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Study of the Hydrological Functioning of the Béjà river watershed, in the Northwest of Tunisia, using the SWAT model

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Abstract

Water pollution from agricultural and human activities has become a hot issue that needs to be addressed. Its qualitative and quantitative evaluation has been well demonstrated by the SWAT model. The application of this model requires prior study of the hydrological catchment of interest and the calibration of a great number of intrinsic factors particular to the area under study. This model was mainly tested on several watersheds in the Nordic countries, including Canada and France. Its adaptation to the Mediterranean context is seldom recognized. In the case of Tunisia, the absence of a long series of continuous measurement data and hydrodynamic soil impede further application of the SWAT model. This work enabled the assessment of the performance of the hydrologic functions of the SWAT model and to adapt it to suit the context of a watershed characterized by the subhumid heavy soils of northern Tunisia, and to better understand the hydrological functioning of this basin. The need to initialize the model at least one month in advance of the desired time period was revealed. In addition, a calibration approach of the various parameters has been proposed by considering in particular the rainfall distribution during the period. In the calibration approach, the sensitivity analysis model showed the importance of some hydrodynamic parameters including the hydraulic conductivity at saturation, bulk density and cation exchange capacity, as well as the interactions of various phenomena related to the hydrological balance of the water at the final outlet, namely runoff, percolation and evapotranspiration.

Keywords: Ks: Hydraulic conductivity at the saturation point of the soil, CH-N: Manning roughness coefficient, Da: bulk density, CEC: cation exchange capacity, SWAT: Soil Water Assessment Tool.

Introduction

Integrated watershed management necessitates conservation of the water quality following pollution resulting from human activities, the most predominant being soil fertilization. The SWAT model has been developed to provide a quantitative and qualitative evaluation of the water features. This approach involves all the processes and activities operating in the watershed. SWAT (Soil Water Assessment Tool) has been shown to be effective in this regard. According to the comparative study of some hydrological models done by Borah and Bera (2003)[1], this model appears to hold out promise for use in the predominantly agricultural watersheds given its ability to model and relate to the main weather, soil, hydrological and geochemical processes.

However, several studies involving the SWAT model have been conducted in areas with rainy and snowy features. Any study of the water quality in a watershed inevitably necessitated a fair assessment of the water balance. Application of the SWAT model was evaluated by different calibration approaches and yielded a generally satisfactory daily performance, except during the summer. According to Michael W. et al., (2007)[2], the application of SWAT provides good model winter estimates but overestimates the summer flows. Despite the successes in the employment of the SWAT, simpler methodologies are required for greater consistency, standardization and high reproducibility. In fact, the full implementation of the model in the regional context of the study area revealed a clear differentiation of the hydrodynamic behavior of the soils in the watershed regardless of the time period adopted. The objective of this work is to propose a methodology for adapting the SWAT model in a subhumid watershed characterized by the heavy soils in the north of Tunisia, against the backdrop of insufficient data describing the hydrodynamic properties of the soil. In fact, the organization of a field measurement campaign over an extended period cannot normally be considered in a majority of the developing countries due to the significant financial resources involved.

This methodology begins with a sensitivity study, enabling clear highlighting of the roles of the various model coefficients in estimating the water balance, followed by a proposal for a seasonal calibration approach to accurately simulate the flows.

Materials and Methods

Data and software work: The work presented in this document necessitated the use of the Digital Elevation Model (DEM - Satellite Mission STRM 2000 resolution 90 m), the river system map on a scale of 1/25000, the soil map on a scale of 1/50000, the land use map on a scale of 1/25000 and the climatic Data Series (average of 17 years: 1989-2006).

