Application of SWAT to Estimate Water Balance in the Aghien Lagoon Basin, South-East of Côte D'ivoire

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Abstract: ***Management and water supply remains a major challenge for the governments in Ivory Coast, that facing demographic pressure associated with an uncontrolled urbanization, the current drinking water sources in the economical capital have become insufficient. The Ivorian government decided to exploit the Aghienlagoon thatwill be in addition to existing water resources. This research aims at evaluating the performance of the SWAT model to simulate of surface runoff in the Aghien lagoon basin. The coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE) statistics were used to evaluate the model performance. It was found that the SWAT model can be successfully applied for hydrological evaluation of the Aghien basin. Values of NSE and R^2 were greater than 0.5.The water balance analysis of the basin indicated that more than 57 % of losses in the watershed are through evapotranspiration.***

Keywords: basin; calibration; Aghien lagoon; SWAT; water balance

1. Introduction

Freshwater is the basis of all forms of life (**Yebdri et al., 2007**). It is the habitat of a part of fauna and flora and is used for drinking, agriculture, transport and industry. Yet, this vital resource is under great pressure stemming from the rapid growth population, rapid urbanization, intensification of socioeconomic activities and climate change already observed which aggravating these pressures . These pressures influence its long-term quality and availability. Today, water quality and quantity issues, including pollution, water stress, flood and drought, have become critical problems in many regions of the world (**Kundzewicz et al., 2008**) in particularity the countries of sub-Saharan Africa. In Côte d'Ivoire, population of economical capital (Abidjan) is facing problems of access to drinking water. Indeed, Abidjan aquifer, which until then has served for drinking water supply for the Abidjan population, has become insufficient in the face of rapid growth population. Currently, a deficit of 58 million m3 / year must be mobilized to meet the water needs of this population. In addition, Bonoua aquifer, which is expected to improve Abidjan's water supply, will not be able to cover the water needs of the Abidjan population according to some studies because it is under strong pressure. Currently, the water needs of populations of the autonomous district of Abidjan have increased. Ivorian government, which wants to make Côte d'Ivoire an emerging country by 2020, is considering to provide water of sufficient quality and quantity to its population. Thus, in order to fill water deficit in the Abidjan economic capital of Côte d'Ivoire, government decided to exploit the lagoon Aghien. This lagoon will therefore be added to the aquifers of Abidjan and Bonoua to cover water needs in the economical capital. But, this water resource is impacted by anthropogenic activities and eutrophication phenomena (**Yao, 2008**). In addition, the lack of integrated management and monitoring tools of this lagoon has increased its vulnerability to various anthropogenic actions. Thus, in order to provide decision-makers and managers decision-support tool for sustainable management of the lagoon Aghien, we have implemented semi-distributed hydrological model, soil and water assessment tool (SWAT) in the Aghien basin. SWAT has been successfully applied in many countries of the world such as California (USA) to evaluate the climate change impact on water resources within agriculture systems of San Joaquin watershed (**Ficklin et al., 2009**), in India to predict the water balance components on the Ken basin (**Murty et al., 2013**), in France to study the climate change impact on availability water resources in Bourgogne (**Brulebois, 2016**), and in Côte d'Ivoire SWAT model had been tested and utilized in the Buyo basin in southwest (**Koua et al., 2014**) and in the Taabo basin in center (**Anoh, 2014**) etc. Another reasons to choose this model is that SWAT integrates both hydrologic and water quality components (**Arnold et al., 1998**). This gives one an opportunity to extend the present work to water quality in future studies. The watershed of the Aghien lagoon has been the subject of several studies; however, none of them had anything to do with the development of hydrological modeling tools. This study is the first to apply a modeling tool in the lagoon Aghien watershed. In this work, emphasis was placed on the calibration, validation and application of the SWAT model on the lagoon Aghien watershed. Thus, the objective of this paper was to validate the performance of SWAT for simulate surface runoff and to estimate the water balance of the watershed under investigation.Knowledge of the water balance of the Aghien basin is essential for decision-makers because it will enable them to better manage and protect this water resource in the perspective of catchment for Abidjan city.

2. Study Area

The Aghien basin is located in the southeastern part in Côte d'Ivoire, in the north of economical capital Abidjan. It is a subwatershed of the Me River basin. The basin area of this river is 4140 km^2(**Fig 1**). The Aghien basin has a surface area of approx. 365 km^2 and lies between 3˚49' et 3˚58' W longitude and 5˚21' - 5˚28' N latitude. The main tributaries of lagoon Aghien are Me river, Djbi and Bété rivers. The average annual rainfall of the study area is about 1500 mm and average annual air temperature range from 23 to 28, 5˚C. The vegetation on the borders of the Aghien lagoon is mainly dominated by Swamp forest composed of mangroves and bamboos. This vegetation plays an important role in the stability of the lagoon environment. It acts as a buffer zone by preventing nutrients and sediments from being discharged into the Aghien lagoon and ensures wildlife habitat.

