Modeling of point and non-point source pollution of nitrate with SWAT in the Jajrood river watershed, Iran

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Abstract: The Latian dam reservoir is one of the most important drinking water sources for Tehran, Iran. Nitrate is a major water quality problem in this reservoir. The Jajrood River, the most important water source for the reservoir, discharges large amounts of nutrients to it every year including high levels of nitrate, a pollutant of particular concern. This study presents the results obtained from simulating different point source and nonpoint source impacts on the fate and transport of nitrate in the 470 km^2 Jajrood watershed using the Soil and Water Assessment Tool (SWAT) model version 2000 (SWAT2000). The SWAT model was calibrated and validated over an extended time period (1997-2005) for this watershed before evaluating the effect of various management practices on nitrate loadings into Jajrood River. The results of monthly calibration Nash-Sutcliffe coefficient of efficiency (E) and R^2 for runoff at the watershed outlet were 0.82 and 0.81 respectively, and for the validation, these statistics were 0.57 and 0.61 respectively. The values for calibration of daily nitrate load at the watershed outlet were 0.55 and 0.59 respectively, and for the validation these statistics were 0.36 and 0.56 respectively. The simulated results indicate that untreated wastewater and leaking or faulty septic systems are the main sources of nitrate loading in the Jajrood river system. Runoff from orchards is the other significant source of nitrate. Moreover, measurements indicate that the maximum flow rate and nitrate load in the Jajrood River occurs from February to June, which implies that at high flow rates the nitrate load increases in the river.

Keywords: SWAT2000, watershed modeling, nitrate, point and non-point source

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1 Introduction

During the last decade in Iran, costly measures have been taken to reduce water pollution caused by point sources. These measures included installation of wastewater treatment for major cities and some towns. However, lack of proper treatment systems in most Iranian towns and villages has resulted in pollution emissions from these point sources, which has resulted in these point sources being an important source of pollution to waterways. In addition, nutrient pollution also occurs from nonpoint sources, including cropland and fruit tree orchards.

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The Latian dam reservoir is one of the most important drinking water resources for Tehran, the capital city of Iran, which supports a population of over 8 million in the metropolitan area. The reservoir provides about 30 percent of Tehran's freshwater. The latest reports indicate that nitrate pollution is a leading cause of eutrophication in the Latian reservoir, much of which is transported to the reservoir by different tributary streams. This is especially true for the Jajrood river, which discharges considerable nutrients (nitrogen and phosphorous) to the reservoir on an annual basis.

Nitrate enters the Jajrood River from a wide variety of sources that vary greatly in magnitude. In recent decades nitrate concentrations in the Jajrood river have increased significantly, due to a lack of sufficient management and uncontrolled application of fertilizers in agricultural production, and entrance of untreated wastewater, which has resulted in eutrophic conditions in the Latian dam reservoir (Caldy, 2004).

Use of physically based or conceptual, distributed parameter models has become increasingly popular to address catchment and higher level water resource management problems (Kannan et al., 2006). The Soil and Water Assessment Tool (SWAT) water quality model (Arnold and Forher, 2005; Gassman et al., 2007), is one of the most widely used models that was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land-use and management conditions over a long period of time. Previous modeling with SWAT in Iran has indicated reasonable results (Omani Tajrishy and Abrishamchi, 2007; Faramarzi et al., 2008; Rostamian et al., 2008). Therefore, SWAT was chosen to evaluate the effect of point and nonpoint sources on nitrate loading into the Jajrood river watershed. The specific objectives of this study were to: (1) Determine the key nitrate sources in the Jajrood watershed, (2) Perform a sensitively analysis of key SWAT hydrological and nitrate parameters; (3) Perform streamflow and nitrate calibration and validation with SWAT.

2 Materials and methods

2.1 Study area

The Jajrood river watershed (Figure 1) is located in the northern part of Iran. The Watershed drains an area of approximately 470 km^2 that consists primarily of crops, pasture, and small pockets of orchards. The Jajrood river has a total length of 40 km; the main tributaries are the Garmabdar, Amame and Ahar rivers. (Figure 1).

