Water Supply

Water Supply Vol 22 No 1, 883 doi: 10.2166/ws.2021.226

A comparative framework to impact assessment of objective function structure and supply/demand scenario on hydropower operation

Negar Gholami and Hesam Seyed Kaboli*
Department of Civil Engineering, Jundi-Shapur University of Technology, Dezful, Iran
*Corresponding author. E-mail: hkaboli@jsu.ac.ir

ABSTRACT

The structure of objective functions in the reservoir optimization problem indicates the type of attitude to operation. This paper presents an analytical framework to improve the structure of the objective function by comparing six various forms of single-objective and bi-objective problems. Problems 1 and 2 were defined to compare two perspectives of operation, water supply versus energy generation. Problem 3 was also designed to examine the effect of the intra-annual electricity demand, which was ignored in problem 2. Comparison of problems 4 and 5 shows the simultaneous effect of realistic water and electricity demand scenarios on finding an optimal Pareto front. Problem 6 considers a supply policy in which maximum hydropower generation in peak months is the main strategy to reduce socioeconomic tensions. These problems were analyzed for a period of 72 months in the operation of the Dez reservoir in the southwest of Iran. The results of comparisons showed that the average annual water supply in problem 1 is 334 Mm^3 higher than in problem 2, while the mean annual hydropower generation in problem 2 compared with problem 1 increases by 58.9 GWh. Hydropower generation in problem 2 compared with problem 3 experiences a 31.8% decrease in the peak period and a 111% increase in the non-peak months, which can impose significant problems on the National Electricity Network. The Pareto front for problem 5 is better than for problem 4 at all points, meaning that the demand coefficient improves the Pareto front. The solutions of problem 6 can result in efficient meeting of water and electricity demand in critical periods and greatly improve practical planning.

Key words: demand scenario, hydropower operation, objective function structure, peak period

HIGHLIGHTS

- We analyzed different single/bi-objective optimization problems to improve the structure of the objective function through a comparative study.
- Considering demand scenarios improves performance parameters of the reservoir.
- Implementation of a strategy of maximum hydropower generation in peak months leads to finding a set of optimal Pareto solutions that can provide practical planning.

1. INTRODUCTION

Over the past decades, significant population growth, rising water demand, limited resources, climate change, and socioeconomic developments have caused severe tensions over water resources, especially in developing countries (Chen *et al.* 2016; Dahal *et al.* 2016; Al-Jawad *et al.* 2019). On the other hand, spatial and temporal variations of freshwater availability often do not correspond with human needs. Therefore, water resource planning and management under climatic conditions and socioeconomic development are needed for accessing sustainable development of water resources and secure supply of water and energy (Haddad *et al.* 2015). Water reservoir construction is one of the main approaches for supplying water and energy demand in arid and semi-arid areas (Chitsaz & Banihabib 2015). A reservoir is managed with a set of predetermined operating instructions that are provided by satisfying the reservoir operation objectives according to the existing limitations, such as the reservoir status and the demands (Haddad *et al.* 2008; Afshar & Hajiabadi 2018; Karami *et al.* 2019).

The operational objectives of a reservoir are defined as mathematical functions, for instance: reliable downstream water supply (Asgari *et al.* 2016; de Santana Moreira & Celeste 2017; Celeste & El-Shafie 2018; Bilal *et al.* 2020), maximum hydropower generation (Aboutalebi *et al.* 2015; Bozorg-Haddad *et al.* 2018; Ehteram *et al.* 2018; Yaseen *et al.* 2018; Al-Aqeeli &

Agha 2020; Rahimi *et al.* 2020), maximum water release (Bozorg Haddad *et al.* 2017; Ehteram *et al.* 2017; Saadatpour *et al.* 2020; Akbarifard *et al.* 2021), and reservoir performance indices (Ahmadi *et al.* 2014; Bozorg Hadad *et al.* 2016; Fallah-Mehdipour *et al.* 2020; Moeini & Soghrati 2020). Since hydropower reservoir planning and operational management is generally based on some economic, social, and hydrological–hydraulic objectives or constraints, the structure of objective functions is defined in accordance with these objectives and constraints. If these functions are not defined accurately or the formulation of them is incorrect, practical operation patterns may not be achievable even by using the best solution method (e.g., Qaderi *et al.* 2018; Choopan & Emami 2019). On the other hand, improving the structure of objective functions can lead to results that ensure the fulfillment of socio-economic goals (e.g., Li *et al.* 2017). As a result, concentrating on the structure of objective functions is essential to improve the performance of the optimizer model in creating a practical plan. In the following, the most widespread objective functions in reservoir planning are reviewed and a comparative study is performed by analyzing and improving the structure of these functions.

The water supply function (Moeini & Babaei 2020) is defined as the minimization of the water supply deficit, which is usually normalized based on the maximum monthly demand in a year. Hence the monthly water demand pattern is considered in the objective function, which leads to determining the reservoir operation pattern based on changes in downstream water demand in different months. Planning a hydropower reservoir using this function may cause increases in water release in months that electricity demand is at non-peak consumption, although there is a significant correlation between intra-year variations in electricity and water demand. However, the outlook of a hydropower reservoir operator is to increase power generation and supply electricity demand in peak months of consumption, which raises hesitations about the use of this objective function.

The goal of energy generation in hydropower reservoirs may be illustrated as the minimization of the difference between the amount of power generation and power plant capacity (Samadi-koucheksaraee *et al.* 2019). Asadieh & Afshar (2019) and Bozorg-Haddad *et al.* (2021) used this objective function to optimize hydropower reservoir operation, while the pattern of monthly electricity demand cannot be considered due to the structure of the mentioned function and the constraints of the problem. In fact, variations in electricity demand over a year had an insignificant effect on determining the pattern of reservoir operation. Ignoring this actuality can lead to overproduction when the water and electricity demand are at the minimum, although total power generation is maximized during the planning period. Consequently, the released water is wasted and the reliability of reservoir storage for peak months is reduced. The use of electricity sales tariffs in the objective function can be helpful to eliminate this deficiency and makes the electricity demand pattern a determinative factor in reservoir operation (Bombelli *et al.* 2019). Due to variations in electricity demand through day and night and the necessity of electricity consumption management, a planning period of 24 hours is usually assumed (Su *et al.* 2020). On the other hand, changes in reservoir outflow during a day have no significant effect on the practical planning of water supply. Water supply policies are long-term and operation patterns are developed on a monthly and annual scale. Therefore, using the sales tariff in the objective function is usually practical in daily power plant managing and short-term planning.

The purposes of operating hydropower reservoirs may have a conflicting nature so that satisfying one of them can make the others worse, such as increasing water supply versus power generation. Hence, creating an optimal bi-objective model by considering two objective functions of minimizing supply shortage and maximizing power generation can make practical planning more achievable. Afshar & Hajiabadi (2019) defined a bi-objective optimization problem by these functions and converted a bi-objective problem into a single-objective by a weighting method. In this method, the importance of power generation and water supply functions is expressed by the weight coefficient, nonetheless, the weight of each of the objective functions is assumed to be the same during the planning time. Indeed, the intra-year priority of the objective functions is neglected. Due to the in-year variations in water and electricity demand, the preference for power generation and water supply functions will be different during the operation period. On the other hand, the inaccurate definition of water and energy supply preference during a period of operation can lead to an increase in surplus water and a decrease in the reliable storage of the reservoir. Therefore, the definition of monthly weighting coefficients, specifically considering peak periods, leads to the creation of optimal Pareto points which will satisfy the policies of decision-makers. Also, using the monthly weighting method allows the operator to apply any policy, observe the results, and make decisions.

