



# Multi-Objective Optimization for Interactive Reservoir-Irrigation Planning Considering Environmental Issues by Using Parallel Processes Technique

Ahmad KhazaiPoul, et al. *[full author details at the end of the article]*

Received: 6 April 2019 / Accepted: 10 November 2019 /  
Published online: 1 December 2019  
© Springer Nature B.V. 2019

## Abstract

Water allocation to different users implies a trade-off between the benefits perceived by different sectors and environmental demands. This conflict, considering the income of different sectors and environmental issues, is very crucial, especially in reservoir operation. In this study, a multi-objective optimization algorithm combined with two simulation models (SWAT and WEAP) has been developed to consider the tradeoff between agricultural benefit and environmental water demand through parallel processing. In this model, decision variables are monthly agricultural demands which are considered as inputs into the Water Evaluation And Planning (WEAP) model. Then, the production of different crops and discharge to the downstream lake are obtained based on the allocated water to each sector using the Soil and Water Assessment Tool (SWAT) model. After the simulation, the objective functions are calculated based on agricultural income and environmental flow discharged to the downstream lake. To evaluate the performance of the proposed model, Mahabad reservoir, in Mahabad river basin (located at the south of the Lake Urmia and northwestern of Iran), was studied during a drought period. This reservoir supplies domestic, industry, agriculture water of the Mahabad plain and downstream environmental demand which is discharged to the Lake Urmia. Non-dominated Sorting Differential Evolution (NSDE) algorithm is used to find the optimal water allocation to different sectors and efficient agricultural irrigation patterns of different crops (winter wheat, alfalfa, apple, and sugar beet). Results showed the optimal operation of the reservoir through irrigation management could improve water stress indicator from 80% in traditional irrigation pattern to 60%, only by 6.5% decrease in agricultural income. Also, the inflow to Urmia Lake was increased from 173 MCM to 354 MCM during the drought period (5 years).

**Keywords** SWAT-WEAP-NSDE · Optimization · Agricultural benefit · Environmental flow · Mahabad Basin · Urmia Lake

## 1 Introduction

Attempts for adequate food production and economic development due to the rapid population growth have led to large amounts of withdrawal from water resources (Malano and Davidson 2009; Pang et al. 2013). Water scarcity and droughts are the main concern in arid and semi-arid regions. The agriculture sector is mostly a major user of water which releases significant amounts of freshwater. This withdrawal which is often more than the capacity of surface water resources leads to a decrease in river discharge (Rumbaer et al. 2015) and drying many lakes and wetlands. Therefore, supplying agricultural and environmental demands are conflicting objectives and its resolution requires comprehensive and accurate studies (King et al. 2003; Sun et al. 2008). There are several methods to solve this problem. A part of these conflict resolution methods is based on game theory and graph theory (Almazan-Gomez et al. 2018; Moradi and Limaie 2018). There are also mathematical models for conflict resolution that can be integrated with optimization tools, for example, the method of Non-Symmetric Nash Solution, Kalai-Smorodinsky, Equal Loss Solution and Area Monotonic Solution (Raquel et al. 2007; Llopis-Albert et al. 2018). Several studies have been done to resolve conflicts between stakeholders or to strike a trade-off between the interests of different stakeholders. Xu et al. (2019) investigated the effect of climate change on the conflict resolution between hydro-power production and environmental flow. Zhang et al. (2018) developed a trade-off between shallow groundwater conservation and crop production by using the Soil and Water Assessment Tool (SWAT) in the Haihe River basin in China. They introduced various strategies for aquifer recovery, no-fluctuation in groundwater level and ultimately the satisfaction of self-sufficiency conditions in winter wheat production with the lowest groundwater drop. Al-Faraj et al. (2016) studied crop production in the transboundary Diyala basin, between Iran in upstream and Iraq at the downstream. They suggested an optimal trade-off between crop production and irrigation water. Perez-Blanco and Gutierrez-Martin (2017) calculated the compensation to farmers instead of more water withdrawal to conflict resolution between agricultural and environmental stakeholders in the Segura River Basin in Spain. In the case of water withdrawal reduction by the farmers, it is possible to allocate more water to the environment. In this case, the flow required for the environmental demands is provided and the satisfaction of the farmers will also be attracted. Another similar study has been done by Xue et al. (2017) to create a trade-off between agricultural development and environmental protection in Qira oasis, in the arid regions of Northwest China.

As mentioned before, in recent years, conflict resolution models have been significantly gained attention for developing policies of water allocation to different sectors. This paper contributes towards developing a mathematical framework for optimal water allocation to different sectors by integrating the SWAT and WEAP models with the NSDE optimization algorithm.

The aim of this work is the optimal operation of surface reservoirs in drought conditions to allocate the maximum amount of water to downstream environmental demand and also to obtain the most possible income from irrigated cropland. Thus, a multi-objective optimization model combined with two simulation models (SWAT and WEAP) has been developed to consider the tradeoff between agricultural benefit and environmental water demand through parallel processing. The application of parallel processing within the optimization routines in the context of water allocation and the array of technical tools (e.g., SWAT, WEAP, NSDE, etc.) employed is another aspect of the scientific contribution in this work.

## 2 Methodology

As mentioned before, agricultural development and environmental issue are conflicting objectives. In the following, an algorithm has been introduced in which the combination of two hydrologic and water resources planning models in the form of an optimization structure was used to find a trade-off between agricultural income and environmental conservation.