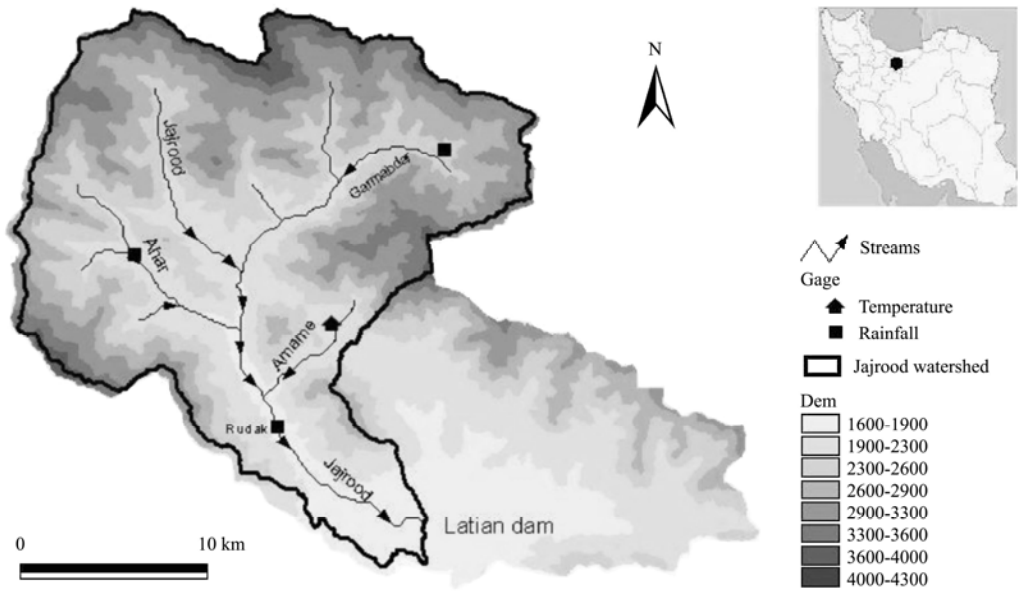


Figure 1 Digital elevation model, river network and meteorological stations for the Jajrood river watershed SWAT application

The watershed is comparatively densely populated with approximately 18,000 (2007 census data) inhabitants, out of which approximately 11,000 live in villages. The area is generally considered to be one of the most favorable for tourism in Iran. Every year during the spring and summer seasons, the weekend population of the watershed area expands to approximately 60,000 people due to the influx of tourists from the city of Tehran. The activities of these tourists can further result in Jajrood river water quality impairment, due to their proximity to the stream system.

The study area also consists of mountain regions with mainly loamy or sandy soil texture and valleys with very steep slopes (Table 1). The watershed has a mountain climate, which is characterized by cold winters and moderate summers. The mean monthly temperature ranges from 14℃ to 26℃ in summer and -6℃ to 5℃ during the winter. The mean annual precipitation for the watershed is 720 mm per year, most of which falls during February to April.

Table 1 Land use and soil proportions in the Jajrood river watershed

Land use				Soil			
Range brush	Pasture	Orchard+Residental	Water	Loamy	Loamy gravel	Loamy clay	Loamy sandy
61.3%	34.6%	3.8%	0.3%	56.4%	25.8%	8.8%	9.0%

The distribution of key land use in the watershed is shown in Table 1 and Figure 2. Range brush is the dominant land-use within the area of study, covering approximately 62% of the land area. The distribution of major soil types is also listed in Table 1. Grazing operations are performed in the spring and summer in the pasture areas. Sheep and cows are the main livestock raised in the study area.

