ORIGINAL PAPER

A new optimized model to control eutrophication in multi-purpose reservoirs

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Abstract

The entry of excess nutrients into the reservoir causes problems such as eutrophication, and as a result, we see a decline in the quality of water in the reservoirs and changes in the downstream ecosystem. In this study, a simulation–optimization model has been developed in the framework of selective withdrawal methods to achieve optimal operation policies that can meet the different objectives of the reservoir. A two-dimensional model called CE-QUAL-W2 was used to simulate the reservoir water quality processes. Also, the non-dominated sorting genetic algorithm (NSGA-II) was used as an optimization algorithm in the developed simulation–optimization model. The results show that the dissolved oxygen concentration of the outlet from the lower gate Seimare reservoir for the optimal operation policy is about 30% better than the current operating conditions. In addition, hydropower energy has increased by about 50%. The eutrophication status in the reservoir improved in relation to the existing condition, in most months of the year; the reservoir is in low eutrophication state for optimal operation policy. The results showed the high efficiency of this method and the considerable improvement of the various objectives of the reservoir.

Keywords Reservoir operation · Water quality management · CE-QUAL-W2 · Simulation–optimization · NSGA-II

Introduction

Reservoirs are built to meet various purposes, such as drinking water supply, hydropower production, flood control, and irrigation. But they change the downstream ecosystem and have negative environmental effects on it. On the other hand, the entry of excess nutrients into the reservoir causes problems such as eutrophication, and consequently, we see a decline in the quality of water in the reservoirs. In order to reduce the negative effects of the construction and operation of reservoirs on the ecosystem, the scheduling concept and operation mode of reservoirs need to be changed.

Communicated by Samareh Mirkia.

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In recent years, researchers have conducted studies to assess the negative effects of dams on water quality and proposed different structural and operational solutions for reducing them (Wang et al. 2013; Kuo et al. 2006; Cong et al. 2009; Xu et al. 2012; Deus et al. 2013; Fontana et al. 2014; Sadeghian et al. 2015; Zamparas et al. 2015; Shourian et al. 2016; Saadatpour and Heravi 2016). Selective withdrawal (SW) is one of the effective strategies to improve water quality in the reservoirs and their downstream rivers. SW allows releasing water at different depths with different physicochemical properties (Castelletti et al. 2013). This ability to release water from various depths offers advantages for meeting water quality goals more continuously, by providing a means to avoid undesirable layers (Gelda and Effler 2007). The simulation–optimization approach is used to develop a model that determines the quantity and quality objectives for optimal reservoir operation strategies. In this approach, the water quality simulation models are linked to a multi-objective evolutionary algorithm (MOEA) to derive optimal operational strategies of the reservoir in the selective withdrawal framework (Saadatpour et al. 2017). Another way to improve the eutrophication status and water quality is to release water from the lower layers of the reservoir in

certain months of the year. Based on these methods, the severe thermal layering is done in summer where a part of the water in the lower layers is released with a lot of nutrients, due to the environmental considerations of the downstream river (Chaves and Kojiri 2007; Kerachian and Karamouz 2006; Gelda and Effler 2007; Dhar and Datta 2008; Rani and Moreira 2010; Castelletti et al. 2013; Rossel and Fuente 2015; Soleimani et al. 2016; Saadatpour et al. 2017; Yu et al. 2018; Moridi 2018).

Although advanced studies have been done in the field of modeling and improving reservoir quality conditions, determination of the optimal operation policy of the reservoir in consideration with quantitative and qualitative targets has received less attention from researchers. In reality, the downstream environmental demands are less considered in the operation of reservoirs. Reducing the concentration of nutrients in the reservoir by releasing water from the lower layers of the reservoir (lower gates) is an effective method that has been neglected, and using this method in the framework of selective withdrawal can provide a new approach to the operation of reservoirs.

In this paper, a simulation–optimization model was developed to improve water quality index in the reservoirs by optimization of reservoir selective withdrawal operation strategies. In order to maximize the reservoir water quality index and hydropower energy generation, the proposed model optimized water release from various outlets to discharge the nutrient water from hypolimnion layer considering the downstream water quality limitations. The most appropriate time, rate, and concentration to release nutrient were determined based on hydropower generation energy demand, downstream water demand and river ecology characteristics. As mentioned above, one of the main objectives of this study was to improve the eutrophication status of the reservoir by selective withdrawal water from different outlets. For this purpose, the dissolved oxygen concentration in the bottom layers of the reservoir is considered as an indicator to determine the eutrophication level of the reservoir. Releasing nutrient water from bottom level will effect on energy generation of the reservoir. So, in this study a multi-objective optimization model is linked with the reservoir water quality model, in order to drive optimal Pareto of reservoir operation policies.

To achieve these objectives, a simulation–optimization method has been developed that uses a two-dimensional model called CE-QUAL-W2 to simulate the reservoir quality processes. Also, a multi-objective evolutionary algorithm (EA) called non-dominated sorting genetic algorithm (NSGA-II) is used in it. In this study, the impact of water release from the bottom layers of the reservoir (lower gates) on reservoir water quality was evaluated. Also, in order to extract the optimal operation policy of the reservoir, this method was used in the framework of selective withdrawal as a new approach to determine the most appropriate time and amount of water release from each of the reservoir outlets.

In this study, the release of nutrients from the lower layers of the reservoir in the framework of selective withdrawal and determination of the reservoir's optimal operation policy are considered effective solutions for improving water quality. For this purpose, a simulation–optimization method has been developed that uses a two-dimensional model called CE-QUAL-W2 to simulate the reservoir quality processes. Also, a multi-objective evolutionary algorithm (EA) called non-dominated sorting genetic algorithm (NSGA-II) is used in it. The dissolved oxygen concentration is considered as an indicator to determine the qualitative water status and the hydropower energy generation as one of the quantity objectives of the reservoirs.

Materials and methods

In order to manage the quantity and quality of the reservoir and determine its optimal operation policy, advanced tools and models have been used. The thermal stratification and reservoir eutrophication status were simulated by using the CE-QUAL-W2 model and calibrated based on the observed data. In the following sections, an optimization simulation model has been developed, and the objective functions and the constraints of the problem are defined. In the next step, considering the conflict between quantity and quality objectives, the NSGA-II multi-objective evolutionary algorithm was used to obtain optimal solutions focusing on selective withdrawal. The structure of the developed methodology is shown in Fig. 1.

Reservoir water quality simulation model

The CE-QUAL-W2 model, version 4.0, was applied to simulate water quality. CE-QUAL-W2 is a two-dimensional (2D) hydrodynamic and water quality model, which is capable of predicting the behavior of aquatic ecosystems, such as dam reservoirs, by mathematical simulation. It uses a finite-difference method and has the ability to simulate the vertical and longitudinal distribution of thermal energy and the chemical and biochemical materials selected in the water column over the time. The governing equations are laterally and layer averaged. Lateral averaging assumes lateral variations in velocities, temperatures, and constituents are negligible. This assumption may be inappropriate for large waterbodies exhibiting significant lateral variations in water quality.

