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Application of SWAT model to simulate nitrate and phosphate leaching from agricultural lands to the rivers

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ABSTRACT

In the present study, the amount of nitrate and phosphate leaching from agricultural lands into the Zanjanrood River in Iran was simulated using the Soil & Water Assessment Tool (SWAT) model. The measured average monthly discharges at the Sarcham station were used to calibrate and validate the SWAT model, and the SWAT Calibration and Uncertainty Program (SWAT-CUP) model was applied to perform the uncertainty and sensitivity analyses. Three scenarios for the irrigation methods and five for the fertilizer rates were defined. The p-factor and r-factor were used for the uncertainty analysis, and two statistical indices of the coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NS) were utilized in the validation model. For the calibration of the monthly runoff at the basin's outlet, the coefficients of r-factor, p-factor, R^2, and NS were obtained as 0.27, 0.11, 0.83, and 0.53, respectively. The results showed that by increasing the pressurized irrigation areas, the nitrate and phosphate pollutions in the river basin were not significantly affected. With regard to fertilizer rates, by reducing the consumption of urea and phosphate fertilizers up to 50%, the amount of nitrate and phosphate leaching into the Zanjanrood River was reduced up to 16.7% and 19.2%, respectively. On the other hand, an increase of 50% in fertilizer application increased nitrate and phosphate leaching into the river by 17.2% and 17.7%, respectively. In addition, by reducing the fertilization rate and preventing unnecessary fertilization by farmers, the pollution of water resources can be largely prevented.

1. Introduction

Rivers usually play a vital role in supplying the water required for different sectors of agriculture, industry, and urban; it is considered one of the important economic and social arteries of society [1]. Water resources include surface and ground waters with surface water resources more at risk for water quality than the ground water resources; therefore, to preserve these resources, the sources of pollution must be identified and appropriate strategies should be adopted for preventing or eliminating these contaminants. Economically speaking, preventing water pollution is more cost-effective than water treatment [2-6]. Therefore, looking at ways to prevent water pollution and enforcing them is necessary. In general, surface water pollution can be divided into two categories. Firstly, the pollution caused by point sources (PS), which refers to a group of contaminants at the point of production and entry into the surface water. This amount can be easily obtained by measuring at the input points that include industrial pollution and urban wastewater, and so on. These pollutants are often heavy metals and chemical contaminants. The second category is nonpoint source pollution (NPS), which results when contaminants are introduced into the environment over a large and widespread area (Figure 1). Similar to the pollution resulting from the chemical fertilizers used in agricultural lands and rangelands, these pollutions cannot be directly measured [7-9]. Nonpoint source pollution is difficult to control

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because it results from many different sources (Figure 1). The most contaminated surface waters are nonpoint source pollution, which generally includes various forms of nitrogen and phosphorus [10]. By applying the best management practices (BMP) in a river basin, the contaminants can be minimized. Land-use changes, creation of river buffer, irrigation practices, fertilizer restrictions, determining the appropriate cropping pattern, and soil conservation practices are among these measures. Moreover, there are many models for simulation of NPS pollution, such as AGNPS, ANSWERS, HSPS, and SWAT. Previous studies have shown that the SWAT model is highly flexible in the simulation of management approaches and can simulate a wide range of structural and non-structural solutions: protective plowing, protective coatings, fertilizer rate and time, buffer strips, flood prevention structures, and parallel terraces [11-15]. The SWAT model is a tool for assessing the water and soil quality and the quantity in the river basin developed by Arnold in the 1990s for the USDA-ARS Research Service for Agriculture [16]. SWAT is a comprehensive model that includes four main sections of sediment and runoff simulations, prediction of NPS pollutions, modification of model components of the natural conditions of each region, and estimation of the uncertainty of parameters and input data. To evaluate the flow discharges, long-term management practices on the water, sediment, and chemicals resulting from agricultural activities have been developed in large basins. In the United States, the use of the SWAT model has been proposed as a tool for evaluating many step-by-step conservation measures at large basins [16]. This model was developed to investigate the effect of land management practices on water, sediment, and agricultural chemical yields in large watersheds with varying soils, land use, and management conditions over long periods. It has been extensively used to study water resource and NPS pollution on different scales and environmental conditions all around the world [11,17-27]. Its proven track record is supported by its many publications in scientific journals. Since March 2016, a total of 2772 peer-reviewed SWAT model applications and developments have been published in about 500 different journals [28]. Abbaspour et al. [29] used the SWAT model to simulate the processes affecting the water quality, sediment, and nutrient cycle in the river basin. Their results showed that the simulation of the runoff of nitrate and phosphate was very satisfactory; however, the simulation of sediment and phosphorus was relatively good. Antje and Martin [30] investigated the effect of different water management practices on water quality and quantity using the SWAT model. They concluded that the SWAT model was appropriate for the simulation of crop rotation and very small changes in management practices. Other studies have been carried out to evaluate the effect of constructing the diversion terraces on runoff and sediment load in the catchment area using the SWAT model. The results of these studies have shown that the SWAT model well-adjusted the seasonal variations of flow diversion terraces and annual sediment load and changes in predicting soluble phosphorus concentration [31]. Additionally, Jiang et al. [32] simulated nonpoint source pollution using the SWAT model for the Liuxi River Basin. The results of the simulation showed that the change in conventional tillage practices and experimental fertilizer rates were effective in reducing NPS pollution with optimal protection and fertilization rates. Gebremariam [33]assessed the capabilities of different models of SWAT, Hydrological Simulation Program--Fortran (HSPF), and Distributed Large Basin Runoff Model (DLBRM) to simulate the critical flow regime for lower ecosystem services in the Maumee River Basin (USA). Given the evaluation criteria and the ability to simulate extreme events and floods, the HSPF model was better than the other models. Lai et al. [34]examined the NPS pollution and water quality in the Kaoping River in Taiwan by preparing a land-use map using SPAT satellite imagery and a high-quality digital map using ERDAS Imagine and ArcView software. They collected the water samples from several stations and measured the values of pH, NH_3, N, and BOD. Their results showed that there was a direct relationship between the low water quality and the land use pattern, such as orchards and agricultural lands, and should be effectively controlled. According to the above-mentioned studies, there are few studies conducted on modeling NPS pollution in surface waters in Iran. In addition, in most studies around the world, the effect of management practices such as control of fertilizer level, land use, coastal buffer strip, and climate changes has focused on the amount of NPS pollution. This study investigated the effect of surface irrigation methods and the development of pressurized irrigation systems on the amount of NPS pollution, especially nitrate and phosphate, in the Zanjanrood catchment in four scenarios along with two different scenarios of fertilizer application and two combined scenarios. The measured values of the average monthly discharges at the Sarcham Station from 1996-2013 were used for the sensitivity analysis, calibration, and validation of the SUFI2 algorithm in the SWAT-CUP model. Three scenarios regarding irrigation practices and five for fertilization were considered.

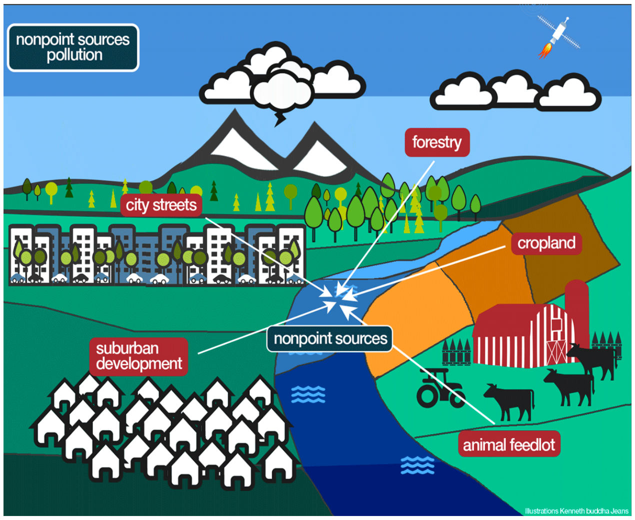


Fig.1. Different sources and locations of nonpoint source pollution (NPS) (come courtesy of National Oceanic and Atmospheric Administration).

2. Materials and methods

2.1. Study Area

Zanjanrood River is one of the most important rivers in Zanjan province (Iran), which is located at the area of 36˚ 13' to 37˚ 02' north latitude and 47˚ 50' to 49˚ 00' east longitude. The Zanjanrood watershed is located in the Caspian Sea basin, which is the main source of the Sefidrood River basin in the North of Iran. The Zanjanrood watershed has a catchment area of 4696 km^2 and flows into the Sefidrood River from the east. The gauged part of the Zanjanrood watershed covers 3750 km^2, and its elevation ranges from 1103 m to 2889 m above sea level (Figure 2). This basin is dominated by a semi-arid climate, with most of the rainfall (70-90%) occurring between November and May. This permanent river has an elevation ranging from 1100 to 1780 m, an average slope of 0.5 %, and is 142 km long.

