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Using the SWAT model to assess the impacts of changing irrigation from surface to pressurized systems on water productivity and water saving in the Zarrineh Rud catchment

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ABSTRACT

Considering global water scarcity, especially in the agricultural sector, many attempts are being made to improve water productivity and save more water. Changing irrigation systems from surface to pressurized has been one of the considerable actions in this regard. However, any attempts to do so must be evaluated in an integrated perspective at the basin level by means of relevant agro-hydrological models before making them operational. This paper aims to address this issue by using the soil and water assessment tool (SWAT). Zarrineh Rud River, the main feeding river of northwest Iran's Lake Urmia, is selected as the case study for exploring this methodology. This lake has been shrinking since 1995, and to save water and increase the basin's water productivity, improvement of pressurized systems is considered as a solution. SWAT cannot directly simulate changing the irrigation system from surface to pressurized. In this study, we use the innovative approach of applying the model to simulate different irrigation systems considering real irrigation management variables such as depth and date of each irrigation event. Also, in order to improve its performance in simulation of such systems, a comprehensive calibration procedure was used based on a wide range of data for hydrological and agricultural variables. The results showed that changing the current irrigation to a pressurized system can increase water productivity up to 15% due to increases in crop yield, better water distribution and greater actual evapotranspiration. However, pressurized irrigation results in no significant change in total inflow to the lake. Notably, these systems can intensify drawdown of the basin's water table up to 20%. So, any significant "real water saving" program in the basin must be associated with reduction of evapotranspiration by adopting measures like reducing cultivated areas, changing cropping patterns to less water consuming plants, or applying deficit irrigation. The applied methodology of this paper as well as the comprehensive calibration and setup of the SWAT model with the readily available hydrological and agricultural variables can be a good sample for similar works. However, further work is still needed to more broadly test this approach in areas with intensive irrigation systems.

1. Introduction

Agricultural water productivity (WP) can be used to effectively evaluate water resources and agricultural management systems (Molden and Sakthivadivel, 1999; Loeve et al., 2004). This concept is very important for irrigated lands where people control water storage and distribution. The main components of WP are crop production and water consumption; these are presented in units like $/m^3 and kg/m^3 (Seckler et al., 2003; Palanisami et al., 2006). As crop production increases and/or water consumption decreases, WP increases.

To improve WP, transitioning from surface to pressurized irrigation is considered to be an important strategy due to increasing water efficiency and assumption of saving water (Bathurst, 1988; Allen et al., 2005; Ali and Talukder, 2008). However, there are some criticisms and doubts about the impact of making this switch (Kendy and Bredehoef, 2006; Clemmens and Allen, 2005). These are mainly due to the perception that on-farm irrigation application efficiencies are often in the order of 20–50%, implying that the remaining 80–50% is somehow lost. However, when we move from an on-farm perspective to a basin perspective, we often find that, because of reuse of "lost water" in the basin, there is

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much less wastage than commonly perceived (Molden et al., 2001). Similar to this concept, Davenport and Hagan (2011) used “recoverable water” versus “irrecoverable water” terminologies. From their viewpoint, real water saving takes place when the amount of “irrecoverable water” is reduced in a basin. Therefore, any attempt (e.g., changing the irrigation system) to save water or increase efficiency and productivity of water use needs to be evaluated in the context of water balance of the river basin, rather than solely at the field level. Specifically, rises in groundwater level and/or increases of environmental flows at the outlet of a basin can be good indicators of improvements in water-saving agricultural management.

An assessment that takes all of this into account can only be done using integrated hydrological models, which are capable of simultaneously simulating flows (surface and groundwater) and evapotranspiration. Cai et al. (2003) used an integrated modeling approach, which included hydrologic and agronomic models for evaluation of basin management scenarios in the Maipo River Basin in Chile. They showed that increased irrigation efficiency in agricultural areas can negatively affect river flow as water consumption increases, even though actual water withdrawals may decline. Törnqvist and Jarsjö (2012) developed a hydro-climatic distributed model for evaluation of water savings through improved irrigation techniques in the Aral Sea drainage basin. Their results indicated that changing the traditional irrigation to new irrigation techniques such as pressurized and surge flow irrigation can lead to basin-scale water conservation. However, they emphasized that doing this saved about 60% less water than on-farm reductions in irrigation water application could save. This is because water can be re-used for on-farm irrigation, and because new irrigation techniques reduce return flows.

Implementation of pressurized irrigation systems has been also considered in the Lake Urmia (LU) basin. LU is the largest lake in Iran, but its water level has declined steeply since 1995. Different strategies have been proposed to save water in the basin and allocate it to the lake, and, as it was stated before, increasing the use of pressurized irrigation systems is among those strategies. This paper evaluates impacts of such a system on water productivity (WP) and inflow into the lake. To address this issue, we have selected the soil and water assessment tool (SWAT) (Arnold et al., 1998). SWAT is capable of predicting the effects of changes in climate and management conditions on basin hydrology. To do this, the model includes many modules, including crop growth, groundwater, and river routing to accommodate the required simulations. The model is also semi-distributed, which divides each subbasin into smaller hydrological response units (HRUs) (Neitsch et al., 2002) based on soil type, crop patterns, and management practices.

The model has been used to evaluate water productivity in a number of research works. For instance, Immerzeel et al. (2008) used this model to evaluate water productivity of cane, sorghum, and millet in the Upper Bhima River basin, which was calibrated by using remotely sensed evapotranspiration data based on the SEBAL algorithm (Bastiaanssen et al., 1998a,b, 2005). In another study, Huang and Li (2010) used SWAT to assess the crop water productivity (CWP) index on a basin scale in fertile basins of China. The model was calibrated using monthly streamflows in order to estimate actual evapotranspiration for the main crops (rice, wheat, maize, and soybean). The simulated hydrologic and crop components were then coupled together to assess basin-scale CWP. In another study, SWAT was used to obtain spatial maps of economic water productivity (EWP) for sugarcane, millet, and sorghum in the Upper Bhima River basin in India (Kaushal et al., 2011).

Similarly, SWAT has been used for assessment of irrigation management practices (field-scale analysis) in a number of research works. However, it has been used to do so much less often than it has been used for hydrological applications at the basin level. Thus, the field-scale simulations are usually done by a lot of manipulations (Xie and Cui, 2011; Panagopoulos et al., 2013, 2014) or by even changing the source code (Dechmi et al., 2012). Moreover, our literature review demonstrated that the model has not been applied to assess the impacts on basin hydrology of changing irrigation systems. Such an analysis needs a deep evaluation of hydrological processes at field and basin scales along with their interactions, which are considered in this research work.

This paper evaluates the impacts of changing irrigation from surface to pressurized systems on water productivity and water saving of the Zarrineh Rud River, the main feeding river of Lake Urmia, which is located in northwestern Iran. This paper attempts to address the effectiveness of such a measure. To do so, a variety of simultaneous, integrated simulations of hydro-climatic variables (e.g., evapotranspiration, runoff, and groundwater), agricultural variables (e.g., crop yield and irrigation planning), and their interactions are studied.

2. Material and methods

2.1. Description of study area and data

Zarrineh Rud is the most important catchment of the Lake Urmia (LU) basin because it provides more than 40% of the total annual inflow into LU. The catchment is located at longitude 45°47′ to 47°20′N and latitude 35°41′ to 37°27′E (Fig. 1). The total area of the basin is about 12,025 km^2, and the length of its main channel is 300 km. The average annual rainfall in the basin is 390 mm. The Zarrineh Rud dam is the only dam in the basin, and it is operated for agricultural and drinking water demands (110 MCM/yr). This dam has a gross storage capacity of 760 MCM and its live storage capacity is 654 MCM. The catchment also includes the four cities Miandoab, Shahindej, Tekab, and Saghez (Fig. 1).

The growing season in the basin is from mid-spring to mid-autumn, and water requirements are partially met by irrigation that relies on surface and groundwater resources. The area of irrigated lands is 74,318 ha. Major crops are wheat, barley, alfalfa, potato, tomato, sugar beet, and apple. Current irrigation efficiency (surface) is 38% for the areas using surface water (dam or river) and 50% for areas using groundwater (CWMP[1], 2006). The Iranian Ministry of Jahade-Agriculture (MOJA) provided other agricultural information including cropping pattern, planting and harvesting dates, irrigation management, cultivated area of major crops, and fertilizer use in the catchment.

Weather input data (daily precipitation, maximum and minimum temperature, monthly solar radiation) were obtained from the Public Weather Service of the Iranian Meteorological Organization (WSIMO) for six synoptic stations that are located in (or close to) the study area. Also, streamflow data required for calibration and validation of the model were obtained from the Ministry of Energy of Iran for six gauging stations. The specifications and locations of the gauging stations are shown in Fig. 1.

