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Simulation of runoff from Atrak River Basin Iran using SWAT model (A case study)

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Abstract

Simulation models have a special role in management of any natural phenomenon. The aim of this study was to evaluate the efficiency of Soil and Water Assessment Tool (SWAT) model for simulation of runoff and calibration and validation of this model in Atrak watershed located in the northeast of Iran. One of the main roles of this model is to investigate the effects of long periods in a basin. The SWAT model and SUFI-2 algorithms in combination with Geographical Information System (GIS) data set comprising various layers such as land use, soil type, and Digital Elevation Model (DEM) was used. For calibration and validation analyses, we use runoff of 6 hydrometric station data from 1975-1991. The results of this study showed that the SWAT model could simulate runoff in Shirabad station properly. In this simulation, the R^2 value for calibration and validation stages were 56% and 58%, respectively. The final results of this study revealed that longer period of data is required for achieving better results. Availability of long-time data can help the managers to control the flood and drought with proper models, and they can protect the watershed.

Keywords: Uncertainty analysis, surface runoff, SWAT

Introduction

In a watershed, topsoil erosion due to different factors such as destruction of pasturelands, change in land use, and inappropriate agricultural practices can cause sedimentation behind dams, further reducing the reservoir's capacity and its water quality (Morgan and Nearing, 2011). Surface soil degradation causing loss of natural resources and agricultural lands result in entering sediments, nutrients, and pesticides to the surface and groundwater resources and thereby reducing the quality of the water and the risk of toxicity to humans and other living organisms (Yang *et al.*, 2009). Soil erosion is one of the critical environmental challenges that have a significant impact on the sustainable development of the world (Bakker *et al.*, 2004). Since the phenomena of surface runoff causes soil erosion and thus are directly interrelated with each other. In the management of basins or watershed, these two parameters are the basic requirements to be addressed. Hydrological models are frequently used globally to simulate hydrological processes, namely precipitation-runoff and sediment generation (Malik *et al.*, 2021). A model that has been widespread around the world in research on runoff, erosion, and sedimentation and management of watersheds is the Soil and Water Assessment Tool (SWAT) (Ndomba *et al.*, 2008; Huang *et al.*, 2009; Coffey *et al.*, 2010; Oeurng *et al.*, 2011; Strauch *et al.*, 2011; Prasanchum *et al.*, 2020). SWAT is a comprehensive watershed model in basin-scale that is developed by the United States Department of Agriculture Research Service to predict the effect of different management practices on water flow, sediment, nutrients, and balance of chemicals in large, complex watersheds with applications of the use of land, soil, and various management requirements for extended periods (Besalatpoor *et al.*, 2014). This model has a physical basis and can be used in watersheds with no regular inventory. Simulation of very extensive basins or different management practices can be performed using this model without investing a lot of time and money. The user will also be able to study long-term effects (Neitsch *et al.*, 2011).

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The SWAT model has been used in many studies as an efficient model for studying runoff, erosion, sediment, pesticides, and nutrients. Chu and Shirmohammadi (2004) validated the capability of the SWAT model in predicting surface and subsurface flow for a 340-hectare watershed in the Piedmont physiographic region of Maryland. The results showed that SWAT underestimated subsurface flow and total streamflow, especially during wet periods. However, it is an excellent basin-based model to simulate long-term management objectives. Sun and Cornish (2005) used the SWAT model to study the flow rate in Liverpool plains in Australia. The results of this study showed that the SWAT model predicted the river flow rate well and showed better results in comparison with point sources modeling. Rostamian (2007) estimated flow rate and sediment load in the Baheshtabad area (located in Northern Karun River) and found that the SWAT model had a good performance in estimating river flow rate but failed at the simulation of peak flow rates of the river. The ability of the model to estimate sediment load is moderate. Oeurng *et al.* (2011) reported that the SWAT model successfully simulated daily-runoff and sediment data in south-western France.

The study of Prasanchum *et al.* (2020) aims to assess flood risk areas by using the SWAT model for analyzing the maximum monthly discharge at each sub-catchment and fitted to the Gumbel distribution in order to evaluate flood risks in return periods of 2, 5, and 10 years. The results indicated that the calibrated SWAT model can reasonably simulate discharge at the observed stations based on the statistical indicators. The methods and results of this study can be useful tools and information for improving an understanding among stakeholders in the affected area in order to reduce damage from flooding in the future. Malik *at al.* (2021) used the SWAT model to simulate the Lidder catchment streamflow located in the Southeastern part of the Kashmir. Also, they used the SUFI-2 algorithm for multi-site model calibration and validation for monthly time steps. The calibration results for the (2009–2012) period displayed an excellent model performance for flow rates with R^2 of 0.89, 0.85, and 0.89, respectively.

Based on the existing study records, the estimation of sediment in the basin through the sediment measurement curve method is more consistent with the recorded values of stations, while the estimation of sediment by the SWAT model depends on the characteristics defined for the catchment. The more accurate the model inputs, the more accurate the model outputs will be. The calibration of the model is directly related to the user's knowledge of the general condition of the basin in terms of climate, hydrology, land use, and management conditions, etc. Therefore, it is necessary to estimate the suspended sediment load in the Atrak basin according to different conditions in the sub-basins and in the uncertainty interval to be used in management planning. In this study, the possibility of using the SWAT model for estimating runoff in the Atrak river basin with a climate data record for six rain-gauge stations was investigated. Also, analyzing the performance of the SUFI-2 algorithm in calibration and validation of the SWAT model was another objective of the study.

Materials and Methods

Study area

Atrak river basin is a basin of the Caspian Sea, and its area spreads over 14913.24 square kilometers within the province of North Khorasan. This basin is located in the Northeast of Iran and lying between longitude 56º 32' 01” to 56º 25' 15” E and latitude 36º 56' 16" to 38º 14' 42" N. The amount of rainfall in Atrak basin has severe spatial changes due to its mountainous nature. Rainfall varies from less than 122 mm in the plain areas northwest of the basin to more than 122 mm in the highlands south of the Atrak basin. The surface current of the Atrak catchment area is high compared to its size. There are about 29 permanent and important rivers in the Atrak catchment area. Atrak basin has the best agricultural lands and pastures that are destroyed and eroded every year, which significantly causes erosion problems. Since the period of climate stations used in SWAT model database must be the same, in this study, data from Location of meteorological stations having similar periods of climatic records were selected.