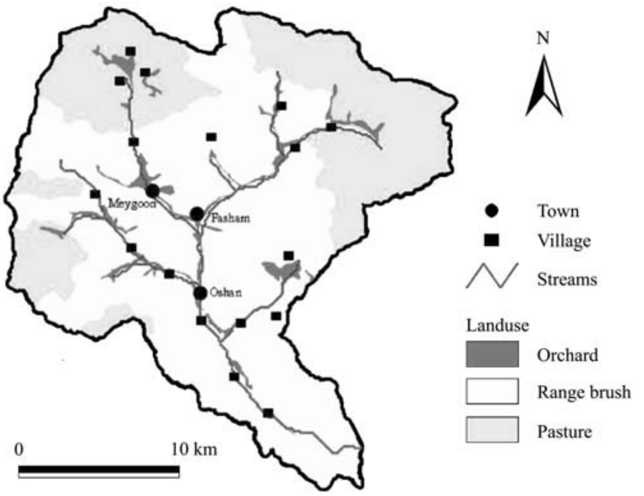


Figure 2 Land-use map, towns and villages locations in Jajrood river watershed

There is only one wastewater treatment plant in the Jajrood river watershed that is near the outlet of watershed. Therefore, untreated sewage from other towns, villages and industries in the watershed can be directly discharged to the Jajrood river and tributaries.

The main sources of water for the Jajrood river are snow melt, rainfall and springs. Water flowing from snowmelt sources is normally upstream from human-impacted areas and enters the stream system in an initially unpolluted form. However, water originating from springs and rainfall often flows near the villages and towns. Therefore, it can become polluted as a result of contact by both point and non-point sources (i.e., wastewater, rubbish, etc.).

2.2 Input data

Data available for modeling Jajrood river watershed with SWAT2000 were the following:

1) A 50 m×50 m digital elevation model grid;

2) Soil map at a scale of 1:250,000;

3) Daily series of precipitation data from 1997 to 2005 recorded at three precipitation gauge stations (Ahar, Rudak and Garmabdar; Figure 1) and monthly meteorological statistics (i.e., wind speed, dew point, solar radiation and temperature) recorded at the Amame gauge station (Figure 1) during the three decades before 1997;

4) Four land-use classes defined as range brush, pasture, orchard and residential (Figure 2). Most of the residential areas are small scale and mixed with orchard land use. The land use was generated using satellite images in 2003. For this purpose LISSIII satellite images with spatial resolution of 23m×23m were utilized;

5) Soil geomorphological and textural characteristics, produced by Sharif University of Technology's Environment and Water Research Center;

6) Management data (i.e., fertilizer application, grazing operation, etc.);

7) Wastewater point sources inlet from towns, villages and tourism population;

8) Daily series of discharge data from 1997 to 2005 recorded at the Rudak gauge (Figure 1);

9) Water quality data, available from 1997 to 2005, recorded at the Rudak gauge (Figure 1).

2.3 Load computation from point sources

2.3.1 Residential population

Point and non-point patterns are quite different in terms of pathways and temporal dynamics (Salvetti et al., 2007). In the Jajrood River watershed, septic tank and direct discharge to creeks are potentially significant sources of nitrate to surface and subsurface water. In order to estimate the nitrate load emitted per any resident, three sets of samples were taken and analyzed upstream and downstream the town of Meygoon (Figure 2). The results are shown in Table 2. To estimate the mass of nitrate contributed by one person per day, a mass balance equation was developed that accounted for the nitrate amounts upstream and downstream of Meygoon. The average nitrate load contributed by one person was estimated to be 7.3 kg/y, based on a mass balance equation developed with the Meygoon sampling data. All other sewage emissions from towns and villages in Jajrood river watershed were assumed to have similar properties as those determined for Meygoon.

Table 2 Sampling results in upstream and downstream the town of Meygoon

Date	Upstream		Downstream	
	Nitrate /mg · L^{-1}	Discharge /m^3 · s^{-1}	Nitrate /mg · L^{-1}	Discharge /m^3 · s^{-1}
26 July 2002	1.4	0.324	4.4	0.458
20 September 2002	2.5	0.106	2.7	0.385
26 October 2002	1.1	0.275	2.5	0.313

2.3.2 Tourism population

During spring and summer weekends, tourists enter the Jajrood river watershed and spend time near the river for short periods of time (estimated to be an average of eight hours). The pollution caused by this transient population can be significant. The daily emitted nitrate load by any tourist during these weekend periods was, assumed to be one third of the residential population. The estimated nitrate load by the tourism population is only for the spring and summer weekends (it is negligible for other days).