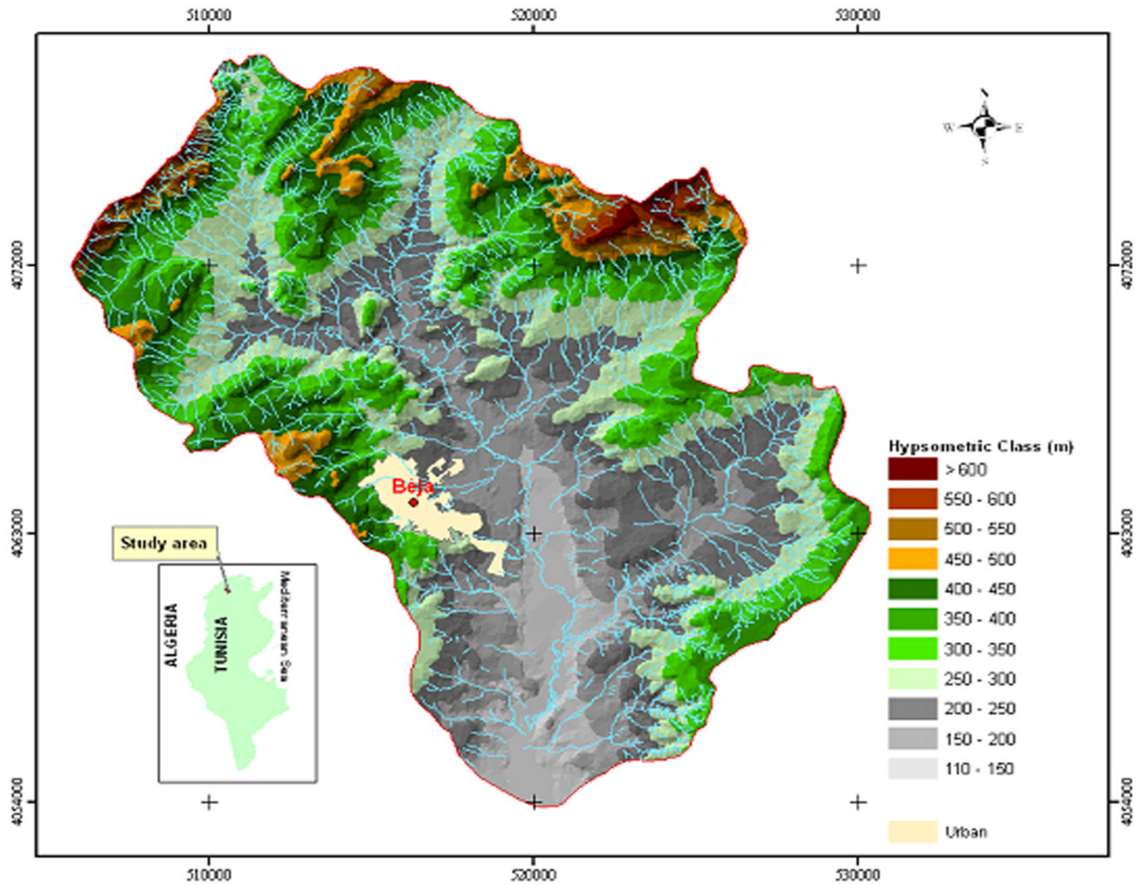

Figure-1
Location and relief maps of the study area

The data observed at our disposal, cover the years 1995-1996 and from January 1999 to October 2003, and include: i. Meteorological data: air temperature and precipitation, ii. Monthly water balance data, iii. Agricultural practices

The 2000 version of the SWAT Arc View extension running 3.2 (geographic information system software) was used.

Characteristics of the study area: The Béjà river watershed covering an area of 343.4 km² is located in the north of Tunisia 100 km from Tunis, and is characterized by the predominance of high relief.

The soil cover is dominated by clayey soil such as vertisols covering 66% of the total watershed area.

The Béjà river watershed characterized by the Mediterranean climate was categorized under the bioclimatic subhumid temperate winter[3]. The average air temperature ranges from 4.7° C in winter (December, January and February) to 36.4°C in summer (June, July and August). The average rainfall was calculated to be around 69mm / year between 1990 and 2006. However, rainfall was highly variable from month to month, from season to season and from year to year. The winter season was marked by heavy rainfall (about 44% of the annual precipitation), while spring and fall experienced average rainfall. The summer season was marked, in general, by low rainfall (about 7% of the annual rainfall).

The prevailing winds in the study area were from the NW and SE at an average speed of about 9.6 km/h.

The watershed predominantly supports cereal crops (81%), imposing a particular growth cycle covering a period of five months a year.

Presentation of the model: The SWAT (Soil and Water Assessment Tool) clearly reproduces the water cycle and agricultural and anthropogenic pollution. Developed by Jeff Arnold, USDA, Agriculture Research Service, in 1993[4], it is a semi-empirical physical conceptual model distributed manipulating and analyzing quantities of hydrological and agronomic data in a watershed through precipitation events, runoff, infiltration and evapotranspiration, besides others. It was designed to study and evaluate the diffuse pollution from the agricultural water sources. It is distinguished by the fact that some parameters are specialized while others are considered globally. This tool allows for finely modeling the various physicochemical processes related to the soil, vegetation and streams. It calculates the water flow, nutrients and sediments to the watershed outlet. It has been validated in many basins around the world, including the United State and Europe.

This model is coupled with a geographic information system, which allows the management of the raster and vector data and alphanumeric products. The SWAT divided the watershed into several almost homogeneous hydrological units called HRU (Hydrologic Response Unit) based on the combination of soil type, a class soil occupation and a sub-watershed. Each HRU is representative of a homogeneous agro-hydrological behavior. Flows estimated for each HRU are summed up for the entire watershed, considered and compared with the observed data. The model is continuous in time and capable of simulating long periods and the effects of the management changes. Also, it has the advantage of being able to model watersheds not having a monitoring database (lack of data flows).

The calibration of the SWAT model is made in several steps, seeking to bring closer, at the watershed outlet, the following observed and simulated balance: i. Water flows, ii. Sediment, iii. Nutrients, in their different forms (nitrogen, phosphorus, etc.)
Several files are required for the proper functioning of the model including Digital Terrain Model, pedology, climatology hydrographic system, climate data (temperature and precipitation), land use, agricultural practices, etc.

The main problem encountered in the use of the SWAT model, is the large number of variables to simulate compared with the variables observed. This enables us to sometimes introduce working hypotheses and do a lot of testing to get the best combination of the parameters.

Primary SWAT calibrated parameters
The SWAT model involves several parameters to be calibrated for the calculation of water flow at the outlet and the water quality. Although the study of the latter can influence the flow at the outlet because of the physical-chemical and biological interactions that may occur, we sought first for an approximation of the most significant parameters (Gassman and al, 2005)[5] in the case of this study (table 1). Moreover, special attention was paid to the physical quantities relating to the study area in the case of saturated hydraulic conductivity of the soil Ks, bulk density Da and water retention capacity of the soil AWC. In the absence of the field measurements, the initial values of these quantities were obtained from bibliographic references. The sensitivity study of these parameters had been made to identify the best approach to correcting these data according to the soil horizon. Horizons considered in this work are defined as follows: H1 (0 - 20 cm), H2 (20 - 40cm), H3 (40 - 80cm), H4 (80 - 150cm).

Methodology

The first phase of work is to delineate the river watershed considered and to introduce all the basic data required for the SWAT simulation. Therefore, we selected the climatic data (rainfall, evaporation) and hydrodynamic and pedology characteristics, and established a digital terrain model, a pedology and land use map. For the first step, we sought to maintain a concordance between the simulated and observed flow at the final outlet by varying the different calibration parameters and analyzing the sensitivity of these parameters on the result from January 1999 to October 2003. The calibration parameters were collected using the bibliographical references of Bel Hassine[6] and Jajarmizadeh (2013)[7] and to select those revealing similarities with the characteristics of the study area.