The flowchart presented in Fig. 1 shows the interaction between simulation models (SWAT and WEAP) and the optimization model. As presented, the WEAP model is prepared for the study area based on available data such as domestic, industrial and environmental water demands information, and inflow time series to the reservoir. Also, the monthly nominal irrigation demand of different crops is given to the model. Nominal irrigation demands of agriculture are decision variables in the optimization model. After simulation by the WEAP model, the amount of monthly allocations is obtained. The next step is to prepare and convert data to the SWAT model with an acceptable format. In this model, domestic and industrial monthly demands are supplied from the river downstream of the reservoir. The SWAT model is prepared based on available data such as digital

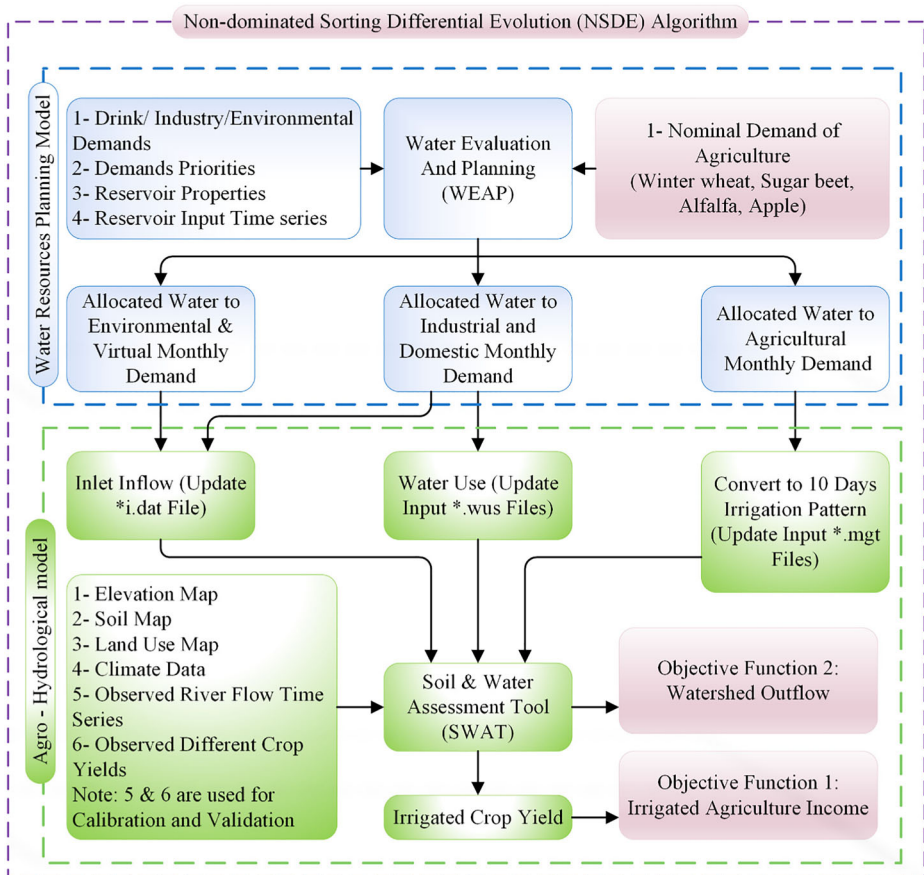


Fig. 1 Flowchart of the proposed model for interactive reservoir-irrigation planning at basin scale

elevation model, land use and soil maps and climate data. The model is calibrated and verified based on available measured data of flow and crop yields in the study area.

As shown in the optimization process the production of the crops per year is obtained based on the results of the SWAT model and agricultural income (first objective function). Also, the amount of outflow at the downstream of the basin as the environmental flow forms the second objective function.

## 2.1 Optimization Framework

### 2.1.1 Objective Functions

In this problem, optimal reservoir operation is the basis of reaching objectives. The objective functions of the optimization model are shown by Eqs. 1 and 2. Equation 1 is the economic objective function that attempts to maximize irrigated crops. Equation 2 refers to the second objective function and it is in favor of environmental interests and tries to maximize allocated water to environmental demand.

$$f_1 : Z_1 = \max \left( \sum_{j=1}^M \left( \sum_{i=1}^N P_i \cdot A_i \cdot YLD_i^j \right) \right) \quad (1)$$

$$f_2 : Z_2 = \max \left( \sum_{t=1}^T (D_t \times 24 \times 3600 \times Q_t) \right) \quad (2)$$

In the first equation, the amount of income is the function of crop production that is estimated in the SWAT model. In this equation, N is the number of total crops.  $YLD_i$  is the yearly yield of crop  $i$  in basin-level (Kg).  $P_i$  is the price of crop  $i$  in (USD/Kg).  $A_i$  is the cultivation area of crop  $i$  and M is the number of total years.

The second equation represents the outflow of the basin, which supplies downstream environmental demands.  $Q_t$  is the amount of monthly outflow in month  $t$  to downstream of the basin in ( $m^3/sec$ ) and T is the number of total months in the simulation period.  $D_t$  is number days of month  $t$ . The coefficients have been applied to convert the flow to volume. The lower the amount of reservoir allocated water to the agriculture, the more released flow to downstream of the basin.

### 2.1.2 Constraints

The water balance equation which is one of the constraints of the optimization problem is satisfied implicitly by running the SWAT model. This equation in SWAT is as follow:

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{sur} - E_a - W_{seep} - Q_{gw}) \quad (3)$$

In which  $SW_t$  is final soil water content in mm,  $SW_0$  is initial soil water content in mm (to 30 cm depth),  $t$  is time in day,  $R_{day}$  is the amount of precipitation on day  $i$  in mm,  $Q_{sur}$  is surface runoff in day  $i$  in mm,  $E_a$  is actual evapotranspiration in day  $i$  in mm,  $W_{seep}$  is amount of water entering to vadose zone in soil profile in day  $i$  in mm and  $Q_{gw}$  is Groundwater return flow to the river in day  $i$  in mm.