Fig. 1 The conceptual model developed for eutrophication reduction in the reservoirs
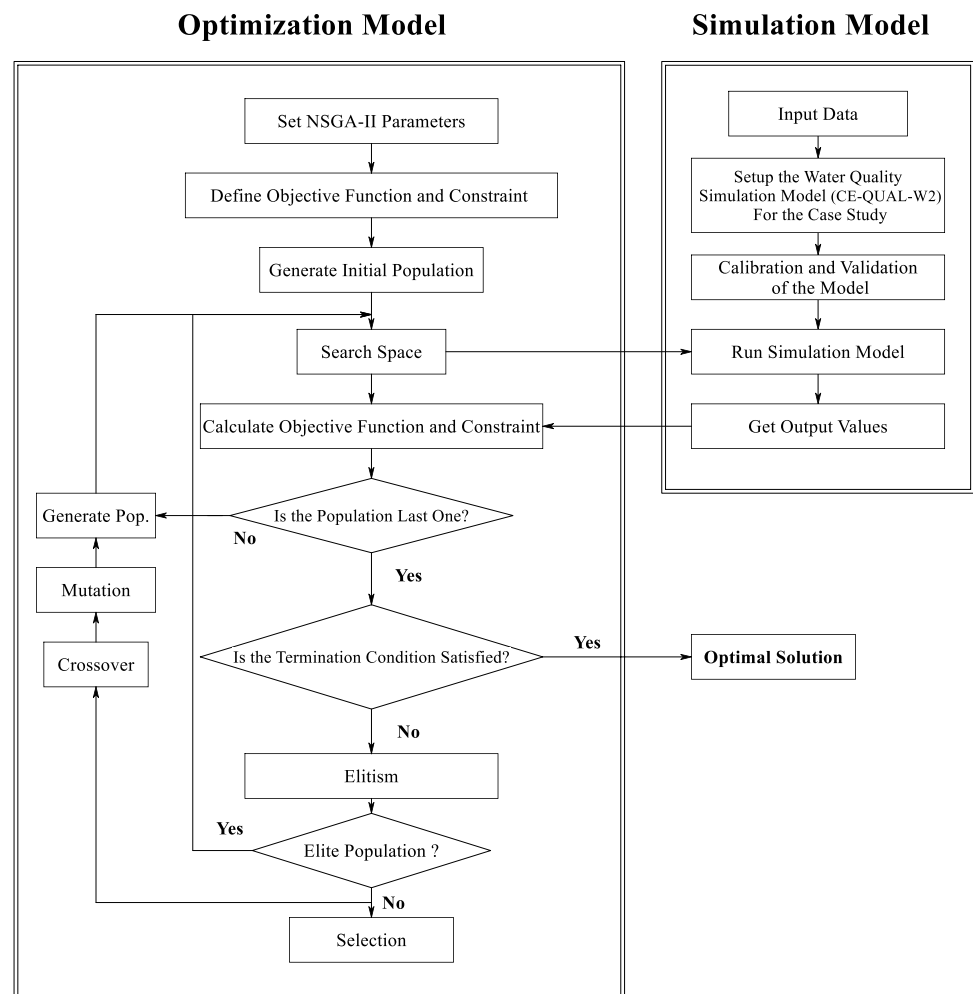
For an application simulation, the CE-QUAL-W2 model requires different data, including bathymetric, meteorological, inflow and outflow volumes, inflow temperatures, evaporation, water quality constituent concentrations, and hydraulic and kinetic parameters. The more accurate and complete the data, the higher the model's accuracy.

This model is very suitable for relatively long and narrow reservoirs and to represent quality parameters as vertical and longitudinal profiles (Cole and Wells 2006). This ability of the model was the main reason for the CE-QUAL-W2 being suited to the simulation of the Seimare reservoir.

Multi-objective optimization algorithm NSGA-II

In this study, a multi-objective evolutionary optimization algorithm called NSGA-II was used to find optimal solutions. Srinivas and Deb introduced the NSGA optimization

algorithm in 1995 to solve multi-objective optimization problems. Deb et al. (2000) introduced the second version of the NSGA algorithm (NSGA-II). They argued that multi-objective evolutionary algorithms with unpredictable sorting and sharing parameters have problems. In their view, the NSGA-II method does not have the limitations and problems of the previous methods. In a series of test functions, they showed that the NSGA-II method has better and faster performance. One of the main features of this algorithm is to store and archive the non-dominated solutions that have been obtained in the earlier stages of the algorithm (elitism).

Simulation–optimization model

As described in the previous section, selective withdrawal has been proposed as one of the effective ways to improve the reservoir quality status as well as to determine the

reservoir's optimum operation policy. In this study, while focusing on this strategy, the quantity and quality objectives of the reservoir were defined so that the quality objective was to improve the dissolved oxygen concentration of the lower layers of the reservoir. This objective, which is one of the ways to improve the eutrophication status of the reservoir, was defined in order to improve the quality of the reservoir. Another objective was the production of maximum hydropower energy, which was defined as the quantity objective. Considering the fact that it is necessary to release water from the upper gate of the reservoir to generate hydropower energy, there was a conflict between the considered objective functions.

Equations (1)–(10) show the mathematical formulation of the optimization model:

$$\text{Maximize } E_t = \eta \cdot r_{k,t} \cdot \text{Gamma}_w \cdot \left(h_t - H_k\right) \tag{1}$$

$$\text{Maximize } C_{k,t}; \quad k = K \tag{2}$$

Equations (1) and (2) represent the objective functions: Eq. (2) to maximize the amount of hydropower energy

generated by the plant and Eq. (1) to maximize the concentration of dissolved oxygen at the bottom outlet of the reservoir to improve the eutrophication conditions.

where E_t is the amount of generated energy in month t, η is the combined efficiency of the turbines, and the electric generator, $r_{k,t}$ is the reservoir release from outlet k, during month t, Gamma$_w$ is a specific weight of water, h_t is the water surface level in month t, H_k is the kth intake level, K is the total number of outlets (Kth outlet is the lowest outlet), and $C_{k,t}$ is the concentration of dissolved oxygen in the release of outlet k in month t.