SWAT model

The SWAT model is a basin-scale model that operates in a daily time step and evaluates the impact of management practices on water, sediment and agricultural chemical performance in uninspected basins (Zhang *et al.*, 2021; Shah and Shahzad, 2008). The SWAT model are divided into two hydrologic components i.e., land phase and water routing phase. In general, the hydrologic part of the land phase has several features as follows (Prasanchum *et al.*, 2020):

A: Crown reserve: Part of precipitation that is retained as leaf-water at the plant surfaces (crown cover), and is possible to evaporate. The user specifies the maximum leaf area index, body, and land use to the water stored at the crown cover.

B: Surface runoff: This is the portion of precipitation that flows overland as surface runoff. The SWAT model uses two methods for its estimation i.e., adjusted Soil Conservation Service (SCS) curve number, and infiltration method proposed by Green and Ampt (1911). To calculate runoff volume, the curve number method is expressed as Eq.1 (Prasanchum *et al.*, 2020):

$$Q_{SURF} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \quad (1)$$

Where Q_{surf} is the runoff or excess rainfall, R_{day} is the precipitation on the day, I_a is the initial uptake, and S is the soil maintenance parameter. All parameters have the same units of water. parameter S is a function of the spatial variables such as soil, land use, management and slope, and the time-dependent variable, that is the available water content of the ground. This parameter is obtained by the following Eq. 2 (Prasanchum *et al.*, 2020):

$$S = 25.4\left(\frac{100}{CN} - 10\right) \quad (2)$$

Where CN is the curve number in the desired day. The initial uptake is usually considered 0.2 of S value. As a result, the final Equation is as follows (Prasanchum *et al.*, 2020):

$$Q_{SURF} = \frac{(R_{day} - 0.2S)^2}{(R_{day} - 0.8S)} \quad (3)$$

Runoff occurs when the value of R_{day} is larger than I_a.C: Infiltration: This parameter depends on the initial moisture content of the soil and the soil saturated hydraulic conductivity. Infiltration can be calculated in two ways in the SWAT model. In the ordinary method, the runoff is calculated using the curve number method Soil Conservation Service (SCS). Then, soil infiltration is estimated by the difference between total rainfall and leaf-water.

In the next stage, with the combination of soil, land use, and slope classes maps, that can be calculated using a DEM and the five classes of slopes 0-5, 5-12, 12-30, 30-60, and above 60%, the hydrological response units are obtained. Then, given the overall levels of soil, slope, and land use in

Table 1: SWAT model input data in simulating the Atrak river basin runoff

Data	Type of data	Source	Year / Resolution
DEM map	Raster	ESRI-SRTM	50m × 50m
Land use map	Vector	North Khorasan Natural Resources Research center	1:250000
Soil map	Raster	FAO	10 km × 10 km
Metrological data	Point (7 stations)	National metrological organization	1985 - 2010 (daily)
Hydrometric data	Point (8 stations)	Ministry of Energy	1968 - 2011(daily)

Table 2: Selected parameters for the calibration after the sensitivity analysis

Parameter name	Parameter description
SURLAG.bsn	Surface runoff lag coefficient
SMTM. bsn	Snowmelt temperature
SFTMP.bsn	Snowfall temperature
SMFMX.bsn	Snowmelt factor on 21 June
SMFMN.bsn	Snowmelt factor on 21 December
TIMP.bsn	Snowpack temperature lag factor
CN2.bsn	SCS runoff curve number for moisture condition II
REVAPMN.gw	Threshold water in the shallow aquifer
GW-DELAY.gw	Groundwater delay time (days)
GW-REVAP.gw	Groundwater revamp coefficient
GWQMN.gw	The threshold water level in the shallow aquifer for base-flow
RCHRG-DP.gw	Aquifer percolation coefficient
ESCO.hru	Soil evaporation compensation factor
SOL-AWC. Sol	Available water capacity factor
SOL-K.sol	Saturated hydraulic conductivity
SOL-BD.sol	Soil bulk density
SOL-ALB.sol	Moist soil albedo
OV-N. hru	Manning's n value for overland flow
CH-K2. Rte	Effective hydraulic conductivity in the main channel
CH-N2. Rte	Manning's n value for the main channel
ALPHA-BF.gw	Base-flow alpha factor for bank storage (days)
EPCO.hru	Plant uptake compensation factor

each sub-basin, the number of HRU units were obtained 829 units. After introducing the characteristics of the reference stations, the statistics of meteorological stations were entered into the model. According to the research subject, maximum and minimum daily temperatures, factors affecting the surface flow and canals, water harvesting, land management, tanks, and some other areas should be included in the model based on the research objective

