in three powerhouses of the sample system is fed to the regional power grid, the performance of each powerhouse affects the performance of the regional power system. Therefore, the maximization of the average reliability of

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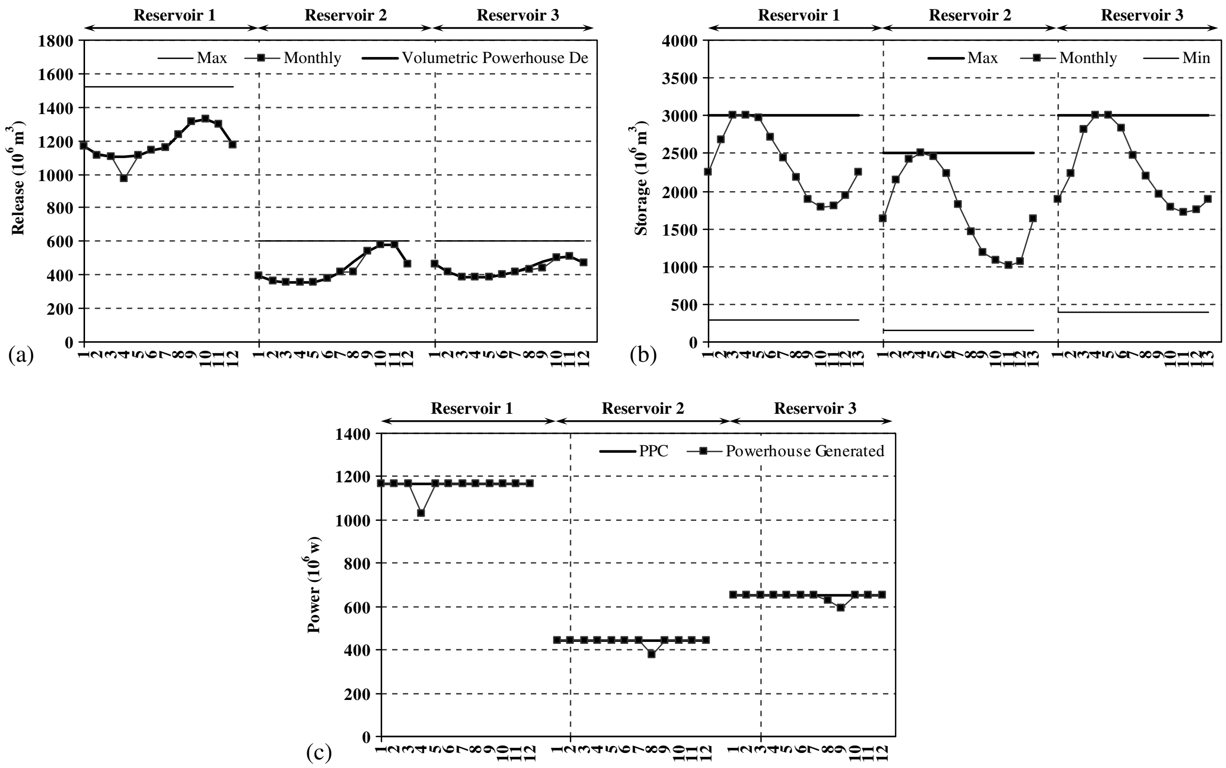

Fig. 7. Monthly variations of the (a) water release from different reservoirs; (b) reservoir storage volume; (c) generated power in different powerhouses, under scenario 3 considering the hydropower generation objective

three powerhouses is used in Eq. (40). Fig. 7 shows the variations of decision and state variables under Scenario 3.

Fig. 7(a) shows the hydropower deficits in Reservoir 1 during summer and in Reservoirs 2 and 3 during fall. There are no deficits in other time steps of the year. This shows that deficits occur at time steps in which the stored water volume is less than the water required to generate hydropower, and the reservoirs are not able to release sufficient water for this purpose. Under this scenario, there is a deficit at only one time step in each reservoir, but under Scenario 1, the deficit of Reservoir 2 occurs during several successive months. It is seen that, in multireservoir analysis, the number of deficit intervals decreases, but the deficit intensity increases in the parallel reservoirs (Reservoirs 2 and 3) and decreases in series reservoirs (Reservoir 1). The variations of the storage volume in all of the reservoirs of the sample system [Fig. 7(b)] are in the allowable range (between $S^{\min}$ and $S^{\max}$). The maximum deficit of the generated power (approximately 139×10^6 W) occurs in Reservoir 1 [Fig. 7(c)], just as it does under Scenario 1. The value of the objective function for the sample reservoirs system is equal to 98.9% under Scenario 3.

