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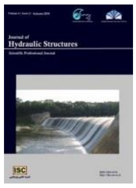

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Investigating Pareto Front Extreme Policies Using Semi-distributed Simulation Model for Great Karun River Basin

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Abstract

This study aims to investigate the different management policies of multi-reservoir systems and their impact on the demand supply and hydropower generation in Great Karun River basin. For this purpose, the semi-distributed simulation-optimization model of the Great Karun River basin is developed. Also, the multi-objective particle swarm optimization algorithm is applied to optimize the developed model and determine the optimum operating policies. The significance of this research is using the semi-distributed simulation model to simulate the supply of system demand sites that leads to obtaining more realistic results compared to the centralized models. The results of this study show that the effects of different system reservoirs on energy production and demand supply are not the same across the basin and they should be considered carefully for achieving maximum efficiency of the multi-reservoir system in meeting different demands and for extracting the optimal operating rule curves.

Keywords: Multi-reservoir water resources system; multi-objective optimization; semi-distributed model; Great Karun River basin; Simulation-optimization approach

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1. Introduction

In recent years due to the construction of large-scale water resources systems in developed countries and the rise of completed projects, the majority of research has been focused on improving operating policies and enhancing the efficiency of existing systems [1]. So far, many mathematical methods and models have been introduced for finding the optimal operating policies of these systems, each providing certain disadvantages and strengths. In recent years, multi-objective analysis has been further studied in the operation of water resources systems. The fact cannot be ignored that water resources systems are often managed to serve several different, at times conflicting, purposes [2]. The coordinated operation of multi-purpose water resources systems is typically a complex decision-making problem with a large number of variables and multiple objectives and is influenced by uncertainties and risk that increase the

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challenges facing decision-makers in this direction. Also, in multi-reservoir systems, the spatial scattering of demand sites at the basin level increases the complexity of the system and needs special attention [3]. Therefore, the use of new optimization models with different approaches and capabilities can be of interest to practitioners in this field of research and practice.

The Great Karun River basin (GKRB) is the most important watershed in Iran, which has not only a very important role in the development of the benefiting provinces but also has become a national capital due to water transfer plans such as Dez-Ghomroud and its place in supplying the national energy network. In addition to the multi-reservoir, multi-purpose properties of this system, the large number of its stakeholders, and the several watersheds which require to be supplied from its resources enhance the system management complexity. To develop a sustainable water resources operating system, the volume and quality of the water resources in the GKRB must be studied as an integrated system by considering all the operating priorities and policies and all the contributing and affected factors.

In a research project, Al-Zu'bi et al. [4] investigated the application of decision-support systems for sustainable management of water resources in the Azraq basin in Jordan. They used Analytical Hierarchy Process (AHP) to account for multiple variables of water demand in agricultural and industrial sectors, as well as the ecosystem protection measures (ecology) and climate impacts in combination with each other in a model. It resulted in the optimal prioritization of water allocation for each sector in the Azraq water basin. Giupponi and Sgobbi [5] conducted a research project in the form of a survey to explore the impact of the results of the DSS projects carried out in developing countries, especially in Africa. the results of the questionnaires show the little positive effects of DSS in these countries. The result of Pierleoni et al. [6] study shows how reservoir systems modeling can be used in line with preventative management in critical conditions in periods of drought. They used SimBaT software to manage water resources system of Montedoglio reservoir by considering the agricultural demands, urban consumption as well as the protection of the Tiber River's environment in Central Italy.

Woldesenbet et al., [7] examined how land use/cover changes affect the water balance at basin scale in the upper Blue Nile Basin in Ethiopia. Different regulatory periods of lake of Tana and its reciprocal effects on the surface of the hydrological regime was investigated. Moreover, based on the available data of inflow, a simple rainfall-runoff model, various scenarios and simulations, a decision support system was developed to understand the impact of predefined water resources programs in the region. George et al. [8] examined four scenarios. The baseline scenario, which is based on water allocation in the current conditions by assuming the hydrological conditions and water demand in the future remain constant. The second scenario was carried out by accounting for increasing water demand in the urban sector and transferring water from the agricultural sector to this municipal sector. The third scenario was investigated by assuming a 10 % reduction in the flow rate of surface water and groundwater without altering water demand, and finally in the fourth scenario, the diversification of crops (shifting a percentage of area under cultivation to less-water consuming crops) was investigated.