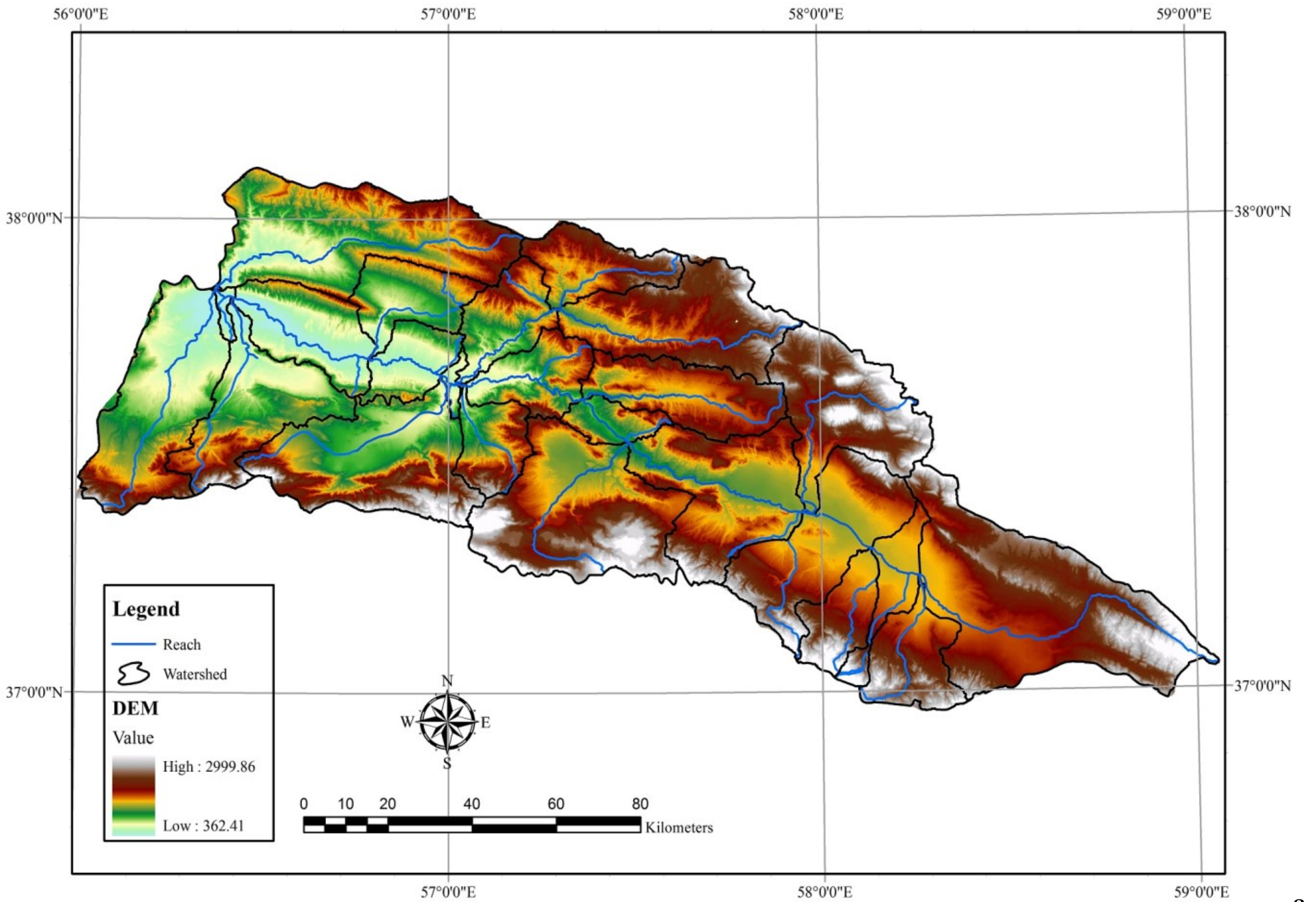

Figure 1: Inputs of the SWAT model in the research (a) DEM

the simulation was performed in the period 1975 to 1991. Then, validation was performed in the period 1987 to 1991.

Input data for SWAT model setup

The number of standard years of stations of the period is 25 years. This information includes daily rainfall (or snowfall) and maximum and minimum temperature for 1985-2010. Reference stations used to consist of Quchan synoptic station with 26 years of data (1984 to 2010), and Bojnurd synoptic station with 32 years of data (1977 to 2010). The required maps included digital elevation model (DEM) maps, land use maps, and soil maps, and all three must be entered in the form of a raster model. Other data, including meteorological data, such as daily rainfall, (Fassio *et al.*, 2005). SWAT model input data are given in Table 1. Figure 1 shows the maps used in the simulation of the Atrak river basin runoff in the SWAT model.

Sensitivity analysis, calibration, and validation

Calibration and validation of watershed models are necessary before they are used as a decision-making tool in the planning and management of water resources. Since hundreds of physical parameters interact in hydrological processes, their optimization is complicated, especially in large basins, and requires time-consuming developed calculations. To simplify the calibration process, sensitivity analysis is useful to identify the parameters that are most

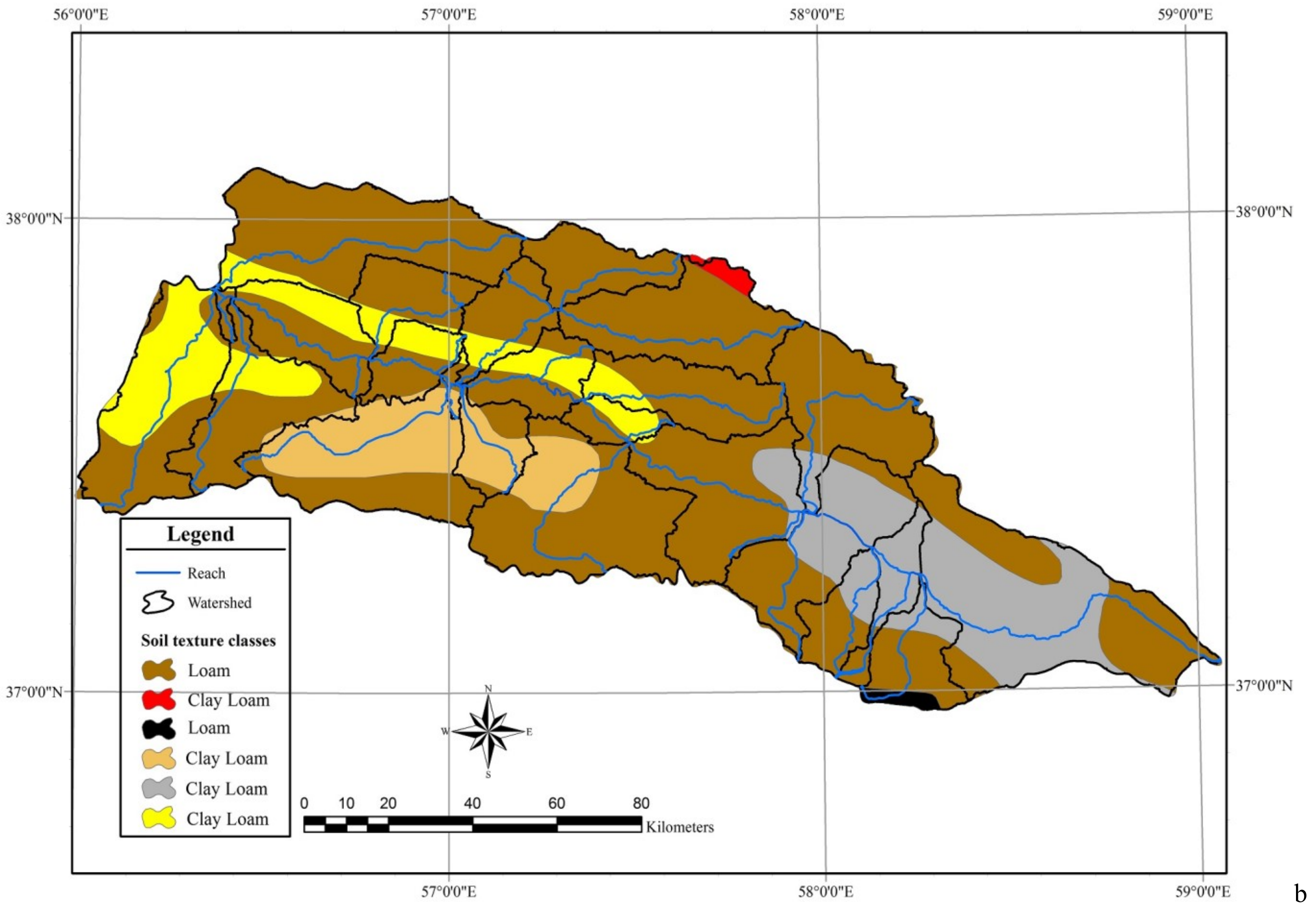

Figure 1: Inputs of the SWAT model in the research (b) Soil type

effective in the variation of model outputs. In the SWAT model, several parameters play a role in simulating the hydrologic components in the basin, and many of them interact with each other.