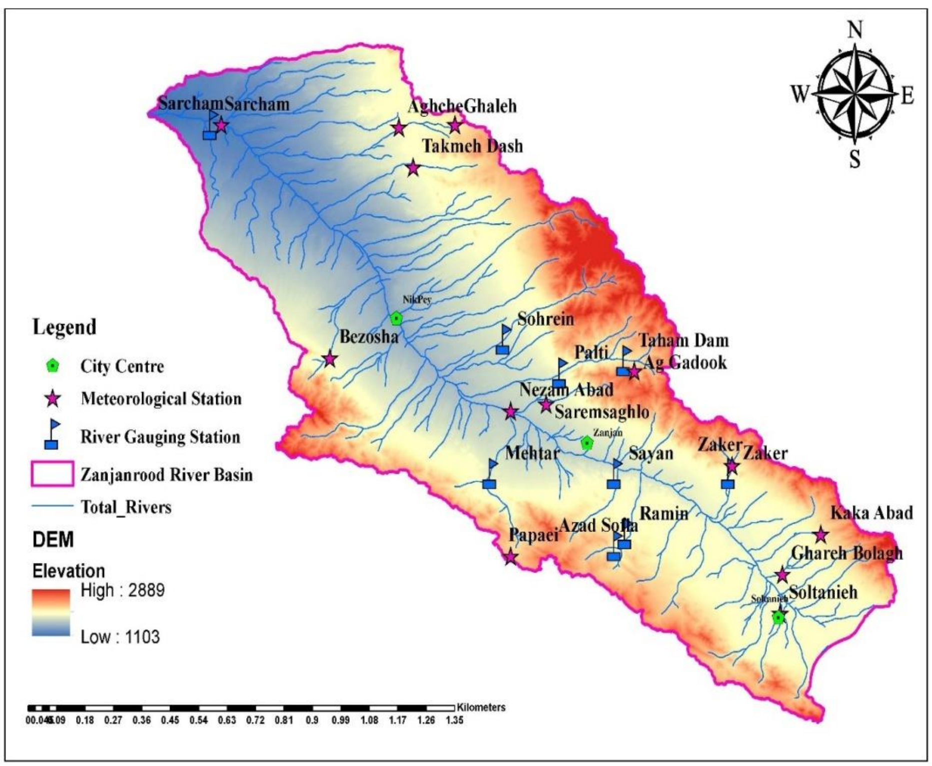


Fig. 2. Location of the Zanjanrood watershed in the Sefidrood River basin including Digital Elevation Model (DEM).

Based on the data resulted from the synoptic and meteorological stations (Table 1), the average annual evaporation and rainfall in the study area were 1683 mm and 312.1 mm, respectively, indicating a very high evaporation rate compared to the rainfall. Also, the daily average, minimum and maximum absolute values of temperatures recorded in the study area were respectively 10.9, 28.6 and 42 °C, with a relative humidity of 54 % with a cold climate.

Table 1. Specifications and location of synoptic and hydrometric stations used in this study.

Altitud	Latitud	Longitu	Station	Station Name
1575	36 11 N	49 11 E	synoptic	Khoram Dareh
1887	36 07 N	48 35 E	synoptic	Khodabandeh
1663	36 41 N	48 29 E	synoptic	Zanjan
1150	37 07 N	47 53 E	hydrometri	Sarcham

2.2. SWAT model

The SWAT model is a hydrological simulation model and it considers a continuous and semi-distributive time-based physical location model [35]. The main objective of the SWAT model is to simulate the effects of various land management techniques on the water and sediment quantity and quality in large basins; it takes the different climatic conditions, land use, and soil types into account over long time periods [36]. In this model, each basin is divided into several sub-basins and each sub-basin into several hydrological response units (HRUs), which consist of unique land-use, management, topography, and soil characteristics. First , the water content in the soil, surface runoff, nutrient cycle, sediment, plant growth, and management approaches are calculated for each hydrological response units, and then for each sub-basin as a weighted average. The SWAT model simulates the hydrological cycle based on the water balance equation as follows:

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

where, SW_t is the final value of the soil water (mm); SW_0 is the initial value of soil water (mm); R_{day} is the amount of rainfall on the day i (mm); Q_{surf} is the surface runoff on the day i (mm); E_a is the amount evapotranspiration on the day i (mm); W_{seep} is the amount of water seepage from the soil profile to the unsaturated zone on the day i (mm); and Q_{gw} is the return flow (mm). In this model, the surface runoff is estimated using an optional SCS curve number procedure and the Green&Ampt infiltration method; it predicts the maximum runoff rate with the modified rational method (MRM), and calculates the evapotranspiration (ETO) using the Penman-Monteith (PM), the Priestley-Taylor(PT) or the Hargreaves (HAG) methods [35,37-38]. The input data is used to calculate the runoff, sediment and nutrient loading from each HRU; then, the total loading from each sub-basin is calculated by aggregating the units [39-40].In addition, the SWAT model simulates the movement and transformation of different forms of nitrogen and phosphorus, pesticides, and sediment in a basin. The SWAT model allows the user to define the management practices adopted in each HRU. Once the water, sediment, nutrients, and pesticide loadings from the land phase to the main channel are specified, the loads are routed through the streams and reservoirs within the basin. More details on the SWAT model can be found in the theoretical report (http://swatmodel.tamu.edu) published by Arnold et al. [16].

2.3. Hydrological Modeling in SWAT

In general, the required data for simulation by the SWAT model are divided into three categories: the first layer includes high-quality digital elevation data, stream networks, land use and soil maps; the second layer comprises the river properties, effective parameters for determining the surface runoff, and parameters affecting the erosion simulation. The third layer contains the daily meteorological data, rainfall, minimum, maximum, and average temperatures, standard deviation, skewness coefficient of the rainfall, probability of wet day followed by a dry day, average dew point, and the average wind speed for each month [37]. The weather data is a major input to the hydrological processes in the SWAT model. Rainfall and maximum/minimum temperatures at the Saremsaghlo and Takmeh Dash meteorological weather stations were used in the period 1972-2013 (Figure 2; Table 1). These data were collected from the Iranian National Meteorological Organization. The relative humidity, solar radiation, and wind speed were simulated using SWAT's built-in weather generator based on the weather data at the Zanjan synoptic station [35]. The weather generator was also used to fill data gaps in the rainfall and maximum/minimum temperature data. The performance of the SWAT simulation was evaluated using monthly streamflow data from the Sarcham River gauging station (Figure 2). The hydrological data was used to calibrate the runoff estimation in the hydrological units (HRUs). The obtained results were used to calculate the soil data and curve number, the water infiltration rate into the soil media, and the root development depth; the contaminant that transferred and moved into the surface water sources was simulated using the equations of solute transport in the soil. The hydrological data were collected from the Iranian Ministry of Power. Figure 3 shows a hydrological modeling diagram by the SWAT model. According to the input data, the Zanjanrood Basin is divided into 19 sub-basins and 238 hydrological response units (HRUs). The basin's outlet is located at the Sarcham hydrometric station and sub-basin No. 1, as shown in Figure 4.

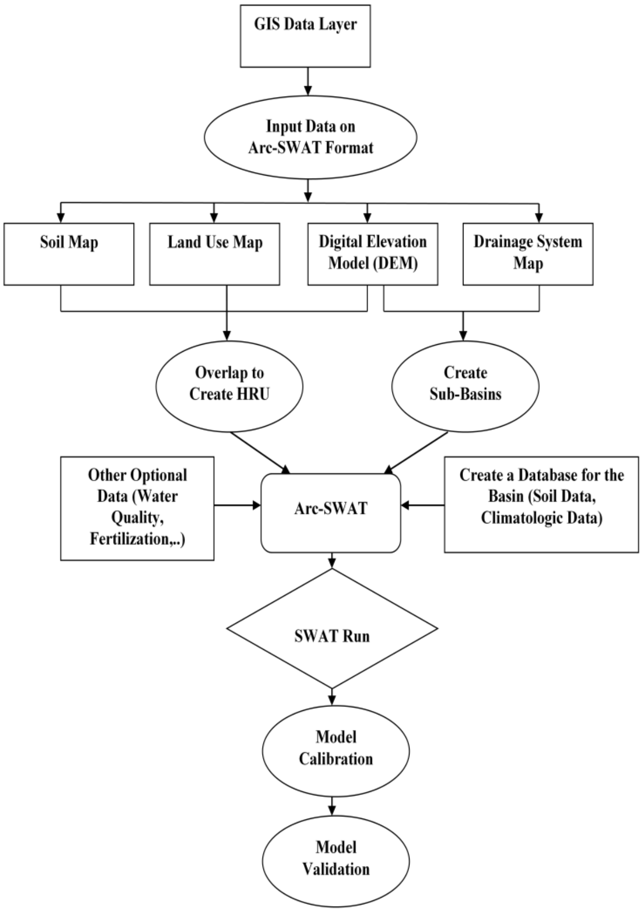


Fig. 3. Diagram for Hydrological Modeling in the SWAT model.

