Reservoir operation management by optimization and stochastic simulation
Ehsan Goodarzi, Mina Ziaei and Naser Shokri

ABSTRACT
The increase of population and socio-economic activities has escalated the water demand for various purposes and put stress on existing water resources across the world, in particular in arid and semi-arid countries. Hence, managing the optimum use of water resources is a crucial issue and it is imperative to adopt realistic policies to ensure water is used more efficiently in various sectors.

This paper presents an optimization analysis to determine monthly operating rules for the Doroudzan Reservoir located in southern Iran. Different strategies under limited water availability conditions have been analyzed by running an optimization model based on observed and synthetic inflow data, and the performance indicators of each strategy are presented. Each strategy includes a minimum requirement release in the optimization process and results in a specific operation policy. In this study, LINGO is applied to determine optimum operational parameters and the synthetic inflows are generated using the Monte Carlo simulation method. The results demonstrated that the applied methods could efficiently optimize the current operation policy of an existing reservoir in a single-objective framework.

Key words | optimization, linear programming, LINGO, Monte Carlo simulation, reservoir operation

INTRODUCTION
Increasing water demands, higher standards of living, growing population, climate variability, and water resource limitations have caused conflicting issues among water consumers and put stress on existing water resources across the world (Ganjí et al. 2007). Arid and semi-arid areas of the developing world principally are suffering from insufficient water supply and lack of adequate quantities and quality of water resources. Therefore, the proper management of water resources and providing comprehensive programs to optimize available water plays an important role in supplying and satisfying existing demands. Constructing dams to create reservoir and storage water allow distribution at the right time into downstream districts. Reservoirs have significant roles in water resource engineering in which their proper design, construction and maintenance contribute considerably toward fulfilling water supply requirements and minimizing the risk of water shortages. In recent years, applying optimization techniques to reservoir operation by mathematical tools has become a major focus of water resource engineers. Reservoir operation consists of several control variables that define strategies for guiding a sequence of releases to meet downstream demands. Wurbs (1995) and Labadie (2004) presented comprehensive reviews about reservoir operation models and their applications in water resources engineering. Bower et al. (1962) recommended Standard Operation Policy (SOP) and the hedging rule to determine necessary releases over desire planning horizon. The SOP releases only require demand in each time period. In other words, if sufficient water is not available to meet the objective, the reservoir releases all the available water and empties, and if there is excess water the reservoir can fill and spill the surplus water. Hence, applying SOP method will not result in preserving water for future requirements, while the hedging rule attempts to store available water and use it in the upcoming periods.
Different optimization models including linear, nonlinear and dynamic programming are using the hedging rule with respect to the economic return or the other system products such as water supply reliability (Hashimoto et al. 1982; Shih & Revelle 1993; Neelakantan & Pandarikanthan 1999; Shiou & Lee 2005). However, the linear based models are still popular and effective tools in dealing with optimization problems (Rani & Moreira 2009). Linear Programming (LP) solves problems that have linear relations among their variables including the constraints, objective functions, and all of the underlying models. Latif & James (1991) maximized the net income of irrigators using a LP-based conjunctive model for the Indus basin in Pakistan. The main objective of their study was finding the optimal ground-water extraction for stabilizing the water table below land surface, while supplementing the surface irrigation supply at the same time. Peralta et al. (1995) developed a LP-based simulation optimization model to obtain sustainable groundwater extractions over a period of five decades, under a conjunctive water use scenario for the Mississippi River Valley alluvial aquifer in northeastern Arkansas. Based on the results of this study, a number of optimal water-use strategies are computed for alternative management scenarios from 1990 to 2039. Shih & Revelle (1995) investigated a discrete hedging rule for water supply operations during droughts and impending droughts by applying a mixed integer LP model. Devi et al. (2005) presented a LP model for optimal water allocations in a large river basin system and applied the model to the Transboundary Subernarekha River in India. The main purpose of their study was finding the maximum annual benefits from irrigation and hydropower and also determining optimal water allocations during the dry and wet years. Loucks & Beek (2005) compared various optimization methods in water resources engineering based on LP. In this study, they tried to address specific water resources planning and management problems, and also introduce optimization methods for infrastructure design and operating policies. Sudha et al. (2008) developed a mixed integer linear programming (MILP) model and used five different management strategies to test their new developed model. The results of their study showed that an appropriate management strategy with deficit irrigation, which supplies less water in non-critical growth periods and maximum water during stress sensitive periods, is the best viable solution to increase the performance of system. Ngo et al. (2007) discussed a combination of optimization and simulation models as an efficient approach for defining reservoir operation. In this study, a simulation model with real-coded genetic algorithm and shuffled complex evolution is applied for optimizing a reservoir operation in Vietnam. The results of this study demonstrated that the applied method can be used efficiently to optimize the rule curves for operating the reservoir in a multi-objective framework. Ejeta & Mays (2002) and Wurbs (1995) reviewed the main simulation and optimization computer programs for reservoir system modeling. Karamouz & Vasilias (1992) investigated a non-linear optimization model, along with a simulation model, to analyze the long-term performance of existing reservoirs. In another study, Sattari et al. (2009) investigated the efficiency of the Eleviyan irrigation dam in Iran by setting up the optimization model that maximized the water release for irrigation purposes after municipal water needs were met. In their study, three phases were considered to investigate the efficiency of desired irrigation dam as: (1) setting up the optimization model using recorded inflows prior to the construction of the reservoir, (2) applied inflows generated by the Monte Carlo simulation method, and (3) using inflows after the construction of the reservoir. The results of their study demonstrated that the operation policy was effectively attained during the operation period.