Water balance equation and other constraints that are used in reservoir simulation are:

$$S_{t+1} = S_t + I_t - E_t - R_t - L_t \quad (4)$$

$$S_{\min} \leq S_t \leq S_{\max} \quad (5)$$

$$S_T = S_1 \quad (6)$$

In Eq. 4,  $S_t$ ,  $I_t$ ,  $E_t$ ,  $R_t$  and  $L_t$  are storage volume, reservoir inflow, evaporation from the reservoir, reservoir outflow and reservoir losses respectively in month  $t$ .  $S_{\min}$  and  $S_{\max}$  are minimum and maximum volume of the reservoir. The constraint in Eq. 6 is for equalizing reservoir volume at the beginning and end of the period. Temporal and volumetric reliability should be 100% for domestic and industrial demands and environmental flow.

Temporal reliability: The ratio of the time steps that the user's demand is completely supplied to the total number of time steps in the simulation period (McMahon et al. 2006).

$$Rel_{Temporal}^j = \frac{N_s}{T} \times 100\% \quad (7)$$

Where,  $N_s$  is the number of time steps that user demand  $j$  completely supplied or water-scarce is zero ( $D_j = 0$ ),  $T$  is total time steps in the simulation period.

Volumetric reliability: The ratio of supplied water of user  $j$  to the required water in the simulation period (Hashimoto et al. 1982).

$$Rel_{Volumetric}^j = \frac{\sum_{t=1}^N Supply_t^j}{\sum_{t=1}^N Demand_t^j} \times 100\% \quad (8)$$

Where,  $Supply_t^j$  is supplied water and,  $Demand_t^j$  is the required water of user  $j$ .

## 2.2 Simulation and Optimization Models

### 2.2.1 Soil and Water Assessment Tool (SWAT)

SWAT is a continuous-time hydrologic, process-based and semi-distributed model (Lei et al. 2014) that is able to simulate flow in large and complex basins with soil, land use and management conditions variables (Arnold et al. 1998; Neitsch et al. 2011). In recent years, the SWAT model is widely used to study the impacts of the land use change, climate change, the land cover change or the simultaneous effect of two or more of the above on water quantity or quality (Kumar et al. 2018).

In the SWAT model, spatial heterogeneity in the basin is done by topography and dividing the basin into several small basins called Hydrologic Response Unit (HRU) based on soil, land use, and slope features. The amount of precipitation runoff is one of the hydrologic variables in determining the total amount of outflow from the basins, the peak flow, and so on. The SWAT model is used for calculating this amount by the SCS curve number and Green-Ampt infiltration equation (Neitsch et al. 2011). Today, the SUFI-2 algorithm is the most common SWAT calibration and validation method used in the SWAT-CUP program which is also used in this study. SUFI determines the uncertainty of the verified parameter with a 95% uncertainty band (95PPU) (Fereidoon and Koch 2018). Then, the performance of the final calibration model is evaluated by two P-factor and R-

factor indicators. The conformance between simulated and observed data is evaluated by the Nash-Sutcliffe efficiency (NS) or Determination coefficient ( $R^2$ ).

### 2.2.2 Water Allocation Model WEAP

Water Assessment and Evaluation System (WEAP) is developed and supported in 1988 by the Stockholm Environment Institute United States Center, a nonprofit research institute based at Tufts University in Somerville, Massachusetts. This program is widely used for studies on the adaptation of climate change and has been used by researchers and planners across hundreds of organizations around the world. WEAP is solving a mass balance equation of water, for each node and connection at time steps in the system. Water is allocated to user's demands and environmental flow demand; based on the priority of demands, source superiority, mass balance equation, and other constraints.

### 2.2.3 Non-dominated Sorting Differential Evolution (NSDE) Algorithm

Differential Evolution (DE) algorithm is an improved version of the genetic algorithm for solving optimization problems presented by Storn and Price (1995). The algorithm has the same operators as the genetic algorithm, but its function is mainly based on the mutation operator rather than the crossover. Here, an improved version of DE is used to obtain the optimal tradeoff between two conflicting objective functions in which the non-domination and crowding distance criteria used in NSGAI is borrowed to apply within the DE framework.

In this study, the NSDE optimization algorithm forms its initial population by 100 members. Then each of these members is in the optimization process. This process will continue to 200 steps until convergence is achieved. In each step, the results are measured with the previous step results and better solutions are selected based on the dominance concept and crowding distance. Thus, 100 best members will be kept in each step and the rest will be set aside. In the final step, the best results remain that form the final solutions to the problem. Problem decision variables include the nominal monthly demand for crops.

## 2.3 Parallel Processing

Typically, a period of several years is studied for simulation. Also, in crop yield simulation, different crops in different months have different water demands. Therefore, the vector dimension of the decision variable is obtained from the multiplication of the number of simulation periods in the number of crops according to the number of modeling years. Since applying the multi-year crop management in the SWAT model due to the bug of the model is with problems, one-year management can be applied to the \*.mgt input files. But it should be noted that in this case, the model should be run each year separately. Since the number of runs of the model in the optimization process is high and the process is time-consuming, the parallel processing can be used in this part. To simulate, a separate core should be allocated to each year. Therefore, the calculations of different years can be done simultaneously in a parallel manner.

## 2.4 Model Assessment

Nash-Sutcliffe efficiency (NSE) and Determination coefficient ( $R^2$ ) are used to evaluate the results of the calibration and validation of the model. They are obtained according to the following equations:

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - O_{avg})^2} \quad (9)$$

$$R^2 = 1 - \frac{\left( \sum_{i=1}^n (O_i - O_{avg})(S_i - S_{avg}) \right)^2}{\sum_{i=1}^n (O_i - O_{avg})^2 \sum_{i=1}^n (S_i - S_{avg})^2} \quad (10)$$

Where,  $S_i$  and  $O_i$  are simulated streamflow and observed streamflow respectively in  $i$  time step.  $S_{avg}$  and  $O_{avg}$  are average of simulated streamflow and observed streamflow in the total period. Besides, two P-factor and R-factor indexes have also been used. P-factor is the percentages of measured data in the 95% prediction uncertainty envelop that expressed in numerical order from 0 to 1. The closer the P-factor to one is more satisfactory (Abbaspour et al. 2007). The R-factor represents the thickness of 95% prediction uncertainty envelope which varies between 0 and infinity, and the value of one for estimating flow is ideal.