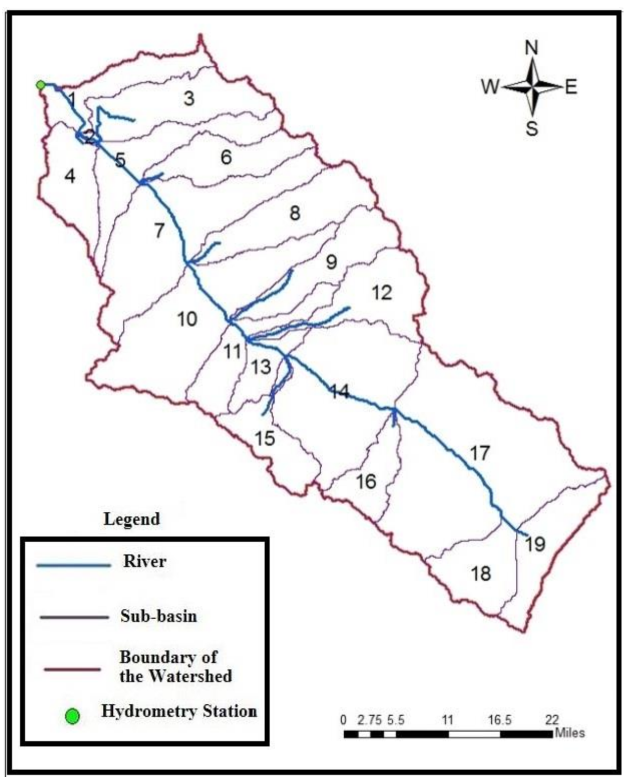


Fig. 4. Zanjanrood basin and sub-basins in the SWAT model.

2.4. Simulation Scenarios

The only way to determine the effect of an increase in the pressurized irrigation area on the amount of nitrate and phosphate leaching from agricultural lands to the Zanjanrood River was to apply changes in the irrigation efficiency. In this study, according to data derived from the Zanjan Agricultural Organization, the surface irrigation and pressurized irrigation efficiencies were respectively 37% and 62%. Based on these data, the total area of irrigated agricultural lands in the Zanjanroud Basin was 47,763 ha, of which 6384 ha (13.3 percent) were under pressurized irrigation, and the remaining 86.7 percent were surface irrigation, which was simulated as the main scenario (current status). In addition, three scenarios were considered to evaluate the effects of the irrigation method and its efficiency.

1. It was assumed that the total agricultural lands were under the surface irrigation method. Therefore, the irrigation efficiency was considered to be 37%.
2. It was assumed that about 50% of the agricultural lands were under the surface irrigation method, and the remaining 50% were irrigated as pressurized. In this case, the irrigation efficiency of the basin was equal to 49.5%.
3. It was assumed that all of the agricultural lands were irrigated as pressurized, and the efficiency of 62% was applied to all irrigation managements. The amounts of urea and phosphate fertilizers in the irrigated land are presented in Table 2 for the dominant cropping pattern in the Zanjanrood basin; the urea and phosphate fertilizers were applied at the beginning and middle of the growing season. In order to determine the effects of fertilizer, five scenarios were defined as follows:
4. The amount of fertilizer was considered to be zero.
5. The total amount of fertilizer in the current status decreased by 50%.
6. The total amount of fertilizer in the current status increased by 50%.
7. This scenario was considered as the best condition and included the combination of two scenarios: 100% pressurized irrigation and the fertilization is zero.
8. Increasing the amount of fertilizer up to 50 percent and the surface irrigation for total irrigated lands.

A total of 155 collected nitrate and phosphate samples at Sarcham hydrometric station were used between the years 1996 and 2013 for the calibration and validation of the model. A summary of data used in this study is given in Tables 3 and 4.

Table 2. Amount of the urea and phosphate fertilizers application in the irrigated lands for the dominant cropping pattern of Zanjanrood basin.

Irrigation Interval (day)	Annual Irrigation Depth (mm)	Urea Fertilizer Application (kg)	Phosphate Fertilizer Application (kg)	Harvest Date	Planting Date	Cropping Percentage	Crop Type
10	1790	200	150	September 21	April 4	47	Alfalfa
10	890	150	150	July 22	October 7	28	Wheat
6	910	150	150	August 6	March 25	13	Onion
14	570	150	150	June 20	September 22	12	Barley

Table 3. The amount of nitrate at the Sarcham station (1000 kg).

Year	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	Annual Sum
1996	0.60	6.45	11.00	9.78	7.03	1.85	0.91	0.50	0.16	0.23	0.09	0.13	38.72
1997	0.44	26.39	0.73	8.26	5.72	3.60	1.52	0.53	0.19	0.17	1.99	2.91	52.44
1998	2.49	34.97	109.90	13.20	4.19	2.34	0.77	0.41	0.20	0.04	0.08	0.04	168.62
1999	2.61	0.81	1.27	7.42	2.21	1.37	1.04	1.45	0.11	0.10	0.38	0.41	19.20
2000	7.23	7.20	20.40	52.21	6.45	1.26	0.41	0.16	0.86	0.25	1.67	3.04	101.15
2001	0.61	0.40	0.43	2.82	0.79	0.83	0.46	0.13	0.04	0.41	0.41	1.04	8.37
2002	2.15	4.59	2.37	10.20	3.13	0.94	0.81	0.24	0.08	0.02	0.09	2.20	26.82
2003	5.01	5.31	4.45	34.68	9.38	9.63	0.83	0.99	0.11	0.04	0.24	2.85	73.51
2004	12.81	8.46	0.62	7.05	4.80	3.55	1.18	0.45	0.13	0.12	1.28	1.95	42.39
2005	24.09	55.03	19.73	2.46	2.24	0.70	0.25	0.29	0.08	0.05	12.25	2.35	119.53
2006	6.84	38.20	3.45	21.22	10.22	2.27	0.33	0.08	0.03	0.81	0.94	0.28	84.67
2007	26.91	4.92	2.47	58.77	27.23	2.71	0.21	0.33	0.06	0.03	0.01	5.40	129.04
2008	0.70	50.20	10.40	0.41	0.24	0.38	0.14	0.07	0.30	0.13	1.37	0.53	64.87
2009	1.19	2.08	0.61	3.57	10.08	1.34	0.49	0.13	0.46	0.59	18.32	9.04	47.90
2010	3.62	10.18	11.18	22.11	38.98	0.32	0.15	0.07	0.06	0.01	0.01	1.20	87.90
2011	1.65	6.21	4.22	25.71	2.99	0.48	0.32	0.16	0.55	0.06	9.68	3.86	55.87
2012	1.56	28.47	3.76	38.27	27.99	0.88	0.32	0.12	0.05	0.06	1.93	1.64	105.04
2013	4.40	16.98	5.32	2.21	3.08	1.70	0.29	0.08	0.04	0.07	11.33	22.80	68.30
Max	26.91	55.03	109.90	58.77	38.98	9.63	1.52	1.45	0.86	0.81	18.32	22.80	168.62
Mean	5.83	17.05	11.80	17.80	9.26	2.01	0.58	0.34	0.20	0.18	3.45	3.43	71.91
Min	0.44	0.40	0.43	0.41	0.24	0.32	0.14	0.07	0.03	0.01	0.01	0.04	8.37
STDEV	7.82	17.46	25.25	17.70	10.84	2.15	0.40	0.36	0.22	0.22	5.47	5.31	41.55
C.V.	75	98	47	101	85	93	146	95	88	81	63	64	173

Table 4. The amount of phosphate at the Sarcham station (1000 kg).

