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Modelling the hydrological balance of the Couffo basin at lanta's outlet in Benin: a tool for the sustainable use of water and land resources

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Abstract

This modelling study of the hydrological balance was conducted in the Couffo watershed at the outlet of Lanta. The main objective was to contribute to the sustainable water resources management in the basin. The SWAT model was runned to partition the watershed into sub-basins and sub-units called Hydrological Response Unit (HRU). With this model, runoff was assessed by the method of curves number. Soil moisture was evaluated by the method of tracking with storage. Evapotranspiration was assessed with the method of Penman-Monteith. Soil erosion rate was quantified using the Modified version of the Universal Soil Loss Equation. The main data included in the model were Digital Elevation Model (DEM), soil characteristics, land cover, management practices and long term climate data. After the calibration and validation of the model, the adjusted water balance indicated that evapotranspiration and water basin production were respectively 72%and 25% of annual precipitation. Regarding the soil erosion, an average value of 1.45tha^{-1}yr^{-1}was obtained for the watershed. The vegetation in the basin has undergone rapid decline due to loss of natural formations namely the gallery forest, savannah and lakes, in favor of new land for agriculture and urbanization.

Keywords: Couffo watershed, Land cover, Modelling, SWAT model, Water balance, Erosion.

Introduction

Many areas of the earth are severely lacking in drinking water. Thus, forecasts indicate that many populations will lack water in the coming years. During these last few decades, indeed, technological and industrial development coupled with sustained population growth in recent decades has increased the pressure on resources like water in all regions of the world[1]. Due to this population growth, water demand for agriculture, domestic use has increased; particularly in the agricultural dependent countries like Benin[2]. Currently, several African countries are facing water scarcity situations. This situation is worsening because of rapid population growth, expansion of urbanization, and economic development increasing[1]. The main challenge that the world will face is water resources management especially in West Africa, where about 25 years of drought have been observed[3]. Due to these reasons, the water resources must be well managed as well as all as other natural resources.

Such modes of variability raise important issues for sustainable development of the entire region, particularly in regard to water resources and, moreover land degradation and food security[4]. According to the General Direction of Water[5], Benin receives on average 1100 mm of annual rainfall. This contributes to a renewal of surface water resources evaluated at about 13 billion cubic meters (m^3) and the annual capacity of the aquifers renewal is estimated at 1.9 billion cubic meters (m^3). In the summary report of the Ministry of Energy, Mines and Water [5]on the national vision of water at the horizon 2025, Benin is a watered enough country as a whole, with sufficient water resources for its socio-economic activities for several years. Water availability can fully cover water needs of the population of Benin provided that the resource is well managed and its quality well monitored. In this country, the distribution of rainfall from one year to another and from one area to another is subject to large variations[6]. The significant decrease, irregular and poorly distributed rainfall in recent years has affected agriculture and water resources. There is some evidence that the total annual rainfall will experience a decline in the coming decades. This reduction will undoubtedly impact stream flow and the water cycle in the basin.

This paper aims to analyze the dynamic of water fluxes within the continuum atmosphere, ecosystem and human activities. Through this work, the annual renewal of water and sediment yield were quantified in the Couffo basin at Lanta outlet, by considering climate variability, land cover, soil and types of soil productions. Results from this work will help for determining suitable characteristics for hydraulics water storage constructions for sustainable water use.

Materials and methods

Study area: Located in the West African region, Benin is watered by a dense river network with Coufforiver as one of the most important. Coufforiver drains a catchment area of 3,000 km² of a total of 3035.38 km²and has its source in Togo in Jami mountains, close to the Beninese-Togolese border near the village of Tchetti (Benin) at 240 m above sea level. The catchment of Couffo at Lanta covers an area of 1,657.67 km^2 (Figure-4). It is located between 7°00 'and 7°45' north latitude and 1°45 'and 2°00' east longitude. Seventy-three percent of the populations of this basin primarily involved in agriculture, livestock and fishing, and 13% engaged in commercial activities, agricultural products processing activities and crafts[7]. Agriculture, dominated by food crops is the main source of income for most of the population of Couffo at Lanta. Agriculture is traditional, extensive and characterized by low yields. The main crops are maize, cotton, rice, sweet potatoes, groundnuts, cassava, pigeon pea, soybean, cowpea, pepper, tomato, okra and vegetable crops. It also meets perennial crops consist of mango, palm groves, orange, cashew, teak etc.