Equations (3)–(10) show the constraints of the optimization model:

$$R_t = \sum_{k=1}^{K} r_{t,k}, \quad t = 1, \dots, 24 \tag{3}$$

$$S_{t+1} = S_t + I_{t+1} - R_t - \text{Loss}_t, \quad t = 1, \dots, 24 \tag{4}$$

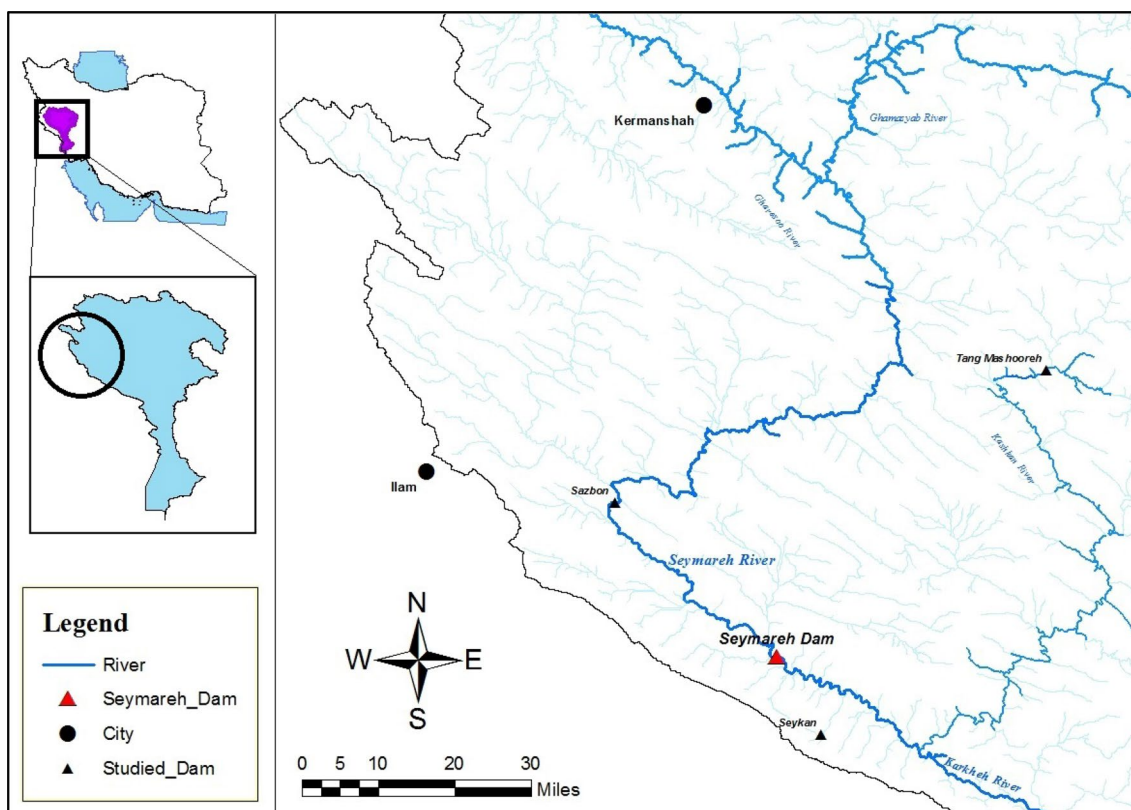$$S_{\min} < S_t < S_{\max}, \quad t = 1, \dots, 24 \tag{5}$$

Fig. 2 Location of Seimare reservoir in Karkheh watershed

$$C_{k,t} = f\left(T_{\text{air},t}, C_{\text{in},t}, I_t, T_{\text{in},t}, r_{k,t}, S_C\right), \quad t = 1, \dots, 24 \tag{6}$$

$$\overline{C}_t = \sum_{k=1}^{K} \left(r_{k,t} \times C_{k,t}\right) / R_t \tag{7}$$

$$\overline{C}_t > C_{\max}, \quad t = 1, \dots, 24 \tag{8}$$

$$H_k > h_t, \quad t = 1, \dots, 24, \tag{9}$$

$$0 \le r_{k,t} < r_{k,\max}, \quad t = 1, \dots, 24 \tag{10}$$

Equation (3) shows that the total monthly release is equal to the total release from different levels of the reservoir in that month, Eq. (4) represents the balance equation of reservoir water in each month. Equation (5) represents the maximum and minimum reservoir capacity. Equation (6) shows that the quality variable concentration of each output layer per month is a function of the inflow temperature, the amount of inflow into the reservoir, the inflow water quality, the air temperature in the reservoir, the release rate from each reservoir outlet, and other variables. Equation (7) shows how to calculate the average concentration of the quality variables in each month. Equation (8) indicates that the average concentration of the quality variables in each

month should not be less than the maximum permissible concentration (3 mg/lit). Equation (9) indicates that the level of water in the reservoir should not be less than the intake level (680 m here). Equation (10) shows that the maximum release rate per month is equal to the discharge capacity of the reservoir gates and at least zero.

where S_t is the reservoir storage at the beginning of month t, I_t is the inflow into the reservoir during month t, R_t is the total release during month t, Loss_t is the total loss during month t due to evaporation, $S_{\min}$ is the minimum permissible reservoir storage, $S_{\max}$ is the maximum permissible reservoir storage, $r_{k,\text{Max}}$ is the capacity of reservoir outlet k, $r_{k,t}$ is the reservoir release from outlet k during month t, $T_{\text{air},t}$ is the air temperature, $C_{\text{in},t}$ is the concentration of water quality variable in the inflow to the reservoir, $T_{\text{in},t}$ is the inflow water temperature, $\overline{C}_t$ is the average concentration of water quality variable in reservoir release during month t, $C_{\max}$ is the maximum permissible concentration of water quality variable in reservoir release, and $f()$ is a function that is presented by the reservoir water quality simulation model.

Solution methodology

As shown in Fig. 1, in the simulation–optimization model, the reservoir water quality simulation model is applied for simulation of the reservoir water quality considering

Fig. 3 **a** Seimare reservoir CE-QUAL-W2 segmentation, **b** Seimare reservoir computational grid and location of monitoring stations

(a)