Rousta and Araghinejad [9] proposed the SMCDM model framework and formulation as a tool to assist in Multi-Criteria Decision Making (MCDM) in water resources management. The model has been developed for the well-known Water Evaluation And Planning (WEAP) system and has a high ability to be linked with it as a software add-in. The researches have used the combination of WEAP and SMCDM to study and prioritize different management strategies to respond to water demand in urban areas (municipal demand) in the Gorganrud River basin in northern Iran. In a research by You et al. [10], water allocation based on evaporation and transpiration control (ET Control) in the Haihe River basin, known as the area with the most serious water scarcity in China, was investigated. A research by Xuan et al. [11] aimed to develop a multi-purpose water allocation model based on Water Resources Security assessment (WRS) to provide a set of alternative reallocations in the Zhangjiakou basin, as a semi-arid region in China. In a paper, Graveline [12] explores the calibrated economic planning models for water allocation in production of agricultural products with a managerial view which are referred to as Water-Programming models (WPM). His goal of publishing this work is to provide a thorough and comprehensive guide on the important modeling choices and challenges associated with water use in farming.

Most water resources management models developed for different watersheds in Iran have been carried out based on centralized modeling of the demand sites regardless of their spatial diversity at the basin level [13, …, 20]. However, to accurately determine the outcomes of adopting management policies, it is necessary to adequately observe the distribution and spatial scattering of demand sites at the basin-level [3]. Many studies have been conducted in different basins in Iran to explore the effects of climate change on water resources and estimate their consequences [21, …, 26]. Albeit these studies did not focus on the optimal water resources operating policy and the calculations are not conducted accurately with sufficient details. Other studies have been conducted to consider the inter-basin water transfer using simulation-optimization models of water resources systems [27, …, 33]. The majority of these studies are mainly aimed at the division of water between adjacent basins based on the overall profitability of each basin or the general demands of the basin. Therefore, the details of the flow distribution in each basin and distribution of consumption centers in each region were not considered.

More recently, Ashrafi and Mahmoudi [34] developed a semi-distributed decision support system to facilitate identification of water resources system components of GKRB and consider their interactions and the direct and indirect effects of the system elements. The model helps decision-makers choose the best operating alternatives using optimal operational policies with respect to desired goals in the general management of water resources. In the present study, the semi-distributed model has been implemented to develop a simulation-optimization model. The integrated model has been proposed to optimize the operating policies of large reservoirs that are simultaneously tasked with producing energy and supplying dispersed demand sites throughout the basin. The objectives are inherently in conflict with each other and dealing individually with one of them undermines the realization of another. Therefore, the best approach in dealing with such a problem is to use multi-objective optimization that can provide the decision-makers with the complete problem-solving environment by accounting for all the objectives simultaneously.

2. The considered water resources system

The considered water resources system consists of six reservoirs of GKRB including; Dez dam reservoir on the Dez River, and the cascade reservoirs of Karun 4, Karun 3, Karun 1, Masjed Soleyman, Gotvand Olya on the Karun River. The agricultural demand sites are located at the downstream of Gotvand Olya and Dez dams. In this system, all reservoirs should serve hydropower plants with different capacities. Fig. 1 illustrates a schematic view of the considered system.