The simulation was performed according to a daily time-scale, while the water balance was calculated monthly and compared with the monthly water volume observed. To refine the choice of the calibration parameters, we performed simulations based on the calibration parameters found in the preceding stage seeking to refine a sensitivity study for two agricultural years, viz., wet 1995-1996 and dry 2000-2001. Agricultural practices were introduced in the SWAT using data provided by the farmers and developed by Ben Hassine et al. (2005)[8].

Table-1
Primary calibration parameters

Parameter	Description	Unit	Calibrated Values	Variation interval of the calibration parameters
ALPHA_BF	Base flow alpha factor	1/day	0.048	0 - 1
CH_K	Channel Saturated Hydraulic Conductivity	mm/h	0	0 - 150
CN	SCS Curve Number		0.014	0. 01 – 0.5
CH_N	Channel Manning's N		0.014	0. 01 – 0.5
EPCO	Plant uptake compensation *factor*		1	0 - 1
ESCO	Soil Evaporation Compensation *factor*		0.95	0 - 1
GW_DELAY	Groundwater delay time	Days	31	0 - 50
GW_REVAP	Groundwater "Revap" *coefficient*		0.02	0.02 - 2
RCHRG_DP	Deep aquifer percolation fraction		0.05	0 - 1
SURLAG	Surface lag	Days	4	0 - 10

The dominance of grain farming in the study area facilitates the consideration of the same parameters of cultural practices for all the simulation years. The water and nutrient needs of the crops were estimated by the SWAT from its database.

Parameterization of SWAT model

The saturated hydraulic conductivity (mm / h) was estimated from the *Cosby's* pedotransfer function[9]:

$$K_S = 25.10^{(-0.6+0.126.Li-0.0064.Ar)} \quad (1)$$

The Ks values obtained by using this formula were used to begin the simulation process. They were slightly corrected for simulation purposes, from the sensitivity study.

The model sensitivity on the past coefficients relating to the principal phenomena that come into play was evaluated by the formula developed by Storm et al.[10]

$$S_r = \frac{(O - O_b).P_b}{(P - P_b).O_b} \quad (2)$$

where Sr : relative sensitivity, O : output variable considered, P : parameter considered. The subscription 'b' describes the variable or the reference parameter considered. The scale of the sensitivity considered (Storm et al., 1986) is given in table 2.

The sensitivity study reduces the number of parameters tested to maximize the model efficiency.

Validation considers not only the statistical Efficiency Index of Nash[7] but the difference between the observed and calculated water balance as well and thus the parameter values were selected.

Table-2
Scale of the Relative Sensitivity

Scale	Relative Sensitivity Sr
Not sensitive	Sr < |0,01|
Low sensitivity	|0,01| ≤ Sr < |0,1|
Moderate sensitivity	|0,1| ≤ Sr < |1|
Sensitive	|1| ≤ Sr < |2|
High sensitivity	Sr ≥ |2|

The consistency of the observed and simulated data was measured using the Nash coefficient.

$$Nash = 1 - \frac{\sum_{1}^{N}(y_{i\_observé} - y_{simulé})^2}{\sum_{1}^{N}(y_{i\_observé} - \overline{y}_{observé})^2} \quad (3)$$

The index ranges from (-∞) to 1. The higher index value was close to unity, therefore, the correlation between the observed and simulated data was considered strong.

Result and Discussion

Calibrated period 1999-2003: The best result obtained from the calibration of several SWAT tests made from January 1999 to October 2003, considering the same hydrodynamic, physico-chemical and biological parameters along the simulation period corresponds to the Nash coefficient equal to 0.37.