(b)
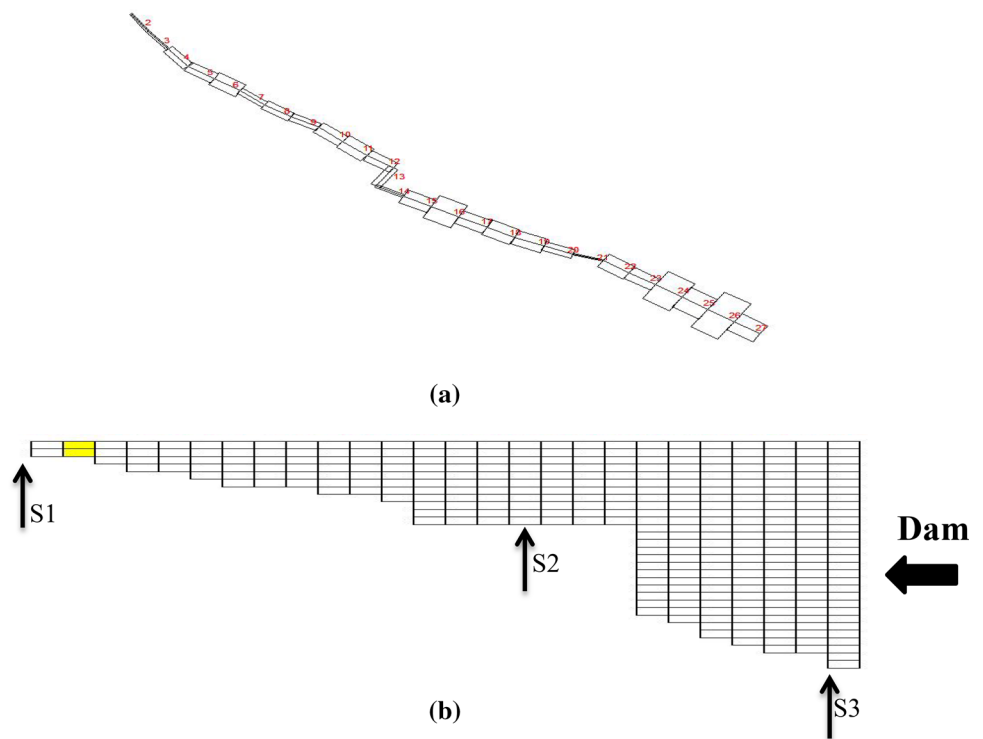
different selective withdrawal scenarios. Also, the value for water release from each outlet (as decision variables in the optimization model) will be determined to achieve the optimal values of the objective functions by applying NSGA-II optimization algorithm. Maximization of hydropower energy production and dissolved oxygen at bottom layer of the reservoir is considered as objective function, and supplying downstream water demand and river water quality downstream of the reservoir are considered as constraint. Downstream water quality and quantity limitations are determined based on limnology study.

The implementation of the simulation–optimization model is described here. The simulation model used in this study is the CE-QUAL-W2 numerical hydrodynamic water quality simulation model. This simulation model is linked to the optimization model (NSGA-II). First, the model parameters (such as population, crossover, mutation, etc.) are set. The elitist-GA-based optimization is utilized to generate the initial population of reservoir release values using a random generator. Each set of generated release values for each of the time periods of operation of the reservoir is sent to the simulation model, which has been implemented for the study area. The simulation model is then solved to obtain the resulting pollutant.

From the first generated community, a number of superior chromosomes whose value is greater than the target function are selected as parent chromosomes to produce the next generation, then these chromosomes are randomly grouped to produce the next generation. In the process of reproduction, parts of the genetic information of two chromosomes are exchanged. This operation is done through mating. This operator usually randomly selects and moves parts of the parent chromosomes. To prevent the convergence of the optimization model responses to local optimal points, the mutations of some of the genes on the chromosomes resulting from the mating process are randomly changed by the mutation operator. This expands the search area of the genetic algorithm into the possible space of answers. By repeating the above steps, the new generations replace the previous generations and the calculations continue until further improvement is not observed in the final answer (Deb 2000). The structure of the developed methodology is shown in Fig. 1.

Results and discussion

One of the large multi-purpose reservoirs in Iran called Seimare has been selected in this study. The Seimare Dam is located over the Seimare River with a watershed area of 27,886 square kilometers, as shown in Fig. 2. This dam was completed in 2013 and has a total storage volume of 3200 million cubic meters. The reservoir's lake is about 60 km long, and the depth of water in this dam can reach 130 m. The average annual discharge of the Seimare River is 85.7 cubic meters per second. The main goals of this dam construction are the supply of drinking water, agriculture, hydropower energy production and flood control. The highest discharge occurs in April, and the lowest occurs in September.

The downstream water quality limitation

The downstream river water quality limitation is defined based on special species limitation and limnologic study near the Seimare Dam site. In order to identify the species of fish in the Seimare River, studies were carried out at three stations, and according to the results, the index species was selected. Then, based on the minimum required dissolved oxygen of the indicator species, the permitted value of this parameter was determined (Yazdi and Moridi 2017a, b).

At the three stations being investigated, 268 fish were caught, most of which belonged to the Cyprinidae family. The Nemacheilidae and Sisoridae families with 2 and 1 species had the lowest number of species. Among the identified species, *C. damascina* and *G. rufa* had the highest relative frequency. Based on the results, *Barbus barbulus* and *Barbus lacerta* were qualified to be considered as indicator species. Finally, the Barbus family, especially *B. barbulus,* was chosen as the indicator of the species in the downstream river to maintain the environmental conditions. Based on the results, in order to observe the environmental considerations and improve the water quality, the minimum dissolved oxygen concentration allowed was considered to be 5 mg/l.

Seimare reservoir simulation model

For quality modeling, the geometric characteristics of the reservoir, including the reservoir shape and reservoir segmentation, were determined, and the vertical layering of the reservoir was also conducted. The number of longitudinal segments is 28. The distance between the segments is 1000 m. The depth segmentation of the reservoir in the model was carried out in the form of layers with a depth of 2 to 4 m and in 32 layers. Figure 3 shows the plan and the final position of the lateral segments. The model was developed for a period of 24 months (February 2011 to February 2013).