2.4 Fertilizer application and grazing activities

The water quality of the watershed is mainly affected by different human point sources. However, the improper management of livestock manure and fertilizer applied to orchards, and deposited from high grazing operations, might lead to increased deterioration of the quality of Jajrood river. Orchards in the watershed are often concentrated near the watering area. As a result, the water quality can be affected by fertilizer applied during irrigation treatments to orchards which subsequently drain to rivers and creeks. About 4,000 kg/ha of fresh dairy manure is annually applied for fertilizing orchards, typically towards the end of November. Therefore, the nitrate load in the Jajrood river increases due to wash-off from these orchard areas during the rainy seasons of late fall and winter. Sheep grazing on pastures (approximately 50,000 sheep) also contribute nitrogen losses to streams during the period of April to November. Table 3 shows all agricultural activities done in this watershed every year. All of the parameters relevant to grazing operation and the manure applied to orchards (e.g., sheep and dairy manure specifications and their equivalent nitrogen rate) are estimated regarding to standard table D384.1 (ASAE, 2000) and study area characteristics.

Table 3 Crops grown and management schedules in the Jajrood River watershed

Land use type	Event data	Management operation	Value of operation
Range brush	5 March	Growing plant season	
	22 November	Kill/End of growing season	
Pasture	5 March	Begin growing pasture	
	4 April	Grazing operation	50,000 sheep for 6 months (3.9 kg/ha fresh manure applied each day)
	22 October	Kill/End of growing	
Orchard	5 March	Growing plant season	
	20 April	Fertilizer application (chemical)	24 kg/ha Urea
	12 October	Kill/End of growing crop	
	23 November	Fertilizer application	4,000 kg/ha fresh dairy manure

Currently, there are no experimental field data to evaluate the impact of the wash-off on the Jajrood river nitrate pollution. The available nitrate data were gathered during dry conditions. However, the effect of wash-off processes would be limited to precipitation events that generate runoff events. These events would likely have a minor impact on the nitrate levels in the river.

2.5 Description of SWAT model

The SWAT model is semi-physically based, and allows simulation of a high level of spatial detail by dividing the watershed into a large number of sub-watersheds. The major components of SWAT include hydrology, weather, erosion, plant growth, nutrients, pesticides, land management, and stream routing (Abbaspour et al., 2007). SWAT simulates evapotranspiration, infiltration, percolation, runoff generation, nutrient cycling and transport for each HRU.

Water and sediment routing as well as in-stream nutrient processes are simulated along the channel length for each subbasin (Neitsch et al., 2002).

Three potential evapotranspiration estimation methods are provided in SWAT. For the Jajrood river watershed, the Penman-Monteith equation (Monteith, 1965) was used to estimate potential evapotranspiration and transpiration. Surface runoff can be calculated on an hourly or daily basis in SWAT. The Green and Ampt equation is used for hourly time step applications and the empirical U.S. Department of Agriculture (USDA) Natural Resource Conservation Service (NRCS) curve number (CN) method is used for daily applications (USDA-NRCS, 2004; Mulungu.and Munishi, 2007).

SWAT monitors five different pools of nitrogen in the soil that include two inorganic nitrogen pools, NH_4^+ and NO_3^-, and three other pools consisting of organic forms of nitrogen. The organic nitrogen pools are associated with crop residual, microbial biomass and soil humus (Neitsch et al., 2002).

SWAT version 2000 (SWAT2000) was used for this study. Additional detailed documentation for SWAT2000 is provided in Neitsch et al. (2002).

2.6 SWAT model calibration and validation

Two stages for nitrate simulation are required: hydrologic calibration and nitrate calibration.

In the first step, for nitrate calibration, water flux parameters should be calibrated. There is one hydrometric station near the outlet of watershed named Rudak. Daily discharges from 1997 to 2005 were recorded at the Rudak gauge; therefore, the data series from March 1997 to December 2002 were used for calibration and January 2002 to September 2005 for validation of discharge.

After hydrologic calibration, the model was calibrated for nitrate. During the period from March 1997 to September 2005 only 69 nitrate concentration data were sampled and recorded at the Rudak gauge. These data were generally recorded in monthly intervals (approximately one sample per month); however, non nitrate samples were collected during the period from June 2001 to May 2002 (Figure 5).

Only daily nitrate calibration and validation were done using these samples due to the limited number of recorded nitrate samples. For this study, the SWAT nitrate simulations were calibrated from January 1998 to December 2002 and validated between January 2002 and September 2005.