Supplying User Demands under Scenario 3

The objective function in this case is the maximization of the relative supply of user demands:

$$\text{Maximize } F_l = \left.\frac{\sum_{t=1}^{12} R_i(l,t)}{\sum_{t=1}^{12} De_i(l,t)}\right|_{i=1} \times \left[\frac{1}{2}\sum_{i=2}^{3}\frac{\sum_{t=1}^{12} R_i(l,t)}{\sum_{t=1}^{12} De_i(l,t)}\right] l = 1,2,3 \tag{41}$$

$$R_i(l,t) = \begin{cases} \sum_{j=1}^{J'} Rw_i'(j,l,t) & \sum_{j=1}^{J'} Rw_i'(j,l,t) < De_i(l,t) \\ De_i(l,t) & \sum_{j=1}^{J'} Rw_i'(j,l,t) \geq De_i(l,t) \end{cases}$$
$$i = 1,2,3; \quad l = 1,2,3; \quad \text{and} \quad t = 1,2,\ldots,12 \tag{42}$$

where $R_i(l,t)$ = minimum value between the release of Reservoir i and demand of user l at time step t. The performance of Reservoirs 2 and 3 affects the performance of the entire system. The performance of Reservoir 1 is affected by Reservoirs 2 and 3, and Reservoir 1 affects the performance of the entire system. It is for this reason that the product of the reliability in Reservoir 1 and the average reliability of Reservoirs 2 and 3 are considered as the objective function in this case, as expressed by Eq. (41). Releases larger than the downstream demand are possible at some time steps in Reservoirs 2 and 3 because they are not operated based on the SOP. In Scenario 3, the operation management and the variations of releases in Reservoirs 2 and 3 have direct effects on Reservoir 1 management. If these two reservoirs are operated based on the SOP, the demand value of each user is considered as the upper bound of release in these reservoirs, and the calculated results would be the same as Scenario 1 in supplying each water demand. In this situation, the concept of integrated management of the reservoirs system does not apply. Accordingly, Eq. (42) is used to define the terms of Eq. (41). It is concluded from Eq. (41) that the optimization of the objective function for the three-reservoir system depends on the maximization of the reliability of supply in Reservoir 1. Achieving a desirable reliability in Reservoir 1 directly affects the performance of the upstream reservoirs and the reliability of their supplies. The variations of water releases to meet user demands are shown in Fig. 8.

It is evident in Fig. 8 that approximately all demands are met during the operation period of Reservoir 1. This is due to larger water release than the demands in Reservoirs 2 and 3 upstream of Reservoir 1. This situation causes a zero active storage volume in Reservoir 1 only in one month of the operation period (time step number 9), in addition to meeting 100% of demands in this reservoir. Sufficient water is stored in Reservoir 1 at other times. The main deficits in Reservoirs 2 and 3 occur during summer and at the