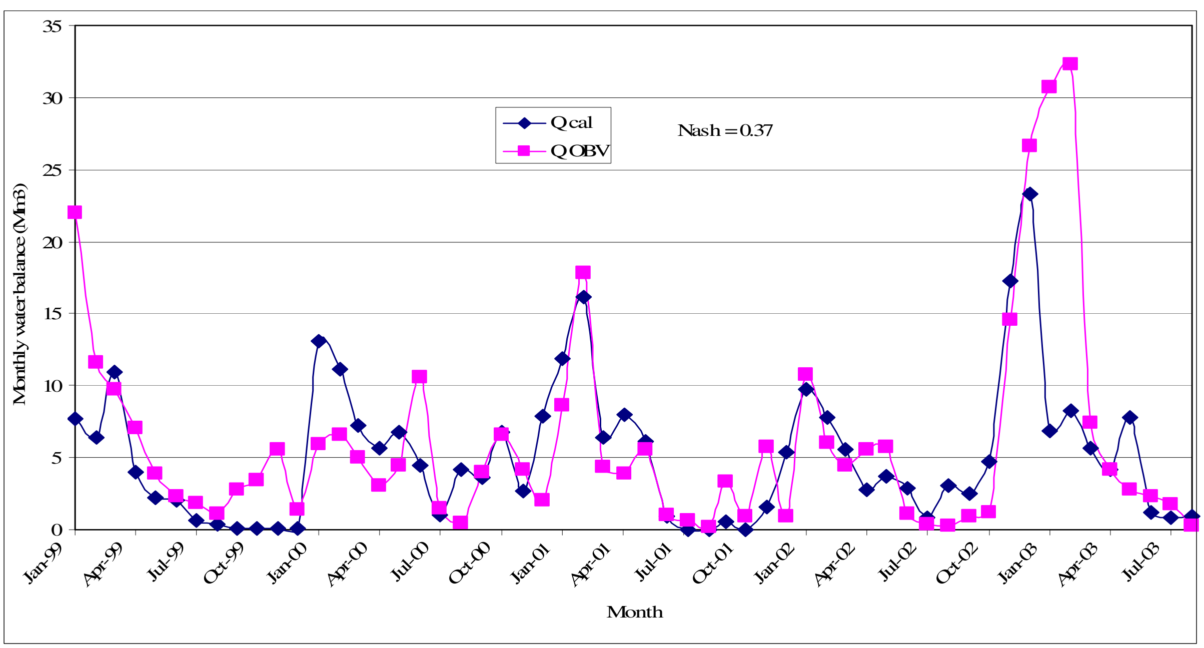

Figure-2

This result presented in figure 2 within the period was considered to reveal the occurrence of significant time lags during certain farming years as seen in the Nash number presented in the table 3. In addition, it is evident that within the same year, a monthly plus or minus deviations occur, necessarily affecting the Nash value calculated for this year. Moreover, the large gap between the observed and simulated flows in January '99 proves that the SWAT model needs to be initialized at least one month in advance of the desired time period. The best result is that of the 2000/2001 agricultural year.

Table-3
Nash number values and the extreme gap between the calculated and observed flows according to the agricultural year

Agricultural year	Nash number	Minimum delay (Mm3)	Maximum delay (Mm3)
1999/2000	-1.24	-6.05	7.19
2000/2001	0.71	-1.69	5.91
2001/2002	0.34	-4.13	4.46
2002/2003	0.28	-24.06	4.95

To reduce the relatively important gaps between the observed and calculated flows, we proposed to refine the simulation approach by seeking a Nash number closest to 1. This was performed by separating a dry year and wet year, and on the other hand, considering the variable calibration parameters from one season to another within the same simulation year. The parameters used in the simulation through the 1999-2003 period, were to initialize the model for the agricultural year selected. We considered the agricultural year to begin from September 1 to August 31 of the following year.

The division approach of the agricultural year into several periods can be justified by the strong contrast in the climatic and soil characteristics present in the study area. We felt it more appropriate to vary the hydrodynamic and physicochemical parameters according to the period considered during the same year, and the temperature and rainfall evolution.

Sensitivity analysis of the important model parameters
The Model sensitivity was tested *vis-à-vis* the soil parameters, evaporation, water storage and infiltration according to equation (2); from a reference position defined by the values shown in tables 4 (*a* and *b*).

Table-4a
Reference values of the predominant soil hydrodynamic parameters

Parameter	Horizon 1	Horizon 2	Horizon 3	Horizon 4
Ks (mm/hour)	7.55	11.15	12.59	13.51
Da (g/cm3)	1.13	1.23	1.27	1.24
AWC	0.19	0.17	0.19	0.18

Table-4b
Reference values of the predominant watershed hydrodynamic parameters

Parameter	Values
GW-DELAY (jours)	31
ALPHA-BF	1
GW-REVAP	0.0225
RCHRG-DP	0.3
EPCO	0.1
ESCO	0.1
SURLAG	15
CH-K	5
CN	0.12
CH-N	0.48

Figure-3 shows the model sensitivity *vis-à-vis* the various parameters listed in tables 4a and 4b. It shows that the flow at the outlet is *sensitive to very sensitive* especially in the summer. The improvement in the Nash number necessarily leads to the conclusion that these parameters cannot be considered constant throughout the study year, but variable allowances must be included depending on the rainy phases of this year. The sensitivity analysis also reveals the direction of change in the calibration parameters to improve the Nash number and subsequently improve the annual water balance.

The wet year simulations: The precipitation and air temperature distribution, as well as the dominance of vertisols in the study area, induce a spatio-temporal evolution of the soil hydrodynamic parameters. This observation requires seasonal calibration (Figure 5) to better reflect these evolutions and evaluate the water balance more precisely.

Thus, during the wet year 1995-1996, five periodic scenarios are considered for calibration; including two assigned to the autumn period and the other three related to the winter, spring and summer seasons, in the following format:

Table-5
Calibration coefficients of the wet year 1995-1996

Calibration Coefficient	S1	S2	S3	S4	S5
ALPHA-BF	0.3	0.5	0.7	0.9	0.04
GW-REVAP	0.08	0.12	0.15	0.18	0.02
GW-DELAY	40	30	24	10	60
RCHRG-DP	0.3	0.3	0.1	0.9	0.05
SURLAG	20	15	5	10	23
EPCO	0.3	0.2	0	0.75	0.6
ESCO	0.55	0.42	0	0.8	0.9
CN	0.014	0.48	0.14	0.14	0.014
CH-N	0.014	0.12	0.014	0.014	0.014