Unfortunately, many areas of Iran have recently been affected by drought, with large portions of the country’s crops and livestock perishing and still there are many difficulties in supplying industrial and agricultural water demands. Hence, appropriate operation policies help managers and decision makers to optimally allocate water resources according to priorities and downstream requirements. This study presents an optimization analysis to determine monthly operating rules for the Doroudzan Reservoir in the semi-arid area of Iran. The efficiency of this reservoir was investigated in seven different strategic perspectives by maximizing amounts of water released downstream. Each strategy includes a minimum requirement release in the optimization process and resulted in a specific operation policy. In other words, an optimal operation policy for assessing the amount of allocated water to all downstream demands (domestic-industrial, agricultural, and power plant) are derived based on available
data in the period of 1986–2006 (21 years). It is important to note that demands are considered to be constant over the desired planning horizon and they have not been changed from year to year. In addition, due to the complete development of downstream areas of the Doroudzan Reservoir over previous years and also the recent droughts in Iran, building any new industries or expanding agricultural area has been stopped. Therefore, the applied data for downstream demands are approximately the same as the demands in 2012.

Furthermore, the optimization model was re-run using synthetic inflow data to determine the effect of alternative scenarios on the reservoir operation in a period longer than the observed data. Then, the achieved results through both observed and synthetic inflow data were compared to evaluate the optimized results in both conditions.

MATERIALS AND METHODS

Study area

Doroudzan Dam is one of the most important dams in southern Iran. The preliminary studies and investigations of the dam were carried out between 1963 and 1966 and the dam construction was started in 1970 and completed in 1974. The basin of this multipurpose earth-fill dam is situated near the city of Shiraz on the Kor River and in the Bakhtegan lake catchment area (see Figure 1). The elevation of the highest watershed point is 3,749 m from the mean sea level and is located northwest of the watershed. The total volume and dead storage of the reservoir are 993 and 133 million cubic meters (MCM), respectively. Basic technical information concerning Doroudzan Dam is shown in Table 1. The dam is a major source of water, supplying 112,000 hectares of agricultural land and the domestic-industrial and power plants requirements of Shiraz, the capital of Fars province, and Marvdasht and Zarghan, two other main cities in the province.

All inflows, reservoir storage, evaporation, and releases from 1986 to 2006 have been collected by the Fars Ministry of Energy Data Center land based/surface data collection. Team members collected all available hydro-meteorological data including inflows, water elevation, rainfall, temperature, etc., for each station along the Kor River, and the recorded data were reported in Microsoft Excel workbooks for data quality assurance and quality control. Table 2 and Figure 2 present the constant monthly downstream demands and monthly inflow data over the observation period of 252 months, respectively. As monthly inflows are less than the average of inflows (97.49 MCM) in 172 of 252 months, it can be concluded that dry periods are more dominant than wet periods in the area of study.