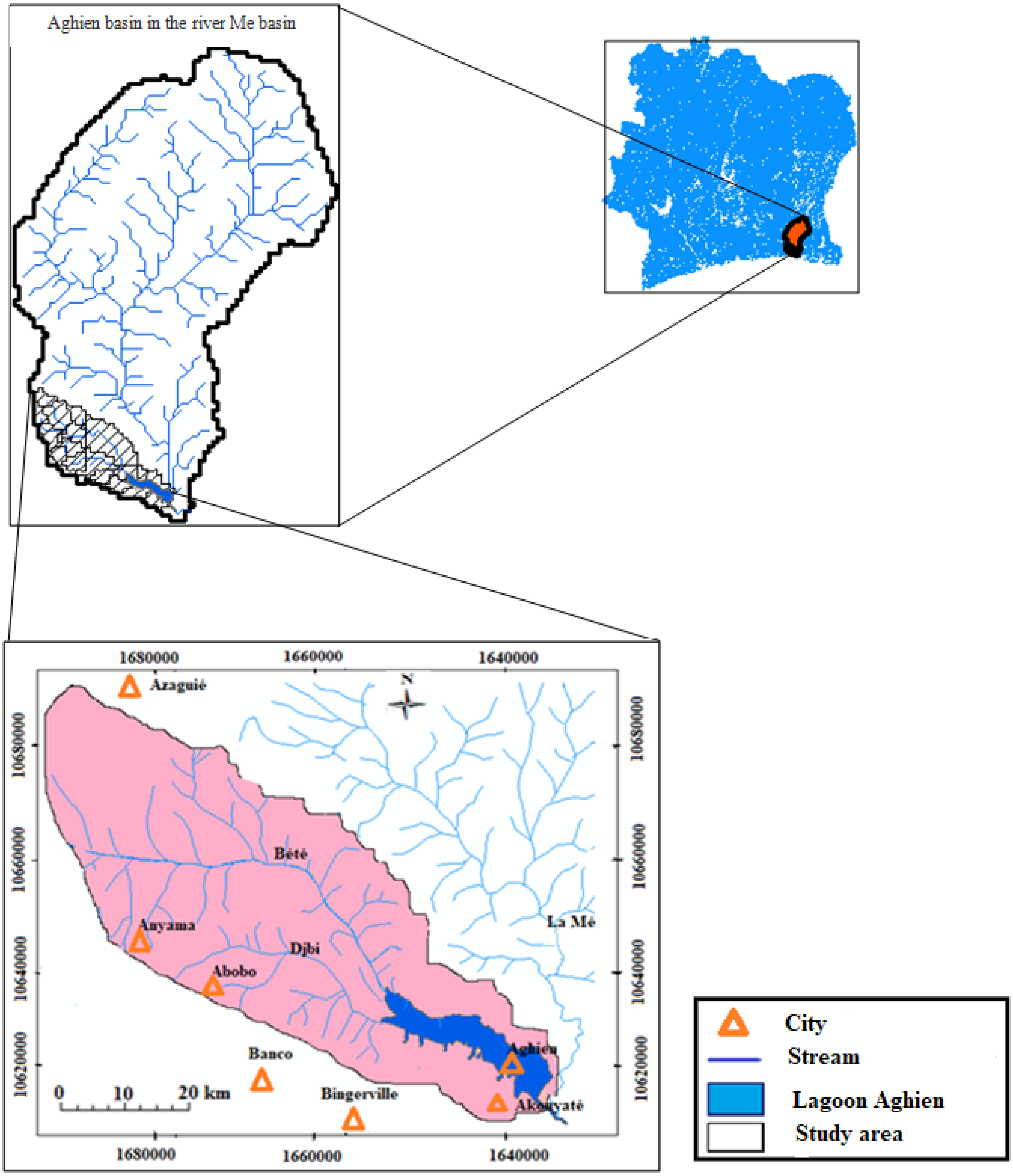

Figure 1: Location of the study area with Aghien watershed and Me

3. Material and Method

3.1. SWAT description

SWAT "Soil and Water Assessment Tool" is a semi-distributed physically-based model, developed to predict the impact of management practices on water and agricultural chemical yields on a basin scale (**Arnold et al., 1998**). It has developed by researchers at the USDA (United States Department of Agriculture) – Agricultural Research Service (**Nietsch et al., 2005; Ogden et al., 2001**). SWAT takes into account all the hydrologic cycle, represented in the watershed, so spatialized. The time step used for analysis is the day. SWAT can analyze the impacts of climate, soil, vegetation and agricultural activities on water flow. The basic space unit at SWAT calculations is the Hydrological Response Unit (HRU). .It is the result of the combination of a soil type, a land use class and a subwatershed. It is coupled with a GIS(geographic information system)such as ArcView GIS 3.2 or Arcgis 9.x. or Arcgis 10.x from ESRI. This has a double interest. Indeed, the use of a GIS makes it possible both to facilitate the pretreatment of the data to be integrated into the model and also to visualize the results of the simulation. Its implementation requires several input data: digital elevation model (DEM), soil data, weather data, land use data, agricultural practice etc. SWAT, subdivides hydrological modeling of the watershed into two phases (**Neitsch et *al.*, 2005**): the land phase and routing phase. The land phase is based on soil water balance equation for each day of simulation (1):

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

Where: SW_t is the final soil water content (mm); SWo is the initial soil water content on day *i* (mm); t is the time (days); R_{day} is amount of precipitation on day *i* (mm); Q_{surf} is the amount of surface runoff on day *i* (mm), E_a is the amount of evaporation on day *i* (mm); W_{seep} is the amount of water entering the vadose zone from the soil profile on day *i* (mm); Q_{gw} is the amount of return flow on day *i* (mm).

3.2. Data sets

3.2.1.Digital elevation model (DEM) data

The digital elevation model (DEM) was downloaded from the shuttle radar topography mission (STRM) website (http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp). It allowed to delineate the watershed, the sub-basins and to calculate slopes and to extract stream network.

3.2.2 Land use data

The land use map of the BVLA was made from an image LandSat Oli-Tirs. It dating from January 2017.Unsupervised classification under the Envi 5.1 software has resulted in the Aghien watershed land use map,(Fig 2). The value of the Kappa coefficient is 0.68. This value gives the proof that the classification carried out is close to reality in the field. Indeed, when the value of the Kappa coefficient is close to 1, the classification is considered well done and when it is close to 0 it is considered poorly done.