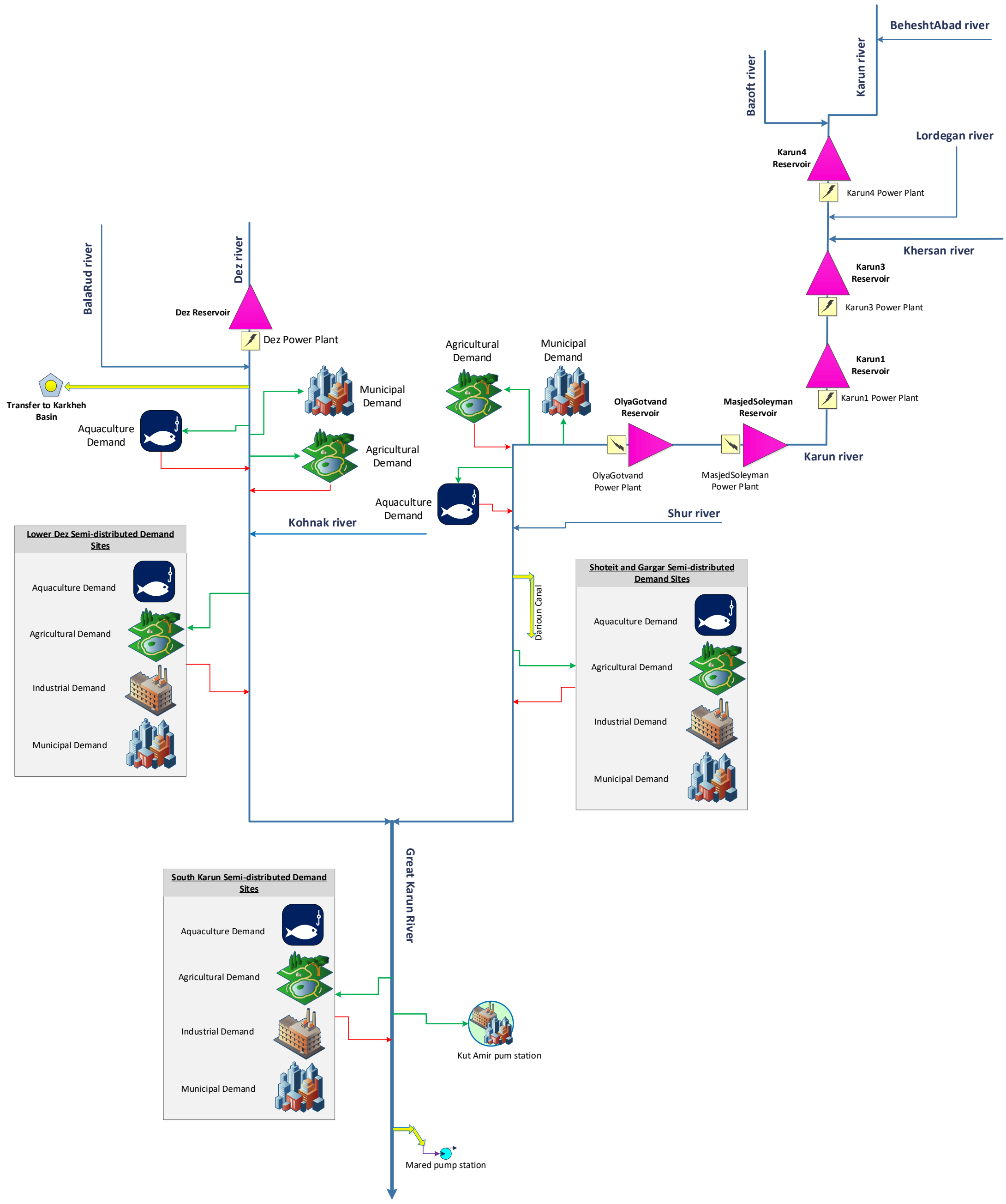

Fig. 1. The schematic view of the six-reservoir Great Karun River basin

As shown in Fig. 1, the distribution of the demand sites throughout the basin are accounted for as much as possible. This increased the accuracy of the simulation model of the system. In modeling, different types of demands including municipal, agricultural, aquaculture, industrial, flow transfer, and so on are considered with different priorities. Also, headflows, sub-basin inflows (if any), return flows and flow loss are considered at different intervals. The values of the return flows and the priorities of demands were determined according to the long term observations of the system and during the model calibration process [34]. The reservoirs characteristics are summarized in Table 1. In this study, a 60-years period (October 1955 to September 2015) data was used for modeling.

Table 1. Characteristics of the Great Karun Water Resources System

	Mean annual inflow *cms*	Normal water level *masl*	Minimum operation level *masl*	Active storage *mcm*	Plant capacity *MW*	Plant efficiency *%*	Head loss *m*
Dez	256.6	352	310	2048	520	89	3
Karun4	190	1025	996	749	1000	92	3
Karun3	332.8	845	800	1689	2000	92.4	4.5
Karun1	392.5	532	500	1318	2000	90	8
Masjed Soleyman	412	372	363	46	2000	92	4
Olya Gotvand	466	230	185	3050	1500	93	4.5

The modeling was carried out systematically, and the reciprocal effect of the reservoirs on the performance of each other can be observed. Also, the optimal operating policies derived from the present model perform optimally when considered systematically with all the reservoirs together. To reduce the amount of computation time, the simulation model of the system was developed in Matlab R2019a by considering the allocation priorities in the study by Ashrafi and Mahmoudi [34] and have been calibrated using the observed streamflows in the basin hydrometric stations.

