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Hydrological study of the water quality of the Beja River according to the SWAT model

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ABSTRACT

The proposed research is an important step in the study of agricultural and human pollution in the various tributaries of the Sidi Salem Dam Reserve. We are contemplating the use of the Soil and Water Assessment Tool model for one of the main tributaries, the Beja River. As a first step, we would like to fit this model here, in order to understand the hydrological functioning of this basin. Subsequently, we would study the sensitivity of the model according to the major hydrological parameters and nutrients, by performing continuous simulation for over eight years, allowing us a better choice of these parameters, and later the global results with the observed data. In the second step, we would refine the calibration parameters of the model in two wet and dry years. In both cases, the seasonal variability of these parameters would be taken into account, to better describe the pedoclimatic context of the study area. This approach had to have a good agreement between the simulated and observed data, as it was confirmed by four measures of accuracy. Furthermore, it was shown that the nitrate and orthophosphate levels were of concern because of the misuse of agricultural fertilisers. The proposed approach would provide the decision-makers a powerful tool for monitoring water pollution in the dam's area, as it would evaluate the water pollution of the ungauged basins around the same dam.

Keywords: SWAT; Modelling; Hydrology; Geochemistry; Subhumid region; Beja River

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1. Introduction

Anthropogenic and agricultural pollution has become a much-discussed topic. Its assessment by the qualitative and quantitative aspects was demonstrated in several models, including the Soil and Water Assessment Tool (SWAT). The application of the latter requires a prior study of the hydrological functioning of the considered watershed and insertion of a large number of intrinsic factors, to the study area. Compared to other known procedures in the literature, the SWAT has the advantage of integrating into a geographical information system, all the biological and physicochemical processes involved, as also the edaphic factor of the study area; (Digital Elevation

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Model [DEM], pedological data, land use, climatic data and agricultural practices).

The SWAT model was implemented by Jeff Arnold [1] for the USDA Agriculture Research Service, in 1998. It is a conceptual, physical and semi-empirical model, distributed to manipulate and analyse many agronomic and hydrological data in a watershed through phenomena of precipitations, runoff, infiltration, evapotranspiration and others. It has been tested and validated in a satisfactory manner in watersheds of various sizes, different geological formations and in several areas of the world, notably in North America [2], Europe [3] and China [4]. This model is coupled with a geographical information system, set according to the versions of ArcView and ArcGIS. This coupling has allowed management of data of the raster, vector and alphanumeric types. The SWAT divides the watershed into several homogenous hydrological units called Hydrologic Response Units (HRUs). The latter are the result of a combination of soil types, a class of land and a sub-watershed. Each HRU is assumed to have a homogeneous agro-hydrological behaviour. The flows estimated for each HRU are summed up for the entire watershed considered and compared with the observed data.

Every year, the American Agricultural Research Services (USDA) and Texas University arrange an international summit for the promotion, extension of knowledge, research studies, as well as exchange of experiences on the SWAT model. The theoretical approach of the SWAT model has been intensely studied by Arnold et al. [1].

This research proposes the study of the eutrophication problems of the Sidi Salem Dam Reserve, which represents the most important hydraulic source located in the north-west of Tunisia. The main problem in using the SWAT model is the necessary reinforcement of quite a few important parameters. These were optimised for the difficult studying conditions, parallelly, in different areas in the world. The dominant clay soils, as was the case in this study, could be another difficulty, because of the different hydrological behaviours of the clay in its initial state and during the dry or humid periods. The watershed of the Beja River has the advantage of having all the data needed, however, the other watersheds have weak measurements, but they have similarities on the edaphic soil properties. Besides, as far as we know, this area has never had a similar study. The main aim of this study is to define a working approach allowing the SWAT model to study the area in a pedoclimatic context. The three main objectives are to:

(a) Find out the combined parameters of the SWAT model, allowing a global characterisation of the watershed hydrological and geochemical functioning,
(b) Find out a working methodology to improve the precision of the water quality assessment sheets during two heavy rainfall years,
(c) Evaluate the chemical pollution by nitrogen and phosphorus.

Indeed, Tunis needs over 80% of the drinking water from this dam. The actual siltation and the degradation of the water quality storage due to agricultural, industrial and urban pollution are the significant concerns of the public authorities.

These reserves are supplied by three main rivers, wherein, the course of the Medjerdah River is the most important one, while the most pollutant one is the Beja River.

This study proposes to study the eutrophication problems of the Sidi Salem Dam Reserve, which represents the most important hydraulic source located in the north-west of Tunisia. Indeed, Tunis needed over 80% of the drinking water from this dam. The siltation and the degradation of the reserve water quality due to agricultural, industrial and urban pollution are the significant concerns for the public authorities.

2. Materials and methods

2.1. Site description

The Beja River watershed drains a surface of approximately 434.3 km^2. It is situated north-west of Tunisia, 100 km from Tunis, the capital the city (Fig. 1). It is has an elongated shape and a fairly rugged relief (maximum altitude = 693 m, minimum altitude = 110 m, total index of the slope = 9.4 m/km, average slope = 31.5% and specific rupture = 174 m). The dominant soils are vertisolic (approximately 67%). As a whole, 81% of the soil surface is used for cereals.