Calibration of simulation model

In this section, after simulating the reservoir and implementing the model, the results of the model have been compared with the observed data. The purpose of this is to find the
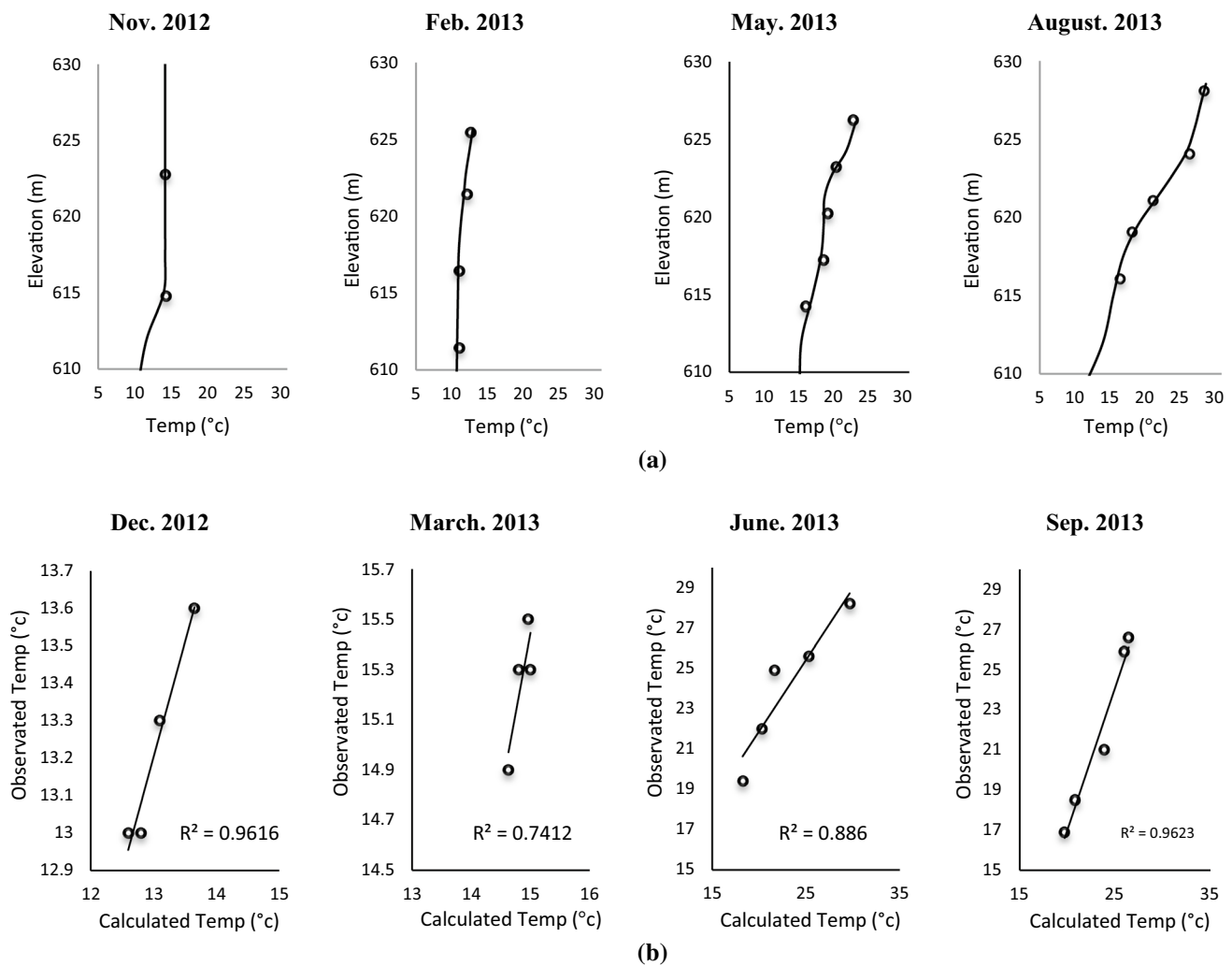
Fig. 4 a Calibration results of temperature in S3 station, b verification results of temperature in S3 station (observed, simulated)

efficiency of the model and the reliability of the results of the simulation model of the reservoir water quality. The temperature and dissolved oxygen were selected for calibration of the reservoir water quality. According to the analogy, from the simulated and observational data, the results indicate the proper functioning of the model and the reliability of the results. The results of this comparison are shown in Figs. 4 and 5.

In this study, due to the limitations of sampling and lack of information, the reservoir water quality simulation period was short and the model was calibrated based on the data collected over a period of one year. So, one of the model uncertainties is related to calibration of the model parameters. Also, in this model changes in water quality and quantity discharged to the reservoir based on externalities such

as climate change, upstream land use changes and other uncertainties related to boundary condition of the model is not considered.

Also, one of the assumptions considered in the model was the constant flow and quality data of the input to the reservoir in situations where these parameters may change in the future, so using the analysis of system response to different scenarios of contamination load input to the reservoir. The input pollution load was investigated on the water quality conditions of the reservoir, and the factor controlling the quality conditions of the reservoir was determined.

In order to identify the different reservoir eutrophication conditions, the reservoir water quality simulation model were run for different scenarios of nitrate and phosphate concentration inflow to the reservoir. In the first scenario,
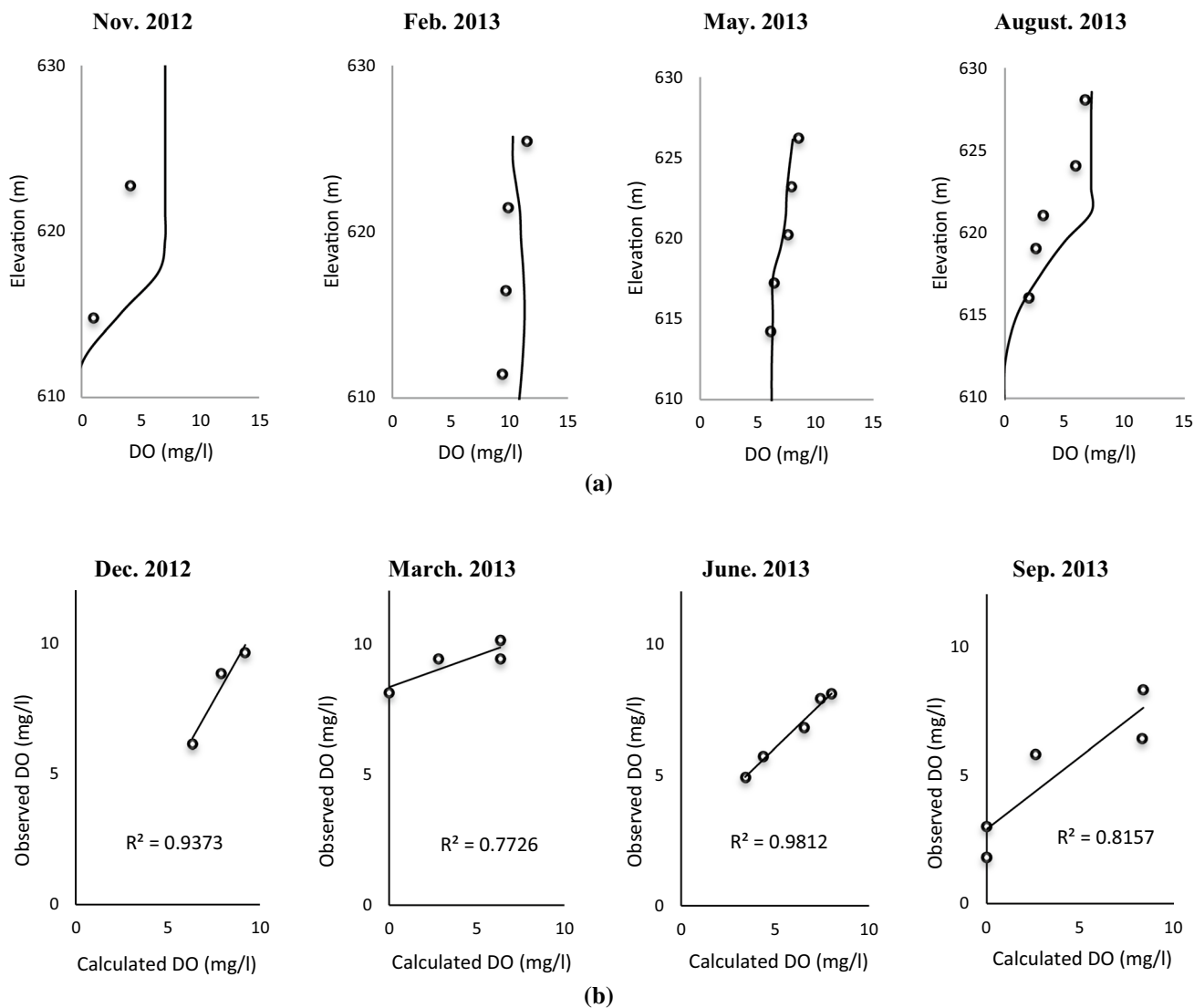
Fig. 5 **a** Calibration results of dissolved oxygen in S3 station, **b** verification results of dissolved oxygen in S3 station (observed, simulated)