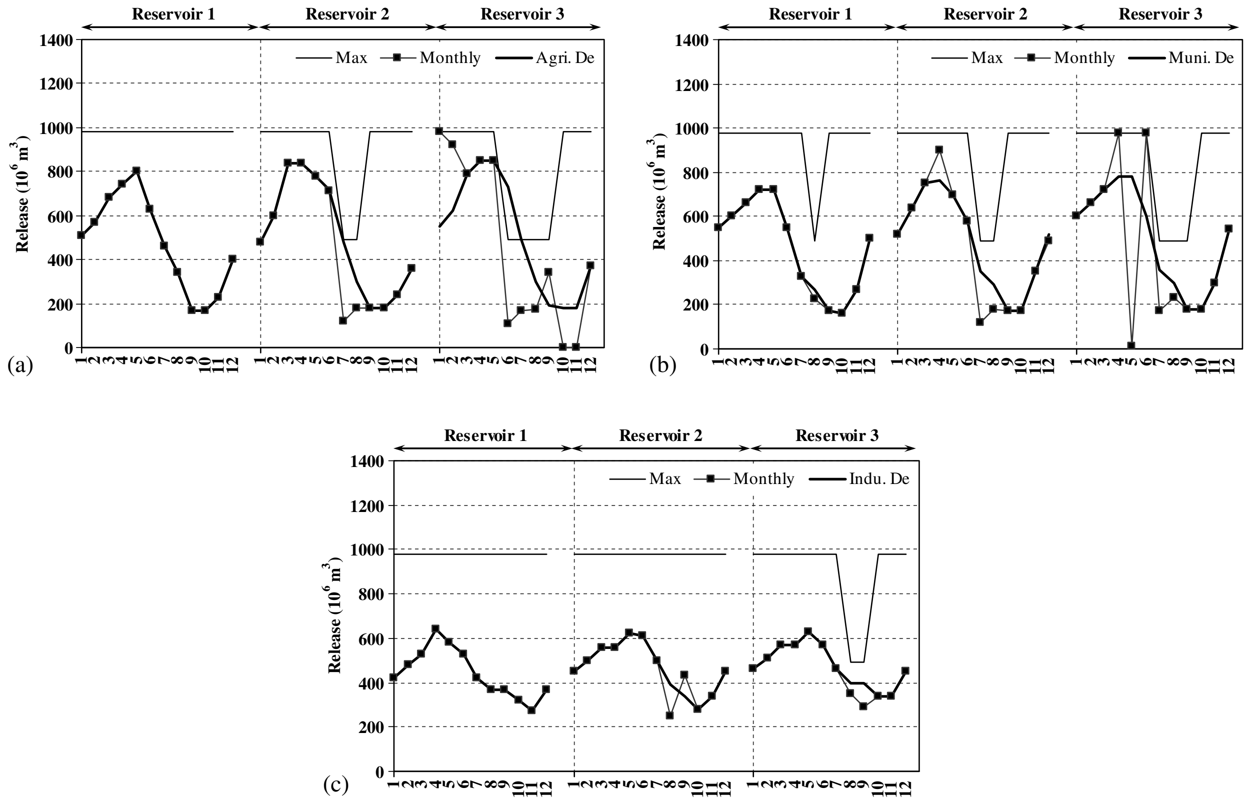

Fig. 8. Monthly variations of water release to meet the (a) agricultural; (b) municipal; (c) industrial demands, under scenario 3

beginning of fall because of the natural river flow reduction at these times. As a result, there is a deficit in these time steps despite the fact that approximately all of the stored water in the reservoirs is released to supply water demands. If there is sufficient water in Reservoirs 2 and 3, the volume of release will be larger than their downstream demands to assist Reservoir 1 in meeting various user demands. However, when there is not enough water, Reservoir 3 incurs major deficits.

It is shown in Fig. 8(a) that the natural river flow in Reservoir 3 is less than that in Reservoir 2 at time steps number 10 and 11, and all of the water stored in Reservoir 2 is used to supply the agricultural demand of this reservoir. Therefore, all of the water stored in Reservoir 3 is transferred to Reservoir 1, and the agricultural demand of Reservoir 3 is not supplied in these months. It should be mentioned that the reliability of Reservoir 1, more than Reservoir 3, affects the whole system reliability. All of the reservoirs' demands are supplied at other time steps (spring and winter).

The volumes of agricultural and municipal demands are larger than the industrial demands. Thus, the capacity of the intake gates is determined based on agricultural and municipal demands. Fig. 8(c) shows that the ability of meeting industrial demand is larger than those of meeting other demands in all reservoirs, and that the industrial deficits are smaller than agricultural and municipal deficits in the reservoirs system. The volume and number of deficits increase in the parallel reservoirs (Reservoirs 2 and 3) and decrease in Reservoir 1, which is in series with the upstream reservoirs. This shows the importance of the integrated operation of the parallel and serial reservoirs.

The monthly variations of reservoir storage are in the allowable range for all reservoirs. The objective function's values for each reservoir are presented in Table 9. The supply reliability of agricultural demand decreases in the system in comparison with Scenario 1 due to the large volume of annual demand for agriculture in Reservoir 3, causing more deficits in this reservoir than in Reservoirs 1 and 2. The supply reliability of municipal and industrial demands is little changed in comparison with Scenario 1. This shows that there is a reasonable balance between the demand values and the reservoirs' capacities in the reservoir system. In general, there is at least an 84% reliability of meeting various water demands in the sample three-reservoir system.