The predicted discharge and nitrate levels were graphically evaluated and also evaluated statistically using the coefficient of determination (R^2) and the Nash-Sutcliffe coefficient of efficiency (E) (Nash and Sutcliffe, 1970). The coefficient of determination is the square of the Pearson's product-moment correlation coefficient. This coefficient describes the proportion of the total variances in the observed data that can be explained by the model, and is defined as:

$$R^2 = \frac{\left[\sum_{i=1}^{n}(o_i-\overline{o})(p_i-\overline{p})\right]^2}{\left[\sum_{i=1}^{n}(o_i-\overline{o})^2\right]\left[\sum_{i=1}^{n}(p_i-\overline{p})^2\right]} \quad (1)$$

Where: O_i and P_i are observed and predicted data points, respectively, $\overline{o}$ is the average of observed data and $\overline{p}$ is the average of predicted values.

The fact that only the dispersion is quantified is one of the major drawbacks of R^2 if it is considered alone. A model which systematically over- or underpredicts all the time will still result in good R^2 values close to 1.0 even if all predictions were wrong (Krause, Boyle, and Base., 2005). To overcome the limitations associated with using the coefficient of determination, the coefficient of efficiency (E) has been widely used to evaluate the performance of hydrologic models. The coefficient of efficiency is defined as:

$$E = 1 - \frac{\left[\sum_{i=1}^{n}(o_i-p_i)^2\right]}{\left[\sum_{i=1}^{n}(o_i-\overline{p})\right]^2} \quad (2)$$

Where: E ranges from -∞ to 1, with higher values indicating a better prediction.

The Sequential Uncertainty Fitting Ver.2 (SUFI-2) algorithm (Abbaspour et al., 2004) was also used to evaluate calibration of discharge while nitrate was calibrated manually. For the flow calibration processes, the Jajrood river average monthly discharged data of six years (1997-2002) were used. In the first step, hydrological sensitive parameters were identified and introduced to SUFI-2. Next, the monthly average discharged data series of Jajrood river in Rudak station were extracted and fed to SUFI-2. Finally the goal function was determined and SUFI-2 was run for 1,000-2,000 iterations. We began the discharged calibration process by initially including 30 parameters in the SUFI-2 algorithm, but in the last iteration only 12 were found to be sensitive to discharge.

The calibration parameters are presented in Table 4. The parameters in Table 4 reveal that the discharge in the Jajrood river is most sensitive to snow parameters. This is due to the fact that the major source of Jajrood river streamflow is from snow melt. Reported SWAT calibrations for two previous mountainous watershed applications indicated that the streamflow predictions were sensitive to variation in snow processes surface runoff lag, ground water, soil and curve number parameters (Ahl et al., 2008; Zhang et al., 2008)

Table 4 List of SWAT parameters that were fitted and their final calibrated values

Sensitive parameters	SWAT variable name	Range	Final value
Parameters calibrated for discharge (SUFI-2 used)			
Snowfall temperature/°C	SFTMP	±5	4.98
Minimum melt rate for snow during the year/mm · ℃$^{-1}$-day	SMFMN	0-10	0.56
Maximum melt rate for snow during the year/mm · ℃$^{-1}$-day	SMFMX	0-10	1.1
Snowmelt base temperature/°C	SMTMP	±5	1.34
Lateral flow travel time/d	LAT-TTIME	0-180	88.7
Surface runoff lag coefficient/d	SURLAG	1-24	4
Minimum snow water content that corresponds to 100% water content/mm	SNOCOVMX	0-500	289
Snow water equivalent that corresponds to 50%water content/mm	SNO50COV	0-1	0.06
Effective hydraulic conductivity in tributary channel alluvium/mm · h^{-1}	CH-K1	0-150	15.5
Snow pack temperature lag factor	TIMP	0-1	0.97
Soil bulk density/g · cm^{-3}	SOL-BD	1.1-2.5	1.71
Soil evaporation compensation factor	ESCO	0-1	0.33
Parameters calibrated for nitrate (manually)			
Nitrogen percolation coefficient	NPERCO	0-1	0.15
Concentration of nitrogen in rainfall/mg · L^{-1}	RCN	0-15	1
Concentration of nitrate in groundwater/mg · L^{-1}	$GWNO_3$	0-1,000	5