SWAT is enhanced with a GIS platform to simulate stream networks of basins and subbasins. A Digital Elevation Model (DEM) layer with a resolution of 30 m was prepared in this regard (http://earthexplorer.usgs.gov.demexplorer). Also, a soil map was obtained from the global soil map of the Food and Agriculture Organization of the United Nations (FAO, 1995) and a land use map was obtained from MOJA (2007) with a resolution of 1000 m (Fig. 1). Based on these layers, as well as locations of gauging stations and the Zarrineh Rud dam, the basin was divided into 11 subbasins (Fig. 1) and 908 HRUs. Cropping pattern and agricultural management data of main crops in study area are shown in Table 1.

[1] Comprehensive Water Management Plan.

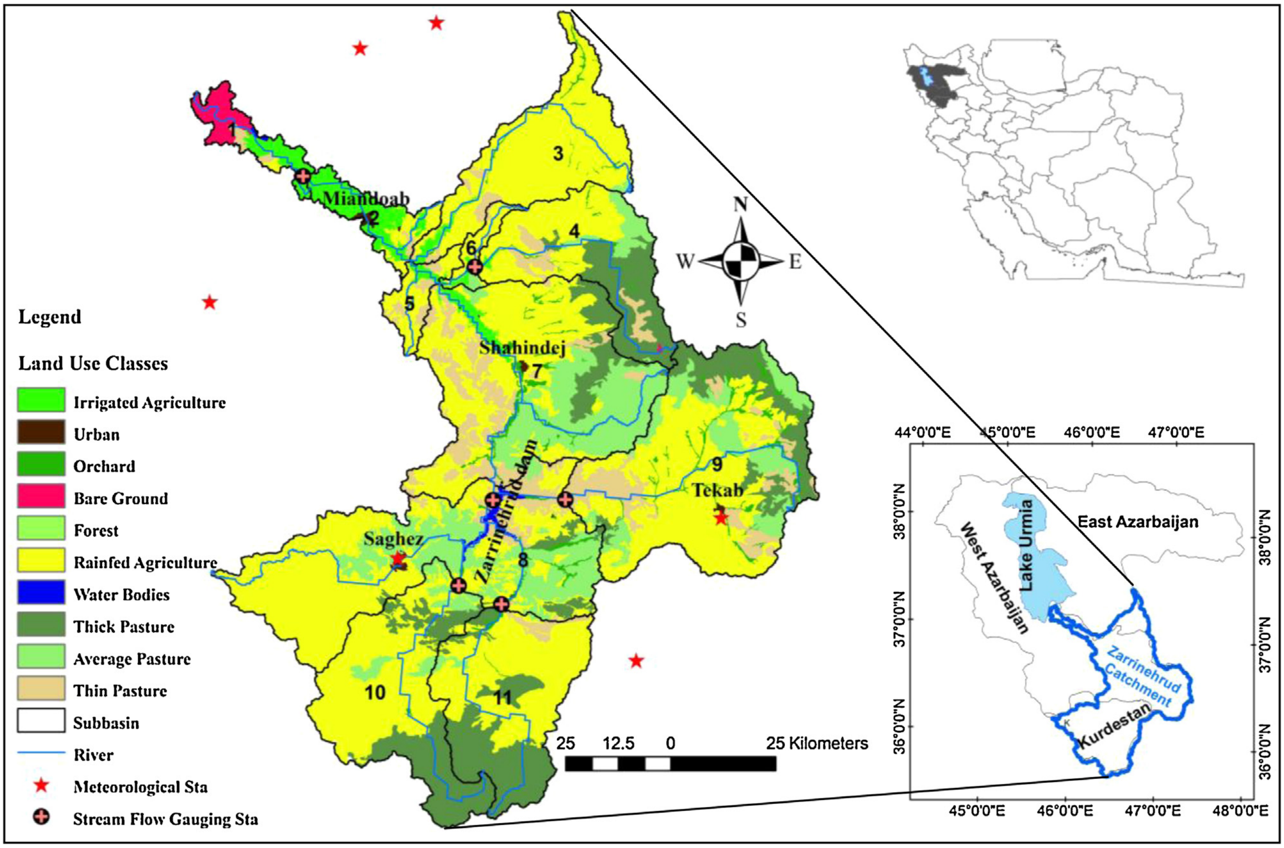

Fig. 1. Map of study area and its land use layer (MOJA, 2007).

Table 1
Cropping pattern and agricultural management data of main crops in study area.

Crop	Cultivation area of crops by city (ha)				Planting date	Harvesting date	Annual consumption of fertilizer (kg/ha)	
	Miandoab	Shahindej	Tekab	Saghez			Nitrate	Phosphate
Wheat	16017	7743	336.7	5042.7	1 Oct.	1 Jul.	120	140
Barley	4140.8	2310	210.5	349.5	1 Oct.	1 Jul.	120	140
Potato	739.5	354	109	156	1 Oct.	1 Oct.	225	260
Tomato	821	623	–	248	1 Jun.	1 Oct.	390	455
Sugar beet	1807	359	–	88.5	1 Apr.	20 Oct.	300	340
Alfalfa	10363	4793	3367	3211.7	1 Apr.	1 Oct.	220	270
Apple	8328	2850	210.5	–	20 Apr.	15 Nov.	350	380

2.2. Agricultural water productivity

There are different indices to quantify WP. Tuong and Bouman (2003) define it as the value of the production of a crop per unit of water consumption (evapotranspiration and/or total irrigated water [effective rainfall + irrigation]). Usually, sere material, business performance, or money units are used to define crop production. However, in this study the produced material (per kg) only is used. This can also be defined as the crop per drop (CPD) index (Ehsani and Khaledi, 2003), defined by:

$$\mathrm{CPD} = \frac{\sum_{i=1}^{n} Y_i \times A_i}{\sum_{i=1}^{n} V_i \times A_i} \quad (1)$$

where i is the crop number, n is the number of cultivated crops in the region's cropping patterns, Y_i is the yield of crop i (kg/ha), A_i is the area of crop i (ha) and V_i is the consumed water volume of crop i (m^3/ha). V_i can be expressed as the sum of irrigation water and effective rainfall ($\mathrm{CPD_{IP}}$) or as actual evapotranspiration ($\mathrm{ET_{act}}$) volume ($\mathrm{CPD_{ET}}$). Both of these ways will be evaluated in this study.

Each subbasin was divided into HRUs based on cropping pattern (Table 1). HRUs that are cultivated with a specific crop were delineated, and Eq. (2) was used to calculate the CPD index for each subbasin:

$$\mathrm{CPD}_k = \frac{\sum_{i=1}^{n_k} \sum_{j=1}^{m_{ik}} Y_{ijk} \times A_{ijk}}{\sum_{i=1}^{n_k} \sum_{j=1}^{m_{ik}} V_{ijk} \times A_{ijk}} \quad (2)$$

where CPD_k is WP of the implemented crop pattern in subbasin k (kg/m^3), k is subbasin number, n_k is the number of crops cultivated in subbasin k, m_{ik} is the number of HRUs allocated to crop i in subbasin k, i is crop number in subbasin k, j is the HRU number related to each crop in subbasin k, Y_{ijk} is the yield of crop$_i$ in the HRU with number j in subbasin k (kg/ha), A_{ijk} is cultivated area of crop i in HRU j in subbasin k (ha), and V_{ijk} is the consumed water volume by crop i in HRU j in subbasin k (m^3/ha).

2.3. SWAT model setup

SWAT is a process-based continuous hydrological model (Gassman et al., 2007). The main components of the model, which are also required for this study, include climate, hydrology, soil temperature, plant growth, nutrients, pesticides, land management, channel routing, and reservoir routing (Neitsch et al., 2002). Furthermore, parameters including crop parameters, agrology (Sol), groundwater, management (e.g., cropping pattern and irrigation planning and efficiency), and river are introduced to the model based on the obtained data and information.

Considering the objectives of this work, it is necessary to simulate crop yield as well as irrigated water and evapotranspiration, which are the main variables of the WP equations. Simulations of streamflow and groundwater are also crucial to predicting the amount of saved water resulting from changing the irrigation systems. The framework of this integrated modeling approach is shown in Fig. 2. The next sections explain briefly how the SWAT model is calibrated and validated to calculate the aforementioned variables.

2.3.1. Agricultural management

As previously stated, 908 HRUs were used in this study to define spatial changes of land use and land management. Out of them, 511 HRUs are irrigated agricultural lands. This extensive division enables us to define aspects of the basin's agricultural management including cropping pattern, planting and harvesting dates, fertilization (timing and amounts), and irrigation planning as closely as possible to the real catchment situation. Unlike most applications of SWAT in rural areas, which use "auto irrigation" (e.g., Liu, 2009; Faramarzi et al., 2010; Parajuli et al., 2013; Pagliero et al., 2014), we had to use the "irrigation schedule by date" option to simulate irrigation practices in surface or pressurized systems. This option requires a lot of manipulation.