Recreation and Flood Control under Scenario 3

The objective function of optimization problem is defined as maximization of the ratio of total storage volume to the total threshold storage (maximization of the reliability) of recreation and flood control:

$$\text{Maximize } F = \left.\frac{\sum_{t=1}^{12} S_i(t)}{\sum_{t=1}^{12} ST_i(t)}\right|_{i=1} \times \left[\frac{1}{2}\sum_{i=2}^{3}\frac{\sum_{t=1}^{12} S_i(t)}{\sum_{t=1}^{12} ST_i(t)}\right] \quad (43)$$

The performances of Reservoirs 2 and 3 directly affect the performance of the reservoir system, but the effect of Reservoir 1 is indirect. Thus, the product of the Reservoir 1 reliability and the average reliability of Reservoirs 2 and 3 is defined as the objective

Table 9. Reliability of Supplying Various User Demands for the Three-Reservoir System under Scenario 3

Parameter	Reliability of supplying (%)
Agricultural demand	84.2
Municipal demand	87.5
Industrial demand	97.3

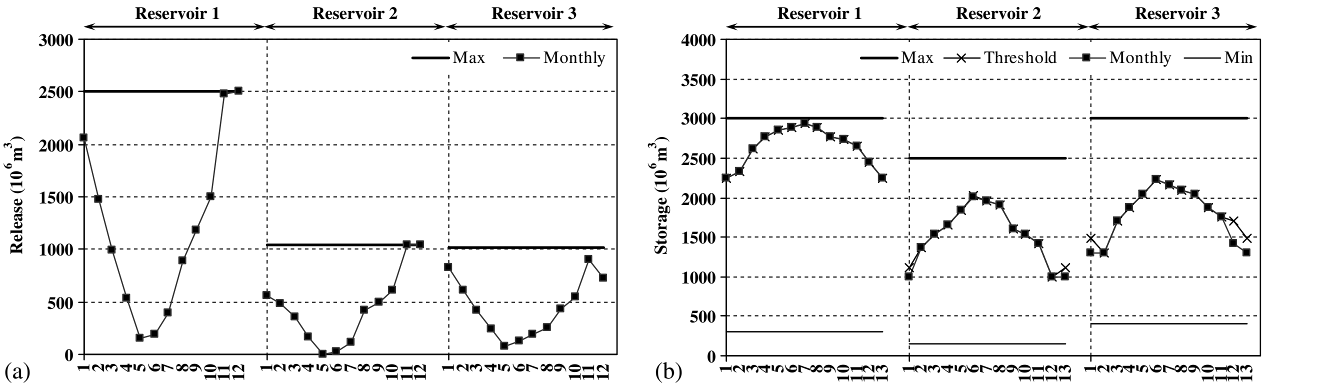

Fig. 9. Monthly variations of the (a) water release from different reservoirs; (b) reservoir storage volume, under scenario 3 considering recreation and flood control objective

function. The monthly variations of water release to control floods and the storage in the sample reservoirs are portrayed in Fig. 9.

It is seen in Fig. 9 that the variations of water release and reservoir storage are in the allowable range in all of the sample reservoirs. The water release is reduced by decreasing natural river flow. Also, the reservoirs' storages do not violate the threshold storage in most time steps. These variations are approximately similar to those displayed in Fig. 4 corresponding to Scenario 1. The water releases adjust the reservoir storage to meet the recreation and flood control objective. In this respect, the results under Scenario 3 are similar to those calculated under Scenario 1. The objective function's value for the reservoir system is equal to 98.2% under Scenario 3, which is not significantly different from the values obtained under Scenario 1 for the three reservoirs.

Scenario 4: MRMO Optimization

The three reservoirs are operated jointly considering all of the objectives simultaneously under Scenario 4. Reservoirs 2 and 3 are operated in parallel and are in series with Reservoir 1. The objective functions are identical to those used under Scenario 2 [Eqs. (37)–(39).