Figure 1 | Schematic view of Doroudzan Reservoir basin that extends between 51°43’ and 52°43’ E longitude and 30°08’ and 31°00’ N latitude.
Linear programming and LINGO

LP is a popular method and the most widely used technique for optimization models. The popularity of LP is because of its presenting of efficient solution algorithms, its availability of generalized computer software packages, and its applicability to wide ranges of water resources problems (Wurbs 2008). Problems such as determining the size of a reservoir, finding the best system yield, and obtaining optimum releases are handled commonly through LP application (Loucks et al. 1981). LINGO is a comprehensive tool for modeling all systems (large or small) for linear or non-linear problems. It provides a completely integrated package that includes a powerful language for expressing optimization models and a full featured environment for building and editing problems. Furthermore, it creates related groups for solving the problem based on the inherent defined problems such as discharge, precipitation, demands, and time period. LINGO allows the placing of similar objects into a set and uses a single statement for all elements of a desire set. This model allows a user to quickly input the model formulation, assess the correctness or appropriateness of the formulation based on the solution, quickly make minor modifications to the formulation, and repeat the process. Many researchers, such as Bozorg Haddad et al. (2008) and Montazar et al. (2010), applied LINGO to evolve an optimal allocation plan of surface and ground water for various hydrosystem types. In another study, Ziaei et al. (2012) combined LINGO and the Hydrologic Engineering Center’s Reservoir System Simulation (HEC-ResSim) models to determine monthly operating rules for the Zayandeh-Rud Reservoir system in the central part of Iran. In their study, system behavior was simulated over 47 years and the results showed that optimizing the operation of Zayandeh-Rud Reservoir could increase its storage by 88.9%, and increase the reliability index of regulated water for all downstream demands by over 10%.

In this study, LINGO is used to determine optimum operational parameters of the Doroudzan Reservoir in different strategies and the results are presented in the following sections.

The optimization model and constraints

Optimization methods are designed to provide the best values of system design and obtain high performance solutions. Hence, the results can increase efficiency of system outcomes and reduce conflict in operating policies (Loucks & Beek 2005). The main objective of this study is to maximize the total reservoir release after fully meeting the domestic-industrial demands and considering different priority coefficients for agricultural and power plant segments over the desired planning horizon. The mathematical form of objective function in this study is considered as follows:

$$\max Z = \sum_{i=1}^{21} \sum_{j=1}^{12} R_{ij}$$  \hspace{1cm} (1)
Subjected to

\[ S_{ij+1} = S_{ij} + I_{ij} - E_{ij} - R_{ij} - SP_{ij} \]  \hspace{1cm} (2)

and

\[ S_{ij} \leq S_{\text{max}} \] \quad \forall i \quad \text{and} \quad \forall j

\[ S_{ij} \geq S_{\text{min}} \]  \hspace{1cm} (3)

where \( Z \) is a target function, \( R_{ij} \) is release supplies to downstream, \( S_{ij} \) is the initial storage in the reservoir, \( I_{ij} \) is inflow into the reservoir, \( E_{ij} \) is evaporation from reservoir surface, \( R_{ij} \) is release supplies to downstream, and \( SP_{ij} \) is spill from the reservoir in year \( i \) and month \( j \). \( S_{\text{max}} \) and \( S_{\text{min}} \) are the maximum and minimum storage volumes of the reservoir. In addition, it is assumed that reservoir volume is not sensitive to the precipitation variable.

Equation (1) has been used for single-objective optimization and its solution will result in maximizing total regulatory releases within 252 months. It should be noted that reservoir water balance must be preserved in all stages of optimization, and thus the reservoir continuity equation is considered as the main constraint in this case. The assumed constraints for the applied LP model in this study are as follows:

1. The water budget equation that includes reservoir input (inflow and precipitation), outflow (domestic-industrial, agricultural, power plant releases, evaporation and spill from the reservoir), and stored water at the end of previous storage period (Equation (2)).
2. As the portion of reservoir capacity below dead storage is not used for operational purposes, the water volume in the reservoir should always be above the dead storage. In the case of Doroudzan Reservoir, the dead storage is 133 MCM, and then \( S_{ij} \geq 133 \) MCM.
3. To minimize unnecessary spills from the reservoir at the time that the stored water in the reservoir exceeds the total capacity, the maximum water volume in the reservoir should always be above the dead storage. In this study, the dead storage is 133 MCM, and then \( S_{ij} \geq 133 \) MCM.
reservoir is assumed to be equal to the total reservoir volume. Thus, $S_{i,j} \leq 993$ MCM.

4. As the maximum inflows into the reservoir typically occur between January and April (Figure 3(a)), January is assumed as the initial optimization month and the average water volume in January over 21 years was considered as the initial condition in the optimization model. Therefore, $S_{1,1} = 654.77$ MCM.