The watershed of Couffo at Lanta has a warm and humid climate of sub-equatorial and average annual rainfall ranges between 900 and 1200 mm. Figure-1 shows the rainfall patterns in upstream, middle and downstream of the basin for the period 1980-2012. Average temperatures vary between 25 and 31°C in with air relative humidity between 40 and 95%. Figures-2 and 3 show respectively the fluctuations of temperature and relative humidity on the basin for the period 1980-2012. Gleysoils and tropical ferruginous soils characterize the basin with 25.75% and 18.27%, respectively of the total area. The entire basin has experienced a general decrease in forests and savannas during the last 50 years, however a sharp increase in croplands (maize, cassava, rice and vegetable), fallow and residential areas[8].

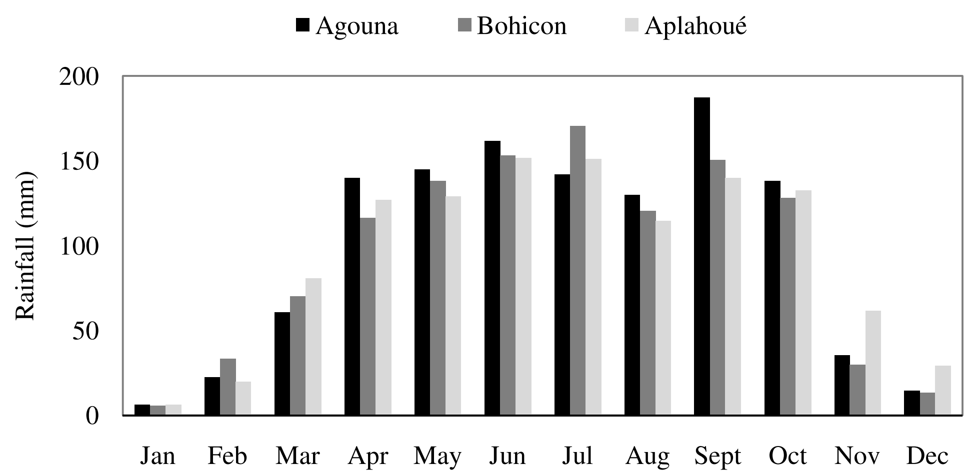

Figure-1: Rainfall regimes compared on station of Agouna, Bohicon and Aplahoué.