The optimization problem was solved with three objectives and three types of decision variables, including hydropower release, releases to supply downstream demands, and the reservoir storage at the beginning of the operation period for each sample reservoir in the system. As explained earlier, the maximum values of releases from each reservoir (based on the stored water and intake gates elevations) are set equal to the upper bound of releases to supply different user demands in Reservoirs 2 and 3, whereas the simulation of Reservoir 1 operation is based on the SOP. An operation to generate hydropower and recreation and flood control is carried out based on the SOP for all sample reservoirs. The priorities of reservoir storage allocation to meet different objectives are the same as those in Scenario 2. The NSGA-II was used to solve the multiobjective optimization problem for 5,000 iterations (generations), 450 members, and 75 decision variables for the whole system. This model was run several times and the final set of calculated nondominant solutions obtained as the result of several runs is considered as the final Pareto solution for the system (shown in Fig. 10). In this scenario, the maximum, average, and minimum calculated values for each variable are displayed in Fig. 11.

Fig. 10 shows that all of the objectives are met satisfactorily, but the Pareto solution does not have an appropriate distribution in the objective space compared with Scenario 2. In Scenario 4, the system is operated as a multiattribute, multireservoir system, whereas in Scenario 2, the system is operated as a multiattribute, single-reservoir system. Because the size and dimensionality of the optimization problem in Scenario 4 are larger than in Scenario 2, the problem becomes more complex. The combination of possible decision options increases, and the nondominant options for system management decrease under Scenario 4.

Based on the average values of different variables at each time step in Fig. 11, it is seen that in months that the river natural flow decreases (end of spring and during summer), the municipal demand incurs maximum deficits, and no water is allocated to the agricultural and industrial demands. On the other hand, sufficient water in the reservoirs system at the end of fall and during winter leads to meeting 100% of the municipal and agricultural demands and at least 50% the industrial demand [Figs. 11(a–c)].

The occurrence of the probable flood increases at the end of winter and at the beginning of spring. Therefore, meeting the recreation and flood control objective requires stored water in reservoirs to be released so that there is a minimum possible difference between the reservoir storage and the threshold storage in each reservoir [Fig. 11(d)]. The reliability of meeting the recreation and flood control objective for approximately all reservoirs under

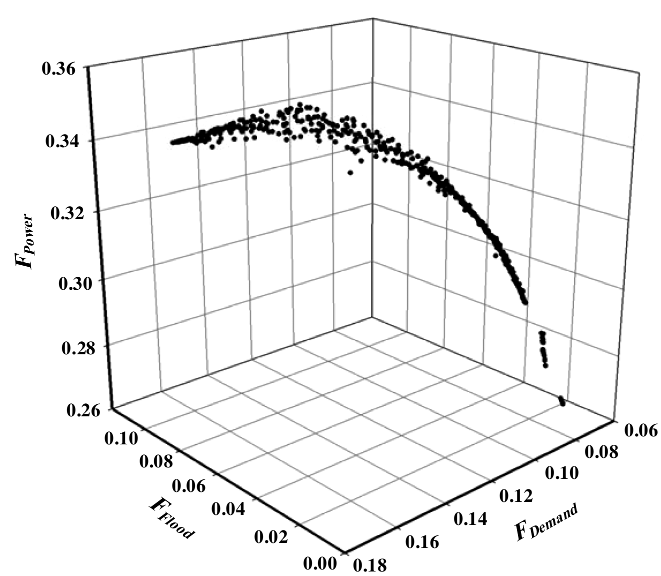

Fig. 10. Pareto solution obtained from several runs of the NSGA-II for the three-reservoir system under scenario 4