This entire area has quite a homogenous climate: The Mediterranean climate, known for its dominant winds, comes from the north-west, with rainfall. The yearly average precipitations are between 350 and 1,000 mm. Most of the rainfall occurs between October and April. It seldom rains in summer. The highest daily temperatures are 14.8℃ in January and 36.1℃ in August. The lowest daily temperatures are between 4.5℃ in February and 19.5℃ in August. The dominant winds come from the north-west during almost the entire year. The monthly average of the wind speed is between 8 and 10 m/s, all year long. The average daily evaporation varies from 2 mm in January to 10.3 mm in July.

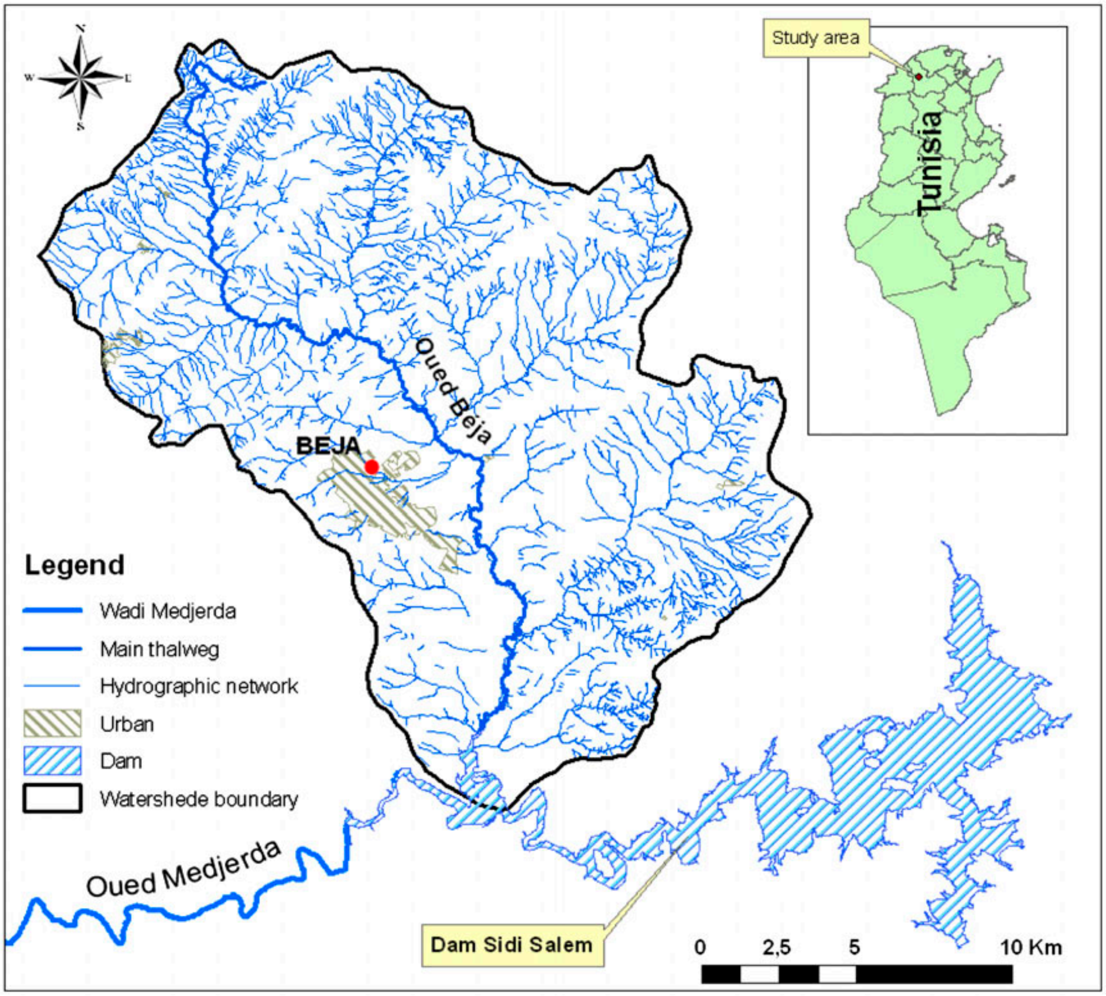

Fig. 1. Area of the study location.

On the other hand, this watershed has an urban area of heavy density, with 107,000 inhabitants (main state inhabitant concentration). It has a heavy concentrated industrial area, with a lot of factories (according to ODNO) [5]: Agricultural and food transformation (60), construction material, ceramic and glass (12), mechanical (11), chemical transformation (5), leather and textile (8) and various factories (25). On account of all of these activities, a water sanitation plant was created in 1994, for 14,000 m^3/d with a biological capacity of 7,800 kg of DBO5/d.