5. Different management strategies have been applied to select the appropriate release policy for Doroudzan Reservoir. According to downstream demands (domestic-industrial, agricultural and power plant sectors), the minimum allowable releases are considered as follows:

$$D_{i,j} + \alpha A_{i,j} + \beta V_{i,j} \leq R_{i,j} \leq D_{i,j} + A_{i,j} + V_{i,j} \quad (4)$$

where $D_{i,j}$ is the sum of domestic and industrial demands, $\alpha$ is priority coefficient of agricultural segment $A_{i,j}$, and $\beta$ is priority coefficient of power plant sector $V_{i,j}$ in year $i$ and month $j$. It is important to note that the hydroelectric generation is not only an in-stream water user, it is also a large consumptive user of water at the plant.

The Doroudzan Reservoir cannot supply the necessary water for all demands simultaneously and there is always a deficiency in providing downstream needs. Therefore, different management policies have been considered to find the appropriate operation policy with the maximum reliability for monthly releases. The model was run for seven management strategies which imply different minimum requirements, as follows:

**Strategy 1**: Only supplying domestic-industrial requirements ($\alpha = 0$ and $\beta = 0$).

**Strategy 2**: Supplying domestic-industrial needs plus 25% of agricultural requirements ($\alpha = 0.25$ and $\beta = 0$).

**Strategy 3**: Supplying all domestic-industrial needs plus 50% of agricultural demand ($\alpha = 0.5$ and $\beta = 0$).

![Figure 3](https://iwaponline.com/aqua/article-pdf/62/3/138/400516/138.pdf)

*Figure 3* | Comparison of total monthly demands and monthly average of observed release with total demands in each strategy and (a) monthly average of inflows, (b) monthly average of optimum releases in strategy 1, (c) strategy 2, and (d) strategy 3.
Strategy 4: Supplying all domestic-industrial requirements plus 75% of agricultural needs ($\alpha = 0.75$ and $\beta = 0$).

Strategy 5: Supplying domestic-industrial needs plus 25% of agricultural and 25% of power plant requirements ($\alpha = \beta = 0.25$).

Strategy 6: Supplying domestic-industrial needs plus 50% of agricultural and 25% of power plant requirements ($\alpha = 0.5$ and $\beta = 0.25$).

Strategy 7: Supplying domestic-industrial needs plus 25% of agricultural and 50% of power plant demand ($\alpha = 0.25$ and $\beta = 0.5$).

The values of $\alpha$ and $\beta$ are summarized for all adopted strategies in Table 3. In this study, the values $\alpha$ and $\beta$ have been determined according to the dam’s administrative recommendations and demands pattern history in the study area. As the highest priority in this study is domestic-industrial, the coefficient of $D_{ij}$ is considered one in all strategies. The second and third priorities are agricultural and power plant, respectively, and so the allocated priorities coefficients to them are considered less than domestic-industrial needs. The values of $\alpha$ and $\beta$ demonstrate that the agricultural and power plant segments will be sacrificed during shortage and a portion of the available water in these sectors will be dedicated to other sectors to minimize deficiencies in main priority areas.

Reliability index

In order to assess the performance of water resource systems, several performance criteria can be applied to characterize demand scenarios, system alternatives and operation policies. In the example of reservoir system considered herein, there is a single variable deciding whether the system performance is reliable or not over the desired planning horizon. If water supply is not lower than water demand, the system is reliable and downstream demands will be met (Kundzewicz & Kindler 1995). In this case, the reliability index ($\eta$) is a major indicator which is defined as the probability of the system not failing in a given period. Hashimoto et al. (1982) investigated reservoir operation system performance with a reliability index as follows:

$$\eta = \frac{N_M}{N_T} \times 100$$  \hspace{1cm} (5)

where $N_M$ is the number of months with standard supply, and $N_T$ is the total months over desired planning horizon.

In this study, the total and monthly reliability of the system have been considered to find the most reliable strategies and also the most harmful months over the desired planning horizon.

RESULTS AND DISCUSSION

The main purpose of this study is to obtain monthly operating rules for Doroudzan Reservoir in southern Iran. The optimization model was run using observed and synthetic inflow data, and optimal operation policies were derived for assessing the amount of allocated water to all downstream demands including domestic-industrial, agricultural, and power plants.