Year	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	Annual Sum
1996	0.22	6.41	20.94	28.39	12.75	1.16	0.92	0.34	0.09	0.09	0.01	0.01	71.34
1997	0.25	9.95	0.44	10.16	4.69	0.99	0.99	0.40	0.12	0.02	2.81	3.48	34.30
1998	3.15	47.74	146.40	23.24	1.93	1.17	0.87	0.27	0.08	0.00	0.03	0.01	224.89
1999	2.23	0.77	1.06	6.59	1.54	0.92	0.98	0.55	0.10	0.02	0.21	0.35	15.33
2000	7.27	9.63	123.80	137.20	5.84	0.57	0.46	0.13	0.25	0.13	1.31	7.81	294.41
2001	0.05	0.14	0.63	5.55	1.89	0.52	0.45	0.11	0.03	0.04	0.28	1.30	10.99
2002	1.64	7.14	2.90	31.53	3.67	0.45	0.48	0.12	0.04	0.00	0.05	12.76	60.80
2003	16.20	11.67	9.30	82.76	10.69	10.49	0.39	0.24	0.04	0.00	0.22	8.35	150.37
2004	17.79	10.26	0.22	7.51	7.70	1.40	0.38	0.14	0.04	0.04	3.88	0.77	50.11
2005	15.81	32.84	14.27	2.32	5.20	0.43	0.26	0.14	0.03	0.00	15.19	0.64	87.13
2006	8.97	128.90	1.32	63.10	18.04	0.47	0.17	0.02	0.01	0.60	0.66	0.13	222.40
2007	25.73	6.04	2.00	87.56	52.97	0.93	0.13	0.09	0.02	0.00	0.00	7.70	183.18
2008	0.15	55.15	3.14	0.20	0.14	0.15	0.12	0.03	0.02	0.01	0.32	0.02	59.46
2009	0.19	1.91	0.13	4.62	5.72	0.23	0.17	0.04	0.16	0.22	17.16	1.45	32.00
2010	2.09	6.29	8.25	94.00	65.90	0.18	0.12	0.02	0.01	0.00	0.00	1.34	178.19
2011	3.29	10.39	3.26	42.52	5.70	0.23	0.34	0.06	0.17	0.52	25.50	0.28	92.28
2012	1.05	115.60	5.91	85.60	27.73	0.19	0.14	0.05	0.02	0.13	5.02	2.30	243.73
2013	7.13	23.48	7.23	3.33	2.92	0.24	0.14	0.04	0.01	0.02	45.65	80.11	170.29
Max	25.73	128.90	146.40	137.20	65.90	10.49	0.99	0.55	0.25	0.60	45.65	80.11	294.41
Mean	6.29	26.91	19.51	39.79	13.06	1.15	0.42	0.16	0.07	0.10	6.57	7.16	121.18
Min	0.05	0.14	0.13	0.20	0.14	0.15	0.12	0.02	0.01	0.00	0.00	0.01	10.99
STDEV	7.66	38.05	42.58	41.59	18.30	2.36	0.31	0.15	0.07	0.18	12.21	18.59	88.19
C.V.	82	71	46	96	71	49	133	106	101	58	54	39	137

2.5. Calibration and uncertainty analysis

The calibration of the SWAT model was performed using the SWAT-CUP model developed by Abbaspour [41]. The SWAT-CUP (Calibration and Uncertainty Procedures) is a standalone program developed for the calibration of the SWAT model [42]. This algorithm contains five different calibration procedures and includes many functionalities for the validation and sensitivity analysis, as well as the visualization of the study area. With this feature, the sub-basins, simulated rivers, outlets, rainfall, and temperature stations can be visualized on the map. This software package includes the Generalized Likelihood Uncertainty Estimation (GLUE) algorithm, Parameter Solution (PararSol), Markov Chain Monte Carlo (MCMC), and Sequential Uncertainty Fitting version2 (SUFI2) algorithm [43-49]. The SUFI2 algorithm has a high computation speed in the SWAT-CUP model; moreover, it is better in determining the uncertainty that has been mentioned in many previous studies [50-54]. The SUFI2 algorithm estimates the optimum value of the parameters of the model by getting the observational data and allowable range of the parameters of the SWAT used in the calibration of the model relative to the study basin.

2.6. Calibration and validation of the model

The results of calibration were evaluated by nine objective functions of mult, SUM, R^2, Chi^2, NS, bR^2, SSQR, PBIAS, and RSR defined as follows [41]:

$$mult = \frac{\sum_i (Q_m - Q_s)_i^2}{n_Q} \times \frac{\sum_i (S_m - S_s)_i^2}{n_S} \times \frac{\sum_i (N_m - N_s)_i^2}{n_N} \times \ldots \quad (2)$$

$$SUM = w_1 \sum_{i=1}^{n_1} (Q_m - Q_s)_i^2 + w_2 \sum_{i=1}^{n_2} (S_m - S_s)_i^2 + w_3 \sum_{i=1}^{n_3} (N_m - N_s)_i^2 + \ldots \quad (3)$$

$$R^2 = \frac{[\sum_i (Q_{m,i} - \bar{Q}_m)(Q_{S,i} - Q_S)]^2}{\sum_i (Q_{m,i} - \bar{Q}_m)^2 . \sum_i (Q_{S,i} - \bar{Q}_S)^2} \quad (4)$$

$$Chi^2 = \frac{\sum_i (Q_m - Q_S)_i^2}{\sigma_m^2} \quad (5)$$

$$NS = 1 - \frac{\sum_i (Q_m - Q_S)_i^2}{\sum_i (Q_{m,i} - \bar{Q}_m)^2} \quad (6)$$

$$bR^2 = \begin{cases} |b| R^2 & \text{if} \quad |b| \le 1 \\ |b|^{-1} R^2 & \text{if} \quad |b| > 1 \end{cases} \quad (7)$$

$$SSQR = \frac{1}{n} \sum_{i=1}^{n} (Q_{i,m} - Q_{i,s})^2 \quad (8)$$

$$PBIAS = 100 \times \frac{\sum_{i=1}^{n}(Q_m - Q_s)_i}{\sum_{i=1}^{n} Q_{m,i}} \quad (9)$$

$$RSR = \frac{\sqrt{\sum_{i=1}^{n}(Q_m - Q_s)_i^2}}{\sqrt{\sum_{i=1}^{n}(Q_{m,i} - \overline{Q}_m)_i^2}} \quad (10)$$

where, Q_i, S_i, and N stand for the variables (e.g. discharge and nitrate), n is the number of observations, and m and s respectively stand for the measured and simulated values, σ_m^2 is the variance of the measured data, b is the coefficient of the regression line between the measured and simulated data, and the bar stands for average. The weights w's can be calculated as follows:

$$w_1 = 1, \qquad w_2 = \frac{\overline{Q}_m}{\overline{S}_m} \qquad w_3 = \frac{\overline{Q}_m}{\overline{N}_m} \quad (11)$$

In this study, for the analysis of the quality of the model results, the p-factor, r-factor, the coefficient of determination (R^2), and Nash-Sutcliffe efficiency (NS) were used. The results are presented in Table 8 and Figure 5. The NS coefficient represents the relative difference between the observed and simulated values (Eq. 2). The value of this coefficient varies from 1 to -∞. The best value is 1, and if its value is greater than 0.5, the simulation by the model will be appropriate (Eq. 3). The coefficient of determination (R^2) shows the relative dispersion between the predicted and measured values, and it is between zero and one; if the predicted and measured values are equal, the value of (R^2) is equal to 1. The average monthly discharge from 1996-2013 was measured at the Sarcham Hydrometry Station, and 26 sensitive parameters of the model were calibrated using the observed values. A summary of all data used in the study area, including number, minimum, maximum, mean, and standard deviations, are given in Table 6.

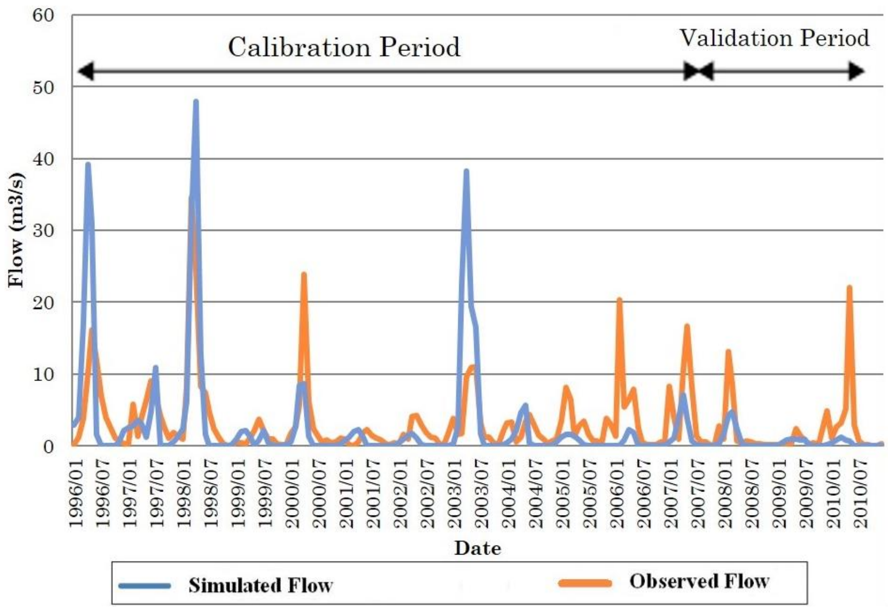


Fig. 5. The observed and simulated discharges at the Sarcham station.

