Investigating the capabilities of the NSGA-II multi-objective algorithm in automatic calibration of the WEAP model for simulating Jareh Dam and network system

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ABSTRACT

In the simulation models of water resource systems, calibration processes should be performed to approximate the simulated values to the observed values due to the errors in such models. However, due to being time consuming and the difficulties associated with manual calibration, an automatic calibration model can be a resolver. In this research, the simulation of Jareh Dam and network system was conducted using the WEAP model. Then, by linking this model to the NSGA-II algorithm, its automatic calibration was performed by this algorithm. Nach statistical parameter was used to check the calibration accuracy of the model. The whole system was in the form of a multi-objective NSGA-II algorithm, in which the first objective function, which was to minimize the difference between the observed and the calculated reservoir storage volumes, was assessed versus the second objective function, which was to minimize the difference in the calculated and the simulated discharges, at two Mashin and Jokank stations. The results showed the remarkable ability of NSGA-II algorithm for automatic model calibration, so that the operation status of the dam and river was of the greatest consistency with reality.

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1. Introduction

The complexity of water resources systems and the existence of different and sometimes contradictory goals together make it difficult to manage these resources properly. In this regard, simulation is a flexible tool, which is widely used for complex analysis of water resources systems. The system of interest should be introduced and described in both aspects of design variables and withdrawal policies, and then can be simulated to determine its performance quality (Bozorg Haddad and Aghmuni 2013). Various simulation models have been developed for this task and have been moved toward decision support systems (DSS) along with the advancement of software capabilities. In basin simulation models, most water resources systems are represented in a network of arms and nodes and the algorithms for solving flow network models are used for determining the spatial and temporal distribution of allocable water resources (Karimi and Mousavi 2011).

Among these models, the WEAP model can be named, which has attracted researchers’ attention in recent years due to its user-friendly structure. For example, Alfarra (2004) employed the WEAP model to examine the status and problems that would be created in the future in a basin in Kenya. The results indicated that in the study area, the water allocation for agricultural sector is more than the demand in some areas, and in some other areas, this demand is not fully met. Abrishamchi et al. (2007) used the WEAP model in the Karkheh Oila River basin to study the effects of water and land resources developments on urban, industrial, and agricultural uses as well as the inflow into Karkheh Dam reservoir. The results showed that the WEAP model has a remarkable ability for studying water resources management scenarios at a river basin scale. Purkey et al. (2008) used the WEAP model to assess the impact of water resources allocation management to the agricultural sector under the climate change conditions in California. The results showed that applying managerial constraints would improve the condition of the water resources of the region. Mutiga et al. (2010) used the WEAP model in order to balance the water demands on water resources of the study area to achieve an appropriate economic and biological sustainability. Alfarra et al. (2012) used the WEAP model to assess the water resources of their study basin. To this purpose, they investigated 5 scenarios by 2050. Hamlat et al. (2013) studied the application of the WEAP model in the western Algeria basins. The results showed that the WEAP model provides planners with reliable results to use in the future.

Lee et al. (2015) used the WEAP model to assess the sustainability of limited water resources in their study area. Hum and Abdul-Talib (2016) utilized the WEAP model to evaluate water resources and the current uses in Selangor by 2050. Rafiee Anzab et al. (2016) presented an optimization simulation model by linking the WEAP model to the PSO algorithm in order to optimally design and operate the water transfer project from Karoon River to Zohreh River in Iran. The results showed that the water transfer project could meet the water required for the development of Dah Dasht and Cheram agricultural lands in the undeveloped areas in the north of Kohkiluyeh province. Movahedian Attar and Samadi Broujeni (2013), evaluated the performance of Zayandehrud Dam using the WEAP model in four scenarios, and finally by comparing the existing reliability indicators and the existing scenarios could choose the superior scenario.

Azari et al. (2015) presented a conjunctive withdrawal model of surface and underground water resources while aiming to observe all the constraints and quality standards along Dez River. To this end, the system was simulated by the dynamic linking between the WEAP and MODFLOW models. Ghandezari et al. (2015) used the WEAP model to study the temperature and precipitation changes in Neishabour River basin and the effect of these changes on the river by means of the outputs of general atmospheric circulation models (HADCIM3) and statistically downsampling methods (SDSM). Reviewing the conducted researches showed that in the models developed to simulate water...
resources systems like the other simulation methods, calibration processes should be performed to approximate the observed and the simulated values to each other due to errors in the model.