Optimization analysis based on observed inflows

The operation of reservoirs is based on some specific policies that present practical guidelines for the amount of stored or released water to meet project requirements. A rule curve is a kind of static policy and practical guideline for determining specific operation policies based on downstream needs. In this study, LINGO 11.0 was applied for a single-objective optimization, and the total releases were optimized by the model for 252 months. The optimized monthly averages of regulatory release in seven water supply strategies are presented in Table 4. These results can be applied as guidelines to find the appropriate way to distribute water among different sectors with minimum deficiency. Figures 3 and 4 compare the total monthly

Table 3 | The agricultural and power plant coefficients in different strategies

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Agricultural coefficient ($\alpha$)</th>
<th>Power plant coefficient ($\beta$)</th>
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<tr>
<td>1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
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</tr>
<tr>
<td>3</td>
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</tr>
<tr>
<td>4</td>
<td>0.75</td>
<td>0.0</td>
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<tr>
<td>5</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>0.25</td>
</tr>
<tr>
<td>7</td>
<td>0.25</td>
<td>0.5</td>
</tr>
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### Table 4 | Monthly average of optimum reservoir releases in different strategies (MCM)

<table>
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<tr>
<th>Month</th>
<th>Strategy 1</th>
<th>Strategy 2</th>
<th>Strategy 3</th>
<th>Strategy 4</th>
<th>Strategy 5</th>
<th>Strategy 6</th>
<th>Strategy 7</th>
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<td>Jan</td>
<td>49.90</td>
<td>50.84</td>
<td>46.63</td>
<td>30.47</td>
<td>49.51</td>
<td>45.48</td>
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<td>56.37</td>
<td>56.37</td>
<td>54.03</td>
<td>34.11</td>
<td>57.04</td>
<td>52.38</td>
<td>41.09</td>
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<td>Mar</td>
<td>148.11</td>
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<td>119.13</td>
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<td>128.10</td>
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<td>Apr</td>
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<td>149.44</td>
<td>142.35</td>
<td>124.71</td>
<td>139.81</td>
<td>143.47</td>
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<td>May</td>
<td>113.35</td>
<td>116.30</td>
<td>128.64</td>
<td>164.94</td>
<td>117.37</td>
<td>97.62</td>
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<td>Jun</td>
<td>57.45</td>
<td>77.38</td>
<td>91.35</td>
<td>161.59</td>
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<td>87.82</td>
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<td>147.62</td>
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<td>37.19</td>
<td>25.93</td>
<td>41.41</td>
<td>37.19</td>
<td>28.74</td>
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### Figure 4 | Comparison of monthly demands and monthly average of observed release with total demands in each strategy and monthly average of optimum releases in (a) strategy 4, (b) strategy 5, (c) strategy 6, and (d) strategy 7.
demands, the monthly demands in each strategy, the average monthly inflows, and the monthly averages of optimized and non-optimized releases in all adopted strategies and demonstrate how optimization changes the monthly distribution of regulatory releases in different strategies compared to the total demands and non-optimized releases. Based on the results, the Doroudzan Reservoir cannot supply the necessary water for all demands simultaneously and dam administrators have to choose the appropriate operation policy based on downstream needs. Therefore, different strategies are considered to supply downstream demands based on historical inflows, existing water in the reservoir, and minimum downstream requirements. According to Figure 3(a), the inflows into the reservoir decrease from April to June, while the total demands increase during this period. These months are the most critical months and the optimized releases have downward trends in strategies 1, 2, 3, and 5 (see Figures 3(b)–(d) and 4(b)). In these cases, low inflows force the optimization model to only provide the minimum requirements in desired strategy and store more water to be released in the following months, such as July, August, and September, that include high demands. On the other hand, the optimized releases are increased by increasing minimum requirements in strategies 4 and 7, and so dam administrators have to release much more water in these strategies to supply downstream needs. As much more water should be released, the volume of stored water will be decreased significantly (see Figure 5 and Table 6).

In addition to release, the yearly averages of stored water in the non-optimized and optimized conditions are estimated for all adopted strategies and the results are presented in Table 5. According to this table, optimization increased the total stored water in the reservoir by 2.9, 4.54, 7.04, 6.69, and 1.75% in strategies 1, 2, 3, 5, and 6, respectively, while stored water decreased about 34.9 and 33.92% in strategies 4, and 7, respectively. These results showed that much more water must be
released to provide downstream needs in strategies 4 and 7. Figure 5(a)–(d) shows the yearly variations of optimized and non-optimized stored water in strategies 1, 4, 5 and 7, respectively.

Besides the monthly averages of releases and stored water, the monthly values of optimized and non-optimized releases and stored water during two certain dry and wet years are also presented based on a particular criterion. In this case, if more than 75% of monthly inflows through a specific year are less than the average of inflows in the period of 1986–2006 (97.49 MCM), that year is considered as a dry year; and if less than 50% of monthly inflows in a certain year are less than the average of inflows during planning horizon, the desired year is considered as a wet year. As the study area is located in a semi-arid region where dry periods are more dominant than wet periods, two different thresholds are considered to determine the wet and dry years. In the case of Doroudzan Reservoir, the years 1993 and 2001 are selected as wet and dry years, respectively, and the associated inflows of each year in conjunction with the average of inflows in the period of 1986–2006 are shown in Figure 6.