After a comprehensive sensitivity analysis on the national scale for Iran, Faramarzi *et al.* (2009) introduced a total of 22 parameters in the runoff generation as the primary and sensitive parameters. This paper employs his proposed parameters to simulate river flow. Table 2 summarizes the selected calibration parameters.

SWAT model calibration and validation using SUFI-2 algorithm

Proper calibration/validation and uncertainty analysis are required to improve the model simulation and analysis for the watershed (Sao *et al.*, 2020). Direct measurement of model input parameters is complicated and very expensive in large watersheds. Therefore, the model input parameters should be optimized under the calibration process (Abbaspour, 2007). Thus, calibration means optimizing the parameters to affect the model, so that the simulated outputs can justify the observed changes and trends in the desired period. Validation is examining the calibrated model in another period, so that the simulated and experimental variables are compared without adjusting any parameters. In other words, validation is determining the reliability of the calibration model to be used in any other time. Calibration requires a repeated change of parameter values and will be very time consuming on a large scale. Programs have been developed for this purpose that can automatically do this in large basins. SUFI-2 algorithm in the software package SWAT-CUP is one of these programs, used in many sources (Abbaspour, 2011). SUFI-2 program, in addition to providing the grounds for calibration and optimization of input parameters, enables analysis of the uncertainty in predicting output variables. Using this algorithm, all the luck in output, such as the uncertainty of inputs, model parameters, and measured data, are defined by offering a range of input parameters. Calibration and determination of fate are studied by measures called P-factor and R-factor (Abbaspour *et al.*, 2015).

$$r^2 = \left(\frac{\sum_{i=1}^{n}(o_i - \bar{o})(p_i - \bar{p})}{\sqrt{\sum_{i=1}^{n}(o_i - \bar{o})^2}\sqrt{\sum_{i=1}^{n}(p_i - \bar{p})^2}}\right) \quad (4)$$

Where r^2 is the coefficient of determinatiom, n is the number of observations, o_i is the corresponding observed values, and p_i is the corresponding predicted values. The coefficient of determination shows how much the regression line between observed and predicted values is close to the maximum amount of coordination between the two series and varies from 0 to 1 (Prasanchum *et al.*, 2020):