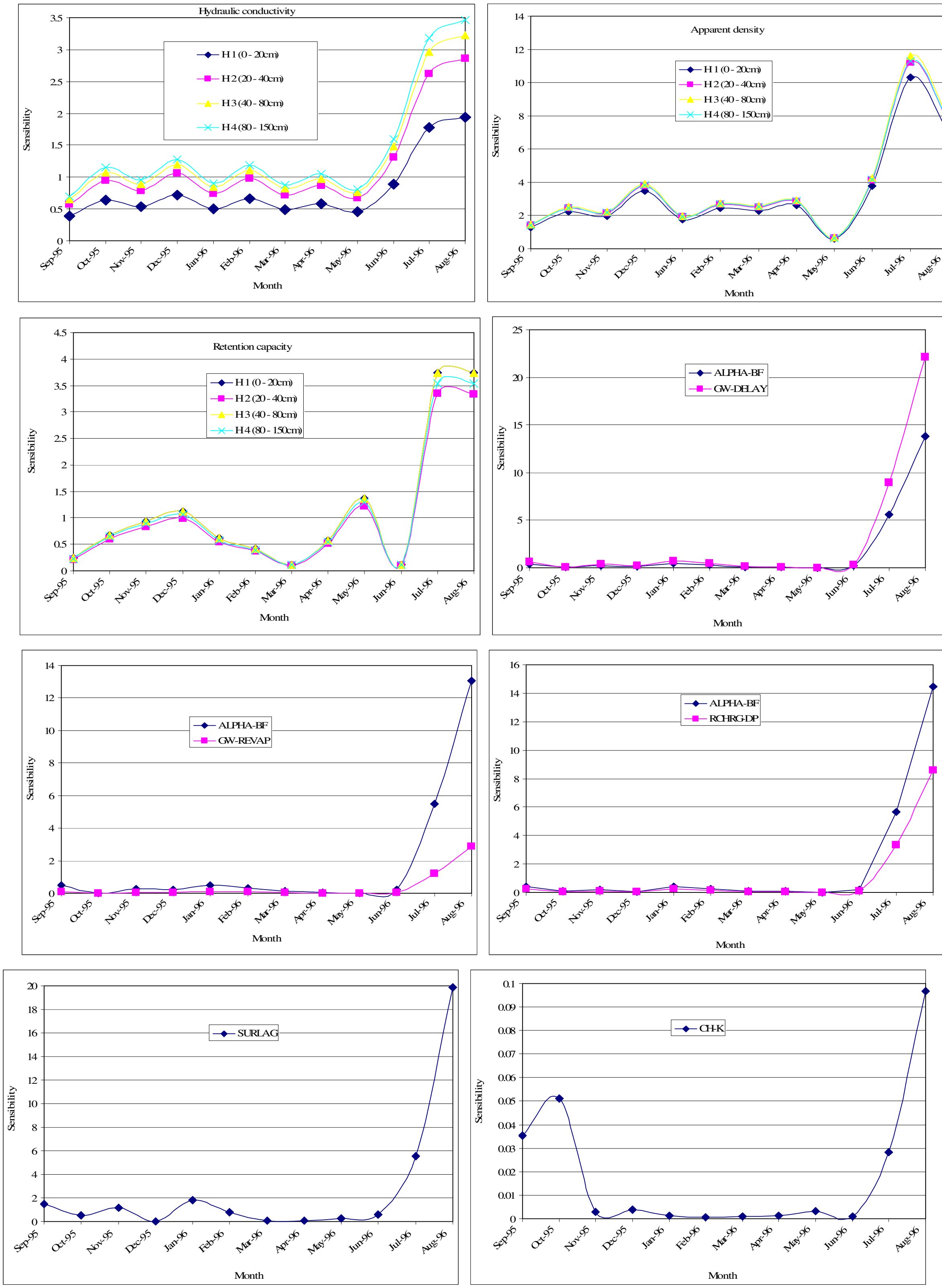

Figure-3a
Results of the Model sensitivity analysis *vis-à-vis* the predominant parameters

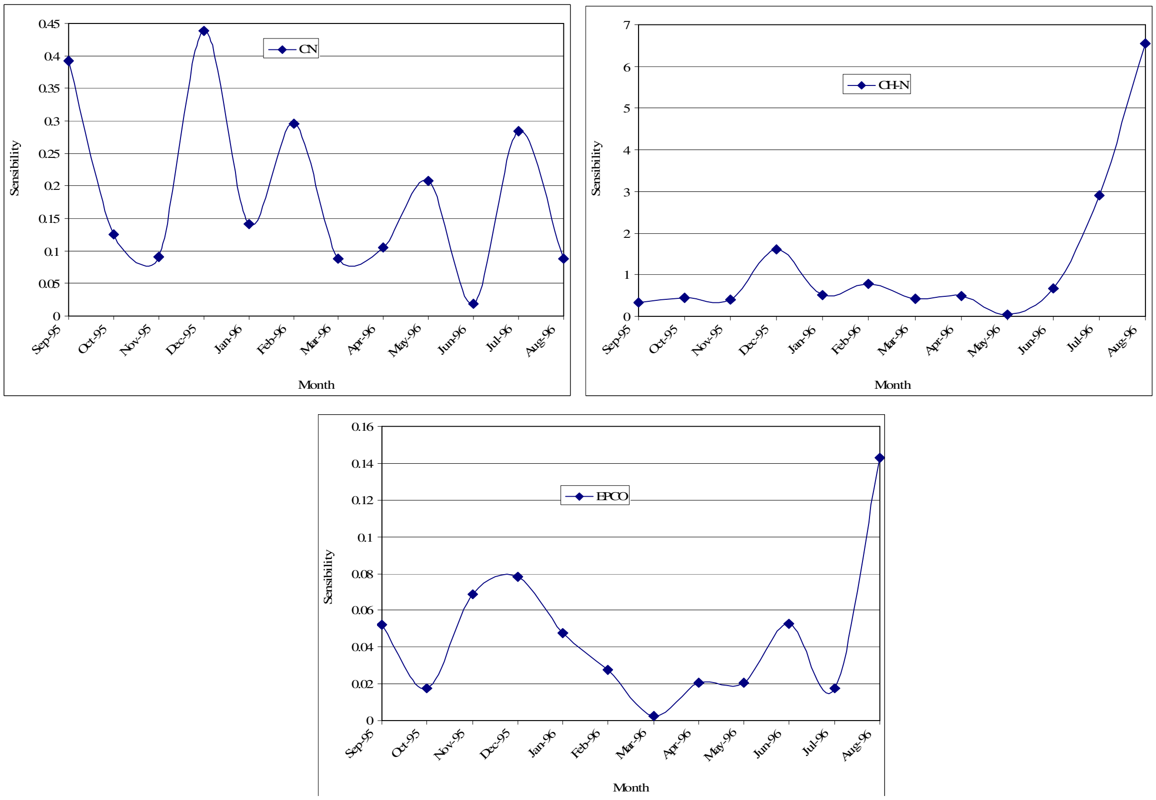

Figure-3b
Results of the Model sensitivity analysis *vis-à-vis* the dominant parameters