Figures 7 and 8 show the monthly values of optimized and non-optimized releases and stored water for strategies 3 and 6 for desired dry and wet years. As can be seen from these figures, the optimized releases during a dry year can only provide the minimum requirement of downstream, while there are more releases and additional storages in the reservoir during a wet year.

### Reliability analysis

If no water is discharged from the reservoir or if the allocated water to the downstream area is below demand requirements, the released flow does not meet demands and a deficit exists. In this study, the performance of

<table>
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<th>Observed</th>
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<th>Strategy 2</th>
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<td>714.50</td>
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<td>691.48</td>
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<td>812.07</td>
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<td>898.00</td>
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<td>628.35</td>
<td>876.44</td>
<td>760.72</td>
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<td>765.08</td>
<td>751.35</td>
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<td>402.05</td>
<td>756.45</td>
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<td>740.06</td>
<td>756.67</td>
<td>769.13</td>
<td>816.35</td>
<td>725.82</td>
<td>763.77</td>
<td>685.18</td>
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<td>2003</td>
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<td>752.14</td>
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<td>685.58</td>
<td>759.67</td>
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<td>2004</td>
<td>756.66</td>
<td>704.76</td>
<td>715.47</td>
<td>771.58</td>
<td>624.46</td>
<td>742.43</td>
<td>717.78</td>
<td>680.55</td>
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<td>2005</td>
<td>731.39</td>
<td>798.39</td>
<td>861.70</td>
<td>832.90</td>
<td>590.17</td>
<td>861.40</td>
<td>816.67</td>
<td>644.74</td>
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<td>2006</td>
<td>589.70</td>
<td>582.91</td>
<td>600.40</td>
<td>613.85</td>
<td>193.33</td>
<td>606.58</td>
<td>581.70</td>
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<tr>
<td>Average</td>
<td>693.56</td>
<td>713.68</td>
<td>725.02</td>
<td>742.39</td>
<td>451.53</td>
<td>739.96</td>
<td>705.68</td>
<td>458.32</td>
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Doroudzan Reservoir was assessed before and after optimization by applying Equation (5). Results showed that there are 211 deficit months and the reliability of the system was only 16.27% before optimization, while optimization analysis increased the reliability index in all adopted strategies (Table 6). Although still there is deficiency under optimized conditions, optimization resulted in fewer deficit months, and the reliability of the system has increased in
all strategies. However, the reliability is considerably lower in strategies 4 and 7 rather than the other adopted strategies. This decreased reliability indicates that the system will face serious problems when supplying domestic-industrial and 75% of agricultural needs or domestic-industrial, 25% agricultural, and 50% power plant requirements in strategies 4 and 7, respectively. In this condition, the dam’s administrator has to provide the necessary water from other available water sources to supply downstream needs with higher reliability. For example, supplementary wells can be used to overcome deficiency during water requirement peaks.

On the other hand, the importance of deficit magnitude has also been considered to find the most harmful months over the desired planning horizon. Hence, the optimized releases are compared with the total water demands in all 252 months and monthly reliabilities are presented in Table 7. Although optimization increased the reliability index in most months, its values are almost under 40% in May–August. Since there are high water requirements and also low inflows between May and August (Figure 3(a)), these months are recognized as the most harmful months, in particular for agricultural and power plant segments. However, it can be concluded that the achieved results prove the success of optimization analysis to supply minimum requirements associated with each strategy and also provide appropriate operational policies for Doroudzan Reservoir.

Figure 9(a)–(d) compares the monthly reliability in optimized and non-optimized conditions for all adopted strategies. These figures show how the reliability of the system in each strategy varies in comparison to the other strategies. For example, Figure 9(c) shows the system is not very reliable in strategy 7 in comparison to strategy 1, while it is more reliable than strategy 4.
Optimization analysis based on synthetic inflow data

In this study, in addition to the observed inflow data which were applied to evaluate optimum releases in different strategies by an LP model, a period longer than the recorded 252 months is examined by using synthetic data to determine the effect of alternative scenarios on the reservoir operation. It is important to note that using synthetic data in optimization analysis is necessary to see the changes in the reservoir operation policies over a longer period. Synthetic inflows were generated for a longer period of 432 months by the Monte Carlo method based on the statistical characteristics of the