This paper concentrates on the analysis of different structures of objective functions to achieve practical patterns in the operation of a hydropower reservoir. Hence, we formulated six problems to analyze the different forms of objective functions. In problem 1, only the water supply function is used particularly, which is defined for comparison with the power generation function in problems 2 and 3. In problem 3, the objective function of power generation is improved by considering the intra-year demand coefficient, in contrast to problem 2. Problems 4 and 5 are bi-objective optimization problems, each with a different structure of objective functions, although the solution method is the same. Comparing problems with each other can answer the following questions: (1) Is practical planning achievable by considering the intra-year demand coefficient in the objective function (i.e., problems 2 and 3)? (2) Will different operational perspectives lead to significantly different results (i.e., problems 1 and 3)? (3) What kind of results will appear when we use the same solution method for solving the bi-objective problems that are designed differently (i.e., problems 4 and 5)? To consider the intra-year priority of water and power supply in a bi-objective problem, the sixth problem is defined with the same structure of objective functions in the fifth problem. Problem 6 will allow Pareto optimal solutions to be created based on the definition of peak and non-peak periods. The sixth problem is also analyzed by defining seven scenarios. These scenarios control the importance of water supply and power generation in different months of the year. Comparing the answer of each scenario can confirm the need to define the operation scenario and provide a model based on each hypothetical scenario.

Finally, we have developed an analytical framework to improve the structure of the objective function by comparing different forms of objective functions. The specific objectives of this study are: (1) Analyzing the effect of the intra-year demand coefficient on the operation of hydropower reservoirs. (2) Developing a bi-objective function structure to consider the intra-year priority of water and power supply according to the operator policies. (3) Finding a set of optimal solutions that guarantees the maximum clean energy production in the peak period with different priorities in the non-peak period. This paper shows the necessity to define supply scenarios and modeling based on them with the aim of achieving more practical results.

2. PROBLEM FORMULATION

Downstream water supply and hydropower generation are the main operational objectives of a hydropower reservoir. These two objectives can be used to determine the reservoir operation pattern where the economic optimization of the reservoir is required. The six problems were designed based on these two main objectives to improve the objective function structure to reach a practical plan.

Problem 1

Reliability of downstream water supply is defined as minimizing water shortage (Ahmadianfar & Zamani 2020):

$$Minimize\ F_1 = \sum_{t=1}^{T} \left(\frac{D_t - R_t}{D_{\max}} \right)^2 \tag{1}$$

where D_t and R_t are water demand and water release in the period of t, respectively. $D_{\max}$ is the maximum value of water demand during a year and T is the number of operation periods.

Problems 2 and 3

Since using the maximum generation of the hydropower plant is expected, minimizing the deficit of generated power to the hydropower plant capacity is illustrated as an objective function (Soghrati & Moeini 2020):

$$Minimize\ F_2 = \sum_{t=1}^{T} \left(1 - \frac{P_t}{PPC} \right)^2 \tag{2}$$

P_t is hydropower generation in the period of t, PPC is hydropower plant capacity, and T is the number of operation periods. In Equation (2), the difference in electricity demand in various months of the year is not considered. Therefore, the amount of hydropower generation will be a function of the water release limits of the reservoir, which may lead to more hydropower generation than demand in non-peak months. This coincidence may be due to the existence of different importance degrees for responding to electricity demand in peak and non-peak periods. For this purpose, Equation (2) is modified by defining a demand coefficient, β_t, as follows:

$$Minimize\ F_3 = \sum_{t=1}^{T} \left(\left(1 - \frac{P_t}{PPC} \right) \times \beta_t \right)^2 \tag{3}$$

β_t is a dimensionless parameter and indicates the importance degree of electricity demand in the month of t. The value of β_t is calculated based on the intra-annual variability in electricity demand for each month:

$$\beta_t = \frac{PD_t}{PD_{\max}} \tag{4}$$

where PD_t is the monthly electricity demand in the t^{th} month, and $PD_{\max}$ is the maximum monthly electricity demand per year. When the electricity demand reaches a peak, the value of β_t is equal to 1, which means the highest importance degree. The lowest value of β_t belongs to the month with the minimum demand for power consumption. Considering the β_t-coefficient in the objective function leads to the limitation of hydropower generation based on the intra-annual changes in electricity demand.

Problems 4, 5 and 6

A hydropower reservoir is designed to meet competing objectives; therefore, herein, two bi-objective optimization problems were defined using functions F_1, F_2, and F_3. Based on a weighting method (Afshar & Hajiabadi 2019), these objective functions were addressed as follows:

$$\textit{Minimize}\ F_4 = W \times F_2 + (1 - W) \times F_1 \tag{5}$$

$$\textit{Minimize}\ F_5 = W \times F_3 + (1 - W) \times F_1 \tag{6}$$

where W is a dimensionless weight parameter in the range of 0–1 and indicates the relative importance of each of the objective functions: water supply (F_1) and hydropower generation (F_2 and F_3). When W is 0 or 1, the function with insignificant importance in reservoir operation will be removed from the optimization problem. Achieving optimal points in Pareto is expected by varying the weight parameter W evenly between 0 and 1. The weight interval is named Δw, the value of which affects the number of Pareto optimal points. Decreasing the value of Δw will result in a greater number of points on the Pareto front. In this paper, the value of Δw was considered to be 0.02. The solution process starts with a value of 0 for the weight parameter, and then in each step, the weight value is summed with Δw and this continues until W reaches 1.

The hydropower generation function is formulated in problems 4 and 5 differently to make a comparative study to obtain the Pareto front. Problems 4 and 5 are defined with and without considering the effect of β_t on the hydropower generation function, respectively. However, in problems 4 and 5, the rate of W is considered constant during the planning period. Since water supply and hydropower generation do not have the same degree of importance in different months or periods of the year, assuming a constant rate for W in different months may not lead to optimal results. Therefore, problem 5 is modified as below:

$$\textit{Minimize}\ F_6 = W_t \times F_3 + (1 - W_t) \times F_1 \tag{7}$$

where W_t indicates the precedence of each objective function in the month of t. Since water and electricity demand may be significantly correlated in some months of the year, the value choice of W_t is more difficult. The value of W_t can be defined according to different scenarios in terms of water and electricity demand. Since maximum electricity generation at the period of peak consumption is one of the main strategies of electricity industry managers to prevent economic losses due to lack of energy supply, problem 6 is designed to meet this strategy by assuming a value of 1 for the W_t parameter in the peak period. Seven scenarios are designed to compare problems 5 and 6, which are listed as follows:

S1: No priority,
S2: Priority of hydropower generation in the peak period with no priority in the other months,
S3: Image of S2 on F_5 assuming the same value for the hydropower generation function,
S4: Image of S2 on F_5 assuming the same value for the water supply function,
S5: Priority of hydropower generation in the peak period with the priority of water supply in the other months,
S6: Image of S5 on F_5 assuming the same value for the hydropower generation function,
S7: Image of S5 on F_5 assuming the same value for the water supply function.