2.2. Data

The following space data for 1995–2003 had been integrated: A DEM, (mission STRM 2000, resolution 90 m), a digital drainage network from the topographic map scale 1/25,000, pedological map and climate data (average of 17 years: 1989–2006).

These observed data are for the years 1995–1996 and 2000–2001. In this particular case:

(a) Weather data: Air temperature and rainfall;
(b) Data of the hydrological assessment and quality;
(c) Agricultural practices.

The SWAT 2000 version extension coupled Arc view 3.2 has been used.

2.3. Methodology

The first phase of the study introduced all the data necessary for simulation in the SWAT (pedology, plot numerical model, cultural practices, etc.). The simulation was performed on daily time steps, while the result was figured out monthly, over an agricultural period of height years, from 1995 to 2003. The requirement of water and nutrients for the crops were estimated by SWAT, from its database.

This long-and-hard working phase allows for the finding of the best combination of adjusting parameters required by the SWAT model. These will first allow to initialise, rather than to again seek the best adjustment parameters for two full years: The wet year (1995–1996) and the dry year (2000–2001), according to the considered rainy periods of each year.

In a first step, we sought to have an agreement between the measured flows and those simulated at the final outlet, by varying the values of the different parameters for modelling approaches and analysing the sensitivity of the model. It was important to be precise and check that the estimations of the measurements describing the water quality depended mainly on the water balance sheet. Therefore, these values were found by figuring out the relation between the concentrations of the total monthly nutrients according to the monthly water balance sheet.

The correlation between the observed and simulated data was evaluated by the Nash–Sutcliffe coefficient (1).

The water balance sheet as well as the water quality were measured through four coefficients [6], as it was.

(a) Nash–Sutcliffe coefficient

The first phase of the study was to introduce all the data necessary for the simulation in the SWAT. The simulation was performed on daily time steps, while the result was calculated monthly. The water and nutrients needed for the crops grown were estimated by the SWAT from its database.

In the first step, we tried to find a match between the simulated and observed debit at the outlet end, by varying the timing parameters and analysing the sensitivity of these parameters on the result.

The concordance of the observed and simulated data was measured using the Nash–Sutcliffe coefficient (1).

$$\mathrm{NSE} = 1 - \frac{\sum_{1}^{N} (y_{i-\mathrm{observed}} - y_{\mathrm{simulated}})^2}{\sum_{1}^{N} (y_{i-\mathrm{observed}} - \bar{y}_{\mathrm{observed}})^2} \tag{1}$$

This index varies from (–∞) at 1. The higher value of this index indicates that the correlation between the observed and simulated data is strong, even as the value of NSE near zero indicates that the scale sizes simulated are closer to the average values.

(b) RMSE-observations standard deviation ratio:

$$\mathrm{RSR} = \frac{\sqrt{\sum_{i=1}^{N} (y_{i-\mathrm{observed}} - y_{i-\mathrm{simulated}})^2}}{\sqrt{\sum_{i=1}^{N} (y_{i-\mathrm{observed}} - \bar{y}_{\mathrm{observed}})^2}} \tag{2}$$

This index figures out the relation of the average quadratic error according to the measured data. The more weak this index is, the better is the simulation.

(c) Percent bias coefficient:

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{N} (y_{i-\mathrm{observed}} - y_{i-\mathrm{simulated}}) \times 100}{\sum_{i=1}^{N} y_{i-\mathrm{observed}}} \tag{3}$$

This index measures the average tendency of the simulated data to be superior or inferior to their observed homologues. The values close to zero show precise simulation, however, the positive values underestimate the measurements of the model and vice versa.

(d) Coefficient of determination:

$$R^2 = \frac{\left(\sum_{i=1}^{N} (y_{i-\mathrm{observed}} - \bar{y}_{\mathrm{observed}}) \times (y_{i-\mathrm{simulated}} - \bar{y}_{\mathrm{simulated}})\right)^2}{\sum_{i=1}^{N} (y_{i-\mathrm{observed}} - \bar{y}_{\mathrm{observed}})^2 \times \sum_{i=1}^{N} (y_{i-\mathrm{simulated}} - \bar{y}_{\mathrm{simulated}})^2} \tag{4}$$

The coefficient of determination (R^2) provides a measure of how well the observed outcomes are replicated by the model. When nil, it indicates the inexistence of a linear relation. A perfect positive or negative linear exists when $R^2 = 1$. Generally, the values higher than 0.5 are acceptable [7].

Even though R^2 is widely used for the evaluation of the models, these statistics are hypersensitive [8] to extremely high values.

The adjustment procedure of the different parameters in relation to the water balance sheet and the water quality should be pursued until at least a satisfactory precision level for a maximum of coefficients is obtained, according to Moriasi et al. [6], as per Table 1.

3. Results and discussion

3.1. Water balance

The best result of the SWAT model adjustment was achieved between January 1995 and October 2003, according to the precision level of Table 2.

Only two of the four accuracy values (PBIAS and R^2) consider that the simulation results are satisfactory.