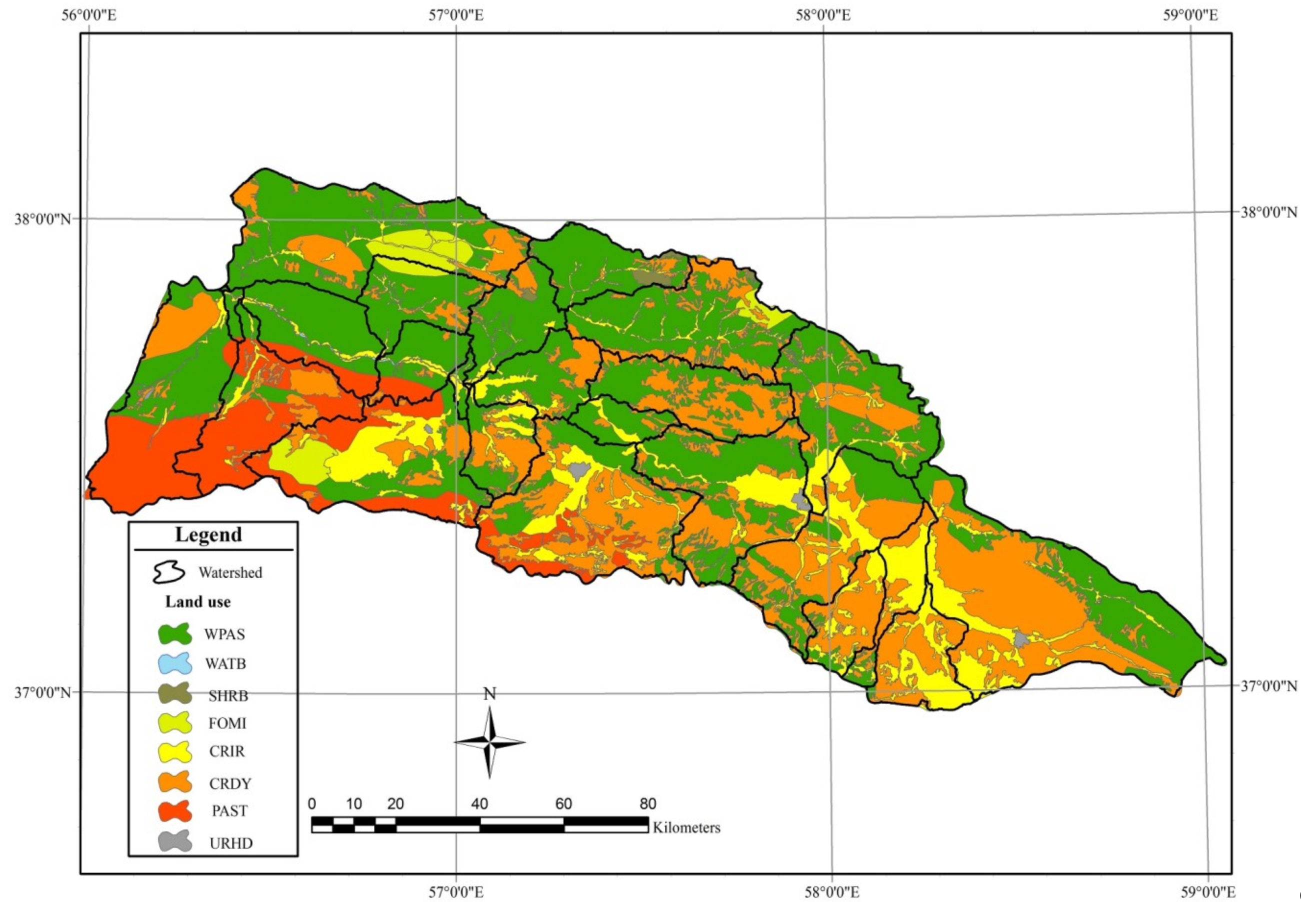

Figure 1: Inputs of the SWAT model in the research (c) Land use

P-Factor is a measure that indicates the percentage of observed data within the range of (expected) uncertainty. Since the effect of all uncertainty factors is reflected in the measured variable, P-Factor is an appropriate criterion to measure the power of uncertainty analysis (Bekiaris *et al.*, 2005). In ideal conditions, it is tried to increase P-factor to 100 percent. R-factor is a measure obtained by the mean thickness of predicted range of uncertainty divided by the deviation of observed data. So, SUFI-2 aims to reduce R-factor as much as possible, and in ideal conditions, reducing it to zero. To compare the predicted and observed values, different indicators have been introduced and used in SUFI-2, which can be listed as follows (Prasanchum *et al.*, 2020):

$$NS = 1 - \left(\frac{\sum_{i=1}^{n}(o_i - p_i)^2}{\sum_{i=1}^{n}(o_i - \bar{o})^2}\right) \quad (5)$$

NS is the Nash-Sutcliffe coefficient, and its parameters are like the r^2 coefficient. Its value varies from minus infinity to 1, and shows how much the regression line between observed and predicted values is close to regression line with a slope of 1. The br^2 coefficient is for the comparison between the measured and estimated flows. This efficiency standard is provided by Muleta *et al.* (2005):

$$\varphi = \begin{cases} |b|R^2 \ \ for\ |b| \le 1 \\ |b|^{-1}R^2 for\ |b| > 1 \end{cases} \quad (6)$$

Where R^2 is the coefficient of determination between the two measured and simulated signals, and b is the regression line slope. In the case of several runoff stations, the objective function is the average φ for all stations (Faramarzi *et al.*, 2009):

$$g = \frac{1}{n}\sum_{i=1}^{n} \varphi_i \quad (7)$$

φ function value varies between 0 and 1. However, the range is not credible for a small number of data that are not well simulated.

After determining the performance indicator between observed and simulated data, these processes (from sampling to choosing the performance indicator) will be repeated until the desired result is achieved. In this study, P-factor and R-factor criteria are considered as a target function for uncertainty analysis of br^2 coefficient (Prasanchum *et al.*, 2020).

Table 3: The initial calibration results of runoff data in the period under study

Station	NS	r^2	br^2	R- factor	P-factor
Ghatlesh	0.29	0.41	0.48	1.36	0.31
Aghmazar	-0.04	0.49	0.73	1.78	0.53
Babaaman	-0.14	0.5	0.47	1.99	0.58
Gharekhanbandi	-0.07	0.55	0.48	2.05	0.54
Darband Semelghan	-0.18	0.58	0.47	2.38	0.57
Shir abad	-0.20	0.65	0.41	2.48	0.61

Results and Discussion

Implementation of SWAT model

The effect of different water management plans on the natural flow regime of the river watershed is investigated using the SWAT hydrological model for the period 1975 to 1991. For this purpose, the created model was calibrated and validated using daily measured flow rate data in hydrometric stations from 1975 to 1991. Calibration and validation were developed in Aghmazar, Babaaman, Darband Samalghan, Darkesh, Ghal'eh Barbar, Gharakhanbandi, Ghatlash, and Shirabad stations. After providing necessary information, the established hydrological model was calibrated for 17 years from 1975 to 1991, by regarding 3 years from 1972 to 1975 for training using monthly measured discharges in six stations Ghatlash, Aghmazar, Babaaman, Gharehkhanbandi, Darband Samalghan, Shirabad, without considering the water transferred to the basin. The results of the calibration of the model in this period are shown in Table 3. Based on the results, the average levels of P-factor, R-factor, br^2, and r^2, in the total basin were 0.55, 1.9, 0.50, and 0.57 for the calibration period. The amounts varied from station to station.

Figure 2 shows the diagrams of the measured flow rate and range of uncertainty of the simulated flow rates for the six selected stations. According to Figure 2, the flow rate variations trend is predicted with a high degree of uncertainty. The base flow and peak flow are often estimated lower and higher than the real rate. As previously mentioned, one of the goals in the calibration process of the SUFI-2 tool is to reduce uncertainty, so that the majority of observed data be in the level of 95ppu. Akhavan *et al.* (2009) stated that if the measured data have good quality, and the hydrological model considers many management processes and variations in the basin, usually 80 to 100 percent of them are in the level of 95ppu. However, in some areas where data do not have good quality, or the hydrological model is produced with greater simplicity due to lack of sufficient information from management variations in the period under study, 50 percent of the P-factor is justified quality of the calibration. Considering what was mentioned above, it was tried to reduce the uncertainty while improving other calibration indicators. For this purpose, the information of water entering the basin is considered in the hydrological basin modeling regardless of the amount of water taken downstream.

Table 4: Final results of calibration of runoff data in the period under study

Station	NS	r^2	br^2	R- factor	P-factor
Ghatlesh	0.75	0.79	0.72	0.93	0.71
Aghmazar	0.17	0.53	0.50	1.07	0.78
Babaaman	-0.14	0.5	0.48	0.99	0.76
Gharekhanbandi	-0.01	0.52	0.51	1	0.71
Darband Semelghan	-0.27	0.47	0.46	1.77	0.66
Shir abad	0.14	0.58	0.45	0.94	0.751

Then, it was tried to optimize and reduce initial sensitive parameters, and improve other calibration indicators while reducing the uncertainty of the model outputs. In optimizing of the initial input parameters, assuming a uniform distribution of the estimated parameters and using Latin hypercube sampling, 200 samples were selected from each interval. Then with the composition of 200 representatives from each of 46 parameters, the SWAT model was run, and calibration parameters were calculated. After five calibration stages and implementation of 200 times, the process led to good results, shown in Table 4. As can be seen, the average value of P-factor, R-factor, br^2, r^2 in the total watershed is 0.73, 1.15, 0.53, and 0.56, respectively, which is improved compared to the initial data of Shirindarreh number (1) to the model, the simulated base flow, which was previously lower than the measured value was adjusted. However, the maximum simulated values in most stations are higher than measured values. This may include a lack of consideration of the possible