The scenarios of S1, S2, and S5 are defined to examine the effect of different perspectives on reservoir operation that can be a confirmation of scenario-based modeling and the flexible structure developed within the research. Scenarios of S2 and S5 are analyzed under two conditions, which are: (1) Constant value of hydropower generation function and water supply growth (i.e. scenarios of S3 and S6); (2) Constant value of water supply function and increase of the electricity supply (i.e. scenarios of S4 and S7). These two statuses can clear the consequences of achieving the objects set in each of the S2 and S5 scenarios when the degree of importance of water and hydropower supply is constant in all months. Table 1 presents the values of W_t in problem 6 and each scenario.

Constraints

The different constraints associated with problems 1–6 are described below:

1. Hydropower equation:

$$P_t = \frac{\rho \times \eta \times g \times R_t \times (H_t - TWL)}{30 \times 24 \times 3{,}600} \tag{8}$$

where P_t is the monthly hydropower generation in megawatts, ρ is the density of water, η is the hydropower plant efficiency, g is the acceleration of gravity, H_t is the average head during the interval (t, $t+1$) in m, and TWL is the elevation of the tail water in m.

2. Storage continuity equation:

$$S_{t+1} = S_t + Q_t - SP_t - R_t - L_t \tag{9}$$

where S_t and S_{t+1} are reservoir storages at time periods t and $t+1$, respectively, in Mm^3, Q_t is the inflow to the reservoir during period t in Mm^3, SP_t is the spill from the reservoir during the period t in Mm^3, and L_t is the evaporation loss during the period t in Mm^3.

3. Equation for spill from the reservoir:

$$SP_t \leq b_t \times M \tag{10}$$

$$\frac{S_{t+1}}{S_{\max}} \geq b_t \tag{11}$$

where b_t is the binary variable and M is an arbitrary large constant. These constraints lead to a value of SP_t when S_{t+1} exceeds the reservoir capacity ($S_{\max}$).

4. Reservoir storage limits:

$$S_{\min} \leq S_t \leq S_{\max} \tag{12}$$

where $S_{\max}$ is the reservoir capacity and $S_{\min}$ is the minimum operational storage.

Table 1 | The values of W_t in different problems and scenarios

		W_t values	
Name	**Abbreviation**	**PP period**	**Other months**
Problem 6		1	0–1
Scenario 1	S1	0.5	0.5
Scenario 2	S2	1	0.5
Scenario 3	S3	0.559	0.559
Scenario 4	S4	0.735	0.735
Scenario 5	S5	1	0
Scenario 6	S6	0.269	0.269
Scenario 7	S7	0.693	0.693

5. Limits on release:

$$R_{t,\min} \leq R_t \leq R_{\max} \tag{13}$$

where $R_{\max}$ and $R_{t,\min}$ are maximum and minimum release from the hydropower plant, respectively, based on maximum hydraulic capacity and environmental water requirements.

6. Limits on hydropower generation:

$$P_{\min} \leq P_t \leq PPC \tag{14}$$

where PPC is the hydropower plant capacity in MW and $P_{\min}$ is the minimum generation of the hydropower plant in MW.

7. Area–storage equation:

The area–storage relationship is defined as a linear function:

$$A_t = a_0 \times \left(\frac{S_{t+1} + S_t}{2}\right) + a_1 \tag{15}$$

where A_t is the average water surface area during $(t,\ t+1)$ in km^2, and a_0 and a_1 are the slope and intercept of the area–storage curve, respectively.

8. Evaporation loss equation:

Evaporation loss is calculated using the evaporation rates and the average water surface area during $(t,\ t+1)$:

$$L_t = E_t \times A_t \tag{16}$$

where E_t is the evaporation rate at time period t in mm per month.

9. Head–storage relation:

The average head is calculated using the head–storage relation, which is defined as a third-order polynomial function:

$$H_t = b_0 \times \bar{S}_t^3 + b_1 \times \bar{S}_t^2 + b_2 \times \bar{S}_t + b_3 \tag{17}$$

$$\bar{S}_t = \frac{S_{t+1} + S_t}{2} \tag{18}$$

where H_t is the average head during the interval $(t,\ t+1)$ in m, and b_0, b_1, b_2 and b_3 are the polynomial regression coefficients.

3. CASE STUDY

Dez reservoir is a multi-purpose reservoir located on the Dez River, 23 km north-east of the city of Andimeshk in the province of Khuzestan, Iran (Figure 1). The main objectives of this reservoir are to supply water to downstream agricultural lands, hydropower generation, and flood control. After irrigating 125,000 hectares of agricultural land in the north of Ahvaz, the released water from the Dez reservoir flows into the Karun River. Now, the reservoir capacity at the highest level is about 2.9 billion cubic metres, which is the third-largest reservoir in Iran in terms of water storage. The capacity of the Dez Dam hydropower plant is 520 MW, which is generated by eight generators, each with a capacity of 65 MW. The average annual power generation of the hydropower plant is 1,783 (GWh), in this case, and the Dez Dam is ranked sixth among the operating hydroelectric power plants (53 hydropower plants).

The optimization models (problems 1–6) are now applied to the Dez reservoir for a 72-month period. Figure 2 and Table 2 show the input variables including inflow, evaporation rate, demand, β_t-coefficient and $R_{t,\min}$. The reservoir details are also given in Table 3. The optimization problems in this study are as Mix-Integer Non-Linear Programming (MINLP), hence, we used the SBB solver for their solution in GAMS format. SBB is based on a combination of the standard branch-and-bound method and nonlinear programming solvers supported by GAMS (for more details please refer to GAMS/SBB 2018).

The effect of addressing problems is investigated by comparing the performance parameters of the reservoir including the amount of hydropower generation, water release, water storage, water supply shortage, and excess water release from the reservoir. The comparisons have been made at different time scales including monthly, seasonal, annual and demand periods. In accordance with recorded statistics, the demand periods are classified into the periods of Peak demand for Power (PP: June

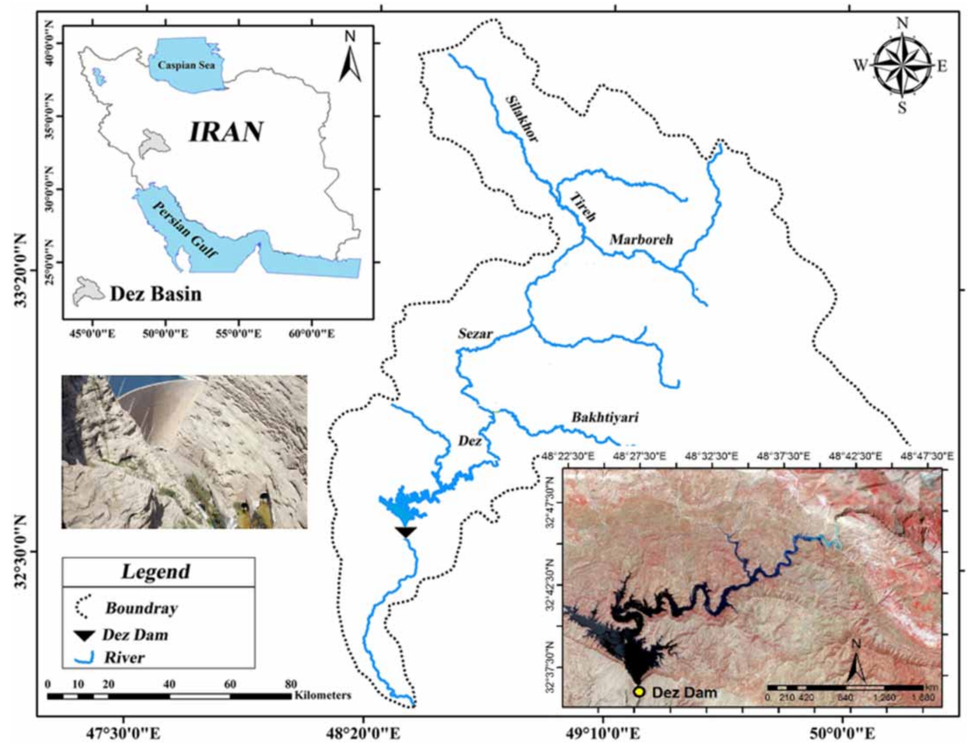


Figure 1 | Dez reservoir and Dez River basin location.