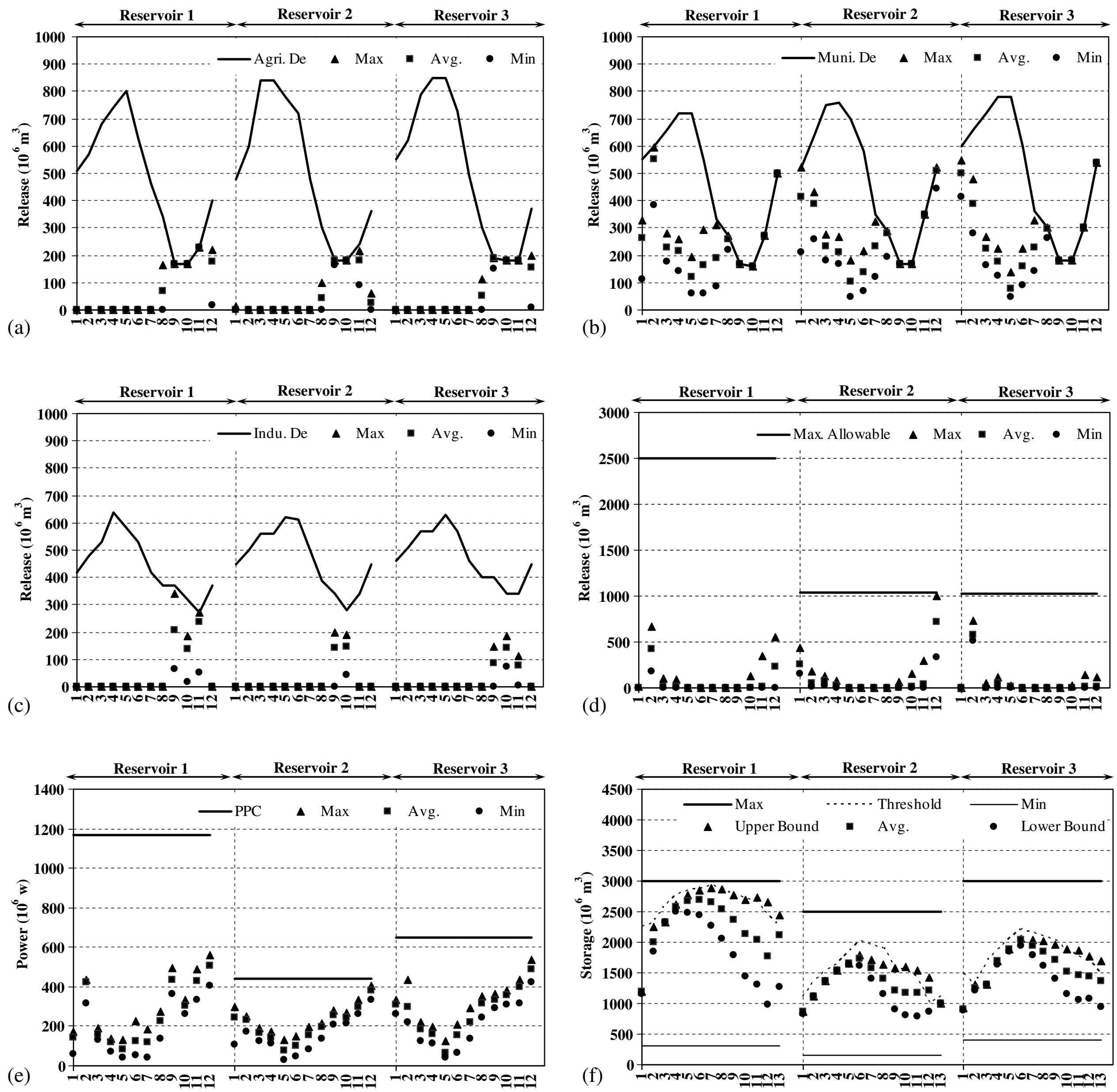

Fig. 11. Monthly variations of the (a) agricultural demands and releases; (b) municipal demands and releases; (c) industrial demands and releases; (d) releases to meet recreation and flood control; (e) generated power; (f) reservoir storages, under scenario 4

Scenario 4 is larger than that in Scenario 2, and the variations of maximum, average, and minimum values of storage are closer to the threshold storage. When the natural river flow decreases (during summer and at the beginning of fall), the reliability of meeting objectives (except supplying the recreation and flood control) decreases due to water shortage. It is concluded that in wet seasons, the hydropower and downstream demands are adequately met, whereas recreation and flood control are adequately met in dry seasons. Because hydropower generation has the highest operation priority, similar to Scenario 2, its reliability of supply is not adequate in some sample reservoirs [Fig. 11(e)]. In this case, the water allocated to the powerhouses is also used to supply the downstream demands after generating power. The deficits of hydropower generation cannot be supplied with other components of the sample system. Therefore, other objectives are more adequately met than hydropower generation in the three-reservoir sample system. The maximum deficit of generated power was approximately $1,082 \times 10^6$ W in Reservoir 1 [Fig. 11(e)]. The variations of reservoir storage are in the allowable range for all reservoirs [Fig. 11(f)].