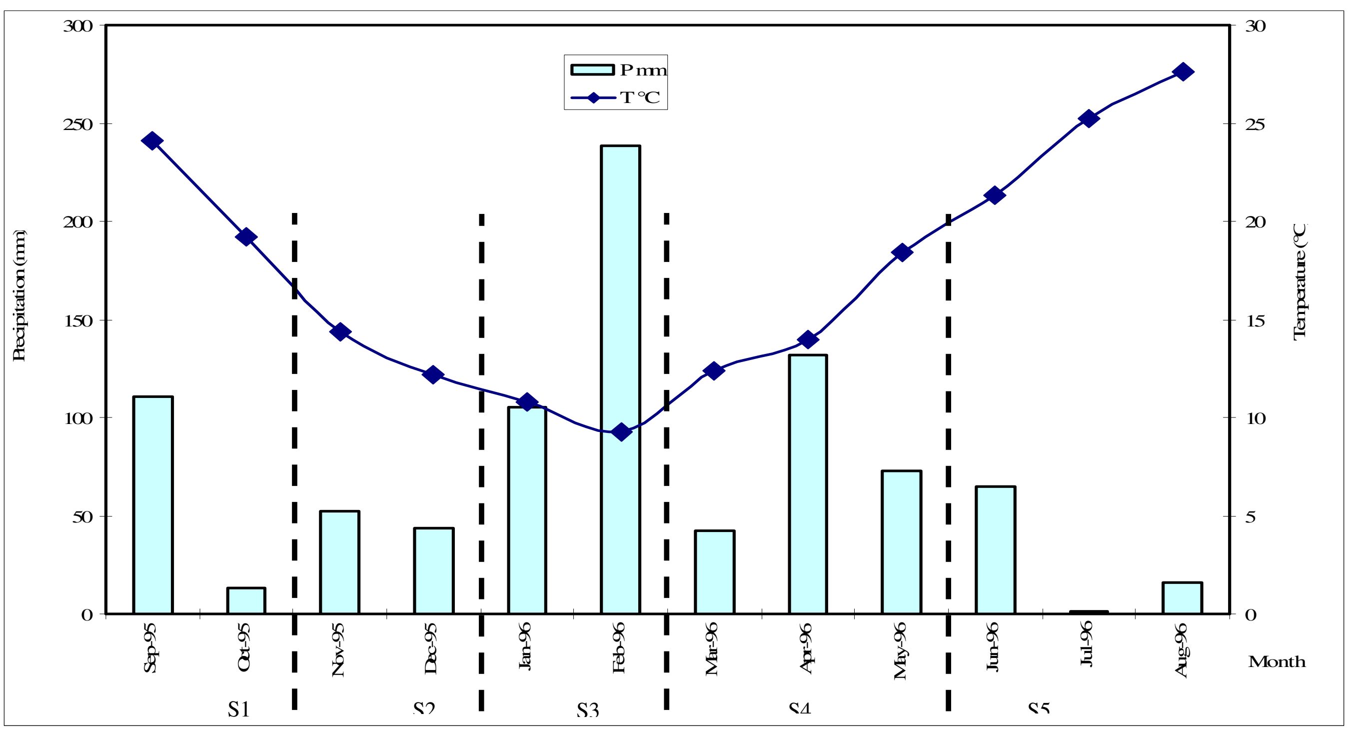

Figure-4
Seasonal division of the wet year

The autumn season that follows the dry phase is divided into two phases: i. The first hot and rainy (S1) period is characterized by the resumption of rainfall which favors soil humidification and consequently groundwater percolation into the underlying aquifer. This phenomenon is limited by evaporation and evapotranspiration. Similarly, the water table contributions will be limited. ii A second phase, cold and markedly drier (S2), is defined by the remobilization and leaching of soil particles tucked away in the cracks, thus inducing strong soil reactivity and percolation towards the deeper aquifers. This phenomenon enables the groundwater to become recharged and encourages greater hypodermic flow contributions for the final outlet. This leaching is affected in part by the fairly significant phenomenon of evaporation in the most superficial horizons of the bare soil. This period is characterized by high water mobility and the parallel strong dynamic of these waters within the watershed; hence, the need to maximize the Curve Number (CN) referring to the sub-basin and the main stream.

The winter season (S3) is characterized by a greater surface runoff following the strong presence of swelling clays causing water logging. Despite this process, the *percolating water is* not negligible.

During spring (S4), characterized by grow-strong crops and an abundance of rainfall events and percolation of the intercepted water are promoted. Thus, the groundwater recharge becomes faster; therefore, the time of transfer of the water from the surface to the aquifer is much less. However, groundwater contributions to the main stream are significantly more pronounced, later in the dry season.

These processes will be limited given the plants' water requirements that would exhaust the fraction stored in the interstices of the surface horizons and induce the remobilization of water from the shallow aquifer. This fraction will be used up by the plants and lost by evapotranspiration and evaporation of the most superficial layer where the maximum coefficients for these two phenomena ie EPCO and ESCO are recorded.

The summer season (S5) is more or less dry. In light of the study year it is listed among the wettest. During this less rainy season period, the water percolation into the deep aquifer is limited. Therefore, the aquifer recharge is slightly marked. This is a direct consequence of greater evaporation from the soil because the watershed is mostly dominated by field crops whose harvesting must be done at the beginning of the summer. During this period, the surface runoff is limited; hence, the curve number on the watershed and the main stream is fixed to its the minimum.