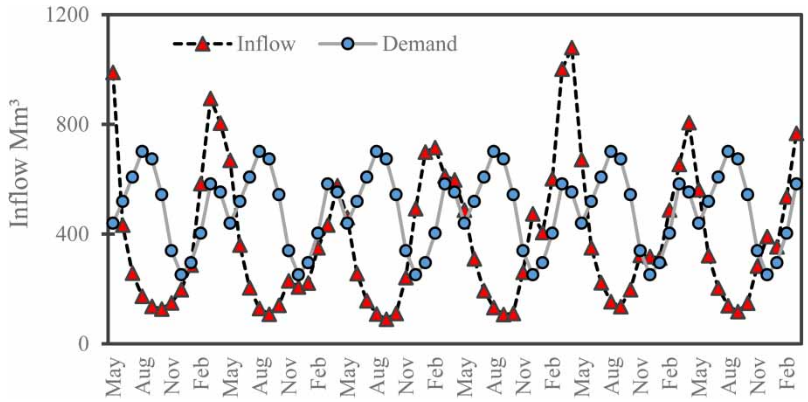


Figure 2 | Monthly inflow and demand for the study period.

to September) and Water (PW: July to October), and a Non-Peak period of demand (NP: November to January). The NP is a period of a year in which the quantity of demand for water and electricity is minimum.

4. RESULTS AND DISCUSSIONS

4.1. Comparison of problems 1, 2 and 3

The single-objective problems (1–3) are compared to examine different perspectives and the impact of electricity demand scenario on reservoir operation. The hydropower objective function in problems 2 and 3 was formulated differently only by considering intra-annual variability in electricity demand. The monthly hydropower generation in problem 2 (227,912.7–112,985.6 MW) has fewer fluctuations than in problem 3 (45,206.2–235,463.5 MW) during a year (Figure 3). Hydropower generation in problem 3 (1,252,791 MW) is more than in problem 2 (988,077 MW) in spring and summer,

Table 2 | Evaporation rates, β_t-coefficient and minimum release

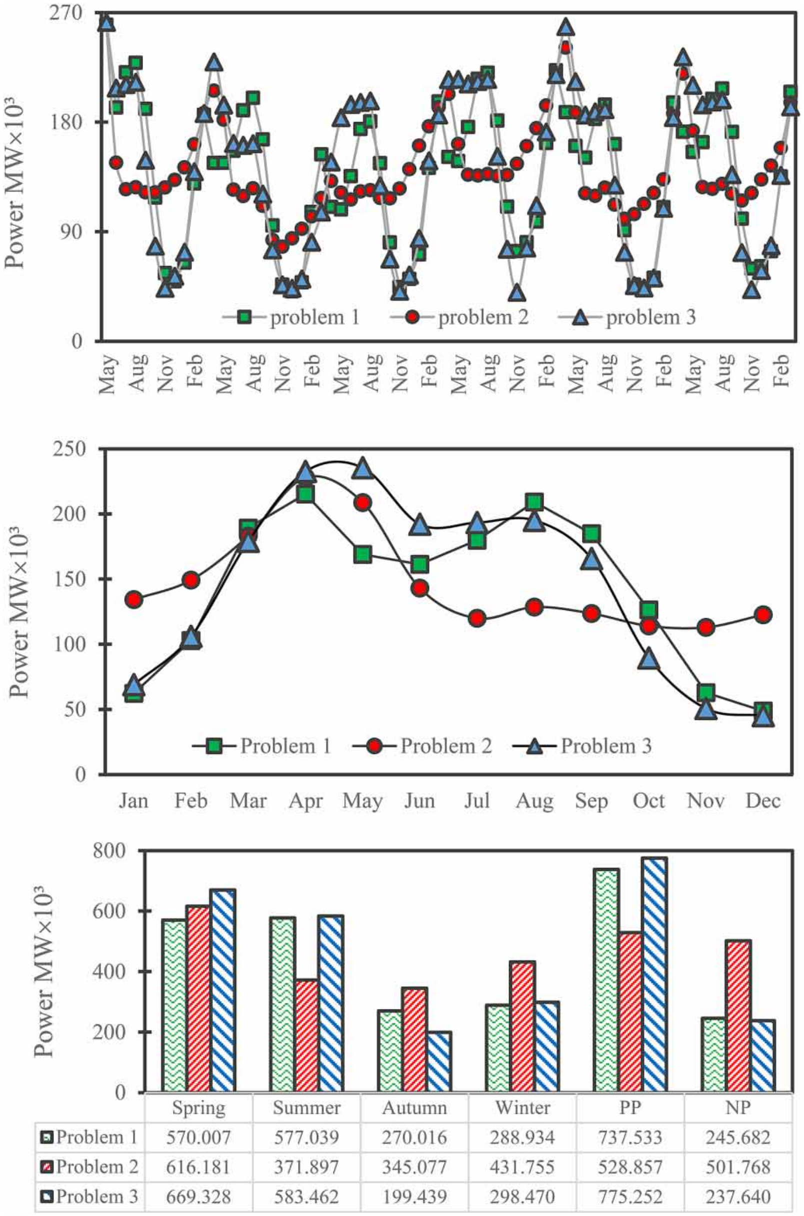
Month	Evaporation rate (mm)	β_t	$R_{t,\min}$ (Mm^3)
Jan	73.5	0.7	129.1
Feb	82.8	0.7	176.1
Mar	114.6	0.8	254.6
Apr	161	0.8	241.5
May	235.7	0.9	192
Jun	318.3	1.0	226.8
Jul	347.2	1.0	265.5
Aug	332.7	1.0	306.3
Sep	279.5	1.0	294.2
Oct	199.5	0.8	237.6
Nov	122.5	0.7	148.3
Dec	87.5	0.6	110.1

Table 3 | Reservoir details

Parameter	Value	Parameter	Value
PPC (MW)	520	a_0	0.0201
TW (m)	200	a_1	15.275
$R_{\max}$ (Mm^3)	900	b_0	3×10^{-9}
$S_{\max}$ (Mm^3)	2,884	b_1	2×10^{-5}
$S_{\min}$ (Mm^3)	1,000	b_2	0.0626
Initial storage	2,749.8	b_3	269.59
Hydropower plant efficiency	0.9		

while in autumn and winter problem 3 (278922.7 MW) has the lower generation (Figure 3). All the problems 1, 2, and 3 have the highest hydropower generation in the spring due to incoming floods to the reservoir. On average, in the period of PP 246,394 MW more is generated in problem 3 than in problem 2 and in the NP period 264,128 MW less is generated (Figure 3). Considering the intra-annual variability in electricity demand in problem 3 has led to hydropower generation in proportion to the need (difference in generation in the PP and NP periods), although the total annual generation has decreased by an average of 0.8% compared with problem 2 (Table 4). An increase of 111% in the NP period and a 31.8% decrease in the PP period in problem 2 compared with problem 3 can impose significant problems on the National Electricity Network due to over-generation and generation less than required.