Table 5. Sensitivity analysis and calibrated parameters of SWAT model for Zanjanrood basin.

Rank	Parameter	Definition	Initial range	Final value	Optimum value	p-factor	r-factor
1	R__CN2.mgt	SCS curve number	-0.3-0.3	0.04-0.12	0.05	0	-13.38
2	R__SOL_BD(..).sol	Wet bulk density in each layer	-0.25-0.5	-0.25_-0.15	-0.23	0	-3
3	V__ESCO.hru	Correction Factor of Soil Evaporation	0.0-1.1	0.11-0.38	0.37	0.05	-1.98
4	V__USLE_P.mgt	Coefficient factor of Land use equation	0.0-1.0	0.51-0.62	0.55	0.06	-1.88
5	V__RCHRG_DP.gw	Lower layer penetration coefficient	0.0-1.0	0.0-0.06	0.02	0.07	1.85
6	R__SOL_AWC(..).sol	Water in any soil layer	-0.3-0.3	-0.4_-0.3	-0.4	0.07	-1.81
7	V__ALPHA_BNK.rte	Alpha coefficient Stream Base to Save	0.0-1.0	0.41-0.57	0.54	0.11	-1.63
8	R__SOL_ALB(..).sol	Soil albido coefficient	-0.3-0.4	0.30-0.43	0.38	0.14	1.5
9	V__REVAPMN.gw	Depth of water threshold in groundwater table	0-500	158-200	171.83	0.18	1.35
10	V__CH_N2.rte	Manning coefficient for the main channel	-0.01-0.3	0.16-0.23	0.18	0.2	1.28
11	R__SOL_K(..).sol	Hydraulic conductivity of saturated soil	-0.3-0.3	0.11-0.38	0.3	0.26	-1.13
12	V__OV_N.hru	Manning coefficient for flood plains	0.01-30	26-30	27.59	0.33	-0.98
13	R__USLE_K(..).sol	Soil erosion coefficient	0.0-0.7	0.16-0.27	0.18	0.4	0.84
14	V__SMFMN.bsn	Minimum snow melt factor during the year	0-20	14-18	16.03	0.4	-0.84
15	V__SFTMP.bsn	Snow threshold temperature	-20-20	-1.8-6.8	4.41	0.47	0.73
16	V__GW_REVAP.gw	Groundwater coefficient	0.02-0.2	0.10-0.13	0.12	0.48	-0.7
17	V__ALPHA_BF.gw	Alpha factor in returning the mainstream flow to the main stream	0.0-1.0	0.51-0.64	0.54	0.49	0.7
18	V__SHALLST.gw	Primary water depth in the groundwater table	0-5000	1190-1800	1737.69	0.5	-0.68
19	V__TIMP.bsn	Late Snow Temperature	0.0-1.0	0.85-0.99	0.87	0.52	0.64
20	V__SMFMX.bsn	Maximum snow melt factor during the year	0-20	0.15-2.4	1.59	0.65	0.46
21	V__CANMX.hru	Maximum Surface Retention	0-100	40.5-57.1	45.42	0.85	0.19
22	V__CH_K2.rte	Hydraulic conductivity in the main channel	-0.01-500	159-220	219.26	0.86	-0.18
23	V__LAT_TTIME.hru	Flow Time on sub-flow channel	0-180	135-176	136.73	0.89	0.14
24	V__SLSUBBSN.hru	The average length of slope	10-150	93-112	103.68	0.94	-0.08
25	V__SPCON.bsn	Maximum Linear Parameter of Returned Sediment to the Channel	0.0-0.0	0.01-0.01	0.01	0.96	-0.05
26	V__SPEXP.bsn	Maximum Exponential Parameter of Returned Sediment to the Channel	1.0-1.5	0.28-0.79	0.76	0.97	0.04

Table 6. Average monthly flow discharge at Sarcham station (m^3/s).

Year	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	Annual
1996	7.36	5.78	8.44	8.68	14.71	9.70	0.00	0.00	0.00	0.00	2.44	9.54	5.55
1997	2.51	3.45	4.87	36.46	44.55	2.32	0.00	0.00	0.00	0.00	0.75	1.97	8.07
1998	2.46	2.55	3.33	3.82	1.65	0.13	15.32	0.00	0.00	0.00	0.00	1.90	2.60
1999	1.87	3.48	11.48	63.11	17.77	2.37	0.00	0.00	0.00	0.00	0.30	1.06	8.45
2000	0.44	1.77	2.37	1.79	0.01	0.00	2.68	0.60	0.00	0.00	0.00	0.00	0.80
2001	0.41	0.93	6.09	11.99	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.78
2002	0.48	0.95	1.73	2.50	1.73	0.07	0.00	0.00	0.00	0.00	0.00	0.12	0.63
2003	0.22	0.79	1.20	1.77	1.54	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.47
2004	0.09	0.60	6.46	48.42	17.91	22.50	2.43	0.00	0.00	0.00	0.00	0.00	8.20
2005	0.30	0.50	1.72	2.80	8.04	0.53	0.00	0.00	0.00	0.00	0.00	0.07	1.16
2006	1.07	1.52	1.63	1.42	1.08	0.24	0.00	0.00	0.00	0.00	0.02	0.25	0.60
2007	0.00	0.00	0.09	2.00	2.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41
2008	0.29	0.85	1.45	8.00	5.18	0.95	0.13	0.00	0.00	0.00	0.00	0.00	1.40
2009	0.29	0.85	1.45	8.00	5.18	0.95	0.13	0.00	0.00	0.00	0.00	0.00	1.40
2010	0.89	3.34	5.76	3.25	0.65	0.00	0.08	0.01	0.00	0.00	0.00	0.00	1.17
2011	0.00	0.20	0.72	0.91	0.97	0.69	1.30	0.00	0.00	0.00	0.00	0.00	0.40
2012	0.39	0.47	1.50	0.67	1.07	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.35
2013	0.00	0.14	0.77	1.76	0.07	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.23
Max	7.36	5.78	11.48	63.11	44.55	22.50	15.32	0.60	0.00	0.00	2.44	9.54	8.45
Mean	1.06	1.56	3.39	11.52	7.05	2.26	1.23	0.03	0.00	0.00	0.19	0.83	2.43
Min	0.00	0.00	0.09	0.67	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23
STDEV	1.76	1.56	3.12	18.26	11.07	5.54	3.62	0.14	0.00	0.00	0.59	2.27	2.94
C.V.	60.1	100.4	108.5	63.1	63.7	40.7	34.0	23.9	-	-	33.0	36.7	82.4

3. Results and discussion

Figure 6 shows the uncertainty concept of the SUFI2 algorithm, which indicates that the parameter with a unit value creates a unit result for the model (Figure 6a). Furthermore, the uncertainty distribution in the parameter creates a response unit (Figure 6b). When the uncertainty of the input parameters increases, the output uncertainty also increases (Figure 6c).

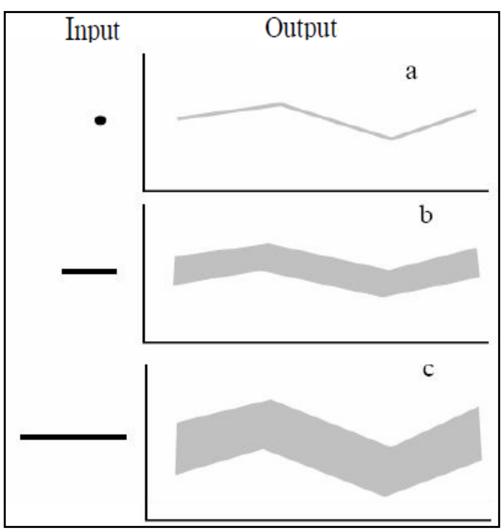


Fig.6. The uncertainty concept in the SUFI2 algorithm.