3. The simulation-optimization model

The problem is to find the optimal operating policy for a six-reservoir water resources system of GKRB using a long-term data with objectives of minimizing the total deficit in the system and maximizing the energy production. To that purpose, the developed simulation model is implemented within an optimization model in different iteration of evolution. As the problem is a multi-objective optimization by nature, the Elitist mutated-Multi-objective particle swarm optimization algorithm (EM-MOPSO) by Reddy and Nagesh Kumar [35] is used. Fig. 2 shows the flowchart of the model used in the present study.

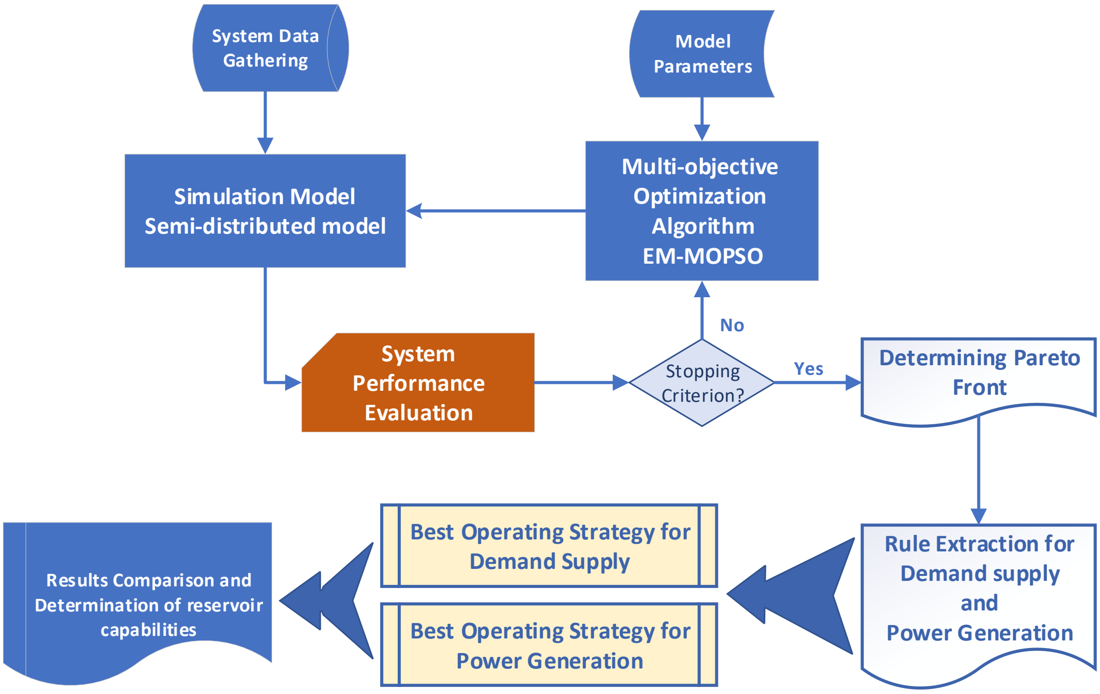

Fig. 2. The flowchart of the model development

The main objective functions of the present study can be represented as follows;

$$Min\ f_1 = \sum_{t=1}^{T} \sum_{j=1}^{n_D} \left(\frac{TD_{t,j} - RD_{t,j}}{TD_{t,j}} \right)^2 \tag{1}$$

$$Max\ f_2 = \sum_{t=1}^{T} \sum_{j=1}^{n_R} HP_{t.j}(S_{t,j}, S_{t+1,j}, RH_{t,j}) \tag{2}$$

where, the first objective function is for the demand supply, and the second one is for energy production. In these equations, $HP_{t,j}$ is the amount of energy generated at the plant *j* in month *t* and $RH_{t,j}$ represents the flow rate at the power station *j* in month *t*. The amount of energy generated per month is calculated based on equation (3). *T* is the total number of time steps in each case, $S_{t,j}$ and $S_{t+1,j}$ are the storage volume of the j^{th} reservoir at the beginning and end of the period *t*, $RH_{t,j}$ is the flow at the j^{th} power plant during the t^{th} studied period, Ef_j is the efficiency of the power plant *j*, $\bar{H}_{t,j}$ is the mean difference between the reservoir storage level at the period *t* and the tail water level of the plant, $HP_{t,j}$ is the amount of energy generated at the reservoir *j* over the period *t* which itself is a function of reservoir storage level at the same period and the flow rate of the power plant. In order to apply the constraints, the penalty function method is used. That is, any answer that constitutes any violation of any system constraints is subject to a particular penalty in the objective function. The constraints of the problem and violations of them are derived from the simulation model. The constraints can be defined as follows:

$$HP_t(S_{t,j}, S_{t+1,j}, RH_{t,j}) = \frac{9{,}81 \times RH_{t,j} \times \bar{H}_{t,j} \times Ef_j}{3600{,}0} \tag{3}$$

$$S_{t+1,j} = S_{t,j} + Inflow_{t,j} - RH_{t,j} - Eva_{t,j} - Spill_{t,j} \quad t = 1,\ldots,T, \;\; j = 1,\ldots,n_R \tag{4}$$

$$\begin{cases} S_{min,j} \le S_{t,j} \le S_{max,j} - FC_{t,j} & If: t \in floodseason \\ S_{min,j} \le S_{t,j} \le S_{max,j} & Otherwise \end{cases} \quad for: \begin{cases} t = 1,\ldots,T \\ j = 1,\ldots,n_R \end{cases} \tag{5}$$

$$HP_{min,j} \le HP_{t,j} \le HP_{max,j} \quad t = 1,\ldots,T, \quad j = 1,\ldots,n_R \tag{6}$$

$$S_{1,j} = S_{T+1,j} \qquad j = 1,\ldots,n_R \tag{7}$$

where, $Inflow_{t,j}$ is the monthly inflow to the reservoir j in month t, $Eva_{t,j}$ is the monthly evaporation of the reservoir calculated by the system simulation model, and $Spill_{t,j}$ is the reservoir overflow. In this study, the minimum monthly energy production is assumed zero, and its maximum value is calculated based on the installed capacity of the power plant and the specified plant factor. To optimize such a complex problem, we need to use adaptive optimization algorithms. The optimization algorithms have different properties, and each has a good performance in a specific set of problems [36]. Among the metaheuristic optimization algorithms, those using self-adaptive operators have greater flexibility and can be used to solve more complex problems [37]. The EM-MOPSO used in this study was introduced by Reddy and Nagesh Kumar [35]. This algorithm is constituted by combining the Pareto dominance principles [38] with the operators of particle swarm optimization. Also, a variable size external repository and an elitist-mutation operator is embedded within the algorithm. The performance of the algorithm was evaluated in comparison to the well-known multi-objective algorithms in solving the basic optimization problems, and its efficiency was demonstrated in solving the Bhadra multi-purpose water resources system in India [35].

In this model, a predefined regression equation is adopted as the reservoir operating rule curves, and the optimum values of the parameters must be determined by the optimization processor [39]. As a result, the decision variables of the problem are the parameters of the system operation curves. The regression relation used in this study is defined to determine the outputs of each reservoir as follows;

$$R_i^t = a_i^t \times S_i^t + b_i^t \times Inflow_i^t + c_i^t \times \sum S_{Upsys}^t + d_i^t$$
$$\begin{cases} i = 1,2,\ldots,n_R \;\; and \quad t = 1,2,\ldots,12 \\ if: i = 1 \; or \; 6 \rightarrow \;\; c_i^t = d_i^t = 0.0 \end{cases} \tag{8}$$

here, R_i^t, S_i^t, $Inflow_i^t$, and $\sum S_{Upsys}^t$ are the reservoir output volume, the storage volume at the beginning of the period, the inflow to the reservoir during the period, and the total storage volume of the upstream reservoirs of the reservoir *i* at the beginning of the period *t*, respectively. a_i^t, b_i^t, c_i^t, and d_i^t are the regression coefficients of the operating relation whose values are determined by the optimization algorithm. Based on this equation, the total volume of upstream reservoirs is considered to be zero for the system's initial reservoirs (i.e. the Dez and the Karun 4 reservoirs).

4. Results discussion

The simulation-optimization model used in this research is developed based on a stochastic search scheme, and therefore the results of individual performances are not certain. Out of these results, 10 independent implementations of the model were integrated together and sorted based on Pareto dominance principle. Fig. 3 shows the final avhieved non-dominated solutions as the trade-off curve of demand supply and energy production objectives.