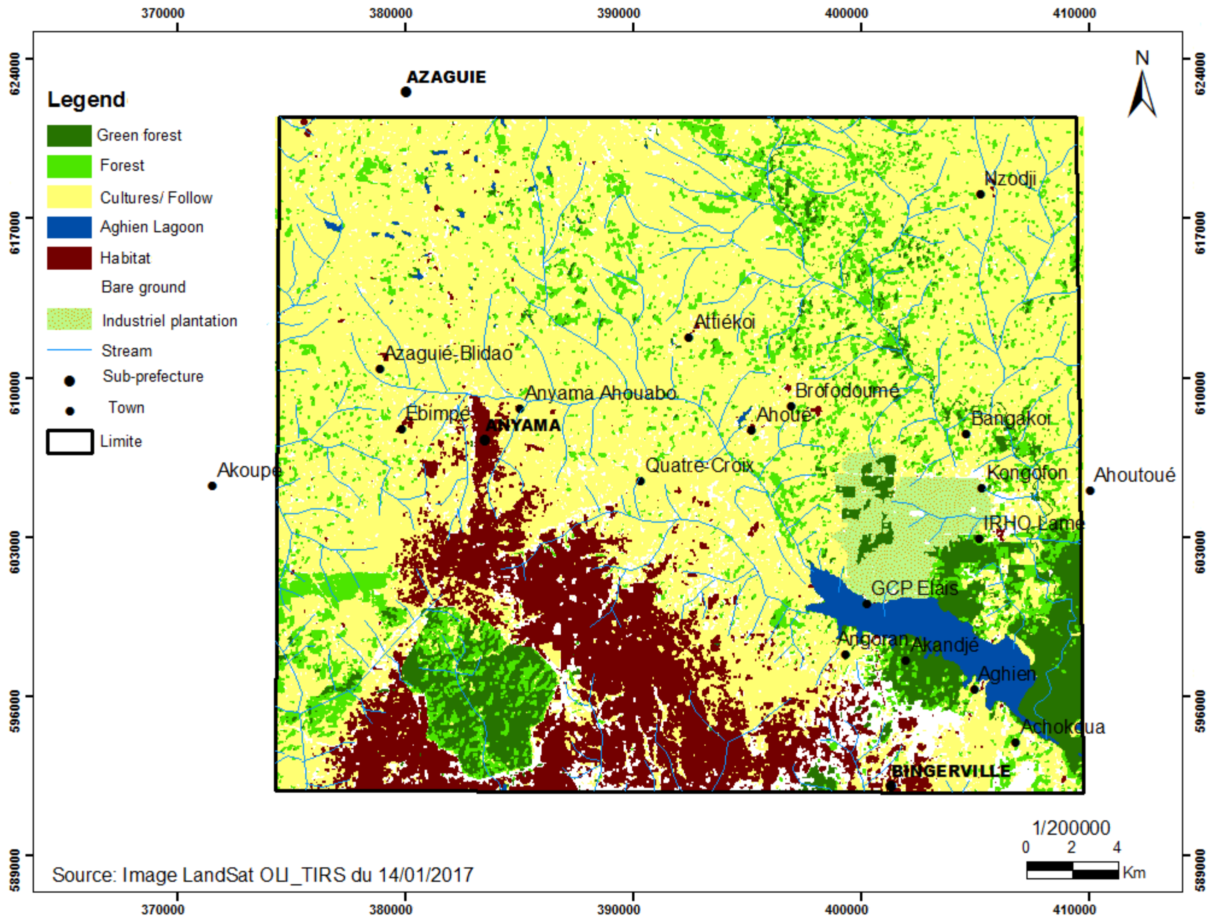

Figure 2: Land use map of lagoon Aghien basin and its surroundings

3.2.3 Soil map and soil type data

The soil map used in this article is that of FAO, established in 1995 at the scale 1/5000000 for all Africa. It takes into account 5000 soil types and includes the physicochemical properties of soils made by Reynolds et al. (1999) for all Africa. These are essential for the implementation of the SWAT model. The soil data to be integrated into SWAT are: the texture, the available water content, the hydraulic conductivity, the apparent density, the organic carbon content of the different soil layers. These data are automatically integrated into the model after having established the correspondence between the soil type on the study basin and that of the ArcSwat database in which the values of the physicochemical parameters of the soils used by SWAT are recorded.

3.2.4 Weather data

The weather data required for this paper are taken from database of SIEREM (http://www.hydrosciences.fr/sierem).These data consist of precipitation and maximum and minimum temperatures at the daily time step and cover the period from 1951 to 1998 ie 38 years. We selected the SIEREM stations near the Aghien lagoon watershed to simulate the flow on this basin, (**Fig 3**). These are the Azaguié, Banco and Bingerville stations. The area of influence of each station is shown in **Fig 4**.The different zones of influence were determined by polygon cutting of the Aghien lagoon watershed using Thiessen's improved polygonation method. This method is developed under "extension analyse tools, Proximity, create thiessen polygons of arc-gis 10.1".

3.2.5 Discharge data

The Aghien catchment taken for the study is an ungauged one, so no observed discharge data were available. We used discharge data from the river Me catchment for model calibration. These data cover the period 1957-1993 and are obtained from the SIEREM database of the UMR Hydrosciences Montpellier. It should be emphasized that they were provided to them by the Côte d'Ivoire water directorate and have been registered at the limnimetric station of "grand Alépé (**Fig 3**)". The availability of discharge data is shown in table I.