Water requirement of crops and sources of irrigation water (dam, surface and/or groundwater) are two important inputs for this part, which are derived from the Iran National Water Document (INWD) (Alizadeh et al., 2007) and Comprehensive Water Management Plan (CWMP) (CWMP, 2006), respectively.

2.3.2. Crop yield and actual evapotranspiration

SWAT uses a simplified version of the EPIC[2] model (Williams, 1995) to simulate crop growth and crop yield. Daily actual evapotranspiration (ET_{act}) is simulated by a user-defined ET_p method and daily leaf area index (LAI). Due to the importance of these two variables as the main components of WP equations, more efforts are devoted to calibrating them.

Also, since crop variables (like LAI) directly affect ET_{act} and crop yield, they are simultaneously calibrated and validated (Fig. 2). For this purpose the steps taken are: (1) specify planting and harvesting dates (growth season) of major crops in the model, (2) adjust the parameters affecting LAI, ET_{act} and crop yield, (3) simulate and calibrate LAI and ET_{act}, and finally (4) simulate the crops yield.

2.3.3. Changing irrigation systems from surface to pressurized

Two main criteria are considered to distinguish surface irrigation from pressurized irrigation systems. The first one is losses and return flows of the irrigation systems. This criterion is very important and, actually, it is where field hydrology links to basin hydrology and vise versa. The second one is irrigation depth and period.

[2] Erosion Productivity Impact Calculator.

The water losses that are considered for surface irrigation include evaporation from the dam storage and water conveyance channels; and return flows that consist of percolation and runoff. Similarly, the considered losses for trickle irrigation include evaporation from dam storage and slight percolation. In the case of sprinkler irrigation, wind drift and evaporation losses are also considered. In SWAT, the runoff from irrigation is directly introduced into the model, and percolation is calculated during the simulations with respect to different factors like irrigation management (irrigation depth and its period), soil characteristics (soil hydraulic conductivity and available water capacity of soil), and crop type (LAI and root depth).

Similarly, the current irrigation condition of the catchment (surface irrigation) and pressurized irrigation including its net depth (from FAO, 1998) and period are defined for each crop (Table 3) and introduced into the SWAT model by changing the *.mgt files for each HRU (Fig. 2). The crop pattern is also indicated for each subbasin (Table 2).

The surface irrigation efficiency of the basin is about 38% and 50% for surface water and groundwater, respectively (CWMP, 2006). Therefore, to simulate current catchment irrigation efficiency, runoff and the soil parameters affecting percolation (return flows) are reasonably adjusted based on the soil map and data collected from MOJA. So, the performance of the model in simulation of the river's base flows (mainly from mid-spring to the end of summer) was considered, too. Fig. 3 shows details of the applied framework for simulation of irrigation water efficiency using the SWAT model.

Irrigation efficiencies of sprinkler and trickle irrigation systems are considered to be 60% and 80%, respectively. It is notable to mention that while applying the pressurized irrigation scenario, the calibrated soil parameters from the previous surface irrigation scenario did not change.

The current cultivated area of major crops, as well as the areas that can potentially undergo pressurized irrigation (sprinkler and trickle) are shown in Table 4. To select which irrigation systems to use, features like irrigation source, distance of farms or HRUs from rivers or wells, the amount of experience applying these systems, technical manuals, as well as consultation with local experts are considered. As seen in Table 4, about 35% of the area currently under surface irrigation isn't suitable for pressurized irrigation.

3. Results

This section includes explanations of the SWAT calibration process and the simulation results for surface and groundwater flows (especially outflows to the lake as representatives of environmental flows) and components of the water productivity equation (crop yield and actual evapotranspiration), while applying the current irrigation system and changing it to pressurized irrigation.

3.1. Flow simulation

3.1.1. Surface runoff

The first step to simulating surface runoff is to indicate the parameters that have greater effects on stream flow. This is accomplished by a sensitivity analysis. In this study's sensitivity analysis, calibration and parameter uncertainty analysis of the model were performed with Sequential Uncertainty Fitting (SUFI-2) using the SWAT-CUP package (Abbaspour, 2008).

To calibrate the model, we used 20 hydrological parameters (e.g., soil, land use, reach, groundwater, surface runoff, snow) that affect streamflow. After sensitivity analysis, the model was calibrated and validated using monthly data from discharge stations (Fig. 1 and Table 5). The coefficient of determination (R^2)

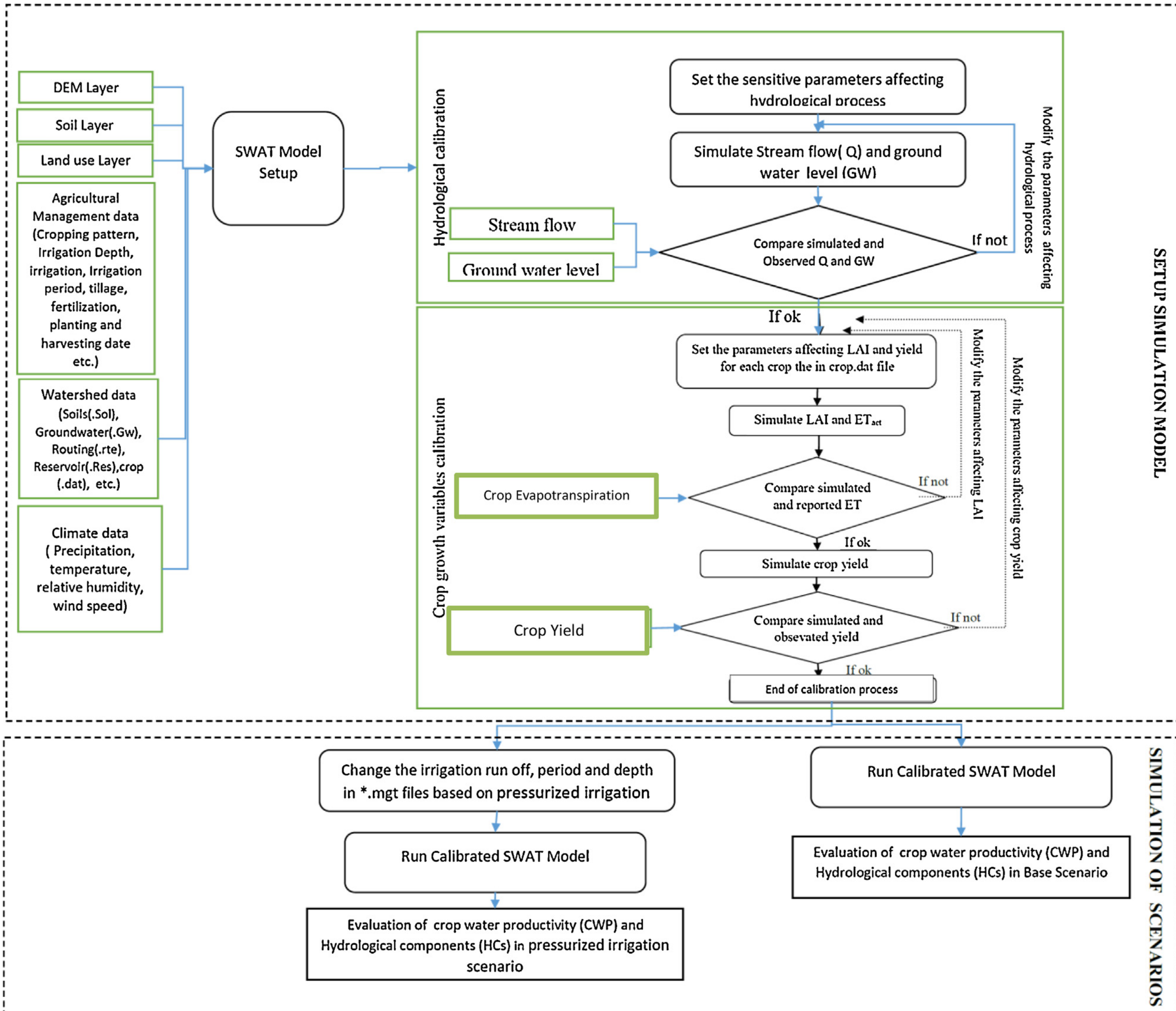

Fig. 2. Integrated modeling framework for simulating irrigation systems, water productivity, and water saving using the SWAT model.

Table 2
Percentage of land allocated to major crops in each subbasin.