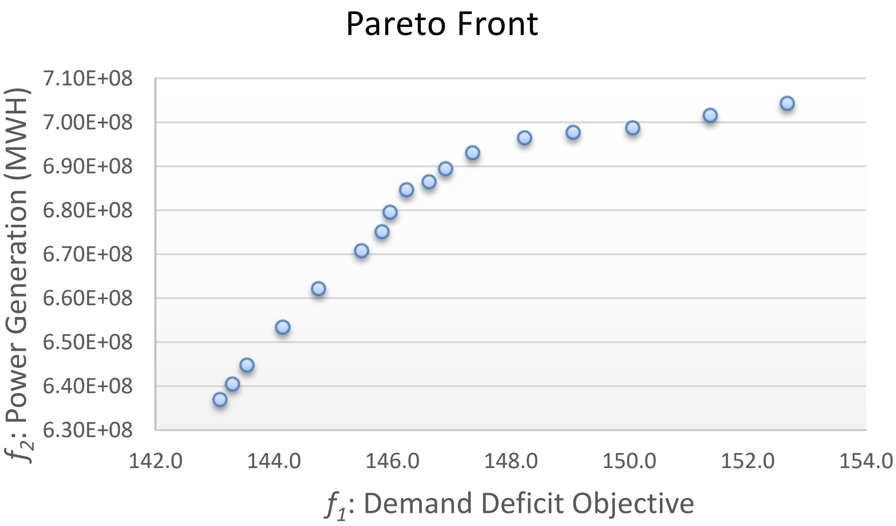

Fig. 3. Pareto trade-off curve of objectives

As can be seen, the maximum hydroelectric energy production is equal to $7{,}04 \times 10^8$ MWH for a long-term period and the best scenario to supply the agricultural demands is when the value of the first objective function is 143.1. These values will be achieved by applying different operating policies to the system's reservoirs. A summary of the simulation results is presented in Tables 2 and 3, respectively, for the best energy generation and optimal demand supply policies.

Table 2. The summarized results of the optimum strategy for demand supply

	Objective function value					
First Object (Demand Supply)	143.1					
Second Object (Power Generation, MWH)	6.37E+08					
	Reservoir					
	Gotvand Olya	Masjed Soleyman	Karun1	Karun3	Karun4	Dez
Mean Annual Power Generation (GWH)	3143.9	2477.4	1998.4	1668.8	838.3	1004.3
Mean Annual Evaporation (mcm)	70.4	29.5	62.7	47.3	33.8	58.3
Mean Annual Spill (mcm)	670.23	1559.8	109.9	2.5	55.5	583.2
Percentage of filling	16.50%	43.0%	4.50%	0.20%	2.50%	13.7%
Percentage of emptyness	11.00%	0.00%	0.00%	0.00%	0.00%	8.35%
	Demand Supply					
	Agricultural	Aquaculture	Municipal	industrial		
Reliability	63.80%	65.40%	100%	97.50%		
Quantitative Reliability	87.30%	88.20%	100%	99.10%		

It can be observed that, with the application of the demand supply policy, the reservoirs release more flow to supply the demands. Thus the storage level in the reservoirs decreased, and the energy production was reduced. The opposite happens in the energy production policy. According to the results presented in these tables, the first objective function which is related to the supply of system demands is not very different in the two policies because of the structural shape of the system. Because of the regulatory dam in the downstream of Gotvand Olya reservoir, all the flows through the turbine that are released to generate energy are also used to supply the demands of downstream regions. As a result, increasing the amount of energy production will increase the amount of demand supply. This reduces the amount of conflict between the two objectives and makes it harder to calculate the trade-off curve of the problem.

Table 3. The summarized results of the optimum strategy for power generation

	Objective function value					
First Object (Demand Supply)	152.7					
Second Object (Power Generation, MWH)	7.04E+08					
	Reservoir					
	Gotvand Olya	Masjed Soleyman	Karun1	Karun3	Karun4	Dez
Mean Annual Power Generation (GWH)	3013.1	2584.24	2105.2	2287.8	1366	1047.7
Mean Annual Evaporation (mcm)	66.1	31.2	63.3	50	36.2	59.1
Mean Annual Spill (mcm)	580.32	1573.4	157.5	53.6	235.8	542.35
Percentage of filling	15.80%	46.2%	4.80%	2.00%	10.00%	14.2%
Percentage of emptyness	0.00%	0.00%	0.00%	0.00%	0.00%	6.32%
	Demand Supply					
	Agricultural	Aquaculture	Municipal	industrial		
Reliability	58.20%	64.1%	100%	96.3%		
Quantitative Reliability	69.70%	76.2%	100%	98.7%		