Table 1
General performance ratings for recommended statistics for a monthly time step [6]

				PBIAS (%)	
Performance degree	RSR	NSE	R^2	Stream flow	Azote, phosphore
Excellent	$0 \leq RSR \leq 0.5$	$0.75 < NSE \leq 1.00$	$R^2 > 0.8$	$PBIAS < \pm10$	$PBIAS < \pm25$
Good	$0.5 < RSR \leq 0.6$	$0.65 < NSE \leq 0.75$	$0.5 < R^2 \leq 0.8$	$\pm10 \leq PBIAS < \pm15$	$\pm25 \leq PBIAS < \pm40$
Satisfactory	$0.6 < RSR \leq 0.7$	$0.50 < NSE \leq 0.65$	$0.2 < R^2 \leq 0.5$	$\pm15 \leq PBIAS < \pm25$	$\pm40 \leq PBIAS < \pm70$
Unsatisfactory	$RSR > 0.7$	$NSE \leq 0.5$	$R^2 \leq 0.2$	$PBIAS \geq \pm25$	$PBIAS \geq \pm70$

Table 2
Accuracy values for the water flow according to a continuous simulation for 1995–2003

Agricultural year	NSE	RSR	PBIAS	R^2
1995–2003	0.24	0.87	−5.59	0.31

In the considered period, we noticed that there was more or less significant shifting (Figs. 2 and 3) in certain agricultural years and likewise in the same year itself, as certified by the accuracy level in Table 3.

The noticed changes could be explained by the fact that we used systematically steady shifting parameters for a continuous simulation (1995–2003); mainly for the hydrodynamic properties. However, the soils in this area were mainly vertisols, with changing physicochemical characteristics along the year.

In this manner, in this study, we suggest improvement of the simulation step, by distinguishing, on one hand, a dry year from a humid one, and on the other hand, by considering variable adjustment parameters (hydrological or of the water quality) from one season to the other within the same year of simulation.

The seasonal cutting for a humid and dry year gives a more significant result for the water flows simulated and observed, as confirmed in Figs. 4–7 and in Table 4.

The scenarios were developed by identifying the seasonal differentiation of the percolation phenomena, runoff and contribution of groundwater. Thus, in general, during the autumn period, in the relatively hot and rainy season, the first intercepted precipitations tend to flow as a surface runoff, clogging the top soil (clay soil). Only part of water reaches the geologic under-adjacent formations in a considerable amount of time. Consequently, the water percolation towards the deep aquifer is markedly average. This phenomenon is more pronounced during winter, when the water transfer is done in a shorter time, as the precipitations are maintained during this phase. Thus, the contributions of aquifers by the basic and hypodermic flow come later at the final outlet. These processes are highlighted during spring where we record a considerable flow, coming mainly from the basic streaming, despite the rarity of rainfall events and intensification of the evaporation phenomenon. This can be explained by the low percolation and re-evaporation coefficient of

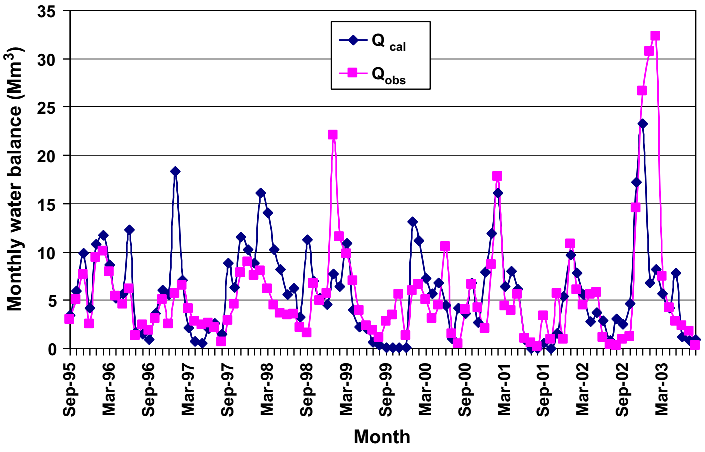

Fig. 2. Temporal evolution of the simulated and observed flow of the Beja River (1995–2003).

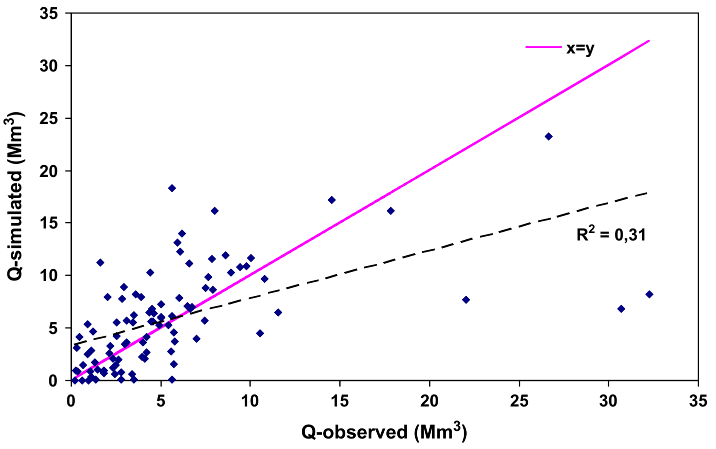

Fig. 3. Comparing the simulated and observed water flows of the Beja River (1995–2003).