The objective function in problem 1 was defined based on supplying water demand and considering intra-annual water demand variations. If there is a significant correlation between water and electricity demand variations over a year, a similarity in the results of problems 1 and 3 can be expected. The small difference in the amount of hydropower generated in problem 1 compared with problem 3 in the periods of NP (+3.3%), PP (−4.8%), and winter (−3.2%), and summer (−1.1%) shows this properly (Figure 3). However, in spring problem 1 generates less and in autumn it generates more hydropower than problem 3. The difference between the two seasons is due to the difference in demand scenarios: in spring the electricity demand is higher than the water demand, and in autumn vice versa. In problem 3, the amount of hydropower generation in the period of PP is more and in NP is less than in problem 1 (as in problem 2), although the difference is small, unlike the comparison of problem 3 with problem 2. The lowest annual hydropower generation belongs to problem 1 (1,705,996 MW) because it does not rely on maximizing hydropower generation (Table 4).



	Spring	Summer	Autumn	Winter	PP	NP
Problem 1	570.007	577.039	270.016	288.934	737.533	245.682
Problem 2	616.181	371.897	345.077	431.755	528.857	501.768
Problem 3	669.328	583.462	199.439	298.470	775.252	237.640

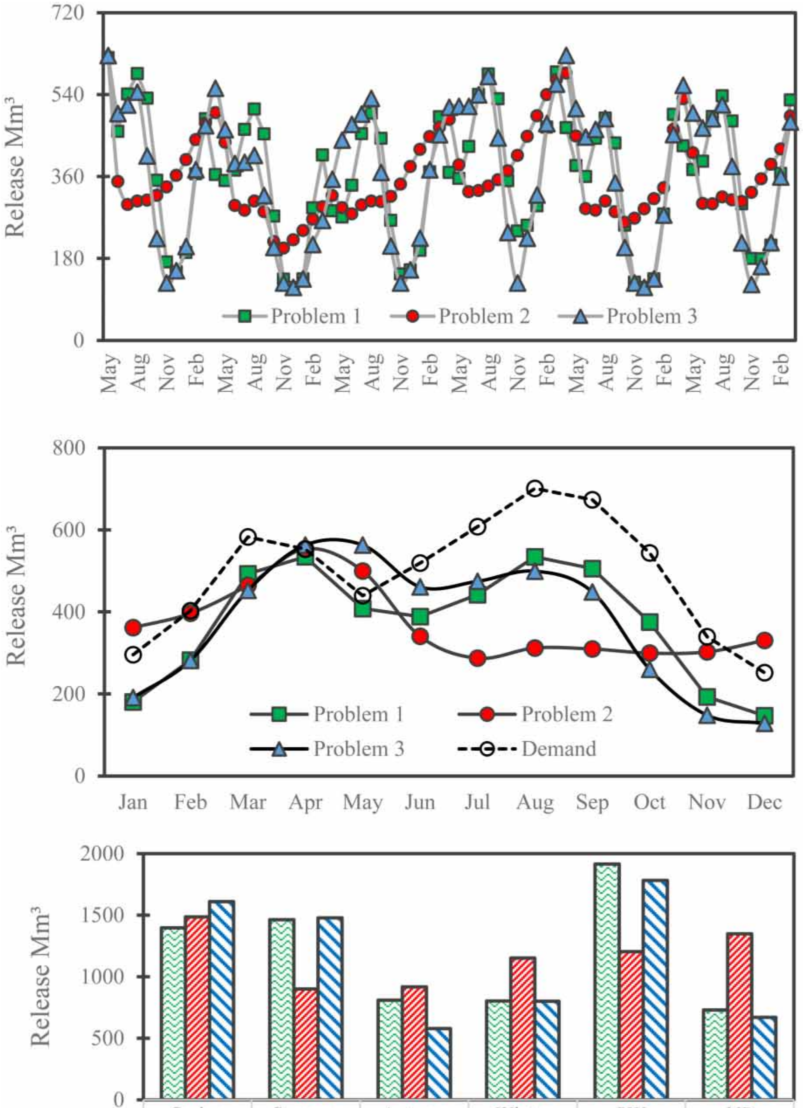
Figure 3 | Comparison of problems 1–3 in hydropower generation.

Table 4 | Mean annual hydropower, release, storage, water supply shortages and excess water

	Problem 1		**Problem 2**		**Problem 3**	
Parameter	**Mean**	**CV**[a]	**Mean**	**CV**[a]	**Mean**	**CV**[a]
Hydropower (GWh)	1,705.996	0.181	1,764.910	0.152	1,750.700	0.143
Release (Mm^3)	4,471.498	0.174	4,453.789	0.159	4,466.768	0.149
Storage (Mm^3)	2,060.668	0.099	2,459.672	0.035	2,211.829	0.066
Water supply shortage (Mm^3)	−1,592.587	−0.334	−1,926.553	−0.184	−1,711.878	−0.295
Excess water (Mm^3)	153.085	2.236	469.342	0.807	267.646	1.092

[a] CV is coefficient variations.

The most optimal water release rate occurs when there is the highest satisfaction of water and hydropower supply and the least excess water is released during a water year. According to the objective functions F_1, F_2 and F_3, it is expected that the values of water supply shortage and excess water in problem 1 will be less than in the other two problems. The average annual water supply in problem 1 is 334 Mm^3 and 119.3 Mm^3 higher than in problem 2 and problem 3, respectively (Table 4), while the annual release rate in problem 1 increases by only about 17.7 Mm^3 and 4.7 Mm^3 compared with the other two problems, which indicates that the amount of annual excess water decreases significantly. Increasing water supply in problem 1 can increase the irrigated area between 26,000 hectares and 9,500 hectares according to the cropping pattern, which will add 13M$ to 4.8M$ to gross income. On the other hand, annual hydropower generation in problem 1 compared with problem 2 and problem 3 decreases by 58,913 MW and 44,703.7 MW, respectively. As a result, the degree of desirability of water and hydropower supply due to the conflict between these objectives will be effective in formulating the objective functions. Problem 2 has the lowest annual water release, while it has the highest water supply shortages and the most excess water. In



	Spring	Summer	Autumn	Winter	PW	NP
▨ Problem 1	1396.499	1463.063	808.975	802.961	1914.999	729.027
▨ Problem 2	1485.453	899.952	916.957	1151.427	1202.623	1348.414
▨ Problem 3	1610.194	1477.431	578.813	800.330	1781.968	669.507

Figure 4 | Comparison of percentage changes in water supply shortages in problems 1–3.