According to the results of previous studies, 26 effective parameters on the runoff were selected for initial simulation; the sensitivity and uncertainty analyses were performed using the SUFI2 program, and 200 simulations were selected [35,30,38]. The p-factor and r-factor were used for the uncertainty analysis. The p-factor represents the percentage of the measured data within the uncertainty band of 95% (95 ppu). This criterion was obtained by calculating the corresponding values with the probability of 2.5% as the lower limit and 97.5% as the upper limit, using the Latin hypercube sampling (LHS), and eliminating 5% of the unsuitable simulations. The values close to 1 represent an appropriate result. The r-factor is equal to the bandwidth (95ppu) divided by the standard deviation of the measured data. The values close to zero indicate better simulation [41]. The results of the sensitivity analysis and calibration of the SWAT model parameters for the Zanjanrood river basin are shown in Table 7 [42,50,52]. The SCS curve number and wet bulk density in each layer is the most sensitive parameter for the calibration period, which is in agreement with the results of previous investigations [50,55].

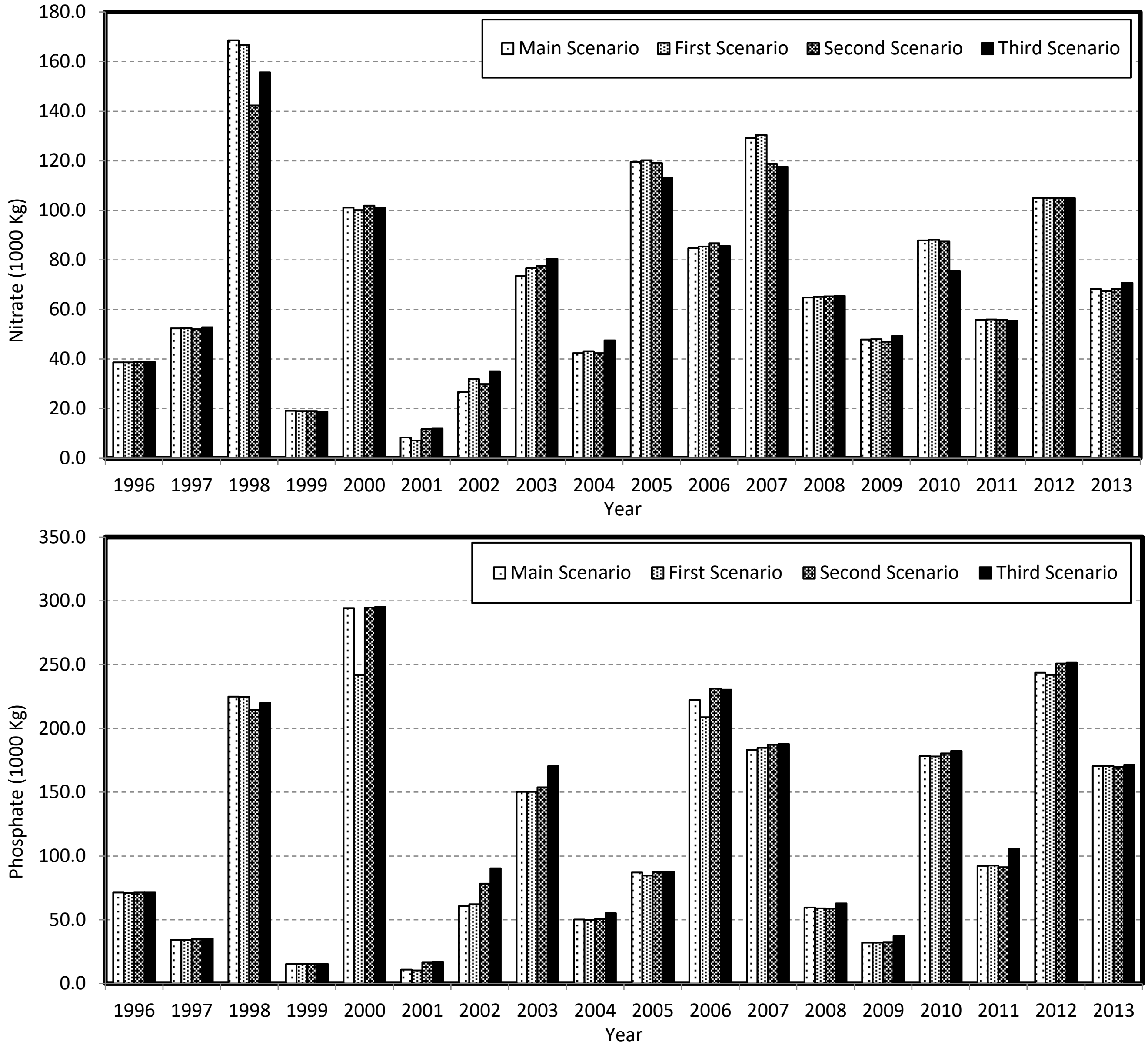


Fig.7. (a) Comparison of changes in nitrate leaching from Zanjanrood Basin in irrigation scenarios during the simulation period from 1996 to 2013 and (b) Comparison of changes in phosphate leaching from Zanjanrood Basin in irrigation scenarios during the simulation period from 1996 to 2013.

The results of the simulation of the nitrate and phosphate leaching from agricultural lands to the Zanjanrood River based on irrigation scenarios showed that the amount of nitrate and phosphate in comparison with the main scenario (current status) increased by 0.54% in scenario 1, decreased by 1.95% in scenario 2, and decreased by 1.11% in scenario 3. Figure 7 shows the comparison of the nitrate and phosphate leaching from agricultural lands to the river by changing the irrigation method during the simulation from 1996 to 2013 compared with the current status. As can be seen, by changing the surface irrigation to the pressurized irrigation method, there was no significant change in the amount of nitrate and phosphate leaching from agricultural lands to the Zanjanrood River. As shown in scenarios 1 and 2, by changing the irrigation systems from the surface system to pressurized irrigation system, no significant change was observed in the amount of nitrate and phosphate entering the Zanjanrood River. Because the main factor in determining the amount of pollution entering the river was the amount of nitrogen and phosphate fertilizers used by farmers, the pressurized irrigation system does not play a decisive role in reducing the inflow of solutes into the surface water sources by reducing the rate of deep infiltration. Also, the changes in the amount of output nitrate and phosphate from the basin over the years in the main scenario (current status) were modeled according to the fertilizer used in agricultural lands under cultivation in each crop year.

Table 7. Calibration and Validation Indices.

Parameter	R^2	NS	r-factor	p-factor
Calibration	0.83	0.53	0.27	0.11
Validation	0.73	0.53	0.60	0.18

The results of the simulation of input nitrate and phosphate to the surface water resources in the fertilizer scenarios showed that the amount of nitrate and phosphate in scenarios 4, 5, and 6 decreased by 33.6%, 16.7%, and 17.2, respectively, in comparison with the main scenario (current status). In Figure 8, the comparison of the changes in nitrate and phosphate leaching from agricultural lands to the Zanjanrood River has been presented by changing the fertilization rate during the simulation period (1996-2013), as compared with the current status. Accordingly, it can be concluded that by reducing the fertilization rates and preventing excessive fertilization by the farmers, one can considerably prevent the pollution of water surface resources in the Zanjanrood Basin. This finding is consistent with the results of Jiang et al. [32], Lai et al. [34], and Akhavan et al. [56].