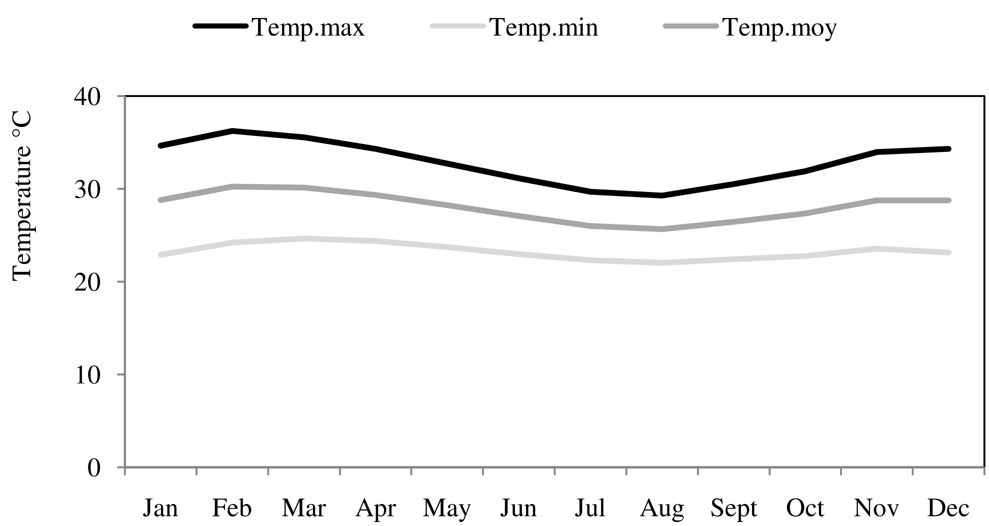

Figure-2: Variations of monthly temperatures in the study area.

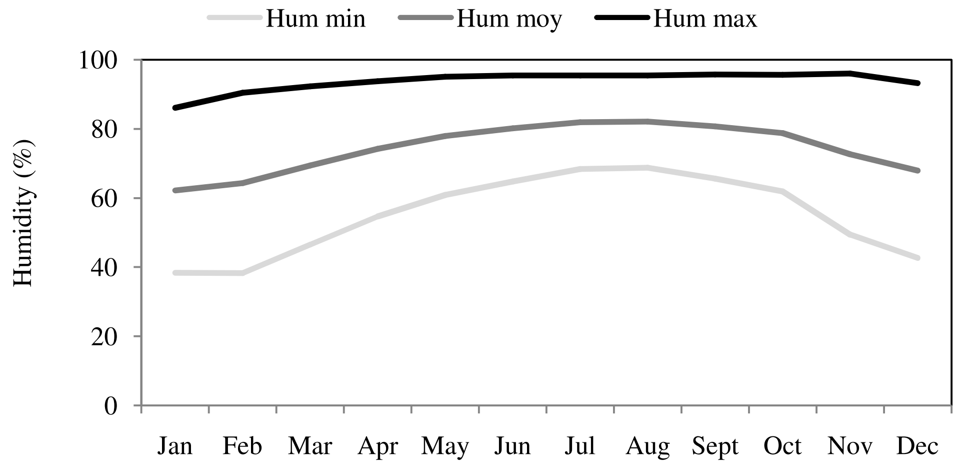

Figure-3: Variation of relative humidity in the study area.

SWAT model description: The Soil and Water Assessment Tool (SWAT) model is a semi distributed and physical based hydrological model with GIS interface (ArcView and ArcGIS) that drives sub-basins and drainage system of a watershed from Digital Elevation Models and computes the daily water balance from the weather data, soil and land maps. SWAT was developed by the Agricultural Research Service of the Department of Agriculture of the United States[9]. This model was developed to predict the impact of land management practices on water, sediment and agricultural chemical transport watersheds with different soils and different land occupations. To achieve this goal, the model is physically based. Also, it is continuous in time and able to simulate the effects of land use changes on soil hydrology over long period. The components of the model include climate, hydrology, sedimentation, plant growth, nutrient cycling, and farm practices. Moreover, SWAT, unlike many models can integrate the dynamics of soil biophysical properties and climate. For this study, we used the 2009 version of the model to calculate the water balance in the basin of Couffo at the Lanta outlet, especially the spatial variation of flows and land use (croplands and fallow, wood land, shrub land, forest and wetland).

Indeed, the model divides the watershed into sub-basins, allowing integrating land use and soil properties. SWAT has already been used in Europe, Africa and Asia. In Benin, this model was used to model the water balance in the upper Ouémé catchment[2]; Zou catchment at Atchérigbé outlet[10], Ouémé catchment at Savè outlet[11], Okpara catchment at Kaboua outlet[12].

The assessment of the current water availability is made through the estimation of hydrological cycle components throughout the watershed.

The Hydrological Response Unit, an area of one soil and its vegetation cover, is the spatial unit of these calculations in the basin.