Wang (1991), Madsen and Torstcn (2001), Zhang et al. (2008), and Huang and Lei (2010) investigated various calibration models using evolutionary algorithms. Also, Arkan and Godal (2014) used a non-dominated sorting genetic algorithm to conduct a multi-objective calibration of the SWAT model, where the results showed the multi-objective calibration of model improved its capabilities. In order to calibrate the CE-QUAL-W2 qualitative model, Afshar et al. (2011) used automatic calibration in their research. The results of automatic calibration showed that the observed and the calculated values approached each other more. In order to calibrate the SWAT model, Bekele and Nicklow (2007) used automatic calibration by the NSGA-II algorithm. The results showed a better accuracy of the model due to the automatic calibration of parameters. Muleta and Nicklow (2005) used automatic calibration to calibrate the SWAT model in their study basin.

In this research, the simulation of water resources systems of Jareh Basin located on Allah River was conducted with the aim of integrated water resources management in this basin. But, due to the complexity of the system caused by the lack of proper information about the significant discharge of the medial basin resulting from the confluence of A'la River with Allah River between the Jareh Dam reservoir and the downstream diversion dam, it was time consuming and difficult to correctly simulate the system. Therefore, the main goal of this study is to investigate the capability of the NSGA-II multi-objective evolutionary algorithm in calibrating this system automatically and to evaluate the results considering the current status of the dam and river operations.

2. Materials and methods

2.1. Study area

The study area is located in the southwest of Iran in Khuzestan province, within the 35-km distance from the northeast of Ramhormoz city near Jareh village, which is in the 90-km distance from the east of Ahwaz and in the southwestern slopes of Zagros and consists of two basins including A'la River and Zard River basins. Zard River is one of the main branches forming Jarrahi River, which is one of the fullest flow rivers in the province of Khuzestan.

Zard River basin is in the northeast and east of Bagmalek city highlands (Mangash Mountain). In the confluence of Abolabas River and Ab-Takht River, Zard River is formed. By joining A'la River to Zard River, Allah River is formed at Zard River village, and after this river joins Maroon River, Jarrahi River is formed. The Jareh Dam reservoir is built across Zard River.

The dam is an earthy type with a clay core with a crown length of 740 meters and a crown width of 12 meters. The dam was built with the aim of providing water for the right and left banks of Ramhormoz irrigation network, and also producing hydroelectric power. The water level of the dam is 255 meters and the crown width is 12 meters.

In this research, in order to prepare the WEAP model, the exact location of the rivers, Jareh Dam, district hydrometric stations, and the water demands of the left and right banks of Ramhormoz were determined using GIS software. Then, by recalling it in the WEAP model, each of the complications was embedded with the provided tools. The schematic model of the studied basin is shown in Figure 1. In the created model, the simulation was considered for 4 years of the operation period of the dam from October 2010 to September 2014 because of the data being available since the start of dam operation in 2010. Then the information about all of the resources and uses, including the data on the operation of Jareh Dam such as dead volume, volume at the minimum operation level, volume at the maximum operation level, ..., information on the recorded discharges at the hydrometric stations of the area, information on the surface and underground water withdrawals on the left and right banks of Ramhormoz and the environmental water demand at the downstream of the dam were introduced into the model as a CSV file.

The water demand of the right and left banks of Ramhormoz irrigation and drainage network was calculated using the regional cropping pattern gotten through the information obtained from Khuzestan Water and Power Organization and the agricultural statistics of recent years. Afterwards, the groundwater withdrawal amount in these two plains were calculated using the information obtained from the operation wells of Ramhormoz left and right banks and were introduced into the model. The amounts of surface and groundwater withdrawal in these plains are shown in Fig. 2.

Also, the information about the discharges recorded at the hydrometric stations of the district from the Khuzestan Water and Power Organization was received daily and their monthly mean was calculated and introduced into the model. Fig. 3 shows the long-term mean monthly discharges recorded at Mashin and Jokank stations.

In order to correctly establish the water balance in the study basin and to simulate it properly, and because there is no hydrometric station for measuring the flow in A'la River, as well due to the massive flow of A'la River entering into the study basin in the rainy seasons, the inflow from A'la River to the basin was simulated. To this purpose, having data recorded at the Mashin and Jokank stations, due to the location of these stations before and after the intersection of A'la and Allah Rivers, the inflow was simulated through this branch and was introduced into the model.