<table>
<thead>
<tr>
<th>Table 7</th>
<th>Monthly reliability in optimized and non-optimized conditions</th>
</tr>
</thead>
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<tr>
<td><strong>Month</strong></td>
<td><strong>Observed release</strong></td>
</tr>
<tr>
<td>Jan</td>
<td>19.05</td>
</tr>
<tr>
<td>Feb</td>
<td>14.29</td>
</tr>
<tr>
<td>Mar</td>
<td>23.81</td>
</tr>
<tr>
<td>Apr</td>
<td>52.38</td>
</tr>
<tr>
<td>May</td>
<td>23.81</td>
</tr>
<tr>
<td>Jun</td>
<td>0.00</td>
</tr>
<tr>
<td>Jul</td>
<td>0.00</td>
</tr>
<tr>
<td>Aug</td>
<td>0.00</td>
</tr>
<tr>
<td>Sep</td>
<td>0.00</td>
</tr>
<tr>
<td>Oct</td>
<td>0.00</td>
</tr>
<tr>
<td>Nov</td>
<td>4.76</td>
</tr>
<tr>
<td>Dec</td>
<td>57.14</td>
</tr>
</tbody>
</table>

Figure 9 | Monthly reliabilities of observed and optimized releases in different months.
252 months of observed inflow data, and then the LP model was re-run in strategies 1 and 5. In this study, only strategies 1 and 5 were considered for optimization analysis based on synthetic inflow data. In the next step, the optimized values of releases were obtained from historical and synthetic inflow conditions in both strategies 1 and 5.

In the first phase, the most common statistical distributions including Normal, Gamma, Gumbel, Log-normal, and Pareto were fitted to 252 monthly observed inflow data and the best distribution was selected based on the goodness-of-fit test. To find the best fitting statistical distribution, the Kolmogorov–Smirnov (K–S) and Chi-Square tests were applied and the results are presented in Table 8. According to this table, the distribution yielding the smaller K–S value, herein the Log-normal distribution, was selected and synthetic inflow data were generated for 432 months. Figures 10 and 11 compare the optimum releases and synthetic optimum releases in strategies 1 and 5, respectively, from 1993 to 2003. Furthermore, variations of stored water in strategy 1 were calculated by the applied optimization model using both data sets, and the results are plotted in Figure 12 for the period of 1993–2003.

There are a number of ways in statistics to quantify the difference between values implied by an estimator and the true values of the quantity being estimated. In this case, three common techniques are the mean error (ME), mean absolute error (MAE) and root-mean-square error (RMSE), which can be applied to measure differences between values predicted by a model or an estimator and the observed values. ME indicates whether the forecasts are biased, MAE measures the average magnitude of the errors in a set of forecasts, and RMSE is a quadratic scoring rule which measures the average magnitude of the error. Lower values of RMSE, ME, and MAE indicate a better fit between the model’s predictions and the

<table>
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<tr>
<th>Distribution</th>
<th>Kolmogorov–Smirnov</th>
<th>Chi-Square</th>
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</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.207</td>
<td>240.35</td>
</tr>
<tr>
<td>Gamma</td>
<td>0.135</td>
<td>62.49</td>
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<tr>
<td>Gumbel</td>
<td>0.155</td>
<td>115.37</td>
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<tr>
<td>Lognormal</td>
<td>0.086</td>
<td>31.73</td>
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<tr>
<td>Pareto</td>
<td>0.223</td>
<td>84.95</td>
</tr>
</tbody>
</table>

Figure 10 | Optimum and synthetic optimum releases in strategy 1 in the period 1993 to 2003.
Figure 11 | Optimum and synthetic optimum releases in strategy 5 in the period 1993 to 2003.

Figure 12 | Optimum and synthetic optimum stored water in strategy 1 in the period 1993 to 2003.
observed data. In this study, ME, MAE, and RMSE are used to quantitatively evaluate the performance of the applied model and estimate deviations of optimum releases ($R_{\text{opt}}$) and stored water ($S_{\text{opt}}$) from synthetic optimums release ($R_{\text{opt-s}}$) and stored water ($S_{\text{opt-s}}$). A performance summary of the predicted and observed values is presented in Table 9. RMSE, MAE, and ME values between optimum release ($R_{\text{opt}}$) and synthetic optimum releases ($R_{\text{opt-s}}$) are calculated as 1.26, 0.79, and -0.36 in strategy 1, and 1.18, 0.82, and -0.32 in strategy 5, respectively. As can be seen from Figures 10–12, and also Table 10, the outcomes of the LP optimization model using observed and synthetic data are well resembled and confirm each other.