It is observed that the storage level of all reservoirs with the exception of Gotvand Olya is kept higher in the scenario where energy production is the main objective of the model to produce more energy. This is evident in the Karun-4 and Karun-3 reservoirs, which have more energy production capability due to the geometry and properties of the reservoirs and their volume-elevation curve change ratio. The annual mean of evaporation from the energy production policy is higher than the corresponding values from the supply policy; the reason is that the storage level of the reservoirs is higher during the operation in the energy production model. This does not apply to the Gotvand Olya reservoir where because of the geometrical shape of the reservoirs and their role in energy production, the system prefers to increase the storage level in upstream reservoirs, especially the Karun-4 and the Karun-3; therefore the storage level decreases in Gotvand Olya reservoir, and its evaporation loss is reduced. Other parameters of the system, such as the annual energy generation and spill, also indicate the same process. Fig. 4 shows the mean difference in the monthly storage volume of the reservoirs with respect to active storage volume with the application of two aforementioned policies.

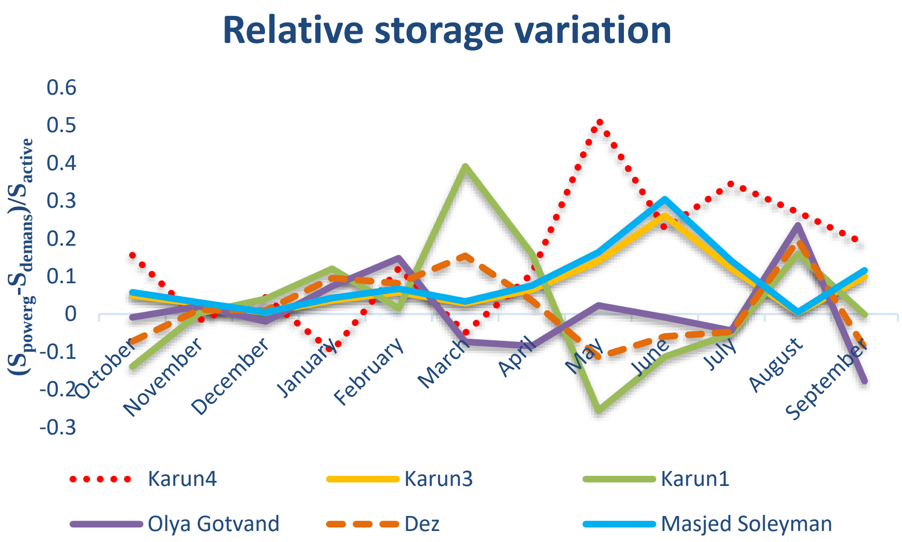

Fig. 4. The monthly mean values of the reservoir storage volume from the simulation of two different policies

As shown in Fig. 4, the mean monthly storage volume of most reservoirs in the energy production policy is higher than its corresponding values in the supply policy. This holds true for the Karun-4, the Karun-3, and the Masjed Soleyman. In Dez, Gotvand Olya, and Karun-1 reservoirs, this procedure is reversed during some months. This indicates that the Karun-4, Karun-3, and Masjed Soleyman reservoirs have more efficiency in the energy production of the system. Therefore, the model attempts to store more resources in these reservoirs in energy production policy. The released flows from the system reservoirs are also spent on the demand supply and will lead to energy production if the reservoir level exceeds the minimum operating level. As a result, the most important contributor to differences in the values of target functions is the storage level of reservoirs in different months.

Fig. 5 shows the average monthly energy generated by different power plants in the long term period. The highest mean energy production in different system reservoirs occurred between March and July. The difference between the energy generated by the implementation of two different policies in the Karun-4 and the Karun-3 reservoirs is larger than the Karun-1 and Gotvand Olya. In Gotvand Olya reservoir, under the supply policy, the amount of energy produced during the period from July to September is significant which is a result of the considerable amount of flow at power plant turbine that is used to respond to the region's demand during these seasons.