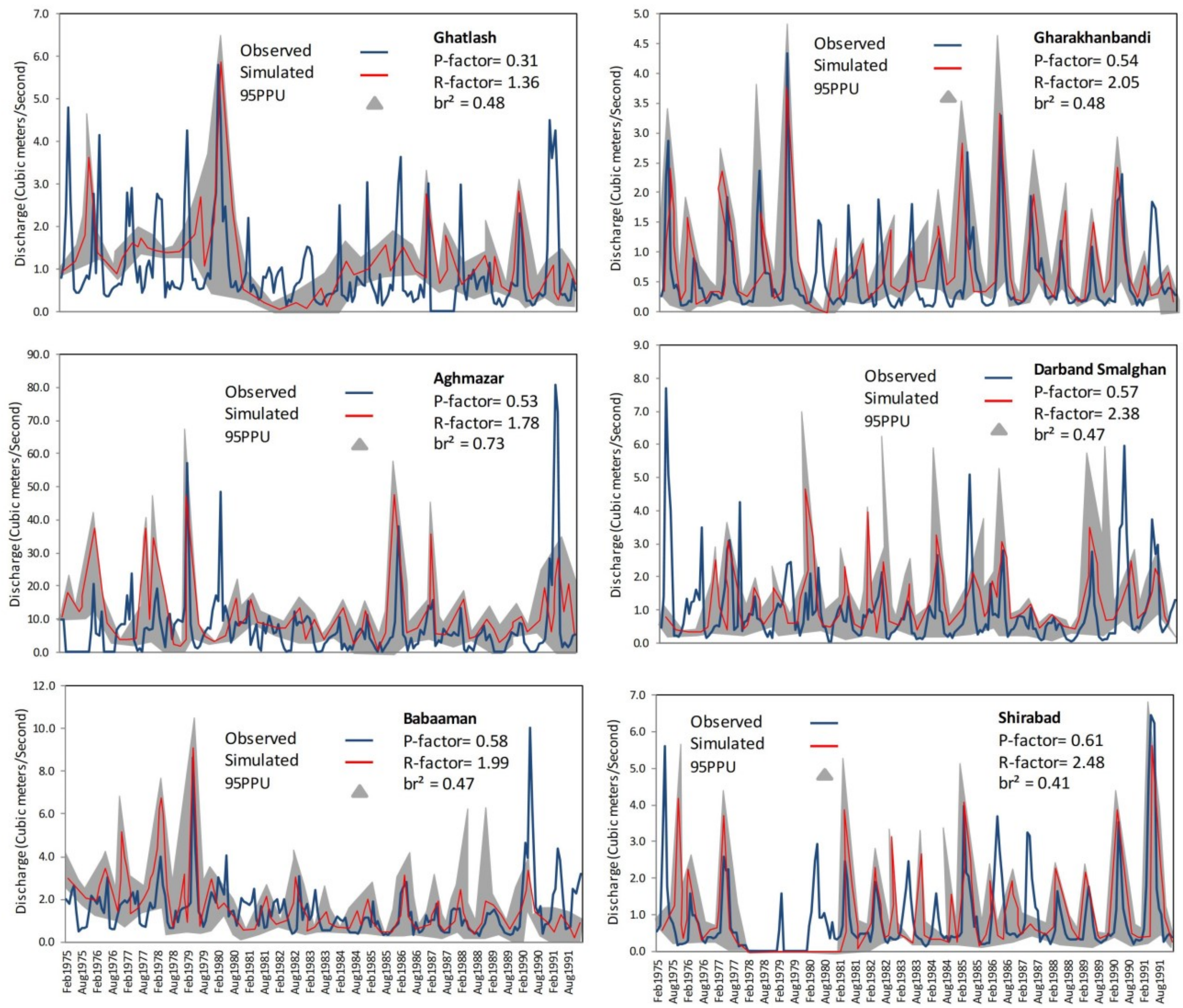

Figure 2: Comparison of measured and simulated monthly flow rates resulted from the model calibration in the period 1972 to 1987 for six selected stations in the Atrak river basin

modeling (Table 3) in whole watershed.

Similar results can be seen in a study conducted by the Akhavan *et al.* (2009) to simulate monthly runoff in the Hamadan watershed. However, these percentages varied from station to station. Figure 3 shows the observed and predicted flow rates in different stations. By comparing Figures 2 and 3, it can be concluded that by entering the interpretations of the hydrological model of the period due to the model's inability to precisely simulated snow and ice in the basin. Due to the incompatibility of the SWAT model with mountainous areas and also the fact that this model does not consider the erosion caused by snowmelt, this issue has caused the rainfall in the model to be converted directly into runoff and with real conditions that some rainfall through it becomes Snow and then it's melting in the coming months will turn into the runoff with a delay, not much match. This has led to the over-simulation of peak discharges in the basin. Similar results have been reported in Rostamian (2007) and Akhavan *et al.* (2009).

Validation of the model in the period 1987 to 1991 in the three years by regarding the three years from 1985 to 1987 for training (the warm-up period) similar to the calibration process. However, invalidation, the input parameters were not optimized, but the optimized calibration parameters were used. The statistics of the measured flow rate new range (1985 to 1991) were used to compare the predicted and measured values. Hydrometric stations used for this purpose included Ghatlash, Aghmazar, Babaaman, Gharehkhanbandi, Darband Samalghan, and Shirabad. Validation results are given in Figure 4. As seen in the Figure, the simulation results show good agreement with the calibration results. Average P-factor, R-factor, br^2, r^2 are 0.77, 1.3, 0.48, and 0.58, respectively, for the entire watershed. Similar results have been reported in Feyereisen *et al.* (2007).