Table 1 Results of different scenarios of nutrient input to the reservoir

	Total phosphorus	Total nitrate	Dissolved oxygen	Eutrophication condition
Scenario 1	5.52	0.56	7.48	Mesotrophic
Scenario 2	5.36	0.96	7	Eutrophic
Scenario 3	6.12	0.96	7	Eutrophic
Scenario 4	6.31	3.19	4.06	Hypertrophic

the value of nitrogen entering the reservoir decreased about 50 percent. The second scenario is the current conditions. In scenario 3, the value of phosphorus increased 3 times. In scenario 4 and 5, nitrogen value increased by 3 and 4 times, respectively. The dissolved oxygen changes are presented in Table 1 for various scenarios. As it is shown in Table 1, dissolved oxygen changes are very sensitive to nitrate concentration changes. For example,

a 5% decrease of nitrate in the first scenario resulted in an increase in dissolved oxygen. Moreover, the dissolved oxygen remained constant for any increase or decrease in phosphate. Therefore, phosphorus change could not lead to any change in eutrophication status of the reservoir. On the other hand, any increase in nitrate concentration will lead to a severe reduction of dissolve oxygen and accordingly worsened the eutrophication status of the reservoir. Therefore, nitrogen was considered as the controlling factor of eutrophication status of Seimare reservoir and most strategies for improving eutrophication condition of the reservoir should be planned with the aim of reducing nitrogen pollution load. Furthermore, releasing nutrient water from the bottom-layer in summer is regarded as one method to improve the eutrophication condition of the reservoir. Finally, thermal stratification in summer and the accumulation of nutrients at the bottom layers, and the asymmetry of the season with breeding and spawning period of the fish provide the opportunity for the operators to discharge water from bottom layers in accordance with the limits of downstream ecosystem and accordingly improve the eutrophication status of the reservoir.

Finally, thermal stratification in summer and the accumulation of nutrients at the bottom layers, and the asymmetry of the season with breeding and spawning period of the fish provide the opportunity for the operators to discharge water from bottom layers in accordance with the limits of downstream ecosystem and accordingly improve the eutrophication status of the reservoir.

After constructing a reservoir simulation model and calibrating it, the NSGA-II evolutionary algorithm was used to determine the optimal operating policy that could achieve the desired objective functions. The decision variables in this problem had to be chosen in such a way that the production of hydropower energy would be maximized, and the lower gate would be used for the maximum release of the lower layers of the reservoir. The simulation period of the reservoir was 24 months. The quality and quantity objective functions were then calculated at each time of model execution, and the fitness value of the chromosome was determined. By repeating the algorithm, the optimal solution was obtained in different steps. To do this, the parameters of the algorithm were set so that the population of 100 chromosomes and the number of 5000 iterations were defined. The time to implement the simulation–optimization model was about 25 h. The results of the simulation–optimization model are as follows.

Optimal solutions and existing policies

In Fig. 6, the Pareto front provided by the implementation of the optimization model (NSGA-II) is presented. The first objective is the maximization of the total energy generated, identified by (Z_1). The second objective is the maximization of the minimum concentration of dissolved oxygen released from gate 2, identified by (Z_2).

In order to decide the best strategy in reservoir operation, four optimum results were compared. Table 2 shows the eutrophication status of the reservoir in different months compared with the hydropower generation for each optimum solution.

As shown in Table 2 and Fig. 6, between A1 and A2, the A1 optimum solution is better because by reducing the hydropower generation by 15%, the DO concentration increased only by 5%. Comparing the A1 and A4 optimum solutions shows that by decreasing the hydropower generation by 22%, the DO concentration increased by 20%. Also, at the A1 optimum solution state, the reservoir is eutrophic most of the time.

The concentration of dissolved oxygen reached its maximum in the months of March and April, but with the onset of summer, a significant decrease in the concentration of dissolved oxygen was observed. In July and August, a decrease in the volume of reservoir water and an increase in the concentration of total phosphorus and nitrogen was observed, with the total phosphorus concentration being about 12.6 mg/lit. Based on Carlson's index, the eutrophication status of the reservoir was in mesotrophic state, while the total phosphorous of the reservoir in the state of current policy in these months reached about 80 mg/lit, and the reservoir was in eutrophic mode. Therefore, it can be inferred that the water discharge from the substrate can play an effective role in improving the eutrophication status of the reservoir (Carlson 1977).

According to Fig. 6, the results showed that for optimal solutions, the amount of hydropower energy generation in a year increases from 372.6 to 182.5 MW compared to the existing operation policy and that means 25–52% improvement in hydropower energy generation in the reservoir, which is very desirable. Meanwhile, policy number 4 shows the highest improvement. Also, with regard to the minimum concentration of dissolved oxygen in the lower gate, an improvement of about 4–32% can be observed as in policy no. 1; the total concentration of dissolved oxygen ranged from 1.92 mg/L to about 2.54 mg/L.

The notable point about the solutions is that the higher the amount of hydropower energy generated, the lower the concentration of the dissolved oxygen observed so that the solution that has the highest improvement in the amount of energy generated has the least improvement in the amount of dissolved oxygen concentration. This is a sign of the contrast between the objective functions in the optimization algorithm.
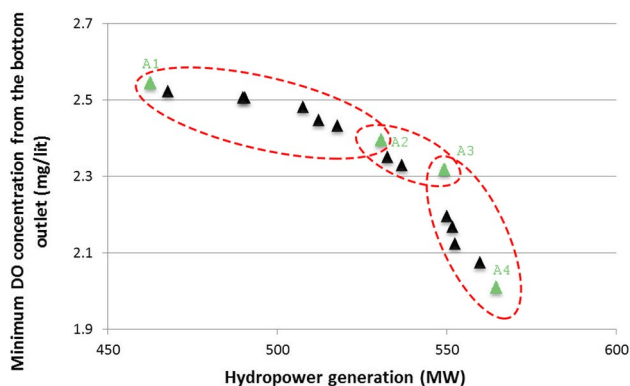
Fig. 6 Pareto optimal front of NSGA-II, showing the trade-off between hydropower generation (Z_1) and minimum concentration dissolved oxygen of release from gate 2 (Z_2) for different outflow scenarios

Flow discharge from the reservoir gates

Figure 7 shows the discharge values of the reservoir gates for the various solutions. In general, it can be seen that the release rate from the hydropower plant gate is the highest in February and lowest in July in all policies. In the current operating conditions of the reservoir, in most months, the output of the lower gate was zero, and the release was conducted only from the upper gate but with optimal policies. Release from the lower gate was significant.