Subbasin Crop	1	2	3	4	5	6	7	8	9	10	11
Wheat	39.37	41.45	29.20	30.50	36.08	41.23	40.55	48.10	7.95	86.55	61.23
Barley	10.10	10.85	6.74	9.65	7.20	12.73	11.99	2.20	4.97	0.00	14.87
Potato	2.09	1.97	0.00	1.84	2.14	2.13	1.79	0.93	2.57	4.04	3.23
Tomato	2.02	1.97	1.69	1.84	2.14	3.60	3.19	2.36	0.00	4.04	3.23
Sugar beet	5.05	3.95	3.61	5.43	3.61	2.13	1.83	1.37	0.00	0.00	0.00
Alfalfa	25.23	27.64	18.53	18.47	20.90	25.46	25.12	45.04	79.53	5.38	17.44
Apple	16.15	12.16	40.23	32.27	27.93	12.73	15.53	0.00	4.97	0.00	0.00

and Nash–Sutcliffe (NS) coefficients were used to evaluate the runoff simulations. The calibration results showed acceptable performance by the model with R^2 values from 0.49 to 0.71 and NS values from 0.14 to 0.7. Similarly, validation indicated acceptable model performance with R^2 values from 0.50 to 0.77, and NS from 0.47 to 0.69. As an example, Fig. 4 shows the time series of observed and simulated discharges for Nezamabad station, which is the last station before the lake and is a good representative station to indicate volume of water inflow to LU. The figure also shows the uncertainty bands of the simulated streamflows that were quantified by P-factor and R-factor (Table 5). The P-factor is the percentage of measured data bracketed by the 95 PPU (95% prediction uncertainty), and the R-factor shows the average thickness of the 95PPU band divided by the standard deviation of the measured data. A P-factor of 1 and R-factor of zero indicate a simulation that exactly corresponds to measured data. Also, a value of less than 1 is a desirable measure for the R-factor. The P-factor and R-factor of flow simulations vary between 0.41–0.76 and 0.34–0.85, respectively, and they showed acceptable performance of the model.

The calibrated model revealed the results of a switch to a pressurized irrigation scenario (Fig. 5). It is notable that the total

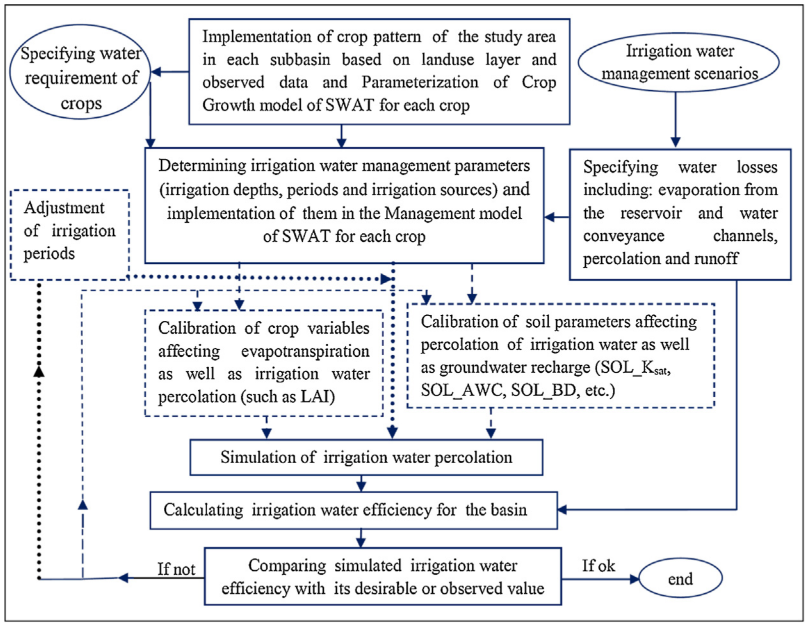

Fig. 3. Applied framework for simulation of irrigation water efficiency using SWAT model in the basin. *The stages showed with dashed line are only done for base scenario while the stages showed with dotted line are only done for increasing irrigation efficiency scenario. The black solid lines are done for both of scenarios.

Table 3
Irrigation depth (mm) applied to SWAT in the irrigation systems scenarios (Surface/Presuriaed) for major crops.

Mon. Crop	Apr.	May	Jun.	Jul.	Aug.	Sep.	Irr. period (day)
Wheat	–	360	360	–	–	–	15
		170	210				3
Barley	–	260	260	–	–	–	15
		170	210				3
Potato	–	115	350	350	350	350	10
		75	125	210	180	130	3
Tomato	–	–	230	230	230	230	10
			100	200	180	130	3
Sugarbeet	200	300	300	300	300	300	10
	0	120	210	235	210	155	3
Alfalfa	–	270	270	270	270	270	10
		175	225	250	210	155	3
Apple	–	310	310	310	310	310	10
		150	190	210	180	130	3

Table 4
Area of cultivated lands (ha) under pressurized and surface irrigated for the two scenarios.

Scenario	Irrigation system	Subbasin										
		1	2	3	4	5	6	7	8	9	10	11
Base	Surface	8988	20296	5191	4626	2850	3755	15280	6439	4235	1259	1399
	Pressurized	–	–	–	–	–	–	–	–	–	–	–
Pressurize	Surface	2270	4668	3052	2347	1391	956	5233	3200	3688	169	335
	Pressurized	6718	15628	2139	2279	1459	2799	10047	3239	547	1090	1065

Table 5
Summary of model performance for calibration and validation periods.

Station	Calibration					Validation				
	Statistical period	R^2	NS	P-factor	R-factor	Statistical period	R^2	NS	P-factor	R-factor
Pole anian	1987–1999	0.7	0.5	0.63	0.39	2000–2006	0.77	0.69	0.68	0.34
Santeh	1988–1999	0.63	0.61	0.58	0.62	2000–2006	0.72	0.66	0.61	0.56
Safakhaneh	1987–1999	0.61	0.53	0.55	0.45	2000–2006	0.54	0.5	0.48	0.41
Zarrineh	1987–1999	0.71	0.69	0.72	0.81	2000–2006	0.66	0.6	0.74	0.67
Chobloche	1987–1999	0.49	0.14	0.41	0.76	1998–2002	0.65	0.47	0.57	0.42
Nezamabad	1993–2001	0.71	0.69	0.76	0.85	2001–2006	0.55	0.53	0.67	0.79

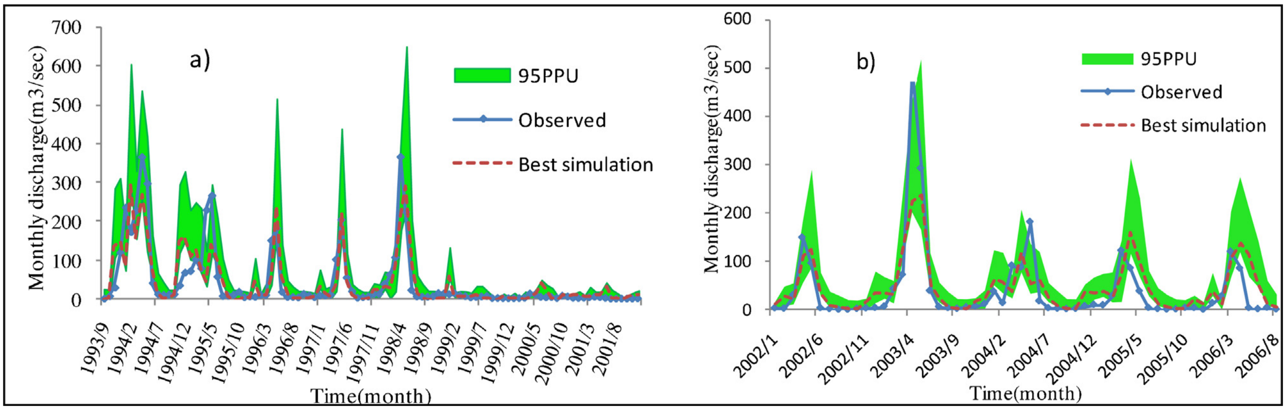

Fig. 4. Monthly discharge simulation at Nezamabad gauging station (a) calibration period; (b) validation period.

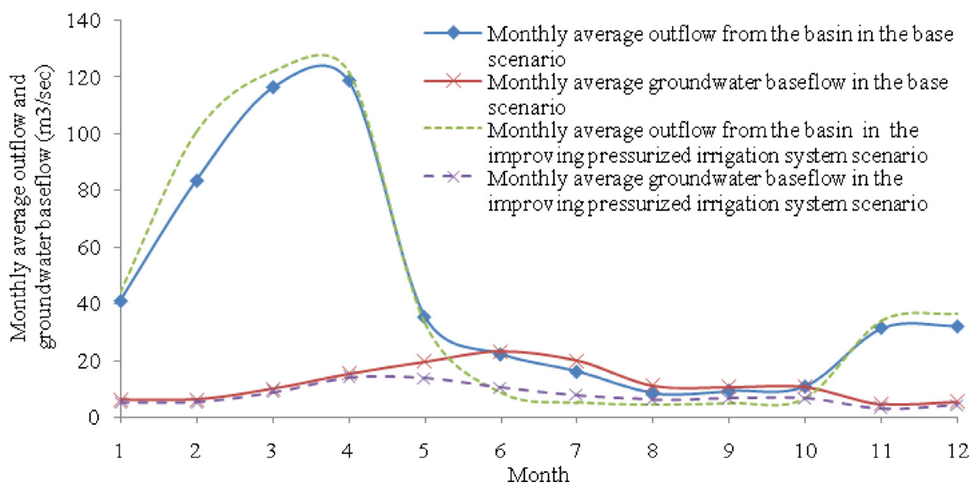

Fig. 5. Monthly average streamflow and base flow in the surface and pressurized irrigation scenarios at subbasin 1 (inflows to Lake Urmia).

annual inflows to the lake are almost the same (1357 MCM for surface irrigation to 1350 MCM for pressurized irrigation). However, the pressurized irrigation system has an impact on the monthly streamflow regime. This is mainly due to changes in base flows and groundwater recharges. Venn et al. (2004) also reported the same by evaluation of the recorded discharges after improving irrigation efficiency in the Salt River basin by changing 75% of the traditional irrigation systems to sprinkler. They observed increased streamflow in May–June and decreased flow in August–November. Similar attempts to improve irrigation efficiency in Gallatin Basin changed the monthly streamflow regime but caused no significant change in total annual streamflow (Kendy and Bredehoef, 2006). More about groundwater changes are presented in the next section.