Table I: Availability discharge data (1957-1993)

		DATE			
Station	parameter	1957 à 1974	1975	1976 à 1981	1982 à 1993
Grand Alepe (ME)	discharge	available	No available	available	No available

No available: little or no data

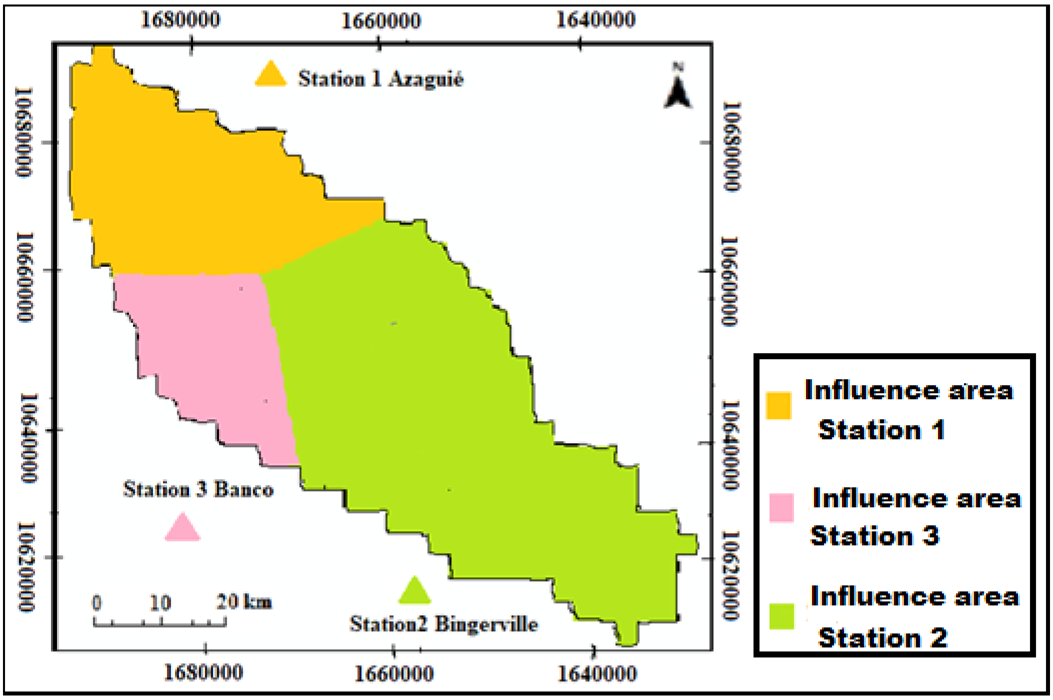

Figure 3: Location of the hydrometric station and rainfall stations

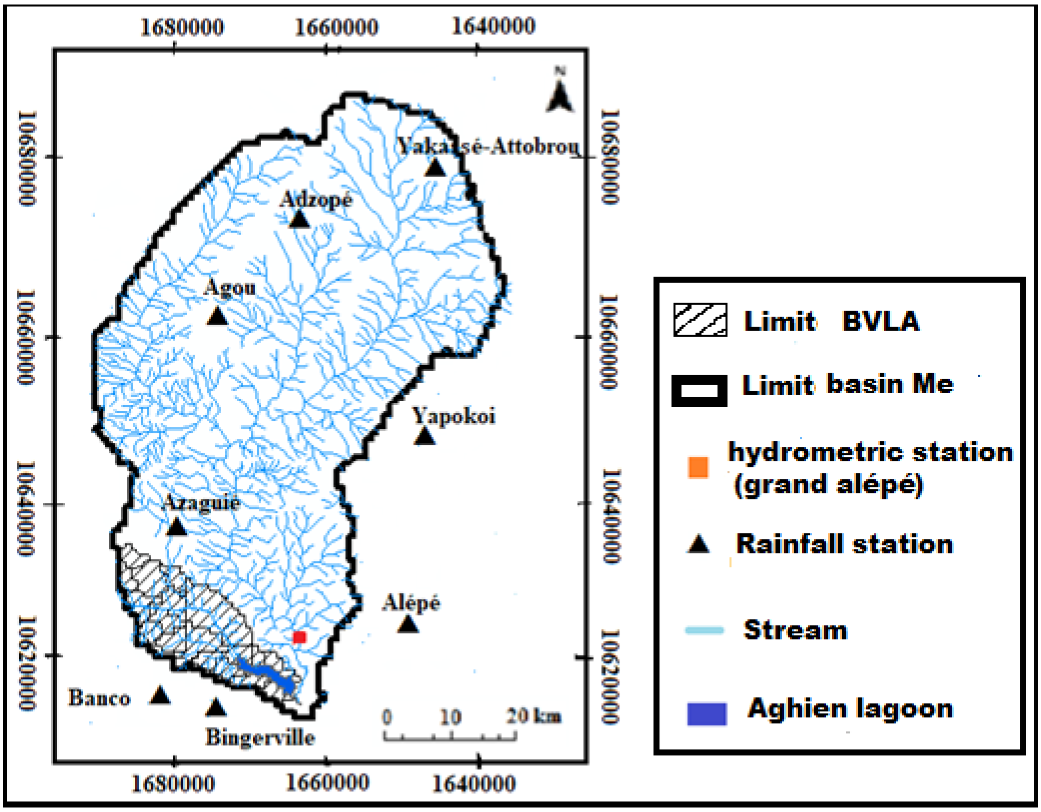

Figure 4: Influence area of rainfall stations

3.2.6 Implementation of SWAT model

Generally, the implementation of the SWAT model involved five main: (1) wathershed delineation and streams delineation, (2) integration of soil data and land use data and create slopes classes, (3) HRU (Hydrological response unit) definition, (4) integration of weather data (5) simulation. SWAT gives the possibility to choose, during the simulation phase, the simulation period, the time step (annual, daily, and monthly), the method of calculating the runoff and evapotranspiration, etc. In this work, the simulation was made over the period 1957-1981 at the monthly time step.Surface runoff is assessed by the Curve Number method (**SCS, 1972**) and the Hargreaves method was used to calculate evapotranspiration because only daily rainfall and temperature data were available in this study.The different steps of the implementation of the Swat model are summarized in **Fig 5** below.