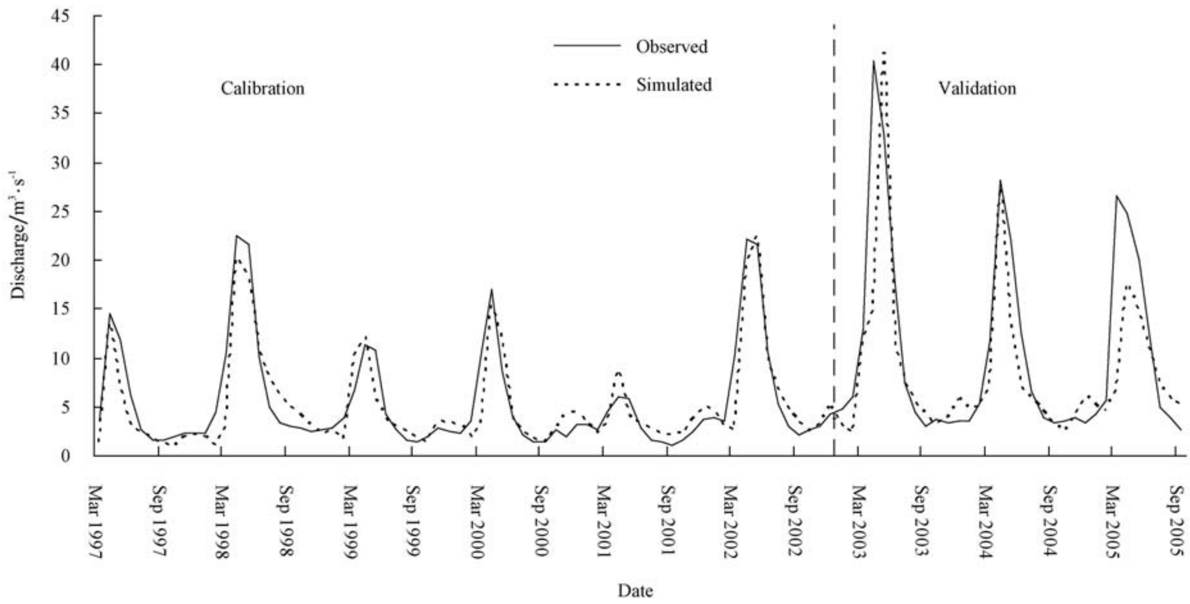
SWAT parameters for snow melt are assumed to be constant for all subbasins. However, in reality they likely vary across different subbasins. This is one of the SWAT weaknesses regarding applications for mountainous regions.

3 Results and discussion

The graphical and statistical calibration and validation results for discharge and nitrate at the Rudak gauge are shown in Figures 3, 4 and 5. Figure 3 shows simulated versus observed monthly discharge at the Rudak gauge for the calibration and validation periods. The *E* statistics for the monthly discharge were 0.82 and 0.57 for the calibration and validation periods, respectively, and the values for respective daily discharge calibration and validation periods were 0.41 and 0.13 (Figure 4). The R^2 statistics were generally similar for the same periods shown in Figures 3 and 4, with a somewhat higher value for the daily validation period. Also, as shown in Figure 5, the *E* statistics determined for the daily nitrate loads were 0.55 and 0.36 for calibration and validation periods, respectively, and the corresponding R^2 values were 0.59 and 0.56.