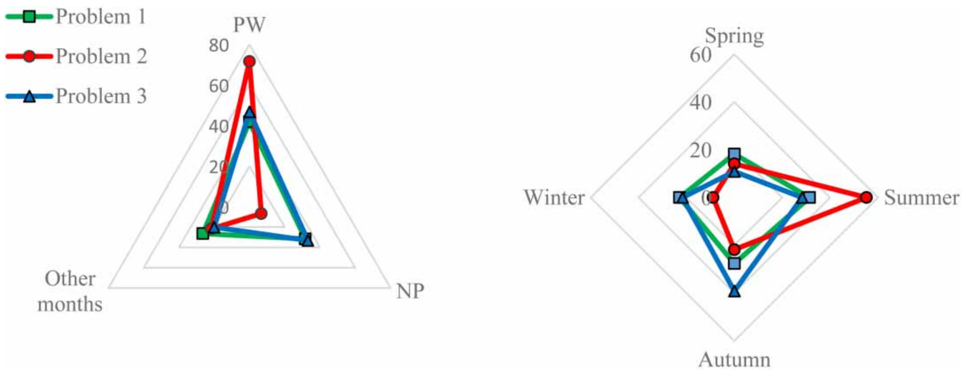


Figure 5 | Comparison of percentage changes in excess water release in problems 1–3.

problem 2, most deficiencies occur during PW (71.7%, 1,380.4 Mm^3) and summer (55.2%, 1,062.6 Mm^3), and most excess water is released during NP (52.2%, 244.8 Mm^3) and winter (33.2%, 155.8 Mm^3) (Figures 4 and 5). Therefore, problem 2 is not properly formulated in terms of both water supply and hydropower generation. Excess water released from the reservoir will be significant in all problems in the spring because the floods usually fill the capacity of the reservoir. The amount of water released during the PW and NP periods in problem 1 compared with problem 3 increases by 7.5% and 8.9%, respectively, which indicates that water supply is prioritized in problem 1 (Figure 6). In autumn, water supply decreases by about 52.4% in problem 3 compared with problem 1, and in spring, it increases by 35.4%, which illustrates the greater importance of hydropower supply in problem 3 (Figure 4).

The storage of the reservoir depends on the purpose of the operation. If hydropower generation is the object, the model keeps the reservoir in its maximum storage state. When water supply is the purpose, storage is done in the months with low water demand. The highest storage occurs in problem 2 in comparison with the other two problems, and due to this storage rate, problem 2 has the highest hydropower generation (Table 4). Also, the range of monthly storage variations in problem 2 is smaller than in problems 1 and 3 (Figure 7). In the NP, PP, and PW periods the reservoir storage is the highest in problem 2, and the reservoir storage in problem 3 is higher than in problem 1, particularly in the NP and PP periods (Figure 7). In the spring, most of the reservoir storage occurs in problem 3 while the water release rate is higher than in the other problems because more electricity is required. The behaviors of problems 1 and 3 in water storage in the summer and PP period are similar to each other, which is due to the equal preference of water and hydropower supply in these periods.

4.2. Comparison of problems 4, 5 and 6

Problems 4 and 5 were developed to formulate a bi-objective problem in which the functions of hydropower are different. Therefore, comparing the solution space of the mentioned problems in the same decision space leads to improving the formulation of a bi-objective problem. Figure 8 shows the Pareto front resulting from the solution of problems 4 and 5. The Pareto front for problem 5 is better than for problem 4 at all points, meaning that the β_t-coefficient improves the Pareto

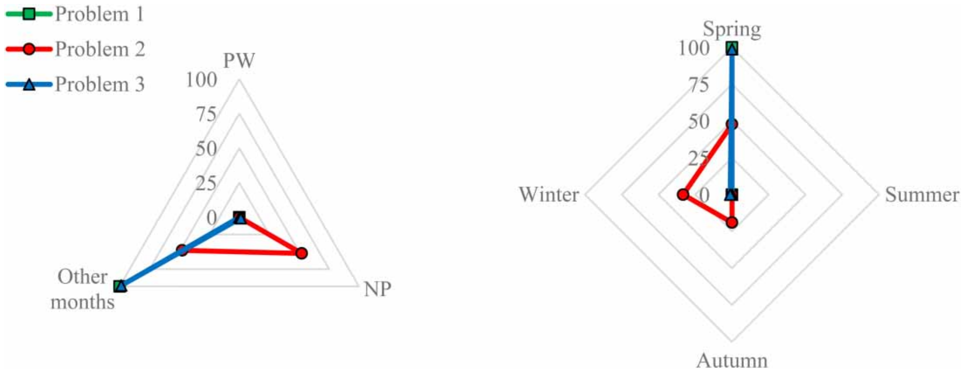
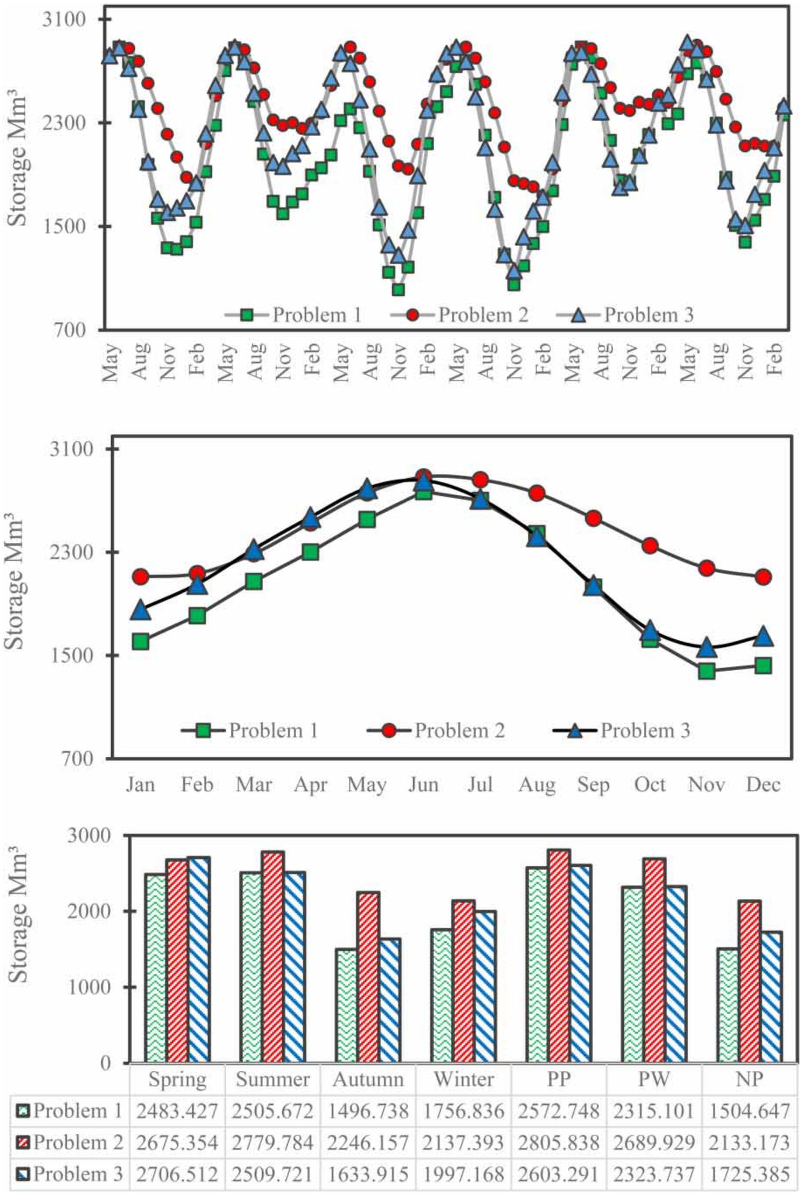


Figure 6 | Comparison of problems 1–3 in released water.