The balance equation for a time interval is written as follows:

$$SWt = SWo + \sum_{t=1}^{t}(Ri - Qi - ETi - Pi - Qri) \quad (1)$$

Where SWt represents final soil water content, SWo corresponds to the initial water content before the event, t is the time, Ri corresponds to the precipitation of the day i, Qi represents the surface runoff amount of the day i, Eti is the evapotranspiration amount of the day i, Pi represents the water amount in the vadose zone on the day i, and Qri is the return flow amount of the day i. All these parameters are in mm H_2O. More explanation on this equation is given by Neitsch et al.[13] Hydrological processes can be grouped in five steps: precipitation, surface runoff, soil and root zone infiltration, evapotranspiration and ground water flow[2]. Runoff was estimated by the curves number method[14] which is related to precipitation, interception, slope, saturated hydraulic conductivity and infiltration rate. The soil water contain was valued by the method of routing with storage[15]. The actual evapotranspiration was quantified by Penman's method[16]. For the sediment loss simulation, we used the modified universal soil loss equation[17].

$$\text{Sed} = 11.8 \cdot \left(Q_{surf} \cdot q_{peak} \cdot area_{hru}\right)^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \quad (2)$$

Where: Sed is the sediment yield on a given day (metric tons), Qsurf is the surface runoff volume (mm H_2O/ha), qpeak is the peak runoff rate (m^3/s), areahru is the area of the HRU (ha), KUSLE is the USLE soil erodibility factor (0.013 metric ton m^2hr/(m^3-metric ton cm)), CUSLE is the USLE cover and management factor, PUSLE is the USLE support practice factor, LSUSLE is the USLE topographic factor and CFRG is the coarse fragment factor.

Model setup: For this work, we used: i. a DEM of 30 m resolution data from the Shuttle Radar Topography Mission.

From the DEM, SWAT derived flow direction and physical properties for each sub basin. ii. a land use / land cover map of 300 m resolution is used; iii. a digital soil map (scale 1/200.000), supported by soil surveys for assessment at the laboratory of the physical parameters that are important for the water dynamics in the soil (satured hydraulic conductivity, organic carbon content, water retention capacity, texture); The soil parameters and soil digital map are an important input of the SWAT model; iv. daily climate data of the synoptic station (Bohicon), the daily rainfall data rain gauges (Aplahoué, Lonkly, Bohicon, Lokossa, Tchetti, Agouna), the monthly climate data (average values) and their standard deviation computed for the period between 1980 and 2012; v. daily flows of the Lanta's flow measurement station for the model running; vi. data on plant physiological growth (LAI, Biomass, PHU) for the vegetation and the main cultivated crops (maize, rice), obtained from the Laboratory of Hydraulics and Water Control of the University of Abomey-Calavi, Benin[18], vii. land cover maps for 1995 and 2006 used for diachronic study of land use.

The different climatic and meteorological data are rainfall, relative humidity, insolation, maximum and minimum temperatures, evapotranspiration over a period at least 30 years were obtained at the Agency for the Safety of Air Navigation in Africa and Madagascar (ASECNA/Benin). A total of six (06) measuring stations are concerned, five of them are rainfall measurement stations (Aplahoué, Tchetti, Agouna, Lonkly and Lokossa) and one is synoptic station (Bohicon).