Table 3
Yearly distribution of accuracy for the water flow according a continuous simulation for 1995–2003

Agricultural year	NSE	RSR	PBIAS	R^2
1995–1996	0.39	0.78	−23.93	0.80
1996–1997	−4.87	2.42	−29.72	0.65
1997–1998	−3.30	2.07	−73.72	0.51
1998–1999	0.10	0.95	20.59	0.19
1999–2000	−1.24	1.50	−6.47	0.18
2000–2001	0.71	0.55	−19.60	0.78
2001–2002	0.34	0.81	3.02	0.42
2002–2003	0.28	0.85	33.33	0.37

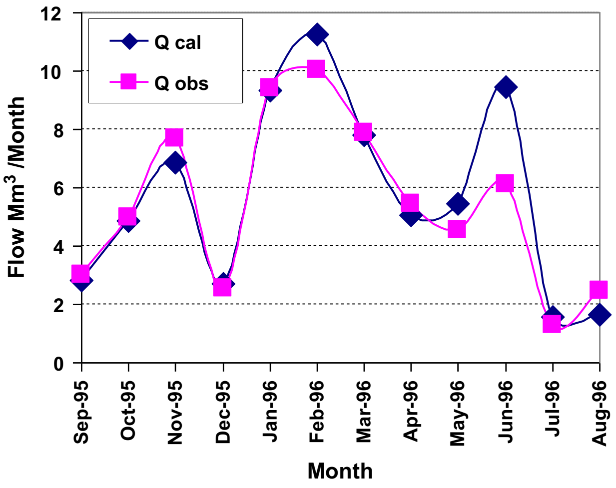

Fig. 4. Variation of the observed and simulated flow for Beja River during the wet year 1995–1996.

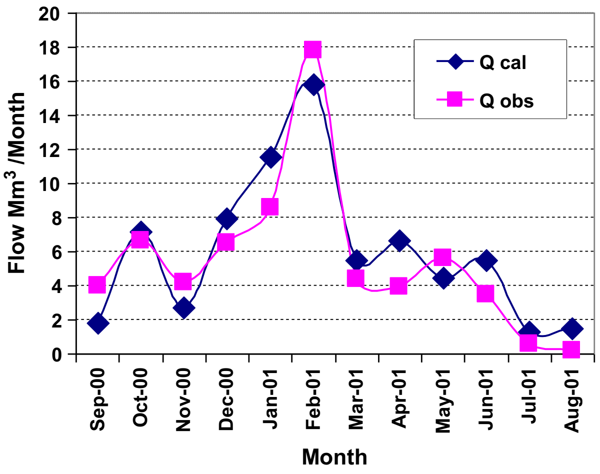

Fig. 5. Variation of observed and simulated flow for Beja River during the dry year 2000–2001.

the surface aquifer. During summer, the water transfer by basic flow is favoured and highlighted by the model at the final outlet. This is affirmed by the low value of the aquifer percolation coefficient (RCHRG-DP) and evaporation coefficient (GW-REVAP), as well as the maximisation of the base flow recession coefficient (ALPHA-BF).

3.2. Water quality

The study of water quality is related to the following parameters: dissolved oxygen, biological oxygen demand, nitrogen, phosphorus and chlorophyll-a. We will restrict ourselves here to the nitrates,

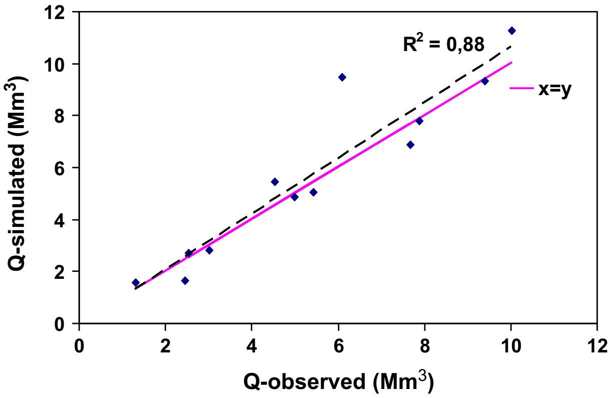

Fig. 6. Comparing the simulated monthly water flow observed in the Beja River during 1995–1996.

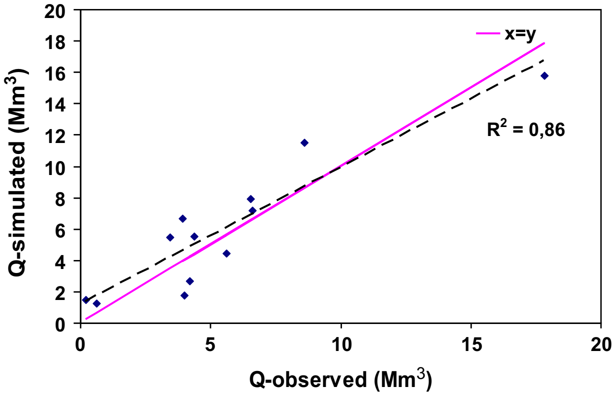

Fig. 7. Comparing the simulated monthly water flow observed in the Beja River during 2000–2001.