	Spring	Summer	Autumn	Winter	PP	PW	NP
▨ Problem 1	2483.427	2505.672	1496.738	1756.836	2572.748	2315.101	1504.647
▨ Problem 2	2675.354	2779.784	2246.157	2137.393	2805.838	2689.929	2133.173
▨ Problem 3	2706.512	2509.721	1633.915	1997.168	2603.291	2323.737	1725.385

Figure 7 | Comparison of problems 1–3 in water storage.

front. The maximum value of the function F_1 in problems 4 and 5 is 0.117 and 0.077, respectively, which shows that a change in the hydropower function (F_2 or F_3) has a meaningful effect on the value of the water supply function. Also, the range of hydropower function changes in problem 5 (0.272–0.259) is much smaller than in problem 4 (0.431–0.397), which illustrates better use of hydropower plant capacity in hydropower generation based on demands.

Problem 6 was developed to consider the degree of importance of water and electricity supply in different months of the year. The analysis of the Pareto front obtained from problems 5 and 6 will lead to an examination of operation policies to meet the competing needs. It is expected that the different preferences between water and electricity supply will lead to more practical results in reservoir operation. Figure 9 shows the obtained Pareto front in problem 6. The difference between the Pareto front in problems 6 and 5 occurs where the importance of water supply is increasing in months that are not included in the period of PP. In other words, the value of W_t has a decreasing trend in these months. When the value of W_t in these months is equal to 0, the values of functions F_1 and F_3 in problem 6 will be equal to 0.061 and 0.267, respectively, which does not happen in problem 5. As a result, the adoption of a power generation strategy based on maximum supply in the PP period will lead to new results that were not achievable previously.

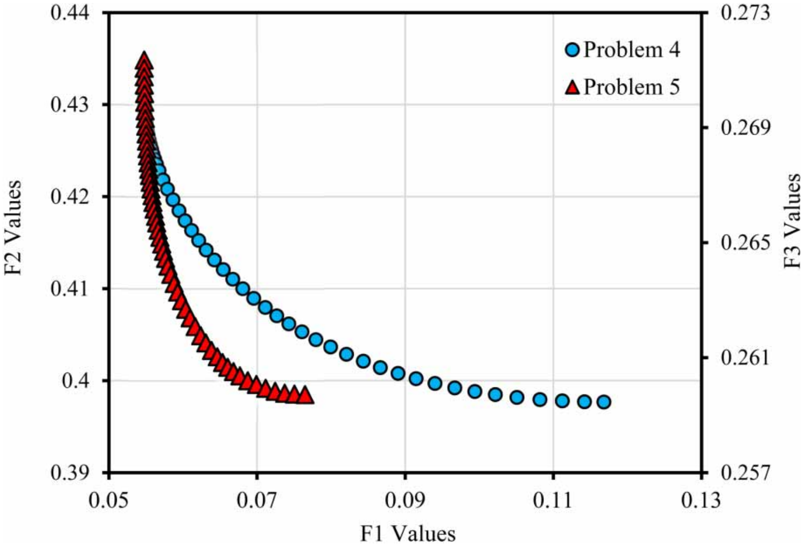


Figure 8 | Final Pareto front of problems 4 and 5.

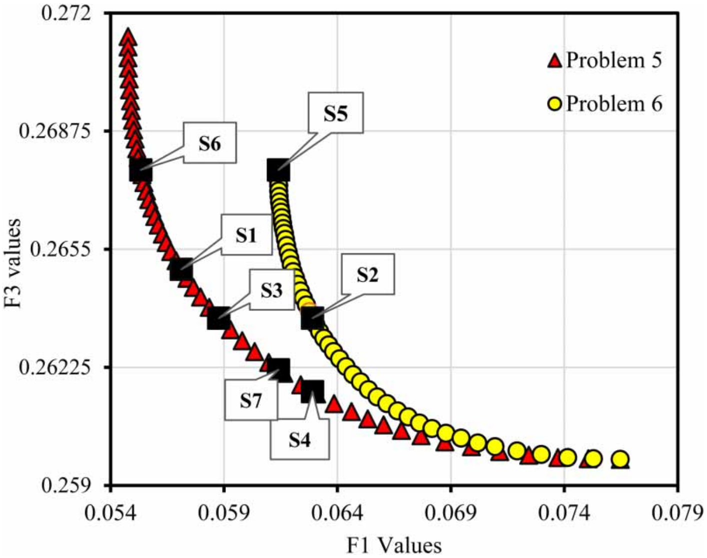


Figure 9 | Pareto front and solutions of problems 5 and 6 and scenarios.

4.3. Scenario analysis

The analysis of problems 5 and 6 was examined using seven scenarios (Table 1). The values of the F_1 and F_3 functions for each of the assumed scenarios on the Pareto front are shown in Figure 9. The differences between the scenarios in terms of release, water supply, excess water, and hydropower generation are presented in Tables 5–10.

The S1 scenario was compared with S2 and S5 to determine the effect of dissimilar importance of the operational objectives throughout the year. The water release rate increases during the PP and PW periods in both S2 and S5 scenarios in comparison with S1 and decreases during the NP period (Tables 5 and 6). Increased release results in better water supply during the period of PW and summer. Most of the lack of water supply pertains to the seasons of autumn and winter, which is due to the occurrence of major precipitations in these seasons; the operator may not face a serious challenge. In other words, the operator prefers that the major deficiencies occur during the rainy seasons, especially in winter. On an annual scale, the rate of water release, deficiency of water supply, and excess water increase in both S2 and S5 scenarios in comparison with S1 but the difference is insignificant. On the other hand, hydropower generation in the PP period in

Table 5 | Comparison of S2 with S1 in terms of water and power supply

Parameter	PP	PW	NP	Spring	Summer	Autumn	Winter	Annual
Release (Mm^3)	118.3	25.4	−33.1	29.6	60.6	−56.3	−32.8	1.0
Water supply shortage (Mm^3)	108.6	25.4	−33.1	19.9	60.6	−56.3	−32.8	−8.7
Excess water (Mm^3)	9.7	0	0	9.7	0	0	0	9.7
Hydropower (GWh)	43.9	5.8	−11.4	13.8	19.6	−20.9	−12.2	0.2
Storage (Mm^3)	−21.6	−50.9	−16.1	34.7	−44.9	−38.3	−6.3	−13.7

Table 6 | Comparison of S5 with S1 in terms of water and power supply

Parameter	PP	PW	NP	Spring	Summer	Autumn	Winter	Annual
Release (Mm^3)	131.0	61.6	−15.4	−24.6	72.5	−17.1	−27.8	3.0
Water supply shortage (Mm^3)	110.6	57.1	−15.4	−27.3	68.0	−17.1	−27.8	−4.2
Excess water (Mm^3)	20.3	4.5	0	2.7	4.5	0	0	7.3
Hydropower (GWh)	46.4	15.6	−8.7	−11.4	22.0	−10.3	−13.5	−13.2
Storage (Mm^3)	−45.5	−77.9	−82.0	−26.7	−69.8	−88.3	−80.1	−66.2

Table 7 | Comparison of S2 with S3 in terms of water and power supply

Parameter	PP	PW	NP	Spring	Summer	Autumn	Winter	Annual
Release (Mm^3)	−109.0	−35.4	26.0	−10.1	−57.3	35.7	30.1	−1.6
Water supply shortage (Mm^3)	−99.3	−35.4	26.0	−6.7	−57.3	35.7	30.1	1.9
Excess water (Mm^3)	−9.7	0.0	0	−3.5	0	0	0	−3.5
Hydropower (GWh)	−39.7	−8.7	10.2	−4.6	−18.0	14.6	12.3	4.3
Storage (Mm^3)	27.6	54.5	37.8	−10.4	48.4	52.2	30.6	30.2