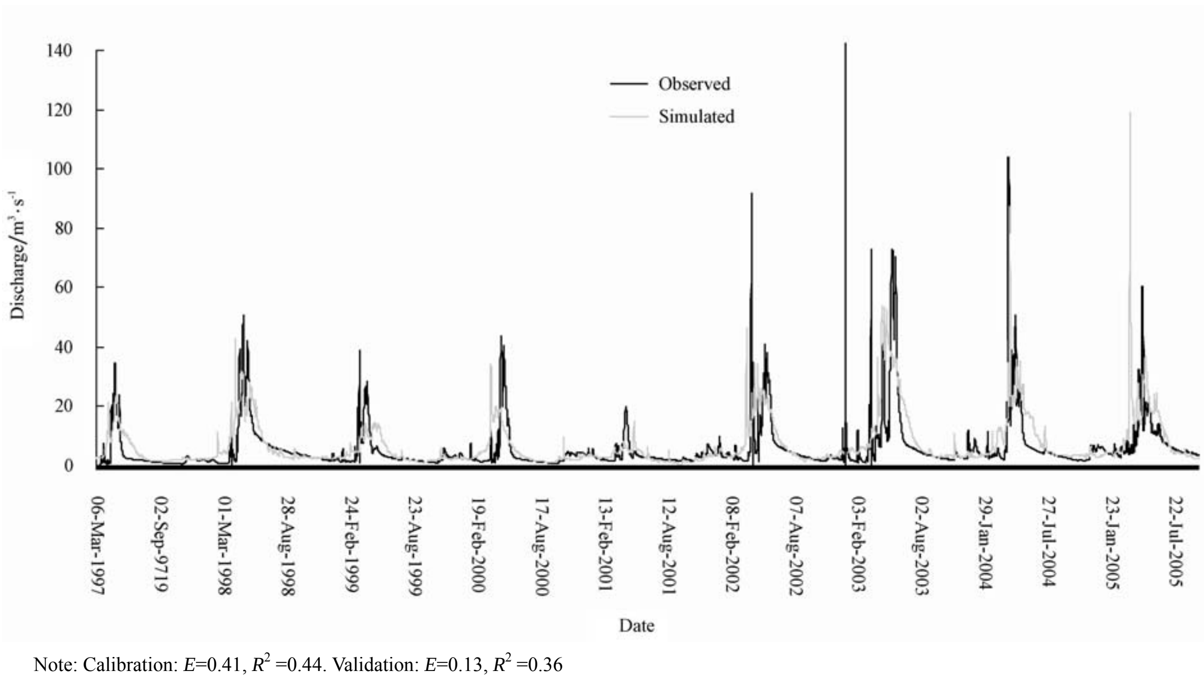
The results of the SWAT2000 discharge predictions (Figures 3 and 4) for the study watershed shows that the model generally performed well in predicting the monthly streamflows but was less accurate for the daily streamflow predictions than expected. The predictions for the validation period are less accurate than the calibration period for both the monthly and daily predictions, as indicated by E=0.57 and 0.13 for monthly and daily discharge validation, respectively. This is due to the fact that the validation period considered is for wet years. During the wet years, the discharge levels are particularly sensitive to daily temperature data. This is due to the mountainous nature of the watershed and the key roles of snowfall and snowmelt in the overall hydrologic balance. Thus, the most hydrologically sensitive parameters are associated with snowfall parameters such as snowfall temperature and the minimum and maximum snowmelt rates. In addition, snowfall is greater during the wet years compared to the dry years.

Therefore, using the SWAT weather generator for estimating temperature inputs, due to the lack of recorded daily temperature data at the Amame climate station as previously noted, had a strong impact on the accuracy of the simulated hydrologic processes.