Table 4
Accuracy values for the water flow per simulation year

Agricultural year	NSE	RSR	PBIAS	R^2
1995–1996 (Wet year)	0.83	0.42	5.25	0.88
2000–2001 (Dry year)	0.83	0.41	−8.68	0.86

phosphorus and chlorophyll-a. These parameters are indicators for evaluating water eutrophication.

3.2.1. Nitrate concentration

The oxygenation level encourages the nitrification reaction processes; liberation of more nitrates. This stable mineral form reaches the final outlet by percolation (hypodermic and base flow). These processes are limited to study during the dry year. The estimation of the concentration of nitrates gives an excellent precision level, as shown in Table 5 and Figs. 8–11.

Table 5
Precision values of the nitrate concentration in a simulation year

Agricultural year	NSE	RSR	PBIAS	R^2
1995–1996 (Wet year)	0.94	0.26	13.46	0.98
2000–2001 (Dry year)	0.98	0.12	−0.51	0.98

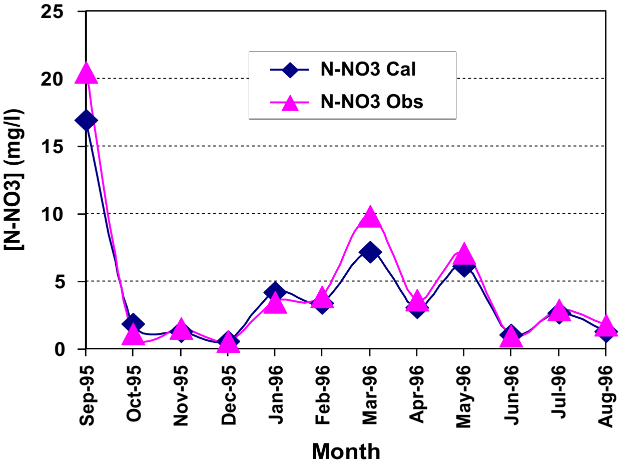

Fig. 8. Temporal evolution of nitrate concentrations simulated and observed in the water of the Beja River 1995–1996.

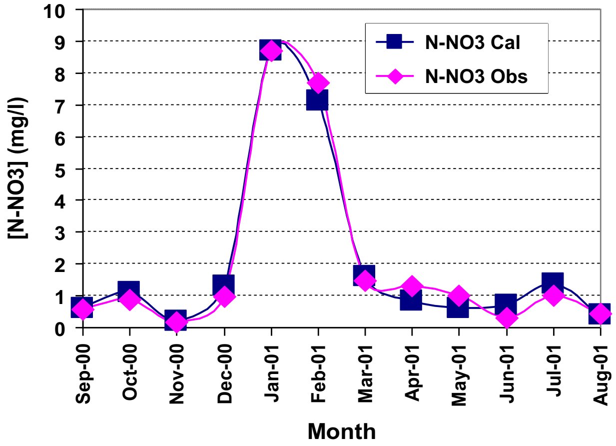

Fig. 9. Temporal evolution of nitrate concentrations simulated and observed in the water of the Beja River 2000–2001.

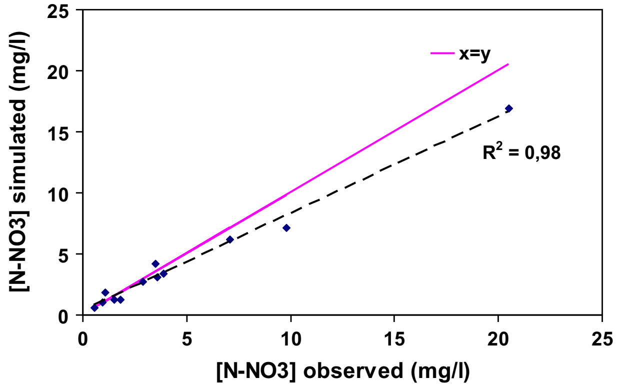

Fig. 10. Comparing the monthly simulated and observed nitrates in the Beja River during the humid year 1995–1996.

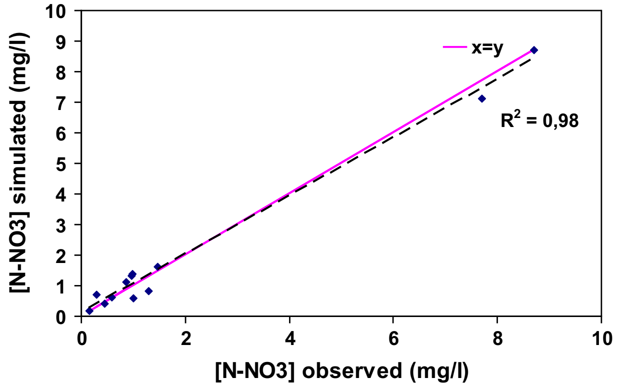

Fig. 11. Comparing the monthly simulated and observed nitrates in the Beja River during the dry year 2000–2001.