3.1.2. *Groundwater recharge and drawdown*

Groundwater data is available for the Miandoab plain (http://www.wrs.wrm.ir/tolidat/ab-zirzamini.asp). This is the main plain of the Zarineh Rud catchment, with a very reach aquifer. It is also connected to subbasins 1, 2, 5, 6, and 7, which include 68% of the irrigated areas. Fig. 6 shows observed and SWAT-simulated accumulated drawdown of groundwater (m) for this plain from 1993 to 2005. Due to the long lasting drought of recent years and over-exploitation, the aquifer is faced with a negative water balance, as also reported by Motagh et al. (2008).

Results of the SWAT groundwater simulation for the two irrigation scenarios are shown in Table 6. The table presents irrigated percentage of subbasin area, groundwater recharge, and water table drawdown for each subbasin during the study period (1988–2007). It is seen that in subbasins such as 1, 2 and 6, where the major land use is agricultural, water table drawdown is more severe due to application of pressurized irrigation. This is due to percolation reduction in the pressurized scenario that escalates the drop in the water table from the current 8.3 mm/yr to 10 mm/yr. Negative impacts of pressurized irrigation on groundwater recharge and return flow reduction are also shown by Butler et al. (2001) and Cannon and Johnson (2004). Fig. 7 shows the average changes in the aquifer's water depth of the entire basin for the two irrigation scenarios for the study period.

3.1.3. *Simulation of LAI and ET_{act}*

LAI is a crop factor that controls actual evapotranspiration (Neitsch et al., 2002). It is expected that the LAI and the crop coefficient (Kc) have similar variation during the growing season (Williams and Ayars, 2005). There is no observed data on LAI for any of the major crops in the catchment. So, simulated LAI averages for a 15-day time step are compared with various K_c values obtained from FAO (1998) for the major crops. Of course, since FAO gives these values for full irrigation (ET_{max}), this comparison is limited to average annual LAI values of wet years (1988, 1991, 1992, 1993, 1994, 2004 and 2006), where we can assume there has been no water stress. The correlation of simulated LAI to K_c shows R^2 values of 0.93 for apples, 0.83 for alfalfa, 0.91 for sugar beets, 0.94 for tomatoes, 0.72 for potatoes, 0.63 for barley, and 0.73 for wheat. Fig. 8 also shows this comparison for apples and barely in the study area.

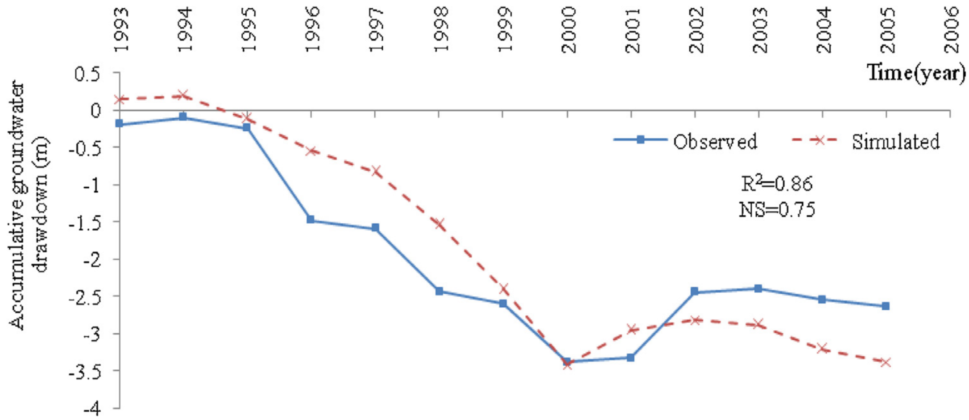

Fig. 6. Comparison of simulated accumulative groundwater drawdown for Miandoab aquifer with observed values in the period of 1993–2005.

Table 6
Comparison of groundwater recharge (mm) and water table drawdown (m) in both of scenarios in each subbasin.

Subbasin	Percent of irrigated agricultural area to subbasin area	Base scenario		The scenario of increasing irrigation efficiency		Variation of water table drawdown(mm)
		Groundwater recharge (mm)	Water table drawdown (m)	Groundwater recharge (mm)	Water table drawdown (m)	
1	37.53	310	9.79	200	13.83	-4.04
2	69.19	440	12.58	237.14	33.52	-20.94
3	5.03	100.7	4.17	94	4.17	-0.00
4	4.70	54	9.50	46.15	9.52	-0.02
5	14.48	192.5	6.21	168.12	6.28	-0.07
6	32.97	244.7	14.80	157.6	20.00	-5.20
7	7.00	123.5	1.68	107.4	1.70	-0.02
8	2.92	81.8	1.81	78.8	1.82	-0.01
9	1.92	59.1	3.40	58.9	3.40	0.00
10	0.95	92.7	0.61	91.9	0.61	0.00
11	1.13	67.7	0.79	66.7	0.79	0.00

As there is no active lysimeter in the catchment to record actual evapotranspiration (ET_{act}), the average SWAT-simulated ET_{act} is compared to values reported by the Iran National Water Document (INDW) (Alizadeh and Kamali, 2007) for the aforementioned wet years (with the assumption that the average annual ET_{act} for these years is equal to ET_{max}). Fig. 9 shows this comparison and the acceptable performance of SWAT ($R^2 = 0.97$).

Simulated application of pressurized irrigation predicts a slight increase in annual ET_{act} (Table 7), which can be attributed to the higher water availability due to shorter irrigation periods. In the case of apples, the opposite is true due to the use of trickle irrigation

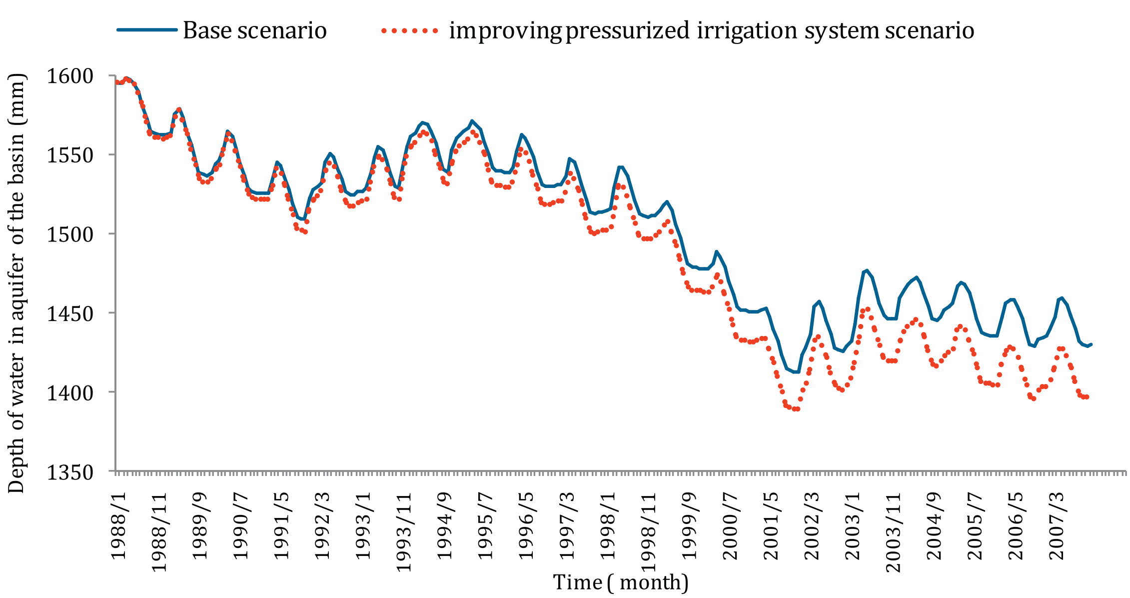

Fig. 7. Monthly time series of simulated average water depth in the aquifers of the Zarrineh Rud catchment in the surface and pressurized irrigation scenarios.