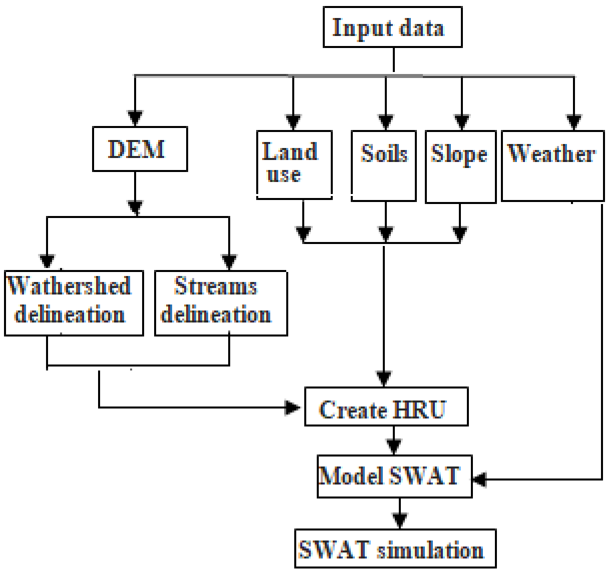

Figure 5: Steps of the implementation of the Swat model

3.2.7 Calibration and validation of SWAT model

The Aghien lagoon basin is an ungauged basin. However, as shown in Figure 1, this basin is a sub-basin of the Me basin. They therefore belong to the same geographical area. This geographical proximity is a sufficient indicator of the hydrogeological, climatic and pedological similarity of these two basins. On the basis of this similarity hypothesis, we used the flux data at the daily time step of the "Grand Alepe" hydrological station on the Me to calibrate the SWAT model on this watershed. Then, the adjusted model parameters for the Me basin were reintegrated into the model to simulate the flow on the Aghien lagoon (ungauged).The calibration procedure requires three steps. It is first necessary to identify the sensitive parameters

(parameters that can influence the performance of the model), then adjust these parameters and finally validate the model over a period different from that used for the calibration phase. Thus, the period 1960-1969 (wet period) was initially selected for calibration of the model and validation was carried out on the dry period (1970-1981). **Fig. 6** illustrates the periods used for calibration and validation.

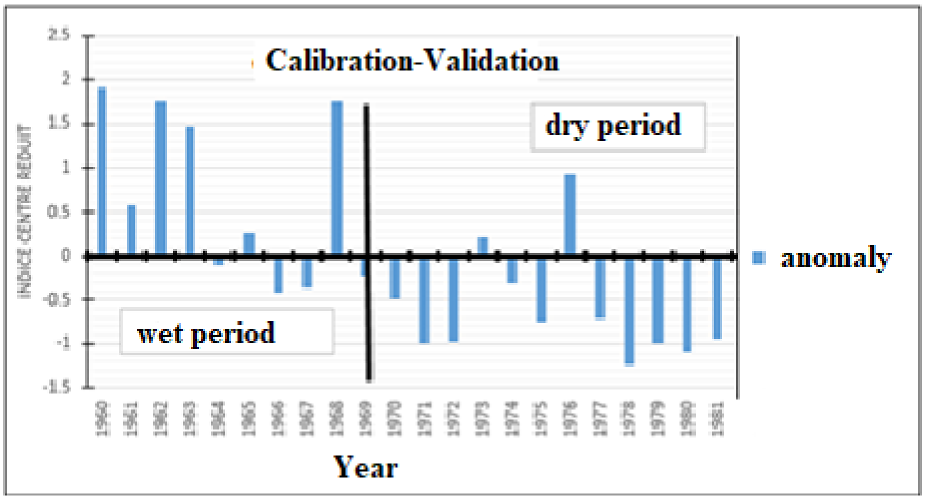

Figure 6: Reduced centered index on precipitation and calibration-validation period retained

The sensitivity of the parameters has been analyzed with the calibration tool SWAT-CUP 5.1.6. The criteria used to evaluate the performance of the SWAT model are those usually used in hydrological modeling: Nash-Sutcliffe efficiency coefficient (NSE) and coefficient of determination (R^2). NSE (**Eq.2**) interpreted as the proportion of variation in the observed values explained by the model. The performance of the SWAT model is considered satisfactory if the Nash value is greater than 0.5 (**Bracmourt et *al*. 2006; Moriasi et *al*., 2007**). The R^2 (**Eq.3**) evaluates the correlation between two variables and ranges from 0 to 1. A value of R^2 greater than 0.5 would reflect a good agreement of observed and simulated data (**Santhi et al., 2001**).Once the calibration is complete; the validation phase can be started. The principle consists in reinserting in SWAT-CUP algorithm (Sequential Uncertainty Fitting Version 2) (**Abbaspour, 2012**), calibrated parameters values and observed discharge of the validation period to reproduce a second set of observation data. This phase makes it possible to check the validity of the calibration on all the data and to estimate the predictive character of the model. Indeed, the calibration was carried out only on part of the data and for it to be accepted, it must be validated globally.

$$NSE = 1 - \frac{\sum_{i=1}\left(Q_m - Q_s\right)^2}{\sum_{i=1}\left(Q_m - \overline{Q}_m\right)^2} \quad (2)$$

$$R^2 = \frac{\left[\sum_{i=1}\left(Q_m - \overline{Q}_m\right)\left(Q_s - \overline{Q}_s\right)\right]^2}{\sum_{i=1}\left(Q_m - \overline{Q}_m\right)^2 \sum_{i=1}\left(Q_s - \overline{Q}_s\right)^2} \quad (3)$$

Q_m: observed stream flow; Q_s = simulated stream flow; $\overline{Q}_m$: mean of measured stream flows**;** $\overline{Q}_s$: mean of the simulated stream flows.