Calibrations performed with reference to the scenarios mentioned above were analyzed and gave the following seasonal fluctuations before and after correction (Figure 5):

Comparison of the observed and simulated flows shows a very small gap with the exception of June, characterized by scarce rainfall events and important contributions of the hypodermic flow.

Overall, the seasonal approach is developed, specified by fixing the hydrodynamic parameters and calibration factors specific for each phase, allowing the reproduction, as closely as possible, of all the hydrological processes within the entire watershed during the period under study. This is confirmed by the value of Nash coefficient of 0.83.

Simulation during the dry year 2000 – 2001: The frequency of rainfall events is much less marked than in the wet year. Thus, compared with the previous period (‘95-‘96), the soil hydrodynamics is primary affected by the change in temperature. Therefore, the low humidification and water-logging would promote the transfer of water to the lower horizons. This is reflected by the measured and calculated flows at the final outlet during the winter and spring seasons.

Based on this, the simulations of the dry year will be represented by four scenarios as shown in table 6.

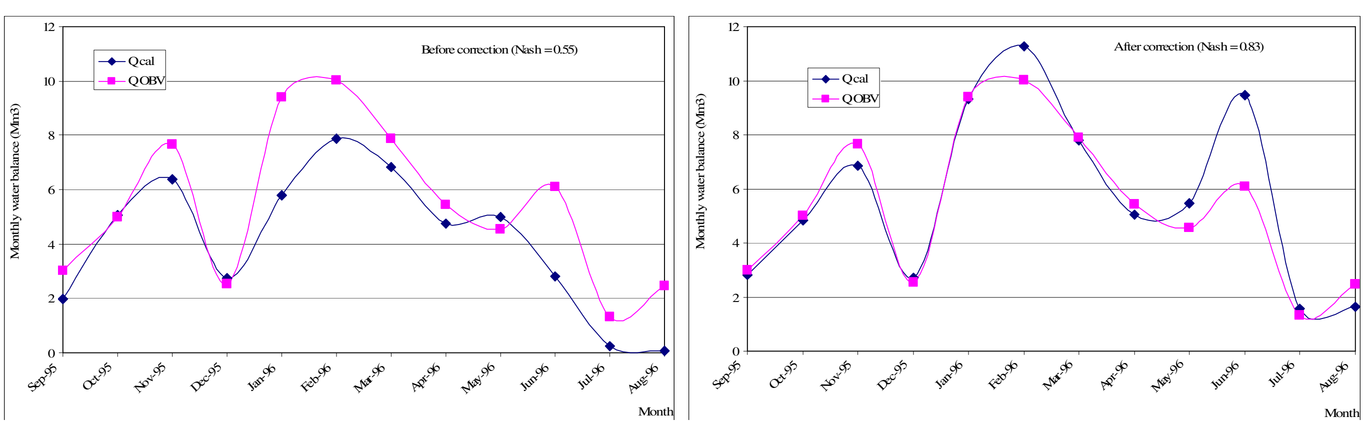

Figure-5
Variation of observed and simulated flow of the Béjà River in the year 95/96

Table-6
Calibration coefficients of the dry year 2000-2001

Calibration Coefficient	**S'1**	**S'2**	**S'3**	**S'4**
ALPHA-BF	0.9	0.9	0.9	0.9
GW-REVAP	0.06	0.1	0.18	0.02
GW-DELAY	30	14	10	40
RCHRG-DP	0.3	0.5	0. 1	0.05
SURLAG	20	20	24	24
EPCO	0.45	0	0.9	0.6
ESCO	0.9	0	0.8	0.9
CN	0.48	0.48	0.48	0.014
CH-N	0.014	0.3	0.48	0.014