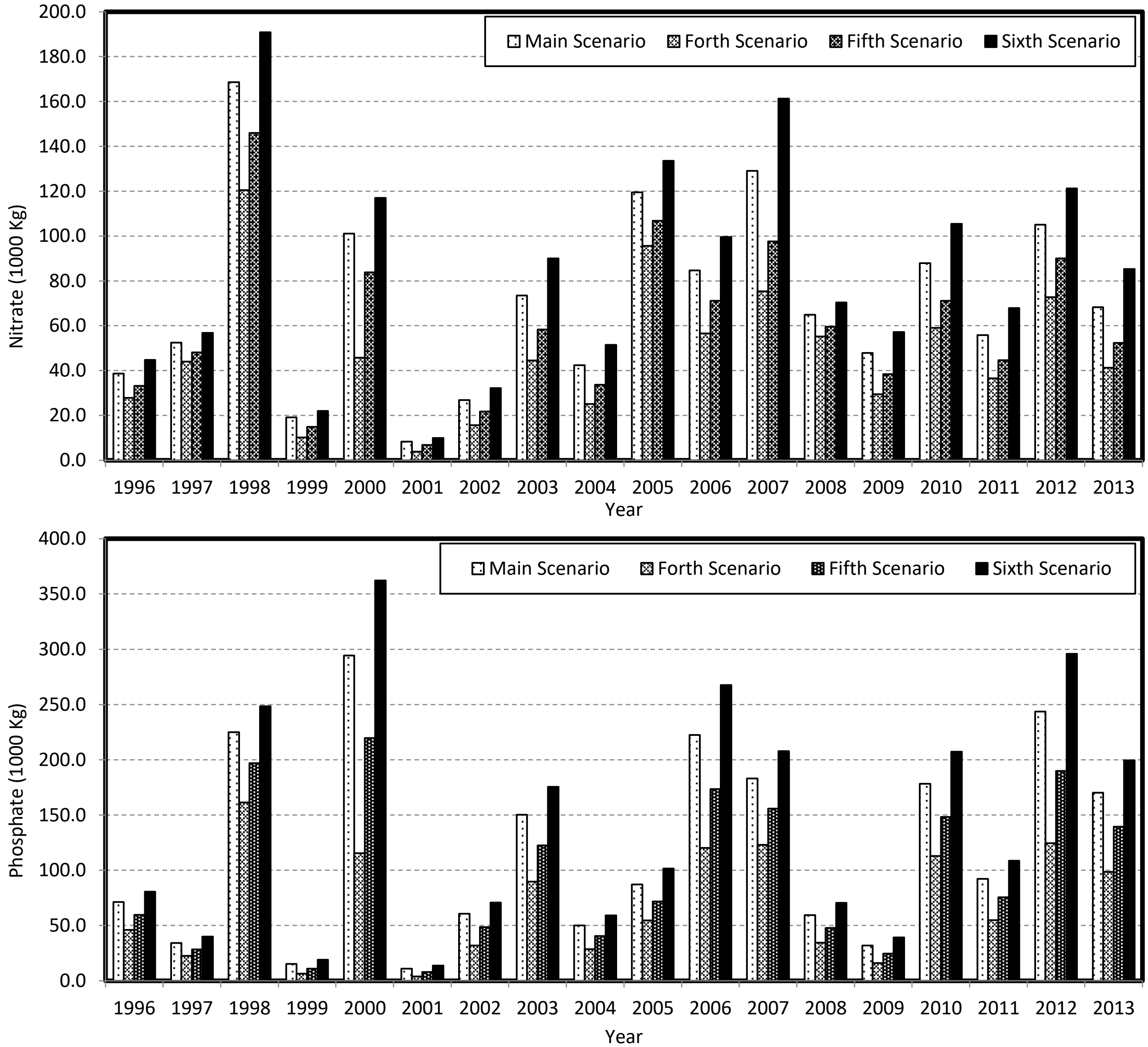
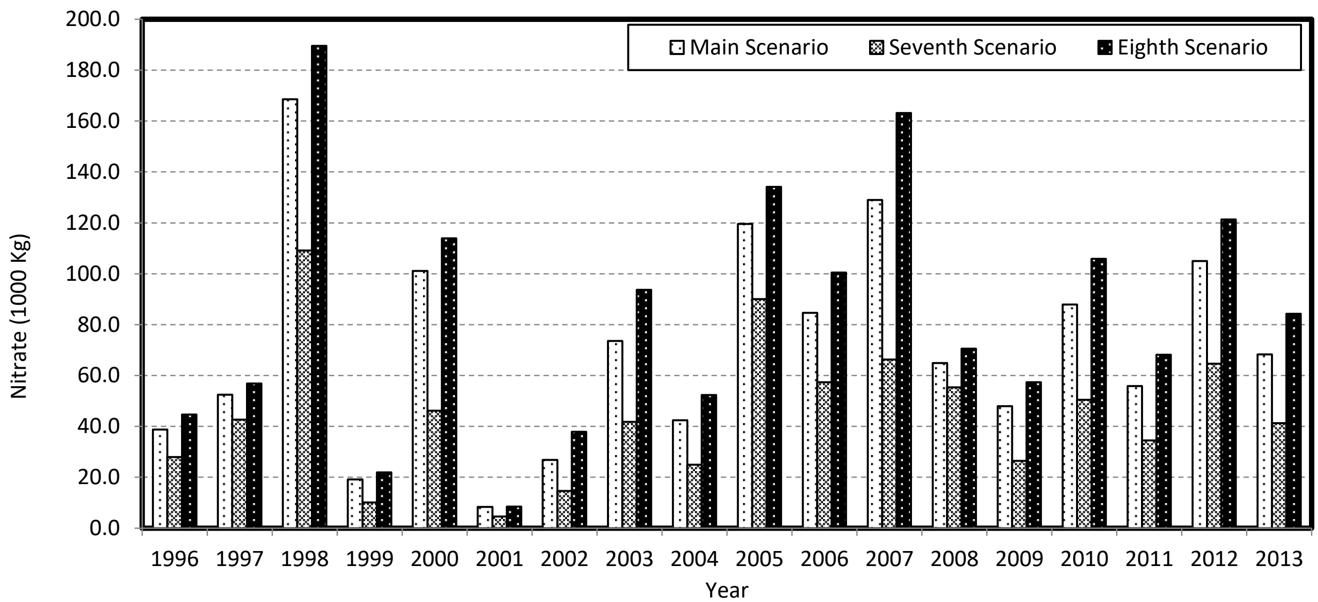


Fig. 8. (a) Comparison of changes in nitrate leaching from Zanjanrood Basin in fertilizer rate scenarios during the Simulation Period from 1996 to 2013 and (b) Comparison of changes in phosphate leaching from Zanjanrood Basin in fertilizer rate scenarios during the simulation period from 1996 to 2013.

In the combined scenario (scenario 7), with 100% pressurized irrigation and zero fertilization, the amount of nitrate and phosphate leaching from agricultural lands to the surface water resources decreased by 37.6%; in scenario 8, i.e., increasing the amount of fertilizer by 50% and irrigation of all irrigated lands, the amount of nitrate and phosphate leaching from the Zanjanrood River increased by 17.8%. In Figure 9, a comparison of changes in nitrate and phosphate leaching from the Zanjanrood basin is presented by changing the irrigation practices and fertilizer rates simultaneously. By comparing the results of these scenarios with the irrigation and fertilization scenarios, it can be concluded that only the changes in fertilizer rates may affect the amount of nutrients in the basin's outlet. The effect of irrigation will be negligible even in the combined conditions.



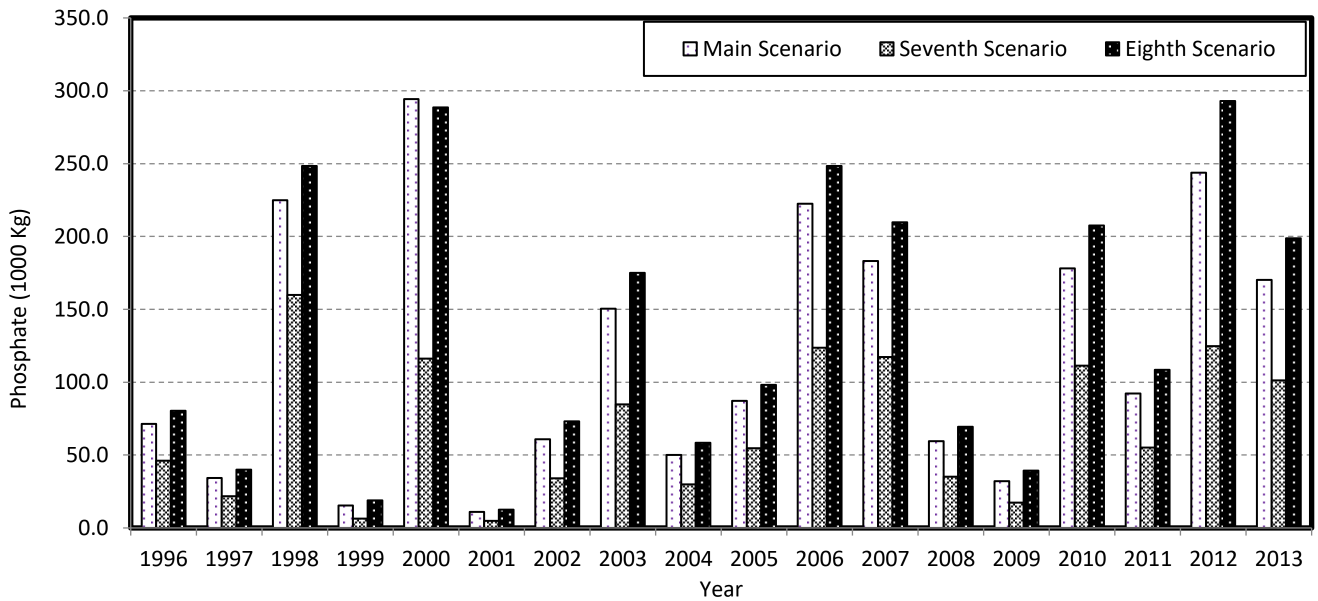


Fig.9. (a) Comparison of changes in nitrate leaching from Zanjanrood basin by changing the irrigation method and fertilizer rate, simultaneously and (b) Comparison of changes in phosphate leaching from Zanjanrood basin by changing the irrigation method and fertilizer rate, simultaneously.