## 2.5 Scenario Assessment

Two indicators, water stress (WS), and economic water productivity (EWP) were used to evaluate the scenarios. According to Eq. 11, adopted by the United Nations Convention, water stress is calculated.

$$WS(\%) = \frac{WU}{WA} \times 100 \quad (11)$$

Where WS is the percentage of water stress, WU is annual water use and WA is the amount of renewable annual water or available freshwater.

Based on (Raskin et al. 1997), in a basin where the percentage of annual water withdrawal to annual renewable water is more than 40%, it is facing to severely water-scarce. If it is between 20% and 40%, encounter with water-scarce. If it is between 10% and 20%, encounter with moderate water-scarce and less than 10% encounter with minor scarcity.

The second indicator is the economic water index that is calculated based on Eq. 12 and shows the income of used blue water (\$/m<sup>3</sup>).

$$EWP = \frac{I}{W_{blue}} \quad (12)$$

$$W_{blue} = ET_{total} - ET_{green} \quad (13)$$

In this equation,  $I$  is agricultural income (\$),  $W_{blue}$  is the consumed blue water (m<sup>3</sup>),  $ET_{total}$  is total evapotranspiration (m<sup>3</sup>),  $ET_{green}$  is green evapotranspiration (m<sup>3</sup>) that is calculable in no irrigation state or rain-fed cultivation.

## 2.6 Study Area

Figure 2a shows the location of Mahabad watershed in the south part of the Lake Urmia basin. Mahabad Dam reservoir constructed on the Mahabad river and supplied domestic, industrial and agricultural demands.

For the simulation of the basin in the SWAT model, the region is divided into 11 sub-basins and 163 HRUs. After allocating water to the various domestic, industrial and agricultural water demands, downstream environmental demand (Lake Urmia) will be supplied. In recent years, the volume of Lake Urmia has been severely reduced due to the construction of multiple dams on the tributary rivers with the aim of agricultural development, and its conservation is so important. Therefore, the study of the Mahabad basin seems to be appropriate as one of its tributary rivers for assessing the effectiveness of this study.

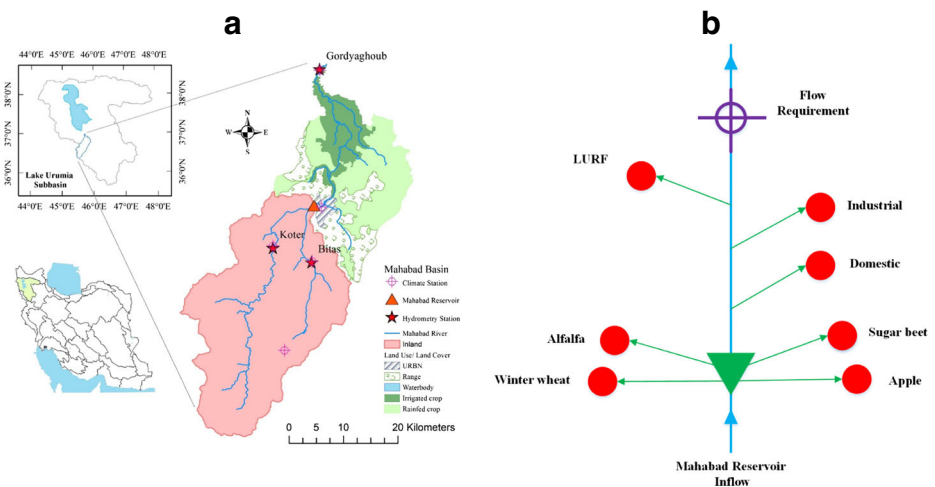
## 3 Results and Discussion

### 3.1 SWAT Setup and Preparation

In order to calibrate the SWAT model, warming up from 1997 to 1999, calibration from 2000 to 2013 and model validation from 1989 to 1996 were considered monthly. Subsequently, a drought period from a 40-year statistical period was selected (years from 2008 to 2012).

#### 3.1.1 Irrigated Agriculture Management

In the study area, the most important cultivated crops are apple (APPL), winter wheat (WWHT), alfalfa (ALFA), and sugar beet (SGBT), which contain 31, 29, 26 and 14% of total cultivated area, respectively.



**Fig. 2** a Location of the Mahabad River Basin, weather stations and the Mahabad dam at the south part of Lake Urmia Basin, b Schematic of different water users downstream of the Mahabad reservoir



### 3.1.2 SWAT Calibration and Validation Results

After preparing the model, monthly observed data were used at the basin outlet for calibration and validation. The  $R^2$  values of Gordyaghoub station are 0.69 and 0.65 respectively for calibration and validation and the corresponding results of NS are 0.65 and 0.61 respectively. This indicates that the model has been able to simulate the flow well.

Also, observed and simulated evapotranspiration of crops are compared using the determination coefficient ( $R^2$ ) which is 0.9754. Mean simulated crop yields are 10.7, 2.3, 10.1 and 48.6 respectively for APPL, WWHT, ALFA and SGBT while mean observed crop yields are 11.5, 2.4, 8.0 and 51.7 respectively. The results show that the SWAT model in this section provides good performance.