Figure 7a shows the amount of discharge flow from the hydropower plant gate during the simulation period and also the range of variations for the optimal solutions. As can be seen, the value of the discharge flow from the upper gate in the current policy is greater than the maximum output value for the optimal solution; this seems to be correct, considering the lack of use of the lower gate in most months of the year in the current policy of reservoir operation. Figure 7b shows the amount of discharge flow from the lower gate of the reservoir and its range of variations for optimal solutions. As can be observed, during some months, the amount of output from this gate was zero for the existing operation policy, while during most months, the lower gate was used in optimal policies.

According to the results, the months of February, September and October have the lowest release from the lower gate, which seems logical, given the decrease in the amount of water entering the reservoir in summer and the increase in casualties during this season. Given the increase in the inflow into the reservoir in April, May and June, it is expected that these months will have the most release from the upper gate.

Table 2 The eutrophication status of the reservoir for different optimum solutions by the Carlson index (Carlson 1977)

Optimum solution	Gate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Hydropower energy (MW/year)
A1	Eutrophication status	O/M	O/M	O/M	O/M	O/M	M	E/M	E	E	E/M	M	O/M	462.73
	DO$_{Bottom\ outlet}$	4.01	3.63	3.37	3.07	2.94	2.73	2.61	2.54	2.70	2.85	3.39	3.74	
A2	Eutrophication status	O/M	O/M	O/M	O/M	O/M	M	E	E	E	E/M	E/M	M	530.55
	DO$_{Bottom\ outlet}$	3.86	3.48	3.25	2.95	2.89	2.50	2.40	2.39	2.4	2.53	2.86	3.27	
A3	Eutrophication status	O/M	O/M	O/M	O/M	M	M	E	E	E	E	E/M	M	549.43
	DO$_{Bottom\ outlet}$	3.92	3.80	3.33	3.06	2.75	2.52	2.39	2.31	2.42	2.76	2.95	3.34	
A4	Eutrophication status	M	M	O/M	O/M	M	E	E	H	E	E	E/M	E/M	564.48
	DO$_{Bottom\ outlet}$	3.53	3.40	2.83	2.96	2.79	2.59	2.10	2.01	2.15	2.35	2.77	3.14	
Current condition	Eutrophication status	E/M	E/M	E/M	E/M	E	E	H	H	E	E/M	E/M	O/M	552.94
	DO$_{Bottom\ outlet}$	2.77	2.63	2.97	2.71	2.32	2.07	1.70	1.22	1.34	1.57	1.66	2.03	

E eutrophic, *M* mesotrophic, *O* oligotrophic, *H* hypertrophic

Fig. 7 **a** Release of gate 1 during the simulation period and the range of variations for the optimal solutions, **b** release of gate 2 during the simulation period and the range of variations for the optimal solutions
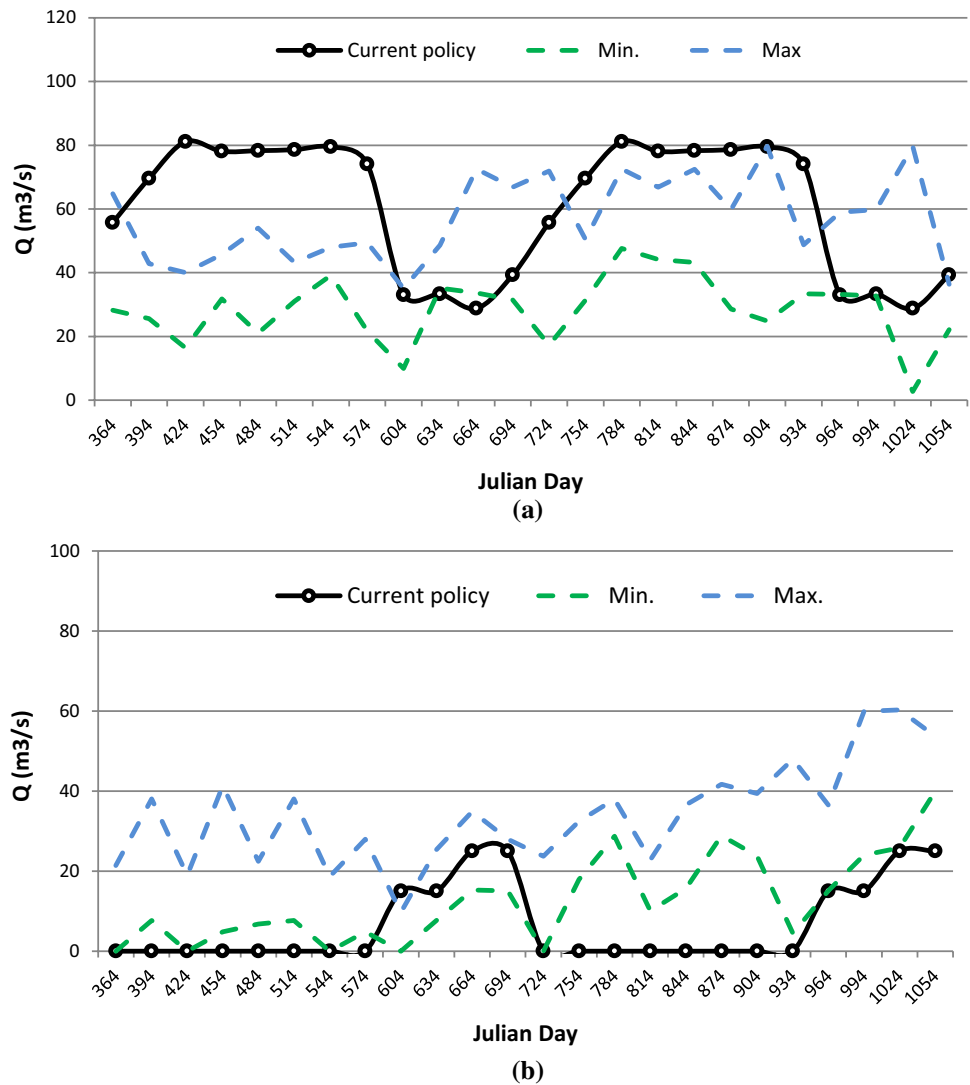

The amount of objective functions per month

Figure 8 presents the monthly values of the objective functions and the range of variations for the optimal solutions. In Fig. 8a, the amount of hydropower energy generated in most months for the current operation policy can be observed to be higher than the hydropower energy generated for optimal solutions. This is due to a reduction in the release from the upper gate and an increase in discharge from the lower gate during those months. According to Fig. 8b, in these months, improvement in the concentration of dissolved oxygen is evident. It should be noted that the amount of dissolved oxygen is zero for months when release from the lower gate is not considered.