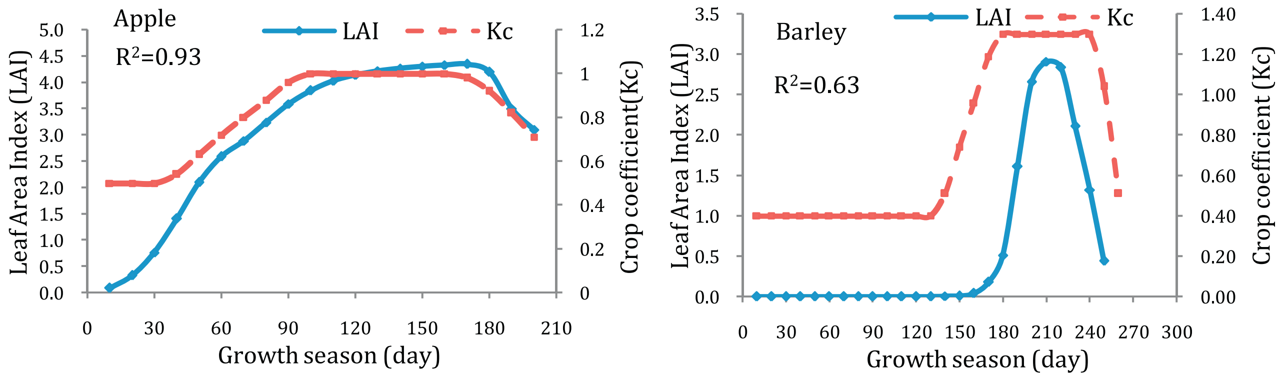

Fig. 8. Comparison of simulated average LAI in the wet years and crop coefficient (Kc) obtained from FAO (1998) for apple and barley crops.

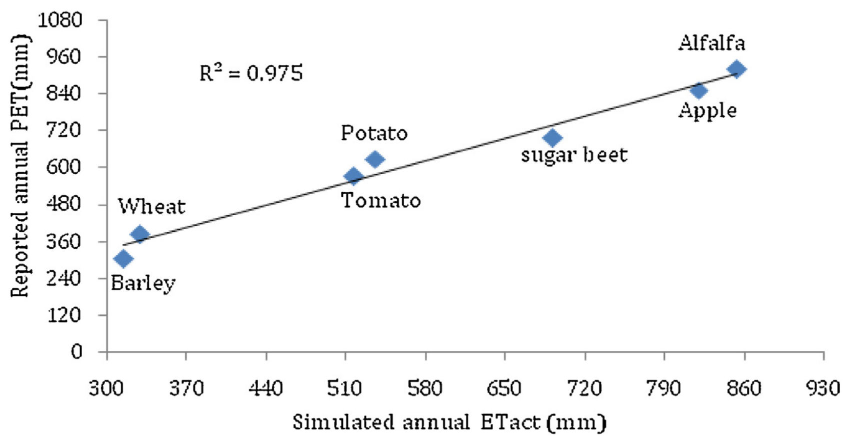

Fig. 9. Comparison of simulated average ET_{act} in wet years with crop water requirement of major crops.

Table 7
Annual average of simulated ET_{act} (mm) for major crops during their growth season in both irrigation scenarios.

ET_{act} (mm)	Wheat	Barley	Potato	Tomato	Sugarbeet	Alfalfa	Apple
Base scenario	360	354	536	517	634	854	757
Increased water efficiency scenario	410	406	651	566	736	857	630

and its significant reduction in wetted area. Fig. 10 illustrates the changes in annual ET_{act} for irrigated lands of the entire basin over time for the current and pressurized irrigation systems. The average annual ET_{act} of the catchment's irrigated land of 430 MCM/yr increases to 447 MCM/yr in the pressurize scenario. Similar results were also reported by Clemmens and Allen (2005). They noted that some irrigation improvement techniques, such as sprinkler and drip irrigation, may not conserve water on a regional basis since ET of irrigated fields is normally not reduced and may actually be increased by improved uniformity and more careful control of water application.

3.1.4. *Crop yield simulation*

Crop yield is one of the most important factors for estimating basin water productivity. Simulation of this variable is not as routine as simulating other hydrological variables like runoff. For calibration and validation of the model for crop yield simulation, we considered previous research works on the same crops. These crops include wheat (Hadria et al., 2006; Ziaei and Sepaskhah, 2003), barley (Mollah and Paul, 2008), potato (King and Stark, 1997), tomato (Singh et al., 2009), sugar beet (Dragovic and DjKaragic, 1996), alfalfa (Saeed and El-Nadi, 1997) and apple (Zhang et al., 2010).

Table 8 compares the calculated crop yields for surface and pressurized irrigation systems to the reported mean yields of the selected crops. There is good agreement between the observed and simulated values of yield ($R^2 = 0.95$). The results also show that the average crop yields can increase about 20% by changing the irrigation system to pressurized, which is the result of better water management and increased ET_{act}.

3.2. *Agricultural water productivity in changing irrigation efficiency*

To assess agricultural WP, the two indices CPD_{IP} (based on the sum of irrigated water and effective rainfall volume) and CPD_{ET} (based on ET_{act} volume) are applied. After simulation of the variables involved in the water productivity indices (WPI) using the calibrated SWAT model, the average values of WPI for each crop for the current and pressurized irrigation scenarios are estimated (Fig. 11). The main point is the difference between CPD_{IP} in Fig. 11(a) and (b), which is the result of allocation of more water to crops in surface irrigation. However, in the case of CPD_{ET}, the difference is much less, due to using the real evapotranspiration instead of allocating irrigation water. Notably, the CPD_{IP} and CPD_{ET} differences are significant only for apple (as the representative of orchards),

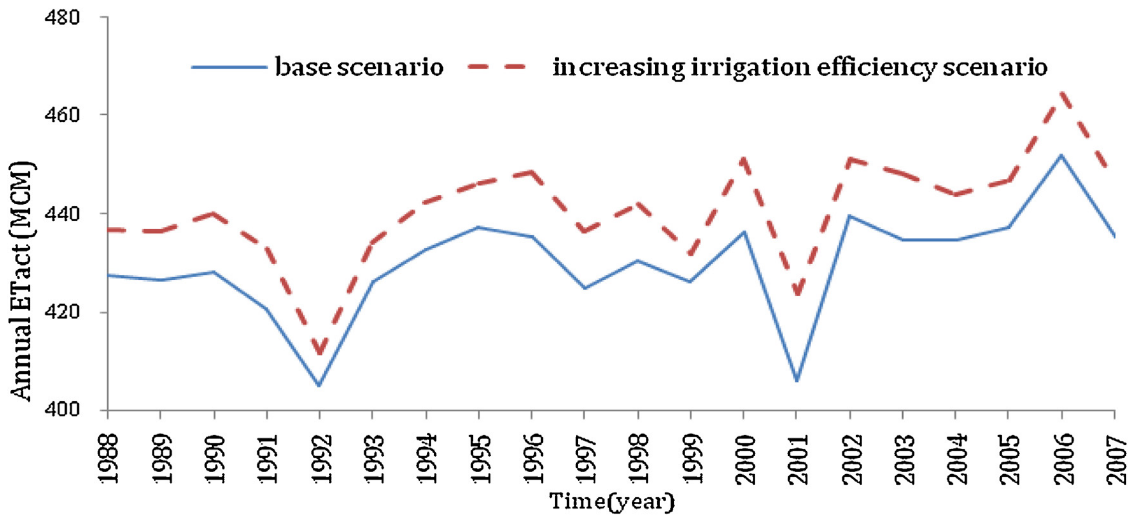

Fig. 10. Comparison of annual ET_{act} from irrigated land in in the surface and pressurized irrigation scenarios.

Table 8
Observed and simulated yield values of major crops of the study area (ton/ha) in both ofscenarios.

Crop	Wheat	Barley	Potato	Tomato	Sugarbeet	Alfalfa	Apple
Mean reported yield[a]	3.46	2.69	21.17	33.03	44.60	8.50	22.14
Mean simulated yield in current irrigation condition	3.49	2.41	23.00	36.00	43.80	9.83	24.22
Mean simulated yield in increasing irrigation efficiency scenario	4.14	3.67	28.73	43.83	50.32	9.91	25.08

[a] Based on the Information Center of Ministry of Jahade-Agriculture (MOJA, 2007) (http://www.maj.ir/Portal/Home).