4. Results

4.1. Parameter sensitivity analysis and model calibration

SUFI-2 (Sequential Uncertainty Fitting) algorithm of the SWAT-CUP calibration tool developed by **Abbaspour et al. (2007)** was used for the sensitivity analysis of model parameters. Eleven hydrological parameters most modified in the literature were tested for sensitivity analysis for simulation of the stream flow in the study area. The most sensitive parameters (**Fig.7**) considered for calibration were curve number (CN2), threshold depth of water in the shallow aquifer (GWQ_MN), saturated hydraulic conductivity (Sol_k), soil available water capacity (Sol_AWC), groundwater "revap" coefficient (GW_REVAP), soil evaporation compensation factor (ESCO) and base flow alpha factor (ALPHA_BF).

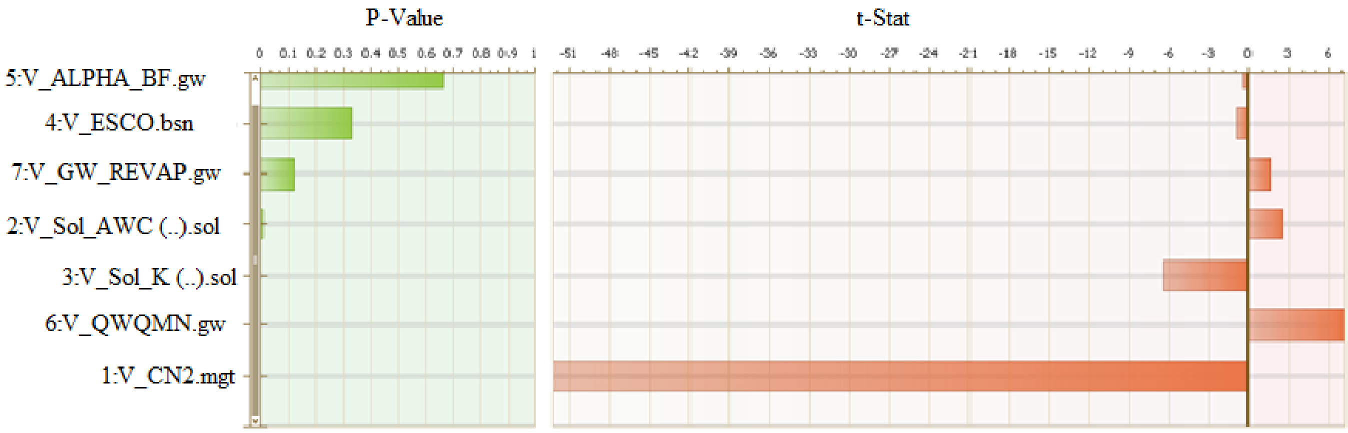

Figure 7: Parameters identified as sensitive during sensitivity

The t-Stat is the parameter coefficient divided by its standard error. A parameter with an absolute value of t-Stat greater is more sensitive. The P-Value gives the importance of the sensitivity. Thus, when P-Value is close to zero then the sensitivity of the parameter is important. The most sensitive parameter is the runoff coefficient CN2 (t-Stat = -52.31, P-Value = 0.0001) and the least sensitive is the recession coefficient ALPHA_BF (t-Stat = -0.43, PValue = 0.67).

4.2. Parameters adjustment and model validation

After identifying the sensitive parameters for the Aghien lagoon basin, these parameters must be adjusted so that they are adapted to the local context. SUFI-2 gives us the choice of three methods for modifying or adjusting the value of the sensitive parameters. The first method (**v_Remplace**) is to replace the default value of the parameter with a given value (by the user). The second (**r_Relative**) consists in modifying the value of the parameter by multiplying the set of its values (in each HRU) by the same coefficient. The last one (**a_Absolute**) consists of adding the given value to the initial value. **Table II** describes the most sensitive flow parameters, their fitted values and modification methods.

Table II: Swat flow sensitive parameters and fitted values after calibration using SUFI-2

Sensitive parameter	Lower bound	Upper bound	Final fitted value	Modification method	Modification scale
CN2	-0.188242	-0.175248	-0.184474	r_Relative	HRU
Sol_AWC	-0.697098	-0.681056	-0.691612		
Sol_K	0.771083	0.776373	0.774712		
ESCO	0.070125	0.076019	0.075418		
Alpha_BF	0.568090	0.591046	0.589439		
GWQMN	0.681359	0.644879	0.663192		
GW_REVAP	0.122689	0.124069	0.123498		

Fig.8 (a, b) and 9 (a, b) show the measured and simulated monthly stream flows for the calibration (1960-1969) and validation (1970-1981) periods. The values of Nash and $R^{2,}$ during the calibration period, were 0.807 and 0.809 respectively. During the validation period, the Nash and R^2 were 0.592 and 0.636 respectively. It should be noted that, both in calibration and validation, simulation does not favor low flows more than high flows (low or high water). Dynamics are good.