Table 8 | Comparison of S2 with S4 in terms of water and power supply

Parameter	PP	PW	NP	Spring	Summer	Autumn	Winter	Annual
Release (Mm^3)	−98.0	−60.3	18.5	24.6	−57	−6.1	35.4	−2.9
Water supply shortage (Mm^3)	−88.3	−60.3	18.5	3.9	−56.7	−6.1	35.4	−23.5
Excess water (Mm^3)	−9.7	0	0	20.7	0	0	0	20.7
Hydropower (GWh)	−33.8	−15.7	10.2	11.9	−16.8	2.1	16.2	13.4
Storage (Mm^3)	42.2	66.4	87.1	34.8	59.3	86.6	82.5	65.8

scenarios S2 and S5 increases by 43,932.2 MW and 46,356.6 MW, respectively, and decreases in the period of NP (Tables 5 and 6). The combination of three events makes the S2 scenario suitable: (1) Increase in annual hydropower generation, (2) increasing the hydropower generation in the PP period, and (3) decreasing the hydropower generation in low load seasons. The decrease in annual hydropower generation in the S5 scenario coincides with an increase in the PP period, which has challenged the use of this scenario, especially since the increase in water supply also occurs in the PW period by 57.141 Mm^3. Therefore, by defining the S2 and S5 scenarios, the operation will be closer to more practical conditions, which are water and hydropower supply following the needs.

Table 9 | Comparison of S5 with S6 in terms of water and power supply

Parameter	PP	PW	NP	Spring	Summer	Autumn	Winter	Annual
Release (Mm^3)	−151.1	−48.2	30.9	−10.5	−80.3	49.1	39.4	−2.3
Water supply shortage (Mm^3)	−130.7	−43.7	30.9	0.9	−75.8	49.1	39.4	13.7
Excess water (Mm^3)	−20.3	−4.5	0.0	−11.4	−4.5	0.0	0.0	−15.9
Hydropower (GWh)	−54.7	−11.5	12.4	−5.1	−25.1	20.4	16.0	6.2
Storage (Mm^3)	38.8	76.2	51.9	−14.2	68.1	70.9	44.0	42.2

Table 10 | Comparison of S5 with S7 in terms of water and power supply

Parameter	PP	PW	NP	Spring	Summer	Autumn	Winter	Annual
Release (Mm^3)	−114.7	−88.2	3.6	66.6	−68.5	−31.2	28.5	−4.5
Water supply shortage (Mm^3)	−94.4	−83.7	3.6	48.3	−64.0	−31.2	28.5	−18.3
Excess water (Mm^3)	−20.3	−4.5	0	18.3	−4.5	0	0	13.8
Hydropower (GWh)	−38.3	−23.0	7.6	31.5	−19.4	−4.2	16.2	24.0
Storage (Mm^3)	62.4	90.6	137.7	81.9	81.8	126.4	140.0	107.5

In the S3 and S6 scenarios, the value of function F_3 and in scenarios S4 and S7 the value of function F_1 were assumed to be equal to the values of these functions in scenarios S2 and S5, respectively. Therefore, in scenarios S3 and S6, the value of the F_1 function decreases and it is expected that not only will the hydropower function indicate similar behavior, but also the water supply will have better security. Similarly, in scenarios S4 and S7, the value of the F_3 function decreases, therefore more optimal hydropower generation is expected. These scenarios were established assuming the same value of W_t for all months, provided that the value of the function F_1 or F_3 is equal to the value of this function in the S2 and S5 scenarios. The values of W_t in S3, S4, S6, and S7 were obtained as 0.599, 0.735, 0.269, and 0.693 for all months, respectively.

Annual hydropower generation in the S3 and S4 scenarios increases compared with S2, while the amount of hydropower generated during the PP period decreases significantly (Tables 7 and 8). On the other hand, hydropower generation increases during the NP period, however in the warm season of the year, generation decreases. The annual water release rate decreases in both scenarios while the water supply during the PW period is extremely deficient (Tables 7 and 8). In addition, water release increases in winter while water supply will be a serious problem in summer. Annual hydropower generation increases in the S4 scenario, but the intra-year variations are not in accordance with demands. Water supply will also face a serious shortage, especially during the PW period, while the excess water has grown significantly. In scenario S3, the intra-year variations of water supply were not well modeled, while there is very little improvement in the annual water supply. Despite an increase in annual hydropower generation, hydropower generation in critical periods will be a serious challenge. Therefore, considering the monthly preference in hydropower generation and water supply can provide much better results with the same amount of objective function.

On an annual scale, the rate of water release, water supply shortage, and excess water in scenario S6 decreases in comparison with S5, but summer and PW will experience 75.8 Mm^3 and 43.7 Mm^3 reductions in water supply, respectively (Tables 9 and 10). Despite the increase in annual hydropower generation in S6 and S7 compared with S5, the amount of hydropower generated in the PP period decreases by 54,726.7 MW and 38,303.2 MW, respectively (Tables 9 and 10). In the NP period, the amount of hydropower generated in S6 and S7 will increase by 12,416.7 MW and 7,603.1 MW, respectively. The decrease in annual water release in S7 is accompanied by a decrease in water supply and an increase in excess water. Also, water supply in the summer and the PW period will face a serious challenge in S7. Despite assuming the similarity of one of the objective functions and expecting an improvement of the other, the water and electricity supply in the S6 and S7 scenarios were not modeled optimally in comparison with scenario S5. This suggests that assuming different degrees of importance for various months can lead to more practical results, especially for months in the PP period.

5. CONCLUSION

The structure of hydropower optimization problems, especially formulating the objective functions, considerably affects reservoir performance and illustrates the exploiter's point of view. If the structure of a problem, especially the objective function, is not defined correctly, even by using sophisticated and powerful solution methods, results may be unreal and impractical. Therefore, before improving the solution method, we should analyze the structure of the problem and achieve an actual structure that is close to the real-world situation. We analyzed different single/bi-objective optimization problems including objective functions of water supply and hydropower generation for a single reservoir system. Formulating the hydropower function based on the intra-annual variability in electricity demand improves the performance parameters of the reservoir, especially in the periods of PW and PP. Obviously, the significant correlation between water and electricity demand over a year has led to the F_3 and F_1 functions behaving similarly, especially in critical periods. Also, considering the intra-year variations of electricity demand in the bi-objective optimization problems led to the improvement of the Pareto front at all points. However, in the real world, water and hydropower supply priorities are different in each month and depend on operating policies. The maximum hydropower generation strategy in the critical period was considered as the main policy of operation of hydropower reservoirs to reduce socio-economic tensions. This strategy makes it possible to obtain optimal Pareto solutions that provide a real and practical plan for operation. The comparison of defined scenarios showed that the solutions of problem 6 can result in efficient meeting of water and electricity demand in critical periods, while water allocation will decrease during the rainy months. However, the final choice of the weight coefficient values of each function in different months depends on the viewpoint of decision-makers. Therefore, decision-makers must have sufficient knowledge of the problem and a clear understanding of the impact of this choice on the Pareto optimal points. Analysis of other objective functions in the developed structure and their application in multi-reservoir systems can be the subject of future work.

ACKNOWLEDGEMENT

The authors would like to thank the Khuzestan Water and Power Authority, Iran, for providing the observed data used in this study.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 2 April 2021; accepted in revised form 2 July 2021. Available online 15 July 2021