Identification of the critical sub-basins

Based on the output results of the runoff simulation in the SWAT model, the flow rate varies month to month. Figure 5 shows the yield of any of the rivers in each sub-basin. Increased output is consistent with increased rainfall calculated for each of the sub-basins. The highest river yield is related to sub-basin 27 in the eastern part and downstream

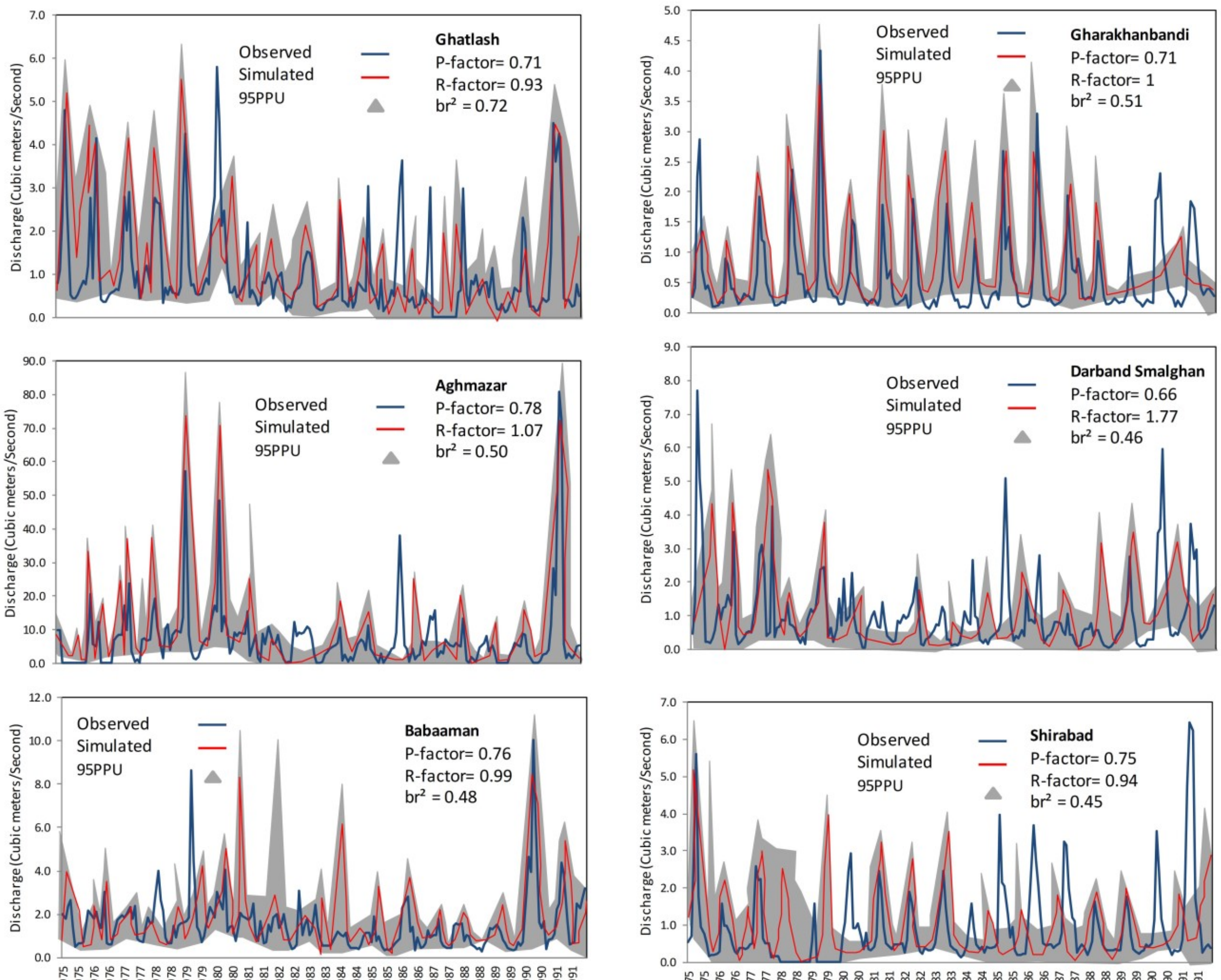

Figure 3: Comparison of measured and simulated monthly flow rates of the final calibration of the model in the period 1972 to 1987 for selected stations in the Atrak river basin

of the basin, and the lowest is related to sub-basins of the northern and central regions (Sub-basins 6, 8, 15, and 18).

Conclusion

Land-use change, population growth, and consequent large and small industries in the watershed surrounding due to the increased level of trust in the production and provision of needed water resources. Therefore, the aim of the present study is to model and estimate the runoff in the case study using the SWAT model and to analyze the sensitivity of the parameters affecting the runoff by the SUFI-2 algorithm. The following is a summary of the results obtained from the research in the Atrak basin.