Actions such as dam construction, increasing water withdrawal along rivers, water transfer, etc. can affect the natural regime of a river. This will reduce the natural flow of the river and will affect the ecosystem of the region, hence, the minimum ecological requirements of the region should be met. Therefore, in this research, in order to meet the minimum ecological demands required by the ecosystem at the downstream of Jareh Dam, an environmental node was defined. To calculate the environmental flow, the fair state of Tentant method (Montana) was applied. This method is one of the hydrological methods for determining the minimum environmental flow that determines the minimum flow as a right of the ecosystem at the downstream of the normal river flow. The calculated values for the environmental flow was 1.78 m³/s (for Oct to Mar) and 5.35 m³/s (for Apr to Sep).

2.3. Calibration of model

Due to lack of sufficient information for the A’la branch, in the initial investigations the simulation of the flow in this river was done using the discharge differences recorded at Mashin and Jokank stations and the initial simulation of the system was carried out. After preparing the surface water model of the area to match the results of the model with the current state, the calibration of the model was implemented through linking the NSGA-II evolutionary algorithm to the body of the WEAP model. To this purpose, the code associated with this algorithm was developed and implemented based on the issue in the MATLAB environment. At each iteration, due to the lack of sufficient information on downstream uses, the total release rate from the dam was considered as decision variables in different months during the 4-year simulation period. The algorithm was defined multi-objective, so that, the first objective was to minimize the difference between the observed and the calculated reservoir storage volumes by the model versus the measured volume, the second objective, which was to minimize the difference between the calculated and the simulated discharges at Mashin and Jokank stations using the Nash function. A 500-iteration run was considered as the optimization stopping criterion of the algorithm so that the objective functions reach their lowest values.
Fig. 1. Satellite image of the study area (rivers, resources, and uses).
Several methods are available to solve multi-objective optimization equations, including Weighted Sum Method, Epsilon-constraint Method, Goal Attainment Method, and Multi-Objective Evolutionary Algorithms (MOEAs). In this research, the non-dominated sorting genetic algorithm (NSGA-II) was used due to its ability to solve complex problems and to provide an optimal exchange curve among the goals. This model can easily deal with problems that do not follow a particular continuous, has no integrated rational decision space, or their objective functions have random parameters. The major problems of the previous multi-objective optimization models include the enormous calculation volume at each iteration, which leads to increase the model implementation time and the inability to maintain a good number of superior values during the implementation of the model. The main structure of this model is shown in Fig. 4.

The implementation steps of this multi-objective optimization model are as follows:
1. Producing $P_0$ randomized parent generation equal to the number of N.
2. Sorting the initial parent generation based on non-dominated sorting method.
3. Allocating suitable ranks corresponding to the non-dominated sorting level of each non-dominated sorting, which includes rank 1 for the best balance, rank 2 for the best balance after 1, and so on.
4. Producing the offspring generation equal to N using selection, coupling and mutation operators.
5. According to the first produced generation, which includes the chromosomes of parent and offspring, a new generation is produced as follows:
   * Combining parent chromosomes, $P_0$, with offspring chromosomes, $Q_0$, and producing generation $R_1$ equal to 2N.
   * Sorting the generation $R_1$ according to the non-dominated sorting method and identifying and categorizing non-dominated fronts ($F_1$, $F_2$, $F_3$, …, $F_L$).
   * Producing parent generate for the next iteration ($P_{t+1}$) using non-dominated fronts generated equal to the number of N. At this stage, based on the number of chromosomes needed for the parent generation (N), first the chromosomes number of the first front of the parent generation is selected, and if this number does not meet the total number needed for the parent generation, then the fronts 2, 3, and etc. are taken sequentially to obtain the total amount (N).
   * Applying coupling and mutation operators to the newly-produced parent...
generation \( P_{n+1} \) and producing the offspring generation \( Q_{n+1} \) equal to the number of \( N \).

* Repeating step 5 to achieve the total number of iterations of interest.