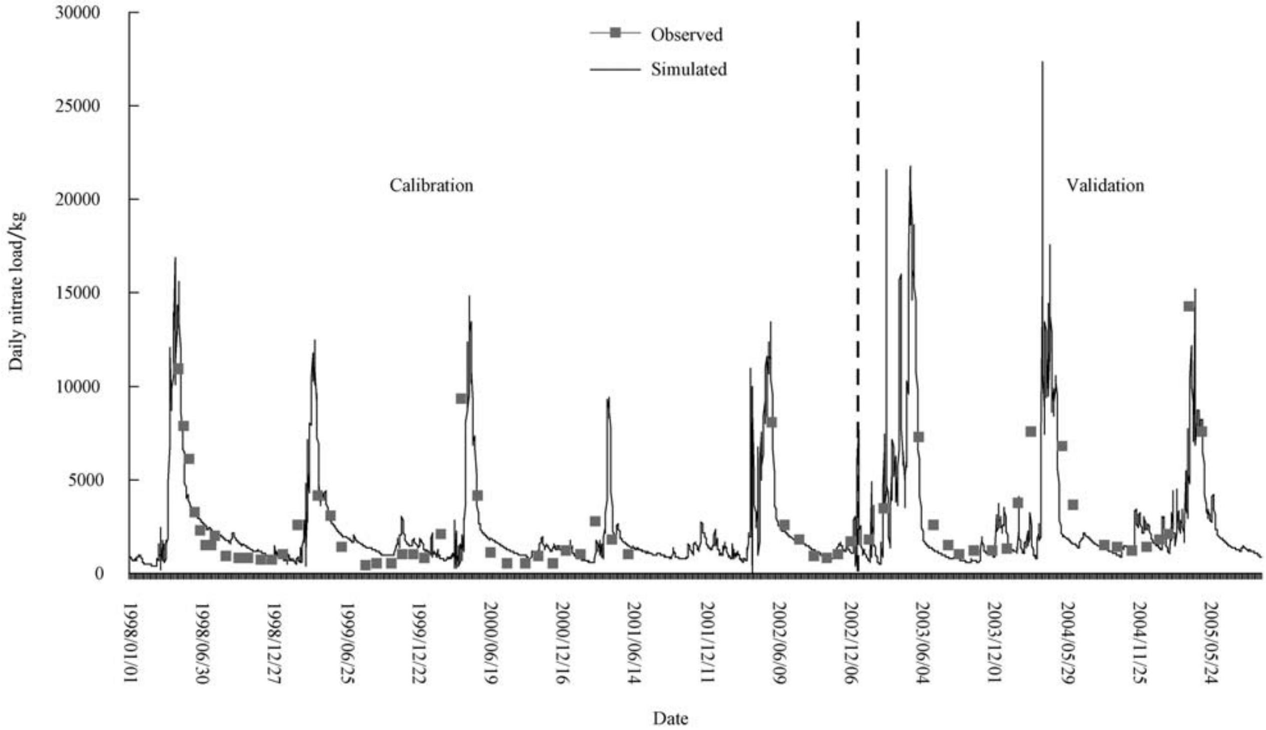
Note: Calibration: E=0.82, R^2 =0.81, Validation: E=0.57, R^2 =0.61

Figure 3 Simulated and observed monthly discharge for the period March 1997 to September 2005 at the Rudak gauge



Note: Calibration: E=0.41, R^2 =0.44. Validation: E=0.13, R^2 =0.36

Figure 4 Simulated and observed daily discharge for the period March 1997 to September 2005 at the Rudak gauge



Note: Calibration: E=0.55, R^2 =0.59. Validation: E=0.36, R^2 =0.56

Figure 5 Simulated and observed daily nitrate for the period January 1998 to September 2005 at the Rudak gauge

As it can be seen in Figure 5, the model performed best during the low nitrate loading periods, in estimating the daily nitrate losses at the watershed outlet. However, the model fit between simulations and observations is less accurate during the peak nitrate load events, due to the lack of adequate data. The SWAT output results indicated a mean annual nitrate load at the watershed outlet of 870 tons per year over the period of 1998 to 2004. Also for this period, manual calculations identify that nitrate emitted by point sources is about 190 ton per year. Therefore, the point source contribution is about 20 percent of the total nitrate load.

As it can be seen from Figures 3 and 4 the maximum flow rate in the Jajrood River occurs during February to June. This is due to the fact that the (rainfall and snowfall) occur during this period. Furthermore, the maximum nitrate load occurred during this period, which implies that at high flow rates the nitrate load increases in the Jajrood River.

4 Conclusions

The SWAT model was used to simulate the effect of both point and non-point sources of nitrate pollution in the Jajrood River watershed. The model was able to simulate the monthly discharge and the agreement between simulated and observed daily nitrate load was reasonably accurate. However, its performance for daily discharge was relatively poor. Daily point source loads were evaluated manually. The results indicated that the wastewater loads from local and tourism populations are the major point source of nitrate load in this watershed and contribute about 20% of the annual total nitrate load. The model setup can next be used for scenario analysis for the watershed including collecting and treatment of wastewater, changing the duration and amount of application of fertilizer in orchards, and improving the application of manure and controlling runoff from fruit orchards. These steps can all reduce nitrate concentration in surface and ground water in the Jajrood river watershed.

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