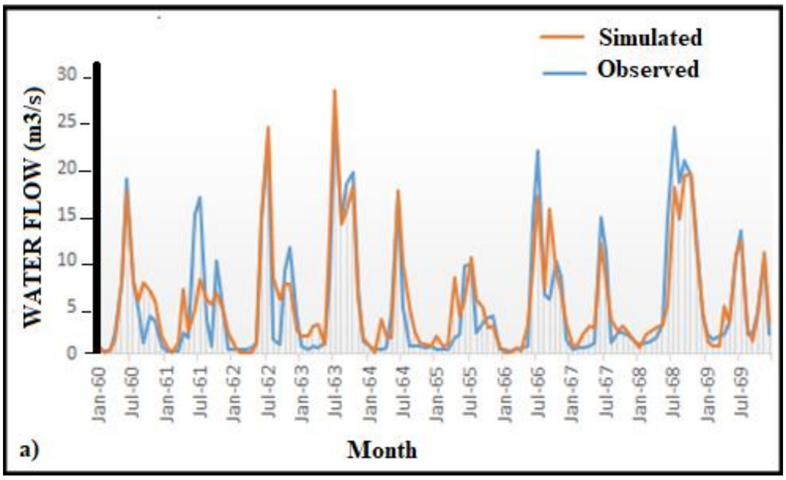

Figure 8 (a): Monthly observed and simulated water flow in calibration for the Me basin (1960-1969); **Nash= 0. 807**

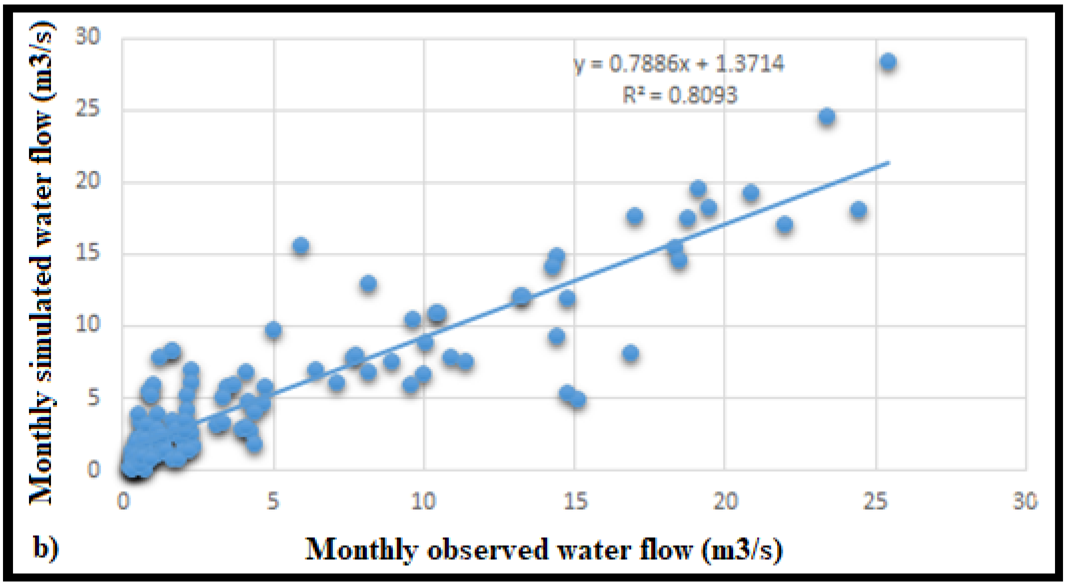

Figure 8 (b): Correlation between the monthly observed and simulated water flow in calibration for the Me basin **R^2= 0.809**

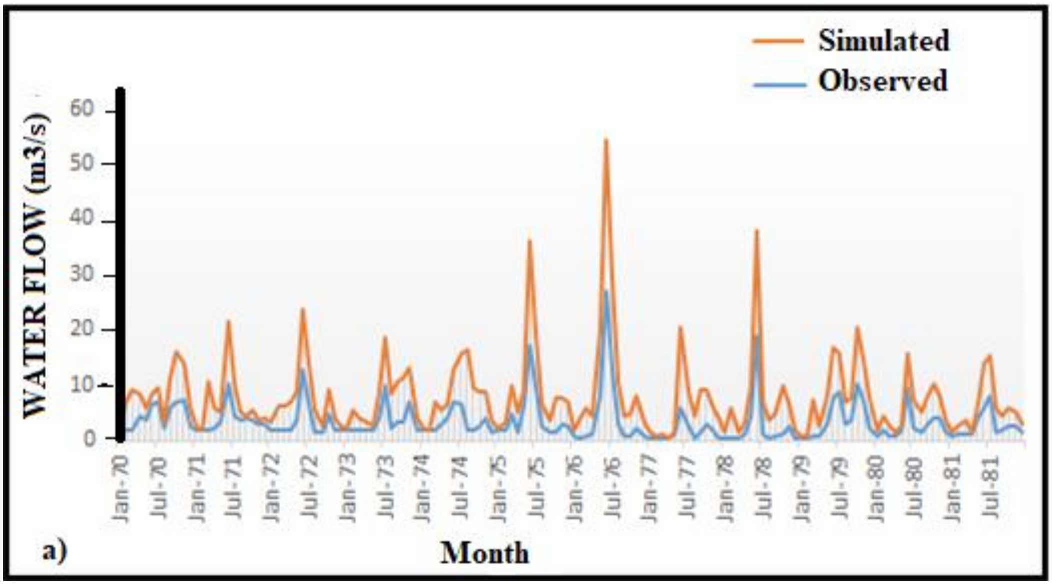

Figure 9(a): Monthly observed and simulated water flow in validation for the Me basin **Nash= 0. 592**