For the calibration of the model, the observed and simulated values (by SWAT model) of nitrate and phosphate leaching from the Zanjanrood River are presented in Figures 10 and 11. As can be seen, the SWAT model is well able to predict the values of nitrate and phosphate on both an annual and monthly basis. In addition, the coefficient of determination (R^2) and Nash-Sutcliffe simulation efficiency (E) values exceeded 0.8 in most cases, indicating the high accuracy of the SWAT model.

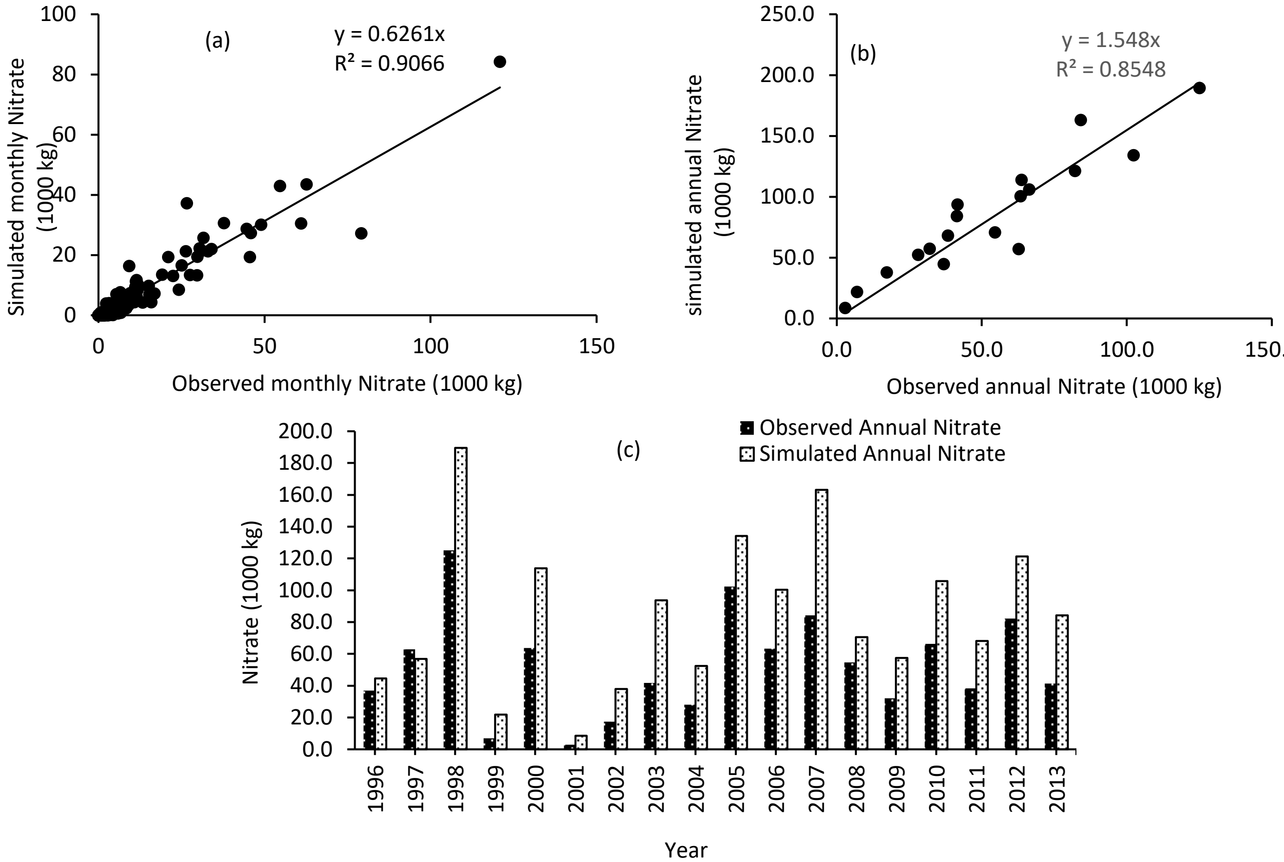


Fig. 10. (a) Comparison of the simulated and observed monthly nitrate; (b) annual nitrate; and (c) annual nitrate on studying period.

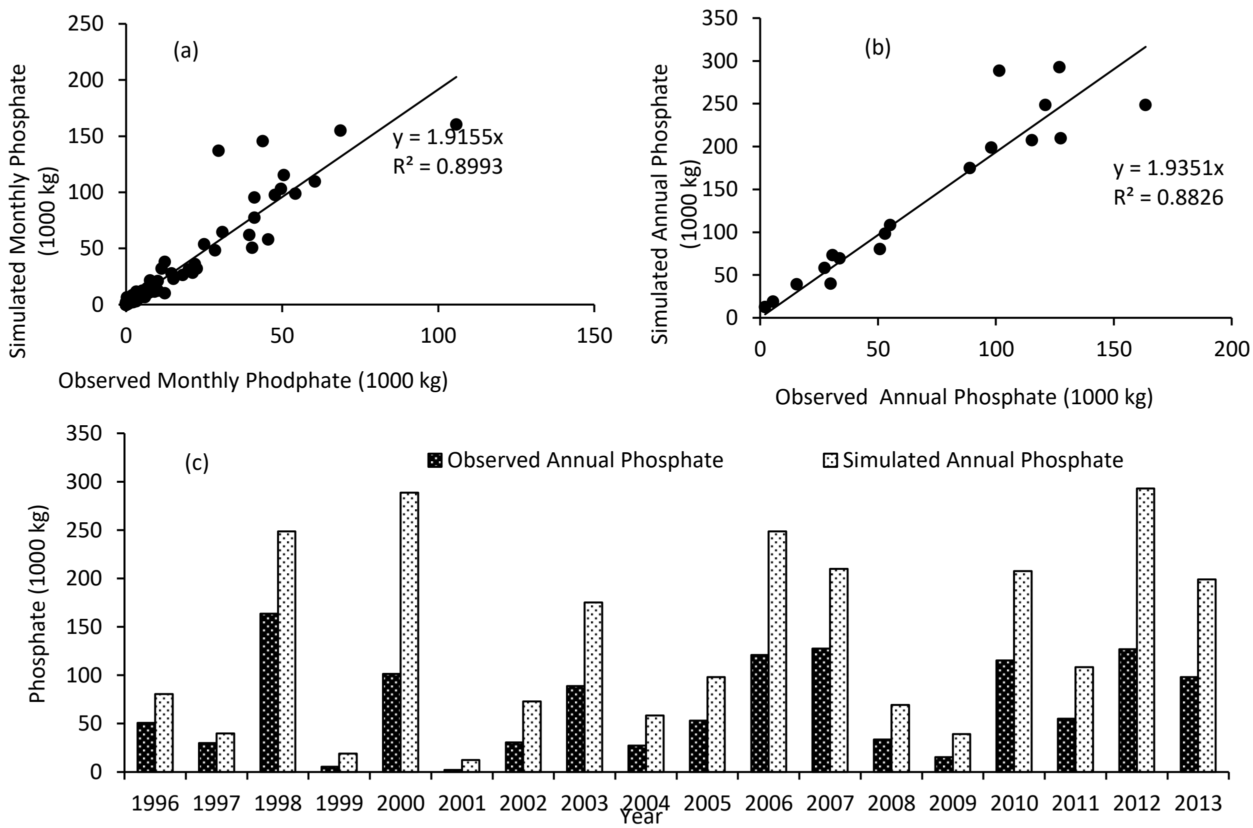


Fig.11. (a) Comparison of the simulated and observed monthly phosphate; (b) annual phosphate; and (c) annual phosphate on studying period.

4. Conclusions

The results of this study indicated the proper performance of the SWAT model and its ability to simulate the runoff, the movement of nitrate and phosphate from the agricultural land to the river as well as the uncertainty of analysis and effective parameters in the simulation. One of the problems and limitations in this study was the lack of field data and accurate information about the consumption of urea and phosphate fertilizers by the farmers in the Zanjanrood River area. However, the specific complexity of the basins with extensive agricultural lands, different cropping patterns, and a great variety of variables affecting the movement of nonpoint sources pollution to the surface water resources resulted in the appropriate results of the SWAT model at the calibration phase (R^2 = 0.83, NS = 0.53). In addition, the validation of the SWAT model showed similar results. After hydrological validation, the results showed that by changing the surface irrigation to the pressurized irrigation method, there was no significant change in the average nitrate and phosphate leaching from the basin. Also, by reducing the fertilization rates and preventing excessive fertilization by the farmers, the contamination of the surface water resources could be considerably prevented.

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