Conclusion

Eutrophication is a serious water pollution problem in many lakes and reservoirs. One of the important and effective strategies for the control of eutrophication in dam reservoirs is to control the pollution load discharged to the reservoir from the upstream watershed. So, developing an integrated model for simulating and evaluating the water quality protection strategies of reservoirs based on controlling the upstream point and non-point sources of pollution and also reservoir operation, integration of catchment and reservoir simulation models with each other, using other models of reservoir water quality simulation, considering existing uncertainties, using different optimization algorithms, use of alternative

Fig. 8 a Monthly power genera-
tion and the range of variations
for the optimal solutions, **b**
monthly values of concentration
of dissolved oxygen of gate 2
and also the range of variations
for the optimal solutions
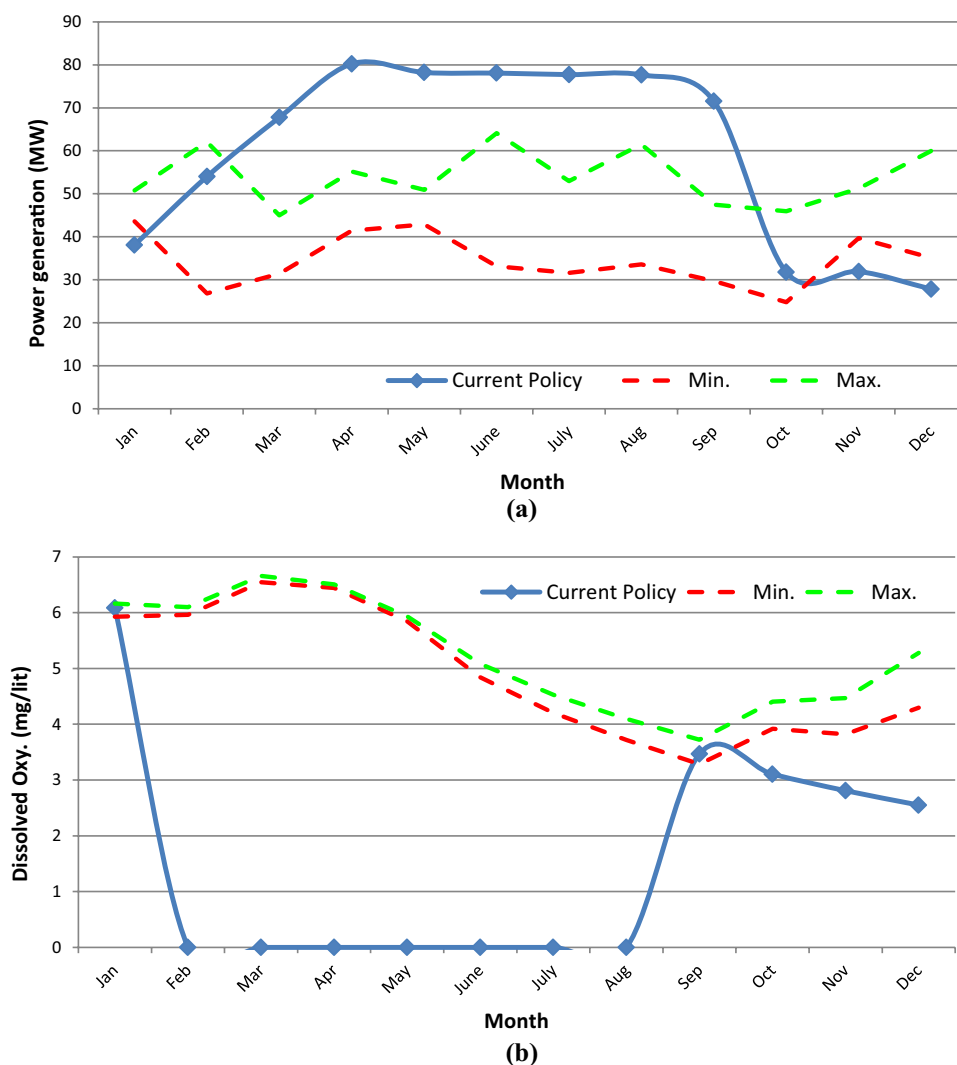
(a)

(b)

models, and considering other quantitative and qualitative
objectives of the reservoir (industry, agriculture, etc.), water
quality control in different parts of the reservoir could be
regarded as applied research topics.

Methods to improve the eutrophication status of the reser-
voirs include suitable quality and quantity operation policies
of the reservoir, which in turn involve releasing the water
from the lower layers of the reservoir in order to remove
nutrients in the seasons in which the reservoir is stratified.
On the other hand, the quantity objectives of the reservoir
should also be provided. In this study, the simultaneous
quantity and quality management of the reservoir was pre-
sented using a non-structural method. The simulation–opti-
mization approach was used to optimize the release rate of
the reservoir gates with the aim of increasing the quality
of the water released from the lower gate and increasing
the amount of hydropower energy generated in this study.

The CE-QUAL-W2 quality simulation model and NSGA-II
optimization algorithm were used to develop the approach.
Finally, the optimal reservoir operation policy was prepared
by taking the quantitative and qualitative objectives into con-
sideration. The application of this method on the Seimare
reservoir shows an improvement of 50% in the hydroelectric
energy generated and also an improvement of 30% in the dis-
solved oxygen concentration discharged from the reservoir.

Simulation–optimization models require a long time
and appropriate computer facilities to achieve the optimal
response. The evolution optimization algorithms, used in
these models, require the high number of function evalua-
tions to achieve the optimal response. In addition, the water
quality simulation significantly increases the computational
intensity so the implementation of the model developed in
this study took about 20 days. Consequently, it is necessary
to consider this issue in future studies.

Based on the results, the release of contaminated water from the bottom layers of the reservoir within the framework of the selected withdrawal method can have a good effect in improving the water quality conditions in the reservoir. However, in dams without water source restriction, the effectiveness of this method can be increased by releasing more water from the bottom layer.

Simulation–optimization models require a long time and appropriate computer facilities to achieve the optimal response. The evolution optimization algorithms, used in these models, require the high number of function evaluations to achieve the optimal response. In addition, the water quality simulation significantly increases the computational intensity so the implementation of the model developed in this study took about 20 days. Consequently, it is necessary to consider this issue in future studies. Another limitation was the lack of information (water quality data) that made the development and calibration of simulation models difficult. Consequently, it is necessary to consider this issue in future studies. Another limitation was the lack of information and hydrological and qualitative data of the reservoir and the existence of many defects in the available data that made the development and calibration of simulation models difficult. Integration of catchment and reservoir simulation models with each other, using other models of reservoir quality simulation, considering existing uncertainties, using different optimization algorithms, use of alternative models, and considering other quantitative and qualitative objectives of the reservoir (industry, agriculture, etc.), water quality control in different parts of the reservoir can be regarded as applied research topics.

Compliance with ethical standards

Conflict of interest We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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