Finally, the four different scenarios are compared in Fig. 12. As shown in Fig. 12(a), the system reliability of supplying all considered objectives except recreation and flood control in Scenario 3 (MRSO) is more than Scenario 1 (SRSO), which shows the necessity of integrated management of multireservoir systems. The importance of integrated management in a water resources system is well known, and the proposed sample three-reservoir system confirms this assertion. The proposed system can be used as a useful basic sample system in various studies of water resources systems. To meet the recreation and flood control objective, the reservoir storage should be controlled in a specific threshold level during each time step of the operational period. In scenario 3, each reservoir performance is affected by others; therefore, the system reliability in supplying the recreation and flood control objective is slightly lower than that associated with Scenario 1.

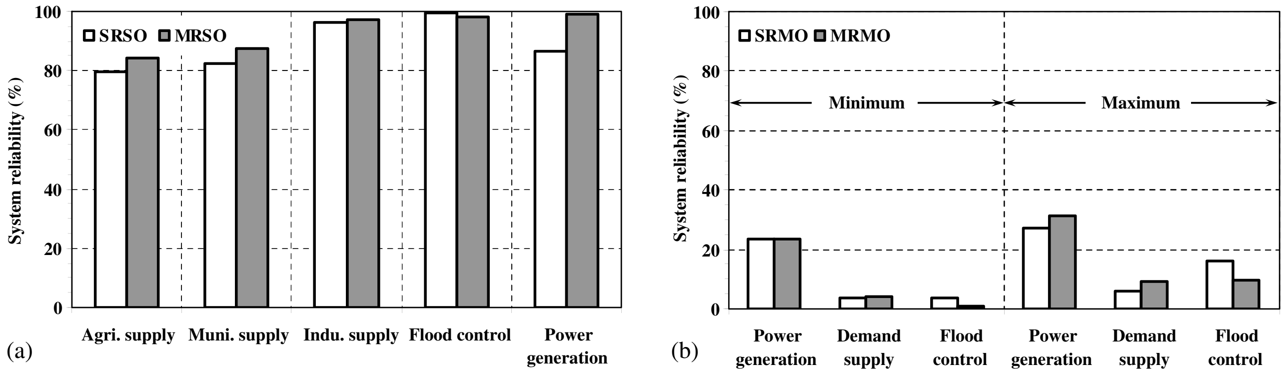

Fig. 12. Comparison of system reliability under scenarios (a) SRSO and MRSO; (b) SRMO and MRMO

The optimal results of the multiobjective problems are presented in a Pareto form. Fig. 12(b) depicts the minimum and maximum values of the final Pareto obtained for each general objective under Scenarios 2 (SRMO) and 4 (MRMO). Results similar to those in Fig. 12(a) can be seen in the multiobjective assessment of the sample system. The comparison of minimum or maximum values of power generation and water shows that the reliability of the multireservoir analysis (Scenario 4) is higher than that achieved with single-reservoir analysis (Scenario 2). Because the recreation and flood control objective is considered as the lowest priority of system operation, the system reliability for this objective in Scenario 4 is less than Scenario 2, although this is not significant in management decisions.

Concluding Remarks

The development of sample reservoir systems is important to test alternative optimization models. This study introduced a sample reservoir system with comprehensive structural and operational data. The performance of existing simulation and optimization models can be clearly assessed, and new optimization and simulation methods could be comprehensively tested with the sample reservoir system. The sample system consists of two reservoirs in parallel and one in series. It was used in this study to develop optimal operating policies considering hydropower generation, supplying three types of water demands (agricultural, municipal, and industrial), and recreation and flood control.

The sample system's operation was optimized under four scenarios (SRSO, SRMO, MRSO, and MRMO). The single-objective scenarios' comparison showed the advantage of integrated management in water resources systems. The system reliability for all objectives calculated under these scenarios was in the range of 84–100%. Also, the comparison of multiobjective scenarios indicated that the system reliability for all objectives is in the range of 0.9–45% according to the objectives' priorities. The calculated results are reasonable and meaningful. Separate components or multiple components of the proposed sample reservoir system can be used as a basic test-case study in multiple types of water resources analyses involving simulation, optimization, and evaluation of different methods for the optimization of reservoir system operations.

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