The results showed that in the monthly runoff

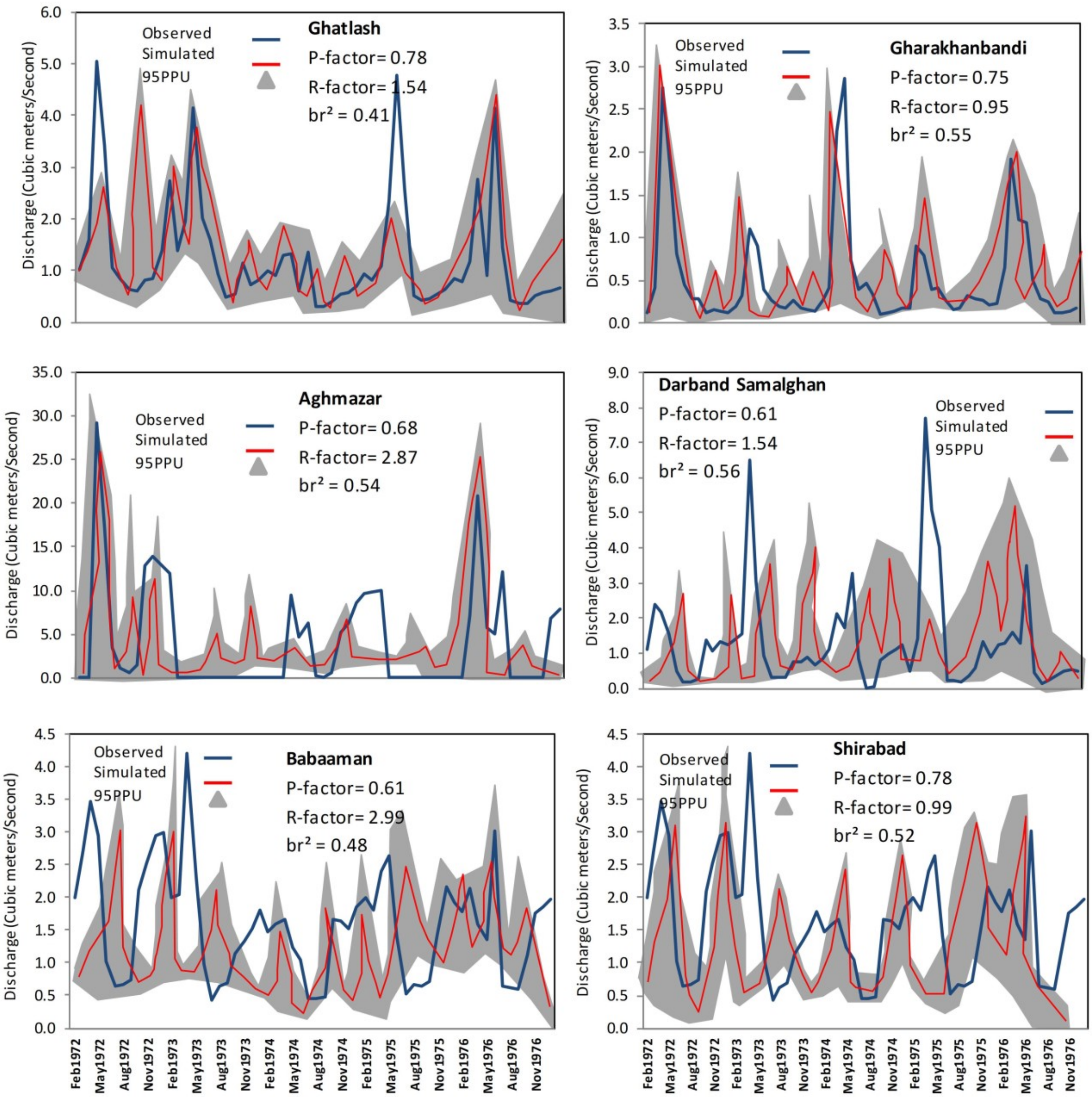

Figure 4: Comparison of measured and simulated monthly flow rates of the final validation of the model in the period 1987 to 1991 for selected stations in the Atrak river basin

calibration stage, the coefficients of P-factor, R- factor, br2 and r2 coefficients at the basin outlet were 0.73, 1.15, 0.53 and 0.56 in the validation stage 0.77, 1.3, 0.48 and 0.58 were obtained, respectively. The best results were obtained at Shirabad station and the weakest results were obtained at Gharakhanbandi station.

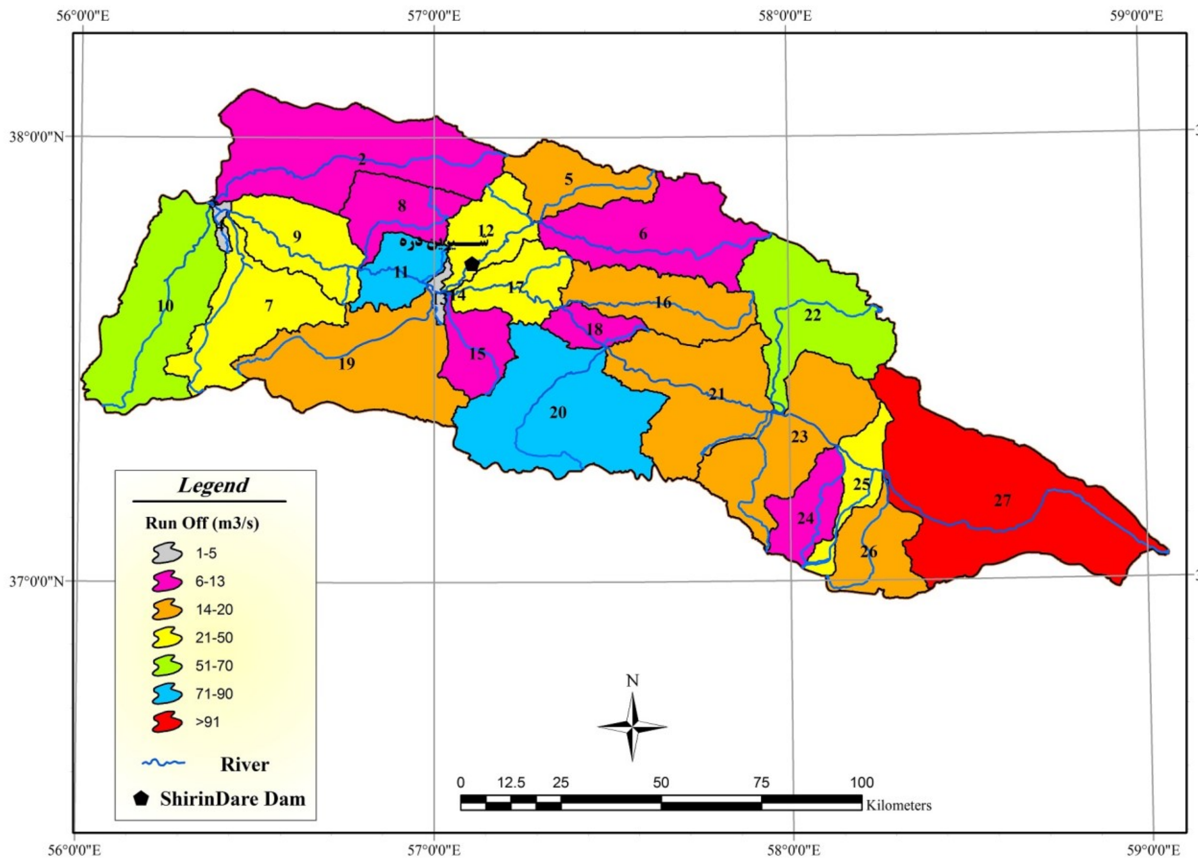

Figure 5: The calculated runoff for each sub-basins using the ARC SWAT model

According to the performance criteria of the SWAT model in the period before and after the construction of Shirindarreh Dam, simulation of the hydrological trend of river flow after the construction of Shirindarreh Dam due to better data in this period than before the construction of better and with no There was less certainty.

Calibration of SWAT model was directly related to user knowledge of the general condition of the basin in terms of climate, hydrology, land use, management conditions, etc.

Due to the complexity of the hydrological conditions of the Atrak watershed and, also the lack of details of management data, the uncertainty of variables simulated by the SWAT model in some large sub-basins.

This research can be used in more advanced studies to evaluate food production, increased efficiency of water use in the basin, or virtual inter-basin water trade. The applied model is able as a possible solution to reduce water crisis, as well as in examining the effect of climate change on water resources and food production, and coping strategies to ensure the security of food and water in the Atrak river basin.

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