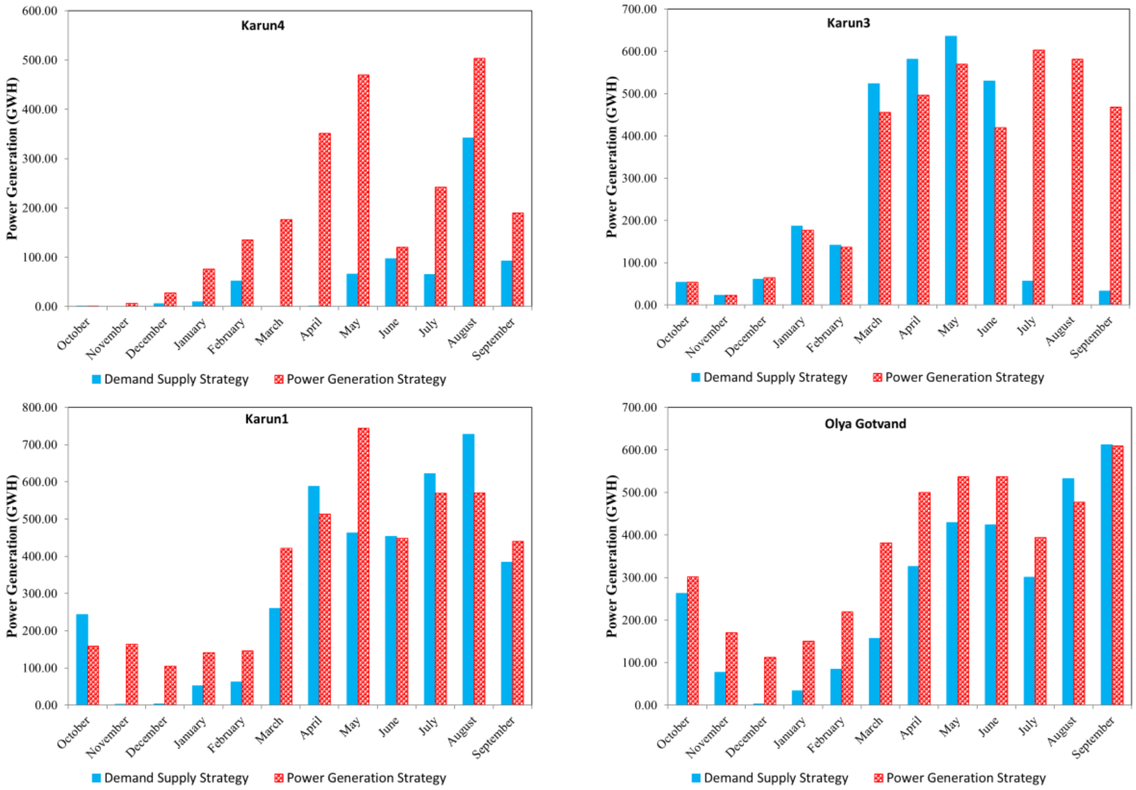

Fig. 5 - Average monthly power generation in power plants using two different operating policies.

In the Karun-4 and Karun-3, which store more water in the energy production policy than the supply policy, the spill values from the application of two different policies differ slightly. The difference is smaller in the Karun-1 and is reversed and negligible in Gotvand Olya reservoir. At the same time, the annual spill in the Karun-4 reservoir is more than the Karun-3. This is due to the lower capacity of the Karun-4 reservoir. The overflows of the Karun-4 along with the significant sub-basin flows enter to the Karun-3 reservoir, which provides a larger storage volume, and are managed there, leading to a smaller annual overflow of the Karun-3.

5. Conclusions

In this research, different multi-reservoir system management policies and their impact on the demand supply rate and hydropower energy production in the Graet Karun system were investigated. The semi-distributed simulation model of the Graet Karun River basin was applied coupled with the modified version of the multi-objective particle swarm optimization algorithm to develop a simulation-optimization model. In this model, the spatial diversity of demand sites throughout the basin is observed in a high-resolution, increasing the accuracy of the simulation model. The main objectives of the system in this study were assumed as maximizing the energy production and maximum supply of different system demands. Using the developed model, the trade-off curve for the aforementioned objectives was extracted, and the extreme points of this curve were examined and analyzed as the points that represent the maximum hydroelectric energy production and maximum supply policies. The results of this study show that the impact of different reservoirs on hydroelectric energy production and demand supply is not the same.

The upstream reservoirs of the Karun River that are located at higher altitudes or in narrow valleys are more efficient in energy production. Therefore, the model utilizes them more than the other reservoirs to produce more energy, whereas the storage volume of the downstream reservoirs is utilized more in the maximum supply policy. This confirms that in order to achieve maximum efficiency, the performance of reservoirs in supplying different demands must be studied and considered in extracting system operating curves.

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