The closer the Nash parameter to one is, the greater the correspondence of the simulated values with the observed values. The abovementioned function was utilized to calculate the calibration accuracy in comparing the monthly simulated and observed values of the storage volume of Jareh Dam reservoir, as well as assessing the calibration accuracy of the simulated and the observed discharges of Mashin and Jokank stations. In which, the objective function in the evolutionary algorithm is to minimize each of the aforementioned values using the Nash function. But because the minimization of the abovementioned function makes it closer to zero, the objective function valuation, \( t \) model, regarding the population size of 96 and after 500 iteration, the model was calibrated with acceptable accuracy. Moreover, the objective exchange curve (Pareto graph) between the desired objectives (the function of model calibration for the observed and the simulated reservoir volumes and the objective function of model calibration for the observed and the simulated discharges at Mashin and Jokank stations) was obtained. The Pareto graph is shown for the 500th iteration in Fig. 6.

According to the non-dominated sorting genetic algorithm, at each iteration, the best answers are selected based on valuating the objective functions and the elitism process and are stored as the optimal set to be transferred to the next generation. The points drawn in the Pareto graph are the appropriate answers for matching the observed and the calculated values of the model better. Besides, the axes of this graph are the objective functions. At the last iteration of the model, 45 optimal answers were presented, of which, according to the objective function valuation, the best answer, which was the one with the least value for the two objective functions, was selected as the superior answer and the results of its implementation were examined in the surface water model.

After calibrating the model by the algorithm, the observed and the simulated values at Mashin and Jokank stations, as well as the observed and the simulated reservoir volumes in the model, were obtained in accordance with Figures 7 to 9. As it can be seen in the figures, the calibration processes are performed with acceptable accuracy, and the observed and the simulated values are in good agreement with each other.

After calibrating the model and ensuring its accuracy, its results can be applied to interpret the current status of the region. The results of implementing the model for supplying percentage and demands reliability are presented in Table 1. As it is clear, it can be concluded that all the demands are fully met during the entire simulation period, which indicates that there are no shortages of supplies for the studied basin. The average values of release from Jareh reservoir were calculated by the model for various uses and are presented in Fig. 10.
Fig. 5. Exchange curve between the objectives at different iterations.

Fig. 6. Optimal exchange curve among the optimization objectives (Pareto curve) at the 500th iteration.

<table>
<thead>
<tr>
<th>Demands</th>
<th>Supplying percentages (Coverage (%))</th>
<th>Reliability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep</td>
<td></td>
</tr>
<tr>
<td>Ramhormo's Right Bank</td>
<td>99.7 100 100 100 100 100 100 100 100 100 100</td>
<td>98.9</td>
</tr>
<tr>
<td>Ramhormo's Left Bank</td>
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<tr>
<td>Environmental</td>
<td>100 100 100 100 100 100 100 100 100 100 100</td>
<td>100</td>
</tr>
</tbody>
</table>
Fig. 7. Observed and simulated values at Mashin station and the outlet of Jareh Dam.

Fig. 8. Observed and simulated values at Jokank station and the entrance of A’la River into Allah river.

Fig. 9. Observed and simulated values of the Jareh Dam volume.
4. Conclusions

The calibration of models is important in order to make their results closer to the observed values in modeling processes. However, due to the unique complexities of these models, especially in the absence of accurate recorded information on the river discharge of the existing medial basins, or in the absence of accurate statistics on the amount of water withdrawal at downstream of the river, manual calibration is difficult and time consuming. In this research, the ability of non-dominated sorting genetic algorithm (NSGA-II) was used by defining multi-objective functions for automatic calibration of WEAP model in the basin of Jareh Dam and network. The results showed that using this algorithm, the systematic simulation of the study area takes less time than manual calibration and is much satisfactory in terms of accuracy. The model was converged and calibrated by selecting the initial population of 96 and after 500 iterations. During the optimization process, the model focused on the reduction of the both objective functions, but at the final iteration, along with a slight decrease in the difference between the simulated and the observed discharge at the stations, it focused on reducing the simulated and the observed reservoir storage volumes more. After calibrating the model by the algorithm, it was observed that the simulated values by the model match very well to the observed values, which was analyzed using the Nash statistical parameter. At the last run of the model and after choosing the best solution among the proposed optimal solutions in the objective exchange curve, the value of this parameter for Mashin and Jokank stations as well as for the reservoir storage volume was 0.96, 0.94, and 0.82, respectively, which was completely acceptable. According to the results, it can be concluded that the algorithm has a great ability to calibrate the corresponding model, which can improve the simulated values in the model and makes them approach to reality.

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