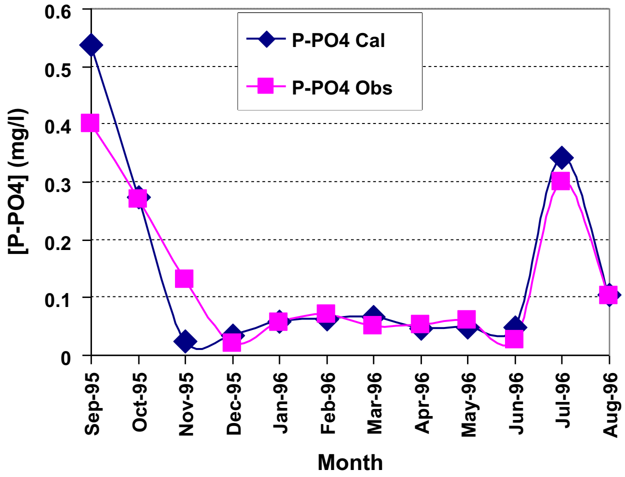

Fig. 12. Seasonal evolution of orthophosphate concentrations observed and simulated for the Beja River water during the year 1995–1996.

Table 6
Precision values for the concentration of orthophosphates in a simulation year

Agricultural year	NSE	RSR	PBIAS	R^2
1995–1996 (Wet year)	0.81	0.44	−7.32	0.92
2000–2001 (Dry year)	0.7	0.55	−2.02	0.79

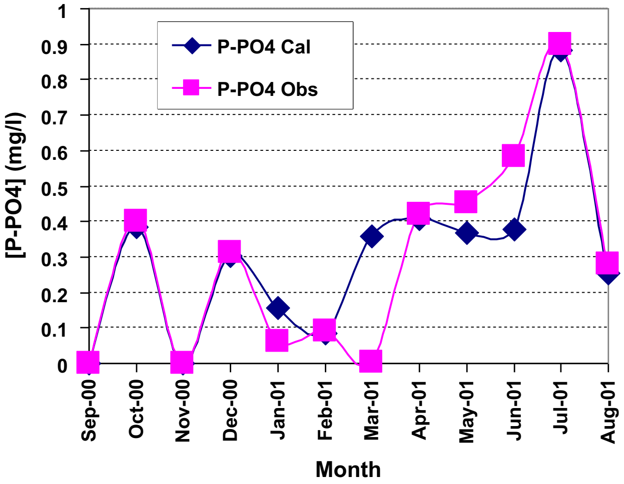

Fig. 13. Seasonal evolution of orthophosphate concentrations observed and simulated for the Beja River water during the year 2000–2001.

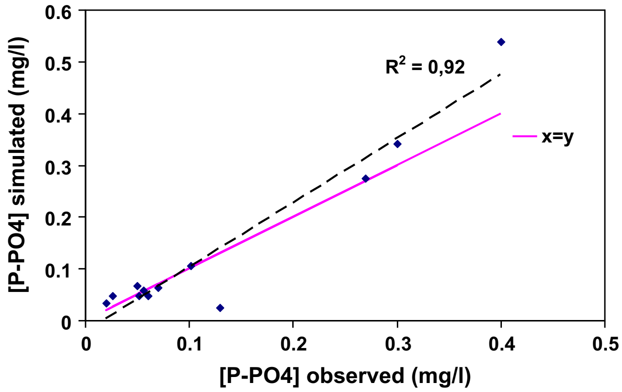

Fig. 14. Comparing the monthly content of orthophosphates simulated and observed in the Beja River waters during the wet year 1995–1996.

3.2.2. Orthophosphate concentration

The research suggests high phosphorus absorption, later encourages the sedimentation of this element and its strong reactivity (Figs. 7 and 8).

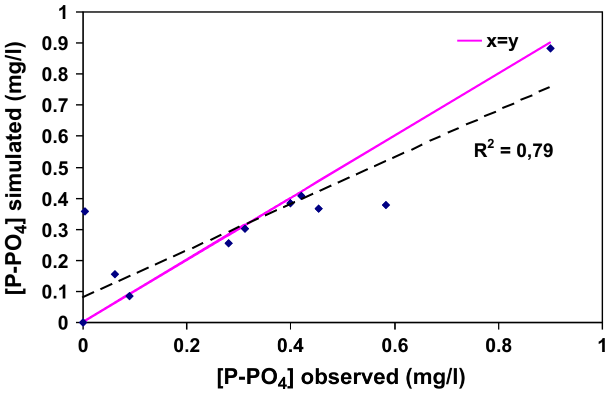

Fig. 15. Comparing the monthly content of orthophosphates simulated and observed in the Beja River waters during the dry year 2000–2001.