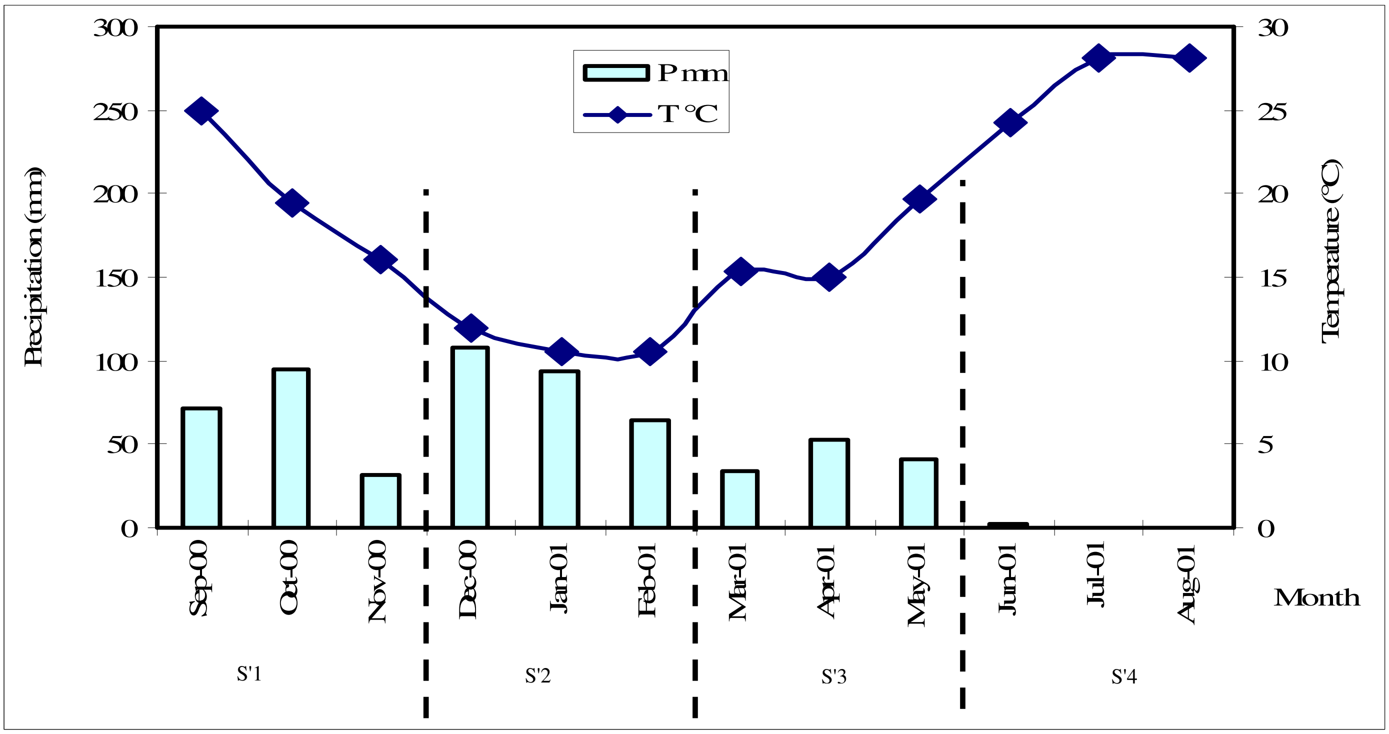

Figure-6
Seasonal division of a dry year

The scenarios were used to highlight the seasonal differentiation of the percolation phenomena, runoff and groundwater contribution. Thus, during the spring, a relatively warm and rainy period, the first rainfall intercepted reached the underlying geological formations in a considerable time.

Accordingly, the water percolation into the deep aquifer was slightly marked. This phenomenon was much more pronounced during the winter season when the water transfer occurred in a lesser time with persistent rainfall during this phase. Therefore, the hypodermic contributions will later be able to transfer to the final outlet. These processes were evident during the spring season when there were considerable flows mainly from the base flows, despite the scarcity of rainfall events and intensified evaporation phenomenon. This is explained by the low percolation coefficients (RCHRG-DP) and re-evaporation (GW-REVAP) of the shallow aquifer. Furthermore, the summer includes specificities, well considered by the model and well supported by the choice of the calibration coefficients. During this extremely dry period, the transfer of the basic water flow is promoted and highlighted by the model to the final disposal, despite the absence of rainfall events. This is affirmed by the low values of the re-evaporation coefficients (GW-REVAP) and percolation (RCHRG-DP), and the maximization of the water transfer coefficient from the deep water tables (ALPHA-BF).

This calibration process leads to simulation results (figure 7) where the calculated flow is approximated as close as possible to those observed. This is affirmed by the Nash coefficient of about 0.83, despite some differences noted during the winter and spring periods when the contributions are most important at the final outlet.

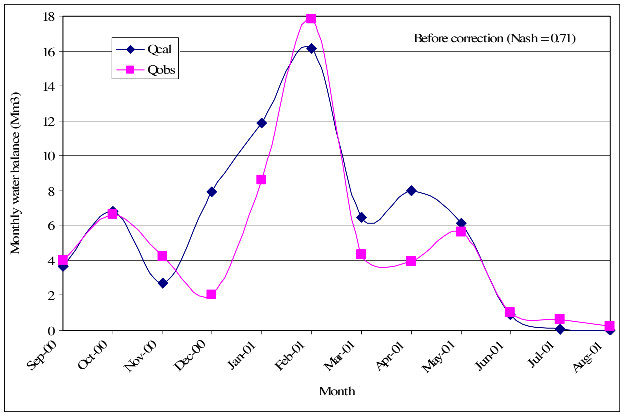

Figure-7
Variations observed and simulated for the Béjà flow in the year 2000/2001

Conclusion

This work evaluated the performance of the hydrological functions of the agro-hydrological SWAT model and attempted to adapt them to the watershed subhumid context characterized by heavy soils in northern Tunisia. It was clearly evident that the model needed to be initialized at least a month in advance for the desired time period. The model sensitivity analysis showed the importance of some primary hydrodynamic parameters of the SWAT model (Ks, Da, AWC, etc.) and the interactions of the various hydrological phenomena related to water balance at the final outlet. Thus, a hypothesis was proposed in which the area under consideration exhibits a different hydrological behavior from one season to another and within the same season. Indeed, the presence of swelling clays characteristic of the Vertisols reveal a variable hydrodynamic behavior, according to the rainfall events. This characteristic has prompted us to propose the calibration approach of the SWAT model differently, within a dry or wet agricultural season within the same season. The investigation of a wet year is characterized by an abundance of rainfall events unevenly distributed from one season to another. This rainwater causes the water-logging highlighted by the presence of the swelling clays characteristic of the vertisols. Thus, the transfer of the basic water and subsurface flow is limited. In this context, the runoff prevails and, therefore, the water collected in the final outlet is mainly managed through leaching and runoff. However, simulations on the dry year are based more on the calibration of the soil hydrodynamic behavior, which promotes the percolation of water to the shallow and deep aquifers throughout the study period. Based on this, the total amount of water at the final outlet is primarily due to the interflow, and base flow; hence, the importance of the groundwater contributions to the final outlet. The SWAT model was able to reproduce the complexity of the hydrodynamic behavior of the water in the watershed under study, while having in place and fixing the curve number which could refine the water partition between the infiltration phenomena and runoff. The maximum value of this coefficient would be allocated to periods in which the contributions are quite marked in winter and spring seasons.

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