### 3.2 WEAP Setup and Preparation

Figure 2b shows the schematic of the different water users downstream of the Mahabad reservoir, simulated by the WEAP model. The environmental flow considered in the WEAP model is equal to the environmental demand of Mahabad river downstream of the reservoir and share of Mahabad basin in supplying the LURF (Lake Urmia Remediation Flow). The use of LURF node is a technique used in the WEAP model to release excess water due to the low irrigation of the agricultural sector.

The yearly demands for the industrial, domestic and environmental sectors are 17.7, 12 and 16.8 MCM. Also, the demands for apples, alfalfa, sugar beet, and winter wheat are 52.5, 53, 25 and 27.8 (MCM/year) respectively in the current condition that was used in the crop calibration process in the SWAT model. Also, these values are the upper bound of decision variables in the optimization model. The orders of the demand priorities are related to domestic and industry, then with the environmental flow, later APPL, and so on for WWHT, ALFA, and SGBT.

Volumetric and temporal reliability values for different demands are calculated for the maximum irrigation (current or traditional irrigation pattern) and no irrigation conditions. The industrial, domestic and environmental water demands are fully met, and their volumetric and temporal reliability is 100%. Among the irrigated crops, winter wheat (95.64%) and sugar beet (33.02%) have the highest and the least volumetric reliability, and hence the temporal reliability respectively. The volumetric reliabilities in the max irrigation condition for APPL, WWHT, ALFA, and SGBT are 56.09, 95.64, 47.6 and 33.02 and the corresponding values for the temporal reliabilities are 48.57, 94.29, 51.11 and 26.67, respectively. The level of reliability decreases relative to prioritization for WWHT, ALFA, and SGBT. Even though the priority of APPL in irrigation is higher than the WWHT, but it is less reliable than WWHT. This is because WWHT does not require irrigation in the summer but the major part of the APPL demand is in the summer season in which the system is facing water-scarce.

### 3.3 Simulation- Optimization Results (SWAT-WEAP-NSDE)

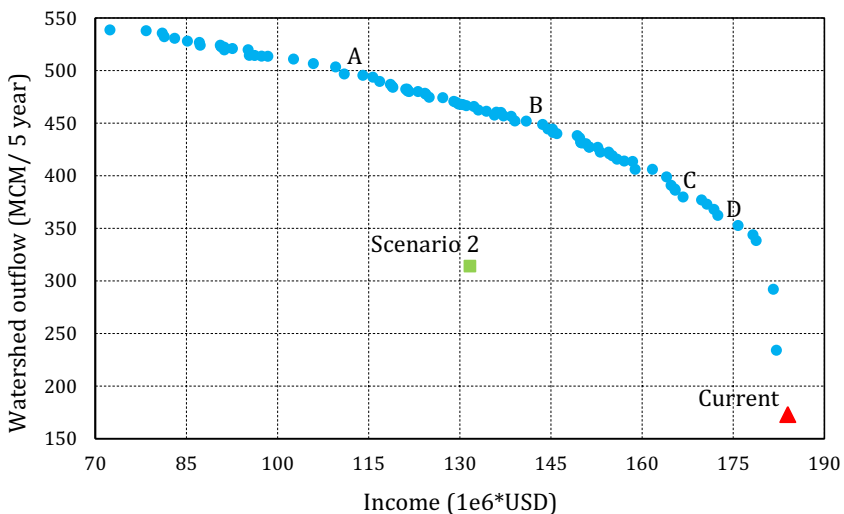
This study considered Mahabad reservoir optimal operation for a drought period (2008–2012) that the agricultural income and the amount of inflow into the Lake Urmia are maximized simultaneously. The parameters of the optimization model are considered based on the recommended values in the research history of the NSDE algorithm (Reddy and Kumar 2006; Yazdi et al. 2017; Yazdi and Moridi 2018). Therefore, the scaling factor, cross over probability, population size, the number of the iteration are 0.5, 0.7, 100 and 100, respectively.

Using these parameters, the Pareto front graph (filled blue circles) was extracted (Fig. 3). The horizontal axis represents the amount of irrigated crop income from 2008 to 2012 in million dollars. The vertical axis is the volume of discharged water from the basin in millions cubic meters over five years that flows towards Lake Urmia. On the graph, from left to right, the volume of irrigation increases. Therefore, by moving from left to right, the volume of inflow to Lake Urmia is reduced and the amount of income is increased.

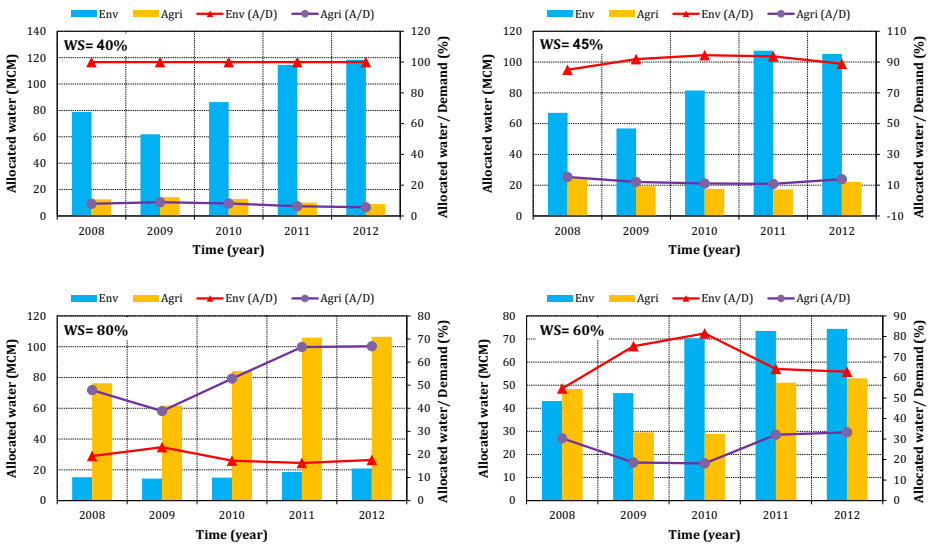
On the graph, a red solid filled triangle is shown (Current condition). This point corresponds to the current or traditional irrigation pattern which plays the role of the upper bound of irrigation through the optimization process. In this case, 173 (MCM) during the 5 years of simulation period will flow to Lake Urmia, which is equivalent to 20% of the volume of the surface water produced in the whole basin over the 5 years (826 MCM). Therefore, the water stress index for the current condition is about 80%. Four points (A, B, C, and D) selected on the Pareto front chart, allocate 60, 55, 45 and 40% of the watershed surface water volume to the Urmia Lake (from the left to right, respectively). The water stress index at these points is 40, 45, 55 and 60%, respectively.