The estimation of the orthophosphate concentrations gives an excellent precision level, as shown in Table 6 and Figs. 12–15.

The model affirmed that deep ploughing encouraged phosphorus leaching in a particulate form through a lateral flow, hence, the low sensibility of the model to the coefficient relating to percolation. To resolve these problems, we should opt for medium tillage and apply plant compost, while enriching the soil with organic matter and nutrients. This has the effect of various monitoring hydrodynamic parameters involved in phosphorus leaching, such as, hydraulic permeability and cation exchange capacity.

4. Conclusion and recommendations

The SWAT model has been tested at the Beja watershed, which is one of the tributaries of the Sidi Salem Dam. This study shows that the SWAT model can be adapted to the Beja area context, taking into account the temporal variability of certain hydrodynamic, physicochemical and biological parameters. This adaptation was necessary due to the pedological, climatic and agricultural practice related to the study area. Despite the underestimation of the nutrient and water balance model during the summer, SWAT allows a better comprehension of the hydrological balance, while considering the physicochemical process. It offers good prevision opportunities for sediment and pollutant transport, and provides information on preserving for decision-making of water quality resources.

This study has been conducted to find out the adaptation of the SWAT model to different areas in the world. It has been possible to adapt the model to the pedoclimatic theme of the watershed of the Beja River, to estimate the water sheet and the water quality. The approach was realised in two steps, first, to find out all the parameters of adjustment necessary and then to improve on them for a dry year and a wet one. We noticed a clear improvement of the precision indicators of stimulation according to the suggested approach in this study. The study demonstrated that the SWAT model could be adapted to the Beja area context, taking into account the suggested approach. Moreover, it allowed estimation of the pollution, conducted in a different chemical manner, for nitrogen and phosphorus. The result showed that the degree of pollution was worrying.

It is recommended to:

- Carry on improving the model of the Beja River watershed in order to come closer to the real conditions, to improve the model predictions to the best, mainly in the summer season.
- Validate the established adjustment parameter values along other humid and dry years for the same watershed.
- Extrapolate the proposed work approach to watersheds that have had weak measurements, have similar characteristics and are located around the Sidi Salem Dam.
- Make the decision-makers aware of the necessity to implement an observatory for checking the water quality, based on the SWAT model, at the Sidi Salem Dam.
- Popularising and encouraging the farmers to use the right practical agricultural work methods in order to protect the environment.

List of symbols

ALPHA-BF — base flow recession coefficient
DEM — digital elevation model
GW-REVAP — evaporation coefficient
HRU — hydrologic response Unit
NSE — Nash–Sutcliffe coefficient
ODNO — Authority for the development of the Northwest—Ministry of regional development and planning
PBIAS — percent bias
R^2 — determination coefficient
RCHRG-DP — Aquifer percolation coefficient
RSR — Root mean squared error RMSE—observations standard deviation ratio
SWAT — Soil and water assessment tool
USDA — American agricultural research services
$(y_{i-\text{observed}})$ — observed data
$(y_{i-\text{simulated}})$ — simulated data
$\bar{y}_{\text{observed}}$ — average of the observed data

References

[1] J.G. Arnold, R. Srinivasan, R.S. Muttiah, J.R. Williams, Large-area hydrologic modelling and assessment: Part I. Model development, J. Am. Water Resour. Assoc. 34 (1) (1998) 73–89.

[2] E. Levesque, Evaluation de la performance hydrologique du modèle SWAT pour de petits bassins versants agricoles du Québec [Evaluation of the hydrological performance of the SWAT model for small agricultural watersheds in Quebec], Thèse, Faculté des études supérieures de l'Université Laval, 2008, 177.

[3] F. Laurent, D. Ruelland, Assessing impacts of alternative land use and agricultural practices on nitrate pollution at the catchment scale, J. Hydrol. 409 (2011) 440–450.

[4] L. Thi Phuong, Q. Billen, G. Garnier, J. Théry, S. Ruelland, D. Nguyen, X.A. Chau, Nutrient (N, P, Si) transfers in the subtropical red river system (China and Vietnam): Modelling and budget of nutrient sources and sinks, Asian J. Earth Sci. 37 (2010) 259–274.

[5] ODNO, Governorate of Beja Key Figures, Authority for the Development of the Northwest–Ministry of Regional Development and Planning, Report, 2011, 130.

[6] D.N. Moriasi, J.G. Arnold, M.W. Van Liew, R.L. Bingner, R.D. Harmel, T.L. Veith, Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, 2007 ASABE American Society of Agricultural and Biological Engineers ISSN 0001−2351, 50(3) (2007) 885−900.

[7] C. Santhi, J.G. Arnold, J.R. Williams, W.A. Dugas, R. Srinivasan, L.M. Hauck, Validation of the SWAT model on a large river basin with point and non point sources, J. Am. Water Resour. Assoc. 37(5) (2001) 1169–1188.

[8] D.R. Legates, G.J. McCabe, Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation, Water Resour. Res. 35(1) (1999) 233–241.