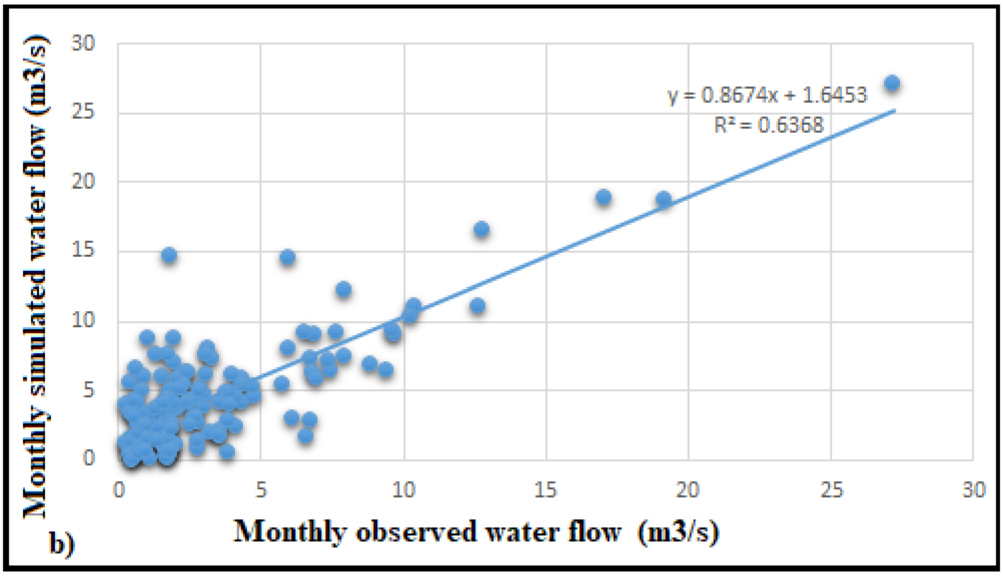

Figure 9 (b): Correlation between the monthly observed and simulated water flow in validation for the Me basin **R^2= 0.636**

4.3. Water balance

SWAT model was calibrated and validated for the Aghien lagoon basin. The water balance of the Aghien lagoon watershed was then evaluated. The various components of the simulated water balance and the variation rate of these components are presented in table III. Decrease in the different terms of the water balance over the reference period (1960-1981) is observed.

Table III: Annual water balance (1960-1981)

		water balance component				
	Period	P (mm)	ET (mm)	I (mm)	R (mm)	Es (mm)
Calibration	1960-1969	1722.45	894.56	267.77	560.46	216.31
Validation	1970-1981	1460.90	876.49	176.96	429.07	134.88
Variation rate (%)	1960-1981	**-15.18**	**-2.06**	**-33.91**	**-23.46**	**-37.64**

P: rainfall, **ET**: evapotranspiration, **I**: percolation, **R** : runoff, **Es** : baseflow

5. Discussion

Fig.8 (a, b) and 9 (a, b) show the measured and simulated monthly streamflows for the calibration (1960-1969) and validation (1970-1981) periods. The performances recorded on the coefficient of determination R^2 = 0.809 in calibration (1960 to 1969) and R^2= 0.64 in validation (1970 to 1981) describe well the degree of collinearity between the simulated and measured data. The NSE criteria for calibration and validation over the two periods are generally acceptable even if this coefficient is less satisfactory in validation over the period 1970 to 1981: NSE = 0.807 in calibration (1960 to 1969) and NSE= 0.59 in validation (1970 to 1981). According to **Saleh et al.,** (**2000**), **Santhi et al.,** (**2001**) and **Bracmourt et al.,** (**2006**), the values of R^2 and NSE upper than 0.5 are considered acceptable. In calibration, there is a slight discrepancy between the curves of the simulated and observed discharge rates. This shift is sometimes marked by a delay time of the curve of the data observed on the curve of the simulated data and sometimes a time in advance. Indeed, if the curve of the simulated data is late or in advance on the curve of the data observed temporally and vice versa, the coefficient of NS can decrease in a very sensible way (**Yazdi, 1995).** Without this offset, the NS coefficient would be even better in calibration. In validation, the discharge are overestimated. This overestimation seems to indicate a flows regulation phenomenon not taken into account by the model. Also the calibration period is wetter than the validation period. The high rainfall over the calibration period can accentuate a bad calibration of the runoff coefficient which is the most sensitive parameter. This parameter when it is too high, generates overestimated runoff heights (**Bougeard, 2008**), which could justify the overestimation of the flow observed in validation. The modest performance in validation can also be explained by the incomplete series of discharge data. Indeed, although flow data are available for the period 1970 to 1981, there are important gaps. Thus, the month of March of 1977 is marked by a total absence of flow data. This could limit the achievement of good model performance in calibration and validation during this period. This could limit the achievement of good model performance in validation (1970-1981). Despite the deficiencies observed in the baseline data series (1960 to 1981), the SWAT model shows satisfactory results. The parameters calibrated on the basin of the Mé River can therefore be integrated into the SWAT model to simulate the components of the water balance of the Aghien lagoon basin. Results of water balance indicate that all the main water balance components of Aghien catchment, display a decreasing trend over the time period of years 1960-1981. However, the decrease of evapotranspiration is less important (variation rate -2.06 %) than the other components of water balance during this period. The variation rate calculates indicate a decrease of 15.18 % of the rainfall, 33.91 % of the percolation, 23.46 % of the surface runoff and 37.64 % of the base flow. This downward trend could have a negative impact on the vulnerable ecosystems and on the Aghien Lagoon. This study is a first step towards integrated management of the Aghien lagoon watershed to reconcile the water needs of the future drinking water production plant with those of the ecosystems.

6. Conclusion

The SWAT model was successfully applied to the river Me watershed.The simulated monthly runoff matched the observed values satisfactorily, with a NSE coefficient of greater than 0.807 (calibration) and 0.592 (validation) and a coefficient of determination 0.809 and 0.636 during calibration and validation respectively. These values indicate a good fit of simulated values to the observed data set. The water balance analysis showed that all the main water balance components of Aghien catchment, display a decreasing trend over the time period of years 1960-1981. This observation should lead us to reflect on the future of this water resource in a context of climate change. Thus, the SWAT model can be used as a good tool for further analysis of effect of climate and land use change on water resource of Aghien.

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