Figure 4 shows the annual allocated water to each of the agricultural and environmental sectors (bars) and its corresponding ratio per annual demand (Lines). For each value of the water stress indicator, the agricultural sector receives a different volume of water. For WS equals 40%, 45%, 60%, and 80%, the allocated water to the agricultural sector is 11.7, 20.12, 42.15, and 86.9 MCM/year, respectively. The allocated water to Lake Urmia is 92.01, 83.6, 61.57, and 16.57 MCM/year. According to the both UN definition of water stress index (WS) and government resolutions related to the remediation of Lake Urmia, the ideal supply for Lake Urmia occurs when WS declines to 40% (92.01 MCM/year). So, the average percentages of allocated water to the lake are 100, 90.78, 67.66, and 18.71 for each value of WS from 40% to 80%.

Figure 5 presents the percentage of the allocated water to each crop relative to the total agricultural allocated water. While WS equals to 80%, the average allocated water to apples,



**Fig. 3** Pareto optimal front (blue filled circles), showing the trade-off between irrigated agriculture income downstream of the Mahabad reservoir and the inflow to the Lake Urmia from the Mahabad watershed (Current: current irrigation pattern, Scenario 2: the situation of do not cultivate high irrigation demand crops)

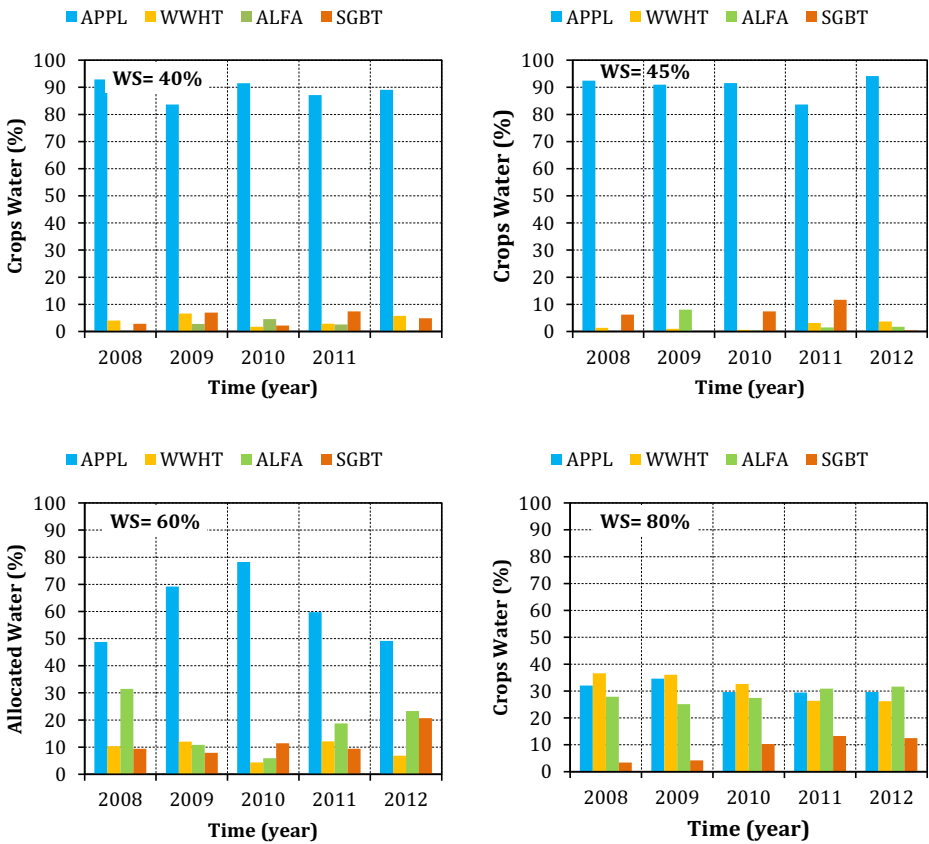


**Fig. 4** Allocated water to the agricultural and environmental sectors (bars), and the ratio of allocated water to demand water (A/D) for each sector (lines); Water stress is 40%, 45%, 80% and 60 % respectively for top-left, top-right, bottom-left and bottom-right panels

winter wheat, alfalfa and sugar beet from the total agricultural water of 86.9 MCM/year is 31.09%, 31.59%, 28.6%, and 8.73%, respectively. Also, it is 61.02%, 9.16%, 18.06%, 11.76%, respectively of 42.15 MCM/year for WS of 60%, 57.9%, 1.96%, 2.33%, and 5.14% of 20.12 MCM/year for WS of 45% and 88.86%, 4.21%, 2.08%, and 4.85% of 11.71 MCM/year for WS of 40%. According to the higher priority of apple to other crops, the model tries to supply its demand first. Moreover, according to its revenue, its economic productivity index (EWP) is higher than other products. For example, under WS of 80%, the EWP for apple, winter wheat, alfalfa, and sugar beet are 4.46, 0.44, 1.2 and 2.77 ( $\$/\text{m}^3$ ), respectively (based on the price of 0.71, 0.33, 0.28, and 0.08 for these crops, respectively). Therefore, the optimization model tends to allocate more water to it.