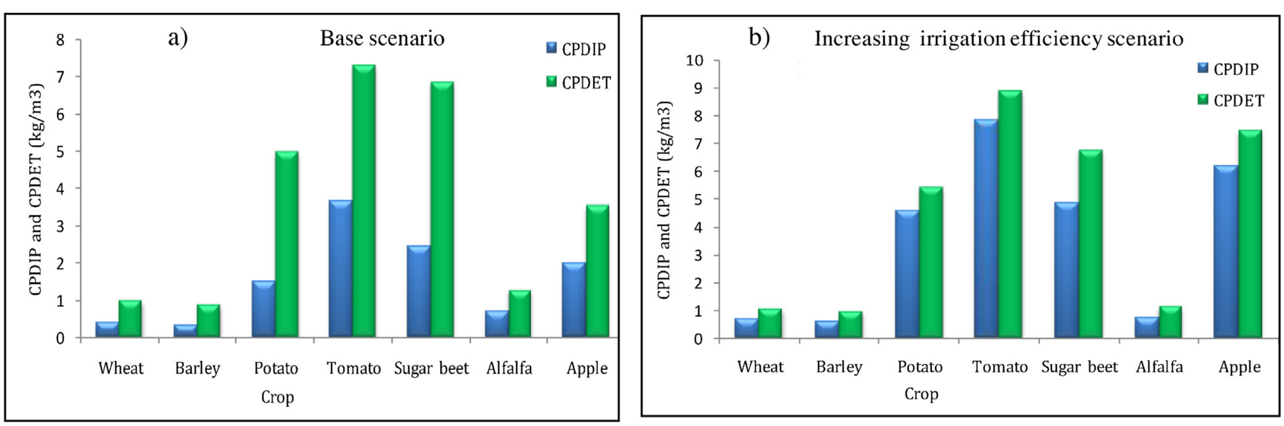

Fig. 11. Model-estimated average values of CPD_{IP} and CPD_{ET} for major crops in the surface (a) and pressurized irrigation scenarios (b).

Table 9
Ratio of WPI (kg/m^3) in the increasing irrigation efficiency scenario to the base scenario in each subbasin.

Subbasin WPI	1	2	3	4	5	6	7	8	9	10	11
CPD_{IP}	1.81	1.83	1.15	1.28	1.26	1.61	1.51	1.22	1.22	1.16	1.13
CPD_{ET}	1.30	1.24	1.00	1.04	1.03	1.17	1.16	1.06	1.19	1.05	1.08

which is due to substantial reduction of evaporation from soil while converting its irrigation system to trickle.

Moreover, Fig. 12 reveals the WPI values simulated by the model for the total cropping pattern at the subbasin scale. The WPI values in the subbasins indicate the role of cropping pattern (the distribution of major crops within the subbasins is shown in Table 2). For instance, the values of the indices are higher in subbasins 3, 4 and 5, where apple, which has a high WP (Fig. 11), is dominant. Subbasin 9, because of allocating a relatively high area to alfalfa, has lower WP.

Table 9 illustrates ratios of WPI in the pressurized to surface system scenarios in the subbasins. Because of high irrigation efficiency in the pressurized scenario (sprinkler 60% and trickle 80%), the ratio of CPD_{IP} is high. This shows that the pressurized system can reduce water removal. However, the CDP_{ET} ratio is much smaller and shows that the amount of water removed from the irrigation source has been close to ET_{act}. Similarly, the WPI values for the entire catchment are estimated for both of scenarios (Table 10). It is seen that at the basin scale, as on the subbasin level, WPI values increase in the pressurized irrigation scenario. According to this

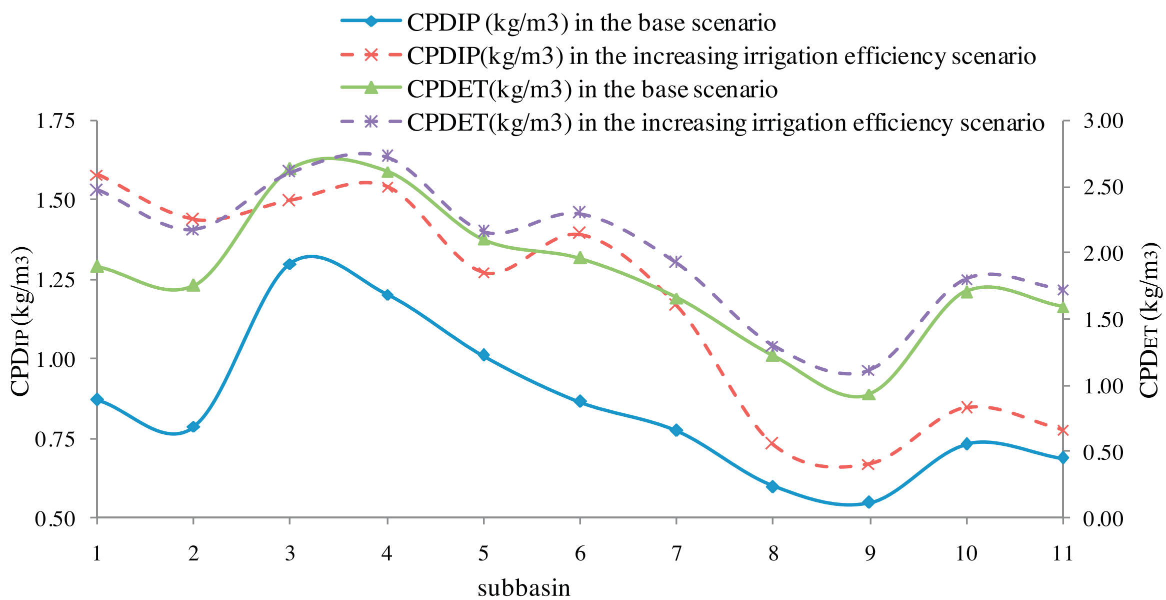

Fig. 12. Simulated average values of WPI in each Zarineh Rudin subbasin for the surface and pressurized irrigation scenarios.

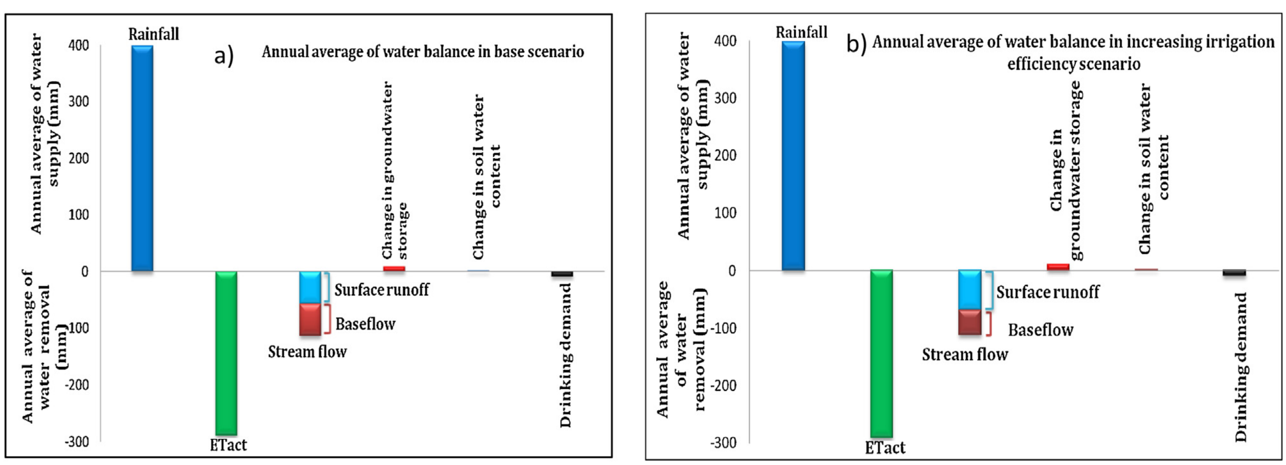

Fig. 13. Annual average water balance of the basin in the (a) surface irrigation and (b) pressurized irrigation scenarios.

Table 10
Estimatedvalues of WPI (kg/m^3) for total of the ZarrinehRud river basin under both scenarios.

WPI	Base scenario (current condition)	Increasing irrigation efficiency scenario	WPI ratio
CPD_{IP}	0.84	1.25	1.50
CPD_{ET}	1.78	2.06	1.15

table, the pressurize irrigation system has the potential to increase CPD_{IP} and CPD_{ET} by 50% and 15%, respectively (Table 10).

3.3. Evaluation impacts of changing the irrigation system on hydrological water balance

To evaluate the impact of changing irrigation systems on the components of water balance at the basin scale and assess the value of pressurized irrigation to real water saving (Molden et al., 2001), the calibrated SWAT model was executed for the period of 1988–2007 for the current and pressurized irrigation systems. Fig. 13 shows the long-term changes in the components of water balance at the basin scale that were emphasized in the study for the two scenarios. As indicated in the figure, while the unique input to the basin is rainfall (390 mm/yr), the major output is ET_{act}, (from agricultural and non-agricultural together) with the amount being 72% (290 mm/yr) of the annual rainfall. The next most significant output from the basin is streamflow (what passes from subbasin 1 and joins Lake Urmia). This component, which is the combination of base and surface flows, is about 28% of the annual rainfall (112 mm/yr) and its total amount is the same for the two irrigation system scenarios. The figure shows that by changing the irrigation system, the amount of water removal from surface sources (dam and river) is reduced. Simultaneously, however, the contribution of base flow to total streamflow declines from 49% to 38% due to decreased percolation to the aquifer (Table 6).