Table 10 presents the monthly averages of synthetic and normal optimized releases in strategies 1 and 5. Although the results of simulation do not always get used because of inflow regime variations due to climate changes and also recent droughts in Iran, they can be applied by dam administrators for future implementation operation policies to create new operational plans as part of novel management strategies with an acceptable range.

### Table 9 | Performance summary of the synthetic and observed values

<table>
<thead>
<tr>
<th></th>
<th>RMSE</th>
<th>ME</th>
<th>MAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{opt}}$ vs $R_{\text{opt-s}}$ in strategy 1</td>
<td>1.26</td>
<td>-0.36</td>
<td>0.79</td>
</tr>
<tr>
<td>$R_{\text{opt}}$ vs $R_{\text{opt-s}}$ in strategy 5</td>
<td>1.18</td>
<td>-0.32</td>
<td>0.82</td>
</tr>
<tr>
<td>$S_{\text{opt}}$ vs $R_{\text{opt-s}}$ in strategy 1</td>
<td>22.34</td>
<td>4.11</td>
<td>19.31</td>
</tr>
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</table>

### Table 10 | Monthly average of optimum and synthetic optimum releases in strategies 1 and 5

<table>
<thead>
<tr>
<th>Month</th>
<th>Strategy 1 (MCM)</th>
<th>Strategy 5 (MCM)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Optimum release</td>
<td>Synthetic optimum release</td>
</tr>
<tr>
<td>Jan</td>
<td>49.90</td>
<td>50.12</td>
</tr>
<tr>
<td>Feb</td>
<td>56.37</td>
<td>56.66</td>
</tr>
<tr>
<td>Mar</td>
<td>148.11</td>
<td>148.46</td>
</tr>
<tr>
<td>Apr</td>
<td>153.60</td>
<td>154.18</td>
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<tr>
<td>May</td>
<td>113.35</td>
<td>114.13</td>
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<tr>
<td>Jun</td>
<td>57.45</td>
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<tr>
<td>Jul</td>
<td>87.82</td>
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<tr>
<td>Aug</td>
<td>141.24</td>
<td>141.55</td>
</tr>
<tr>
<td>Sep</td>
<td>155.27</td>
<td>155.29</td>
</tr>
<tr>
<td>Oct</td>
<td>75.02</td>
<td>75.23</td>
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<tr>
<td>Nov</td>
<td>60.97</td>
<td>61.09</td>
</tr>
<tr>
<td>Dec</td>
<td>42.82</td>
<td>43.15</td>
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### CONCLUSIONS

This study focused on the Doroudzan Reservoir operation using observed and synthetic inflow data in different strategies. The objective function of the applied LP model was maximizing allocated water for various downstream needs by considering the domestic-industry as the main priority and assuming various priorities coefficients for agriculture and power plant segments. Different strategies were analyzed by running the optimization model for observed inflows during 252 months, and then seven different operation policies with each strategy's performance figured out. The achieved results can be briefly summarized as follows:

1. There were 211 deficit months before optimization and the reliability of the system was only 16.27%, while optimization analysis increased the reliability index from minimum 29.76% in strategy 4 to maximum 74% in strategy 1.
2. The optimization increased the stored water in the reservoir by 2.9, 4.54, 7.04, 6.69, and 1.75% in strategies 1, 2, 3, 5, and 6, respectively.
3. The Doroudzan Reservoir cannot supply the necessary water for all demands simultaneously and dam administrators have to choose the appropriate strategy based on available water and downstream priorities. However, the optimization analysis increased efficiency and decreased the conflict in the management of tradeoffs between available water and downstream demands.
4. Furthermore, the optimization model was re-run based on the synthetic inflow data to consider the performance of the model based on synthetic inflows and obtaining appropriate operation policies. The results demonstrated that the outcomes of the LP optimization model using observed and synthetic data are well resembled and confirm each other. Therefore, it can be concluded that applying synthetic data in optimization analysis is useful to see the changes in the reservoir operation policies over a longer period.

It can be concluded that optimization with mathematical modeling techniques can enhance reservoir operation
efficiency throughout scientific allocation of the available water, and determine the appropriate operational releases regarding downstream demands.

**FUTURE STUDIES**

As inflows decreased intensely during April to July, while agricultural and power plant demands increase over these months, considering the impact of agricultural and power plant requirements to shortages at different times of year and various strategies needs additional considerations. In addition, the results of this study can be applied to develop operating rules using a simulation model over both sets of observed and synthetic hydrology data.

**REFERENCES**


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