For different points highlighted in Fig. 3, the percentage of water discharged to the Lake Urmia compared to produced water, water stress, crop yield, income, and economic water productivity index are presented in Table 1. According to these results, the amount of income in the implementation of the existing irrigation pattern is 184 (million \$) (Current condition point).

For reaching from the current condition (80% water stress) to 40% water stress (Point A), the income will decrease by 38% to 114 (million \$). Also, the water stress index decreases to 60% (Point D), agricultural income will decrease by 6.5% compared to the current situation (traditional irrigation pattern) and will be equal to 172 (million \$). For Points B and C, 25.5% and 10.3% of the agricultural income will be reduced. It may be unprofitable to reduce water stress from 80% to 40%, due to a significant reduction in income. But with a waiver of 6.5% of income (point D), it doubles the discharged water to Lake Urmia. Also, the EWP index is calculated for different points. For A, D and Current points, the EWP index is 3.64, 1.60 and 1.06 ( $\$/\text{m}^3$ ) of blue water, respectively. So, on the chart, moving from left to right, although the income is increased, the water productivity decreases. Moving from the Current Point to Point A increases the EWP index from 1.06 to 1.60 ( $\$/\text{m}^3$ ).



**Fig. 5** Water allocation to the crops based on different water stress (WS) indices during the drought period of 2008–2012; Water stress is 40%, 45%, 60% and 80 % respectively for top-left, top-right, bottom-left and bottom-right panels

In another scenario that is shown by the point named Scenario 2 (Fig. 3), a state has been investigated to eliminate high irrigation demand crops (HIDCs) such as sugar beet and alfalfa in the drought period. The removal of HIDCs is a condition that some experts recommend during drought periods. It is observed that in this case, the income will decrease by 29% and will reach 132 (million \$). The water stress rate is 62% in this case. This approach is close to the results of Point D in terms

**Table 1** Properties of selected points on Pareto optimal front in comparison with current condition point

Points	Q <sub>Env</sub> / Q <sub>In</sub> (%)	WS (%)	Yield (ton/ 5 years)				Income for 5 years (1e6*USD)	EWP (USD/m <sup>3</sup> )
			ALFA	SGBT	APPL	WWHT		
A	60	40	47,326	154,922	111,713	23,686	114	3.64
B	55	45	48,791	123,072	148,784	23,465	137	2.55
C	45	55	77,638	235,651	164,380	23,259	165	1.77
D	40	60	82,774	255,925	168,437	28,880	172	1.60
Observed	20	80	109,703	299,433	166,729	35,328	184	1.06

WS Water stress indicator, ALFA Alfalfa, SGBT Sugar beet, APPL Apple, WWHT Winter wheat, EWP Economic water productivity (versus blue water)

of water stress, but generates less agricultural income and is between Points A and B. Although the scenario for the reduction of HIDs cultivation area does not provide better solutions than the proposed in the Pareto front. This scenario can significantly reduce water stress but has social consequences due to the reduction of farmers' income. Optimization of crop and irrigation patterns in the study area considering social, economic and environmental issues is suggested for further studies.

## 4 Conclusion

In this study, the possibility of balancing between incomes from agricultural activities and providing the environmental flow of rivers and lakes was investigated by using the simulation-optimization approach. This balance is of great importance, especially during drought periods. The SWAT hydrological model accompanied by the WEAP planning model (as simulation models) have been linked to the NSDE algorithm in an optimization framework to obtain optimal operation of the reservoir considering economic and environmental issues. The parallel processing technique is used for reducing the run time of the model. To evaluate the performance of the proposed method, the optimal operation of the Mahabad reservoir (south of Lake Urmia basin) is obtained during the dry period 2008–2012. In the current situation (traditional irrigation pattern), the water stress index of the basin is 80% which is corresponded to severe water stress and water productivity is 1 (\$/m<sup>3</sup>). Two water allocation strategies were investigated including a) irrigation management; b) the elimination of the cultivation of high irrigation demand crops such as alfalfa and sugar beet. The results showed that by decreasing only 6.5% of the agricultural income, the water stress index can be reduced from 80% to 60% according to one of the irrigation patterns of the first strategy and 180 MCM more water was discharged to Lake Urmia during the 5-year drought period. In contrast, under the second strategy, water stress can be reduced to 62%, with a 29% reduction in income. Therefore, using the first strategy is not only more economical but also without any social consequences. In the second one, farmers of sugar beet and alfalfa will not earn any income. This issue highlights the importance of irrigation management in improving the environmental conditions of the basin. This study can be implemented in other basins and its results will help managers and planners to balance economic and environmental conservation. Although the effectiveness of irrigation management with the elimination of high irrigation demand crops was studied in this study, the study of land-use change with irrigation management is another effective strategy, which is suggested to investigate in future research.