For more clarification, Fig. 14 shows the differences in surface and groundwater sources for irrigation in the two scenarios. Pressurized irrigation is predicted to reduce annual average water withdrawal from 800 MCM/yr to 620 MCM/yr (a 160 MCM/yr reduction). Fig. 15 illustrates the total flow into the lake as well as the annual base flows. Notably, total flows into the lake are almost the same for the two irrigation scenarios, while the base flows are higher for the surface irrigation scenario. The annual average base flow is 665 MCM/yr for surface irrigation and 520 MCM/yr for pressurized irrigation (a reduction of 145 MCM/yr). Therefore, the

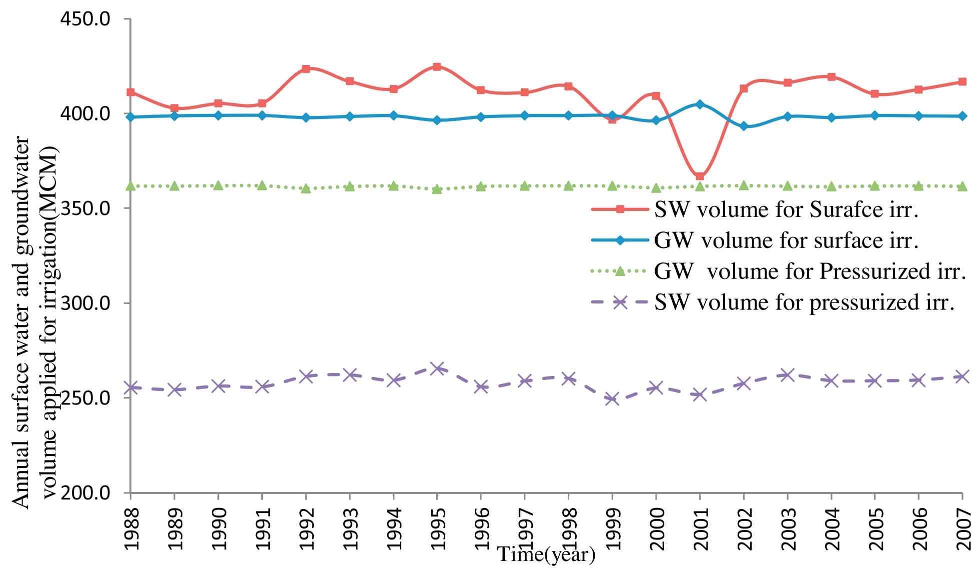

Fig. 14. Simulated time series of annual water intake from surface and ground water resources for irrigation in the surface and pressurized irrigation system scenarios.

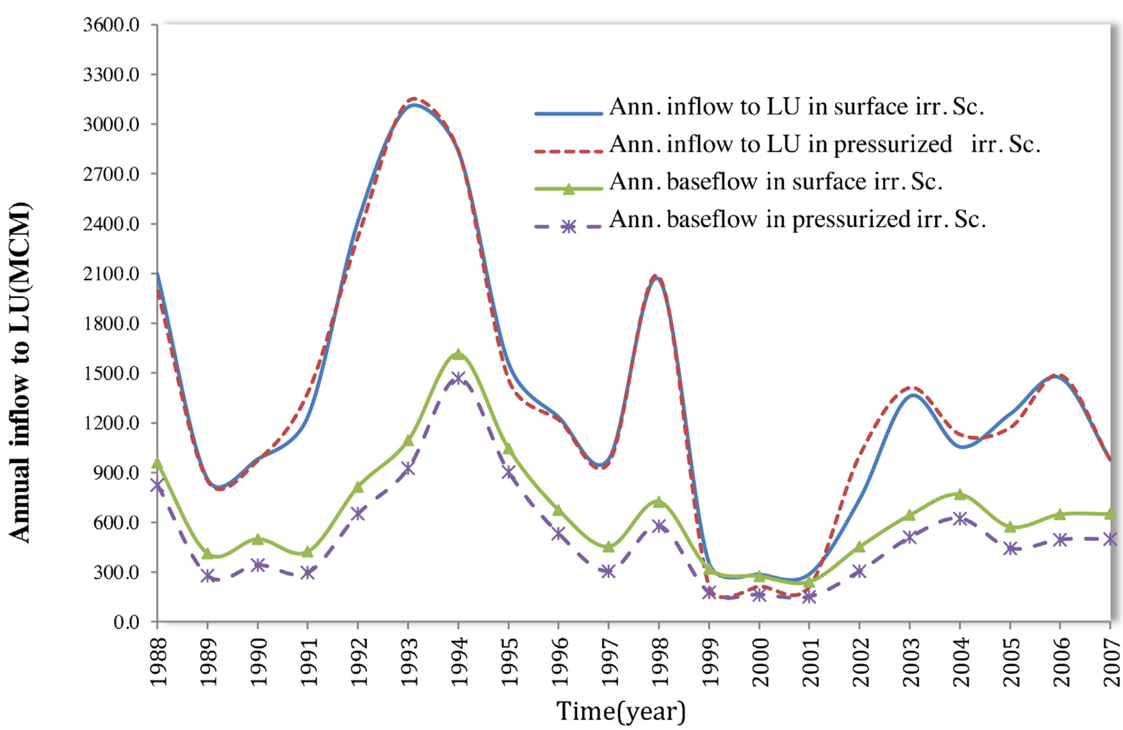

Fig. 15. Simulated time series of annual inflows to Lake Urmia and base flows for the surface and pressurized irrigation system scenarios.

amount of water that is expected to be saved in the pressurized system is the same amount that was in return flows that were used for the surface irrigation scenario. Therefore, our model indicated that changing the irrigation systems will cause no significant water saving to take place. This is a characteristic of closed basins where water consumption and interaction of surface and groundwater are high, which is also reported by Kendy and Bredehoef (2006) and Clemmens and Allen (2005).

4. Summary and conclusions

This paper aimed to evaluate impacts on water productivity and water saving of changing surface irrigation systems to pressurized irrigation in the Zarrindeh Rud basin, which is one of the main agricultural areas in northwest Iran and the main water supplier of Lake Urmia. To analyze the required hydrological and agricultural variables in an integrated and multi-scale framework (at field and basin levels), the SWAT model was comprehensively calibrated and set up. The applied water productivity index is crop per drop (CPD), which is calculated based on applied irrigation depth (CPD_{IP}), actual evapotranspiration (CPD_{ET}), and crop yield simulated by SWAT. The following conclusions can be drawn from this study:

- In general, the average value of CPD_{IP} in the current agricultural management of the basin is 0.87 kg/m^3, which is low compared to areas in other developing countries like the Nile delta in Egypt, where it is 1.52 kg/m^3 (Zwart, 2010). This study showed that changing to a pressurized system can increase CPD_{IP} and CPD_{ET}

up to 50% and 15%, respectively. This increase in WP indices is due to increases in crop yield that are also the result of better water distribution and greater ET_{act}. On average, the increases in crop yield and ET_{act} are expected to be 20% and 12.5%, respectively.

- The groundwater simulations showed that increasing irrigation efficiency can have a negative impact on recharges and can intensify drawdown of the basin's water table up to 20%. This is due to the high interaction of surface water and groundwater in the basin, such that pressurized irrigation reduces percolation and consequently reduces groundwater recharge.
- Pressurized irrigation can reduce water uptake about 165 MCM/yr compared to current surface irrigation in the study area. However, pressurized irrigation reduces the return flow by about the same amount, which results in no significant change in total inflow to the lake.
- Moreover, the pressurized system mainly changes the monthly pattern of streamflow. It causes increased streamflow in May and June and decreased streamflow in the August to November period. The annual average water inflow to the lake was1357 MCM for the study period for surface irrigation, and it remains almost the same when you change to pressurized irrigation, with a predicted flow of1350 MCM. Therefore, such a policy does not have a significant potential to save water in the basin.
- This study, with its extensive simulation and integrated framework, is one of the rare cases of multi-variable calibration of the SWAT model that can be considered for similar works. In this regard, the coefficient of determination (R^2) for the simulation of monthly streamflows varied from 0.5 to 0.77. Also, R^2 was 0.86, 0.97 and 0.95 for annual groundwater, Et_{act}, and crop yield, respectively.

The main message of this study is the necessity of serious pre-assessments and analyses of side effects of any measure meant to enhance water productivity and water saving before implementation through an integrative framework at basin scale. Also, to effectively create "new" water in a regional context, a conservation program must in some way reduce real loss of water from an irrigation project by evaporation or ET_{act}, and not simply reduce diversions. This usually takes place in the form of reducing cultivated areas, eliminating high water consuming crops, using deficit irrigation or a combination of these measures.

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