**Acknowledgements** This paper is based on Ph.D. dissertation results done in Shahid Beheshti University, Tehran, Iran.

## Compliance with Ethical Standards

**Conflict of Interest** There is no conflict of interest.

## References

- Abbaspour KC, Yang J, Maximov I, Siber R, Bogner K, Mieleitner J, Zobrist J, Srinivasan R (2007) Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. *J Hydrol* 333(2–4):413–430
- Al-Faraj FA, Tigkas D, Scholz M (2016) Irrigation efficiency improvement for sustainable agriculture in changing climate: a transboundary watershed between Iraq and Iran. *Environmental Processes* 3(3):603–616

- Almazan-Gomez MA, Sanchez-Choliz J, Sarasa C (2018) Environmental flow management: an analysis applied to the Ebro River basin. *J Clean Prod* 182:838–851
- Arnold JG, Srinivasan R, Mutiah RS, Williams JR (1998) Large area hydrologic modeling and assessment part I: model development. *Journal of the American Water Resources Association* 34(1):73–89
- Fereidoon M, Koch M (2018) SWAT-MODSIM-PSO optimization of multi-crop planning in the Karkheh River basin, Iran, under the impacts of climate change. *Sci Total Environ* 630:502–516
- Hashimoto T, Stedinger JR, Loucks DP (1982) Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resour Res* 18(1):14–20
- King J, Brown C, Sabet H (2003) A scenario-based holistic approach to environmental flow assessments for rivers. *River Res Appl* 19(5–6):619–639
- Kumar N, Singh SK, Singh VG, Dzwairo B (2018) Investigation of impacts of land use/land cover change on water availability of tons River Basin, Madhya Pradesh, India. *Modeling Earth Systems and Environment* 4(1):295–310
- Lei F, Huang C, Shen H, Li X (2014) Improving the estimation of hydrological states in the SWAT model via the ensemble Kalman smoother: synthetic experiments for the Heihe River basin in Northwest China. *Adv Water Resour* 67:32–45
- Llopis-Albert C, Merigó JM, Liao H, Xu Y, Grima-Olmedo J, Grima-Olmedo C (2018) Water policies and conflict resolution of public participation decision-making processes using prioritized ordered weighted averaging (OWA) operators. *Water Resour Manag* 32(2):497–510
- Malano HM, Davidson B (2009) A framework for assessing the trade-offs between economic and environmental uses of water in a river basin. *Irrig Drain* 58(S1):S133–S147
- McMahon TA, Adeloye AJ, Zhou S-L (2006) Understanding performance measures of reservoirs. *J Hydrol* 324(1–4):359–382
- Moradi S, Limaei SM (2018) Multi-objective game theory model and fuzzy programming approach for sustainable watershed management. *Land Use Policy* 71:363–371
- Neitsch SL, Arnold JG, Kiniry JR, Williams JR (2011) Soil and water assessment tool theoretical documentation version 2009, Texas Water Resources Institute
- Pang A, Sun T, Yang Z (2013) Economic compensation standard for irrigation processes to safeguard environmental flows in the Yellow River estuary, China. *J Hydrol* 482:129–138
- Perez-Blanco C, Gutierrez-Martin C (2017) Buy me a river: use of multi-attribute non-linear utility functions to address overcompensation in agricultural water buyback. *Agric Water Manag* 190:6–20
- Raquel S, Ferenc S, Emery C Jr, Abraham R (2007) Application of game theory for a groundwater conflict in Mexico. *J Environ Manag* 84(4):560–571
- Raskin P, Gleick P, Kirshen P, Pontius G, Strzpek K (1997) Water futures: assessment of long-range patterns and problems. *Comprehensive assessment of the freshwater resources of the world*. SEI
- Reddy MJ, Kumar DN (2006) Optimal reservoir operation using multi-objective evolutionary algorithm. *Water Resour Manag* 20(6):861–878
- Rumbaur C, Thevs N, Disse M, Ahlheim M, Brieden A, Cyffka B, Duethmann D, Feike T, Frör O, Gärtner P, Halik Ü, Hill J, Hinnenthal M, Keilholz P, Kleinschmit B, Krysanova V, Kuba M, Mader S, Menz C, Othmanli H, Pelz S, Schroeder M, Siew TF, Stender V, Stahr K, Thomas FM, Welp M, Wortmann M, Zhao X, Chen X, Jiang T, Luo J, Yimit H, Yu R, Zhang X, Zhao C (2015) Sustainable management of river oases along the Tarim River (SuMaRiO) in Northwest China under conditions of climate change. *Earth System Dynamics* 6(1):83–107
- Storn R, Price K (1995) "DE—a Simple and Efficient Adaptive Scheme for Global Optimization Over Continuous Space." *International Computer Science Institute, Technical report TR-95-012*:1–12.
- Sun T, Yang Z, Cui B (2008) Critical environmental flows to support integrated ecological objectives for the Yellow River estuary, China. *Water Resour Manag* 22(8):973–989
- Xu Y, Fu X, Chu X (2019) Analyzing the impacts of climate change on hydro-environmental conflict-resolution management. *Water Resour Manag* 33(4), 1591–1607
- Xue J, Gui D, Lei J, Sun H, Zeng F, Feng X (2017) A hybrid Bayesian network approach for trade-offs between environmental flows and agricultural water using dynamic discretization. *Adv Water Resour* 110:445–458
- Yazdi J, Moridi A (2018) Multi-objective differential evolution for Design of Cascade Hydropower Reservoir Systems. *Water Resour Manag* 32(14):4779–4791
- Yazdi J, Yoo DG, Kim JH (2017) Comparative study of multi-objective evolutionary algorithms for hydraulic rehabilitation of urban drainage networks. *Urban Water J* 14(5):483–492
- Zhang X, Ren L, Wan L (2018) Assessing the trade-off between shallow groundwater conservation and crop production under limited exploitation in a well-irrigated plain of the Haihe River basin using the SWAT model. *J Hydrol* 567:253–266

## Affiliations

Ahmad KhazaiPoul<sup>1</sup> · Ali Moridi<sup>1</sup> · Jafar Yazdi<sup>1</sup>

✉ Ali Moridi  
a\_moridi@sbu.ac.ir

Ahmad KhazaiPoul  
a\_khazaie@sbu.ac.ir

Jafar Yazdi  
j\_yazdi@sbu.ac.ir

<sup>1</sup> Civil, Water and Environmental Engineering Faculty, Shahid Beheshti University, Tehran, Iran