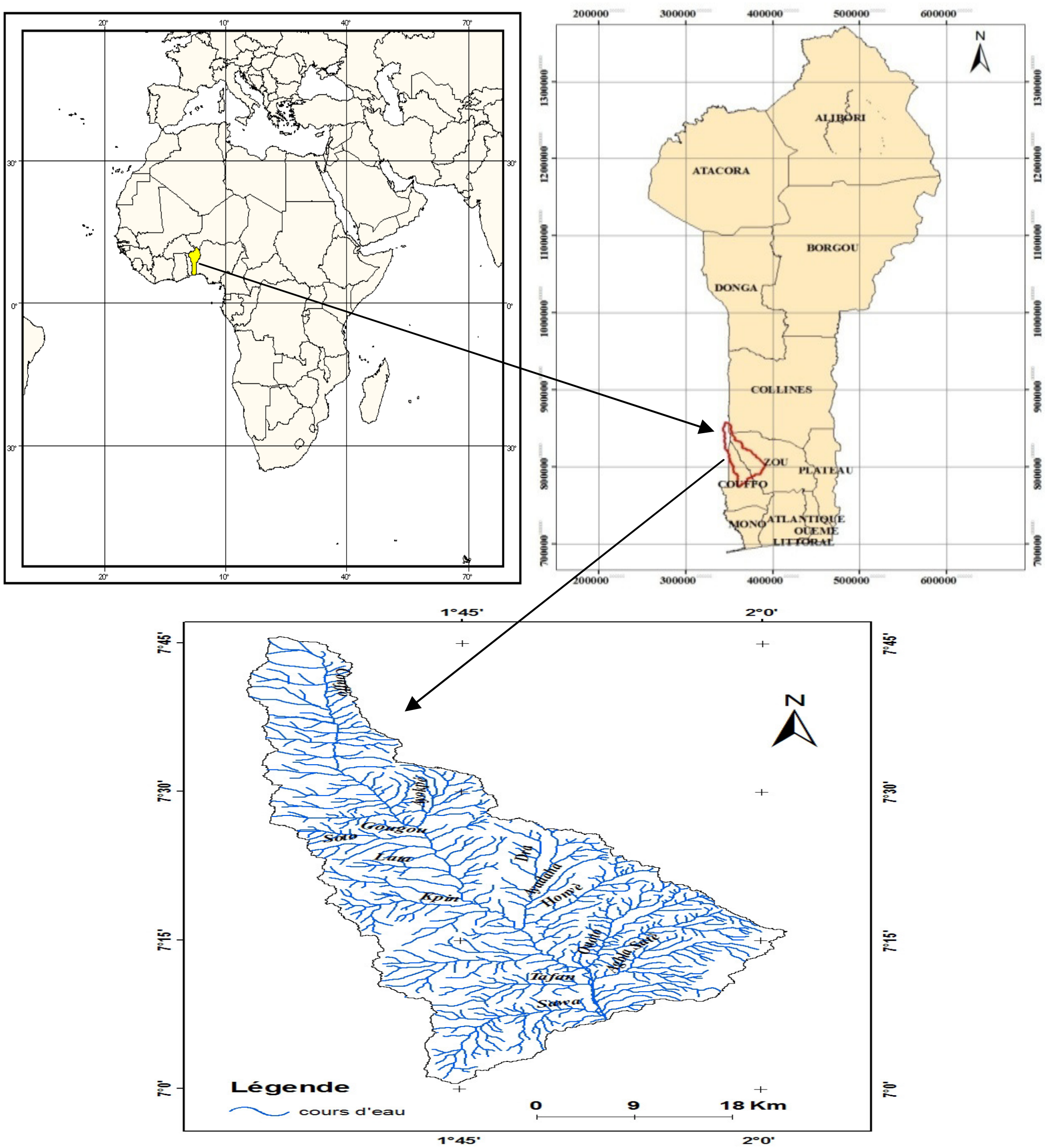

Figure-4: Couffo catchment at the Lanta outlet.

Calibration, validation and model evaluation procedures: The model was run from 2000 to 2005 with the first year as the warm-up period to stabilize the model conditions. Thus, the first is not considered in the analyses of the model output. The results presented in this paper were obtained after various simulations under the time period from 2001 to 2003 for the model calibration and from 2004 to 2005 for the model validation.

The base flow automated digital filter program[9,19] was used to separate the observed flow and estimate base flow recession constant at the outlet of Couffo basin.

The simulated surface runoff was firstly adjusted using the estimated base flow recession constant and the observed flow. The goodness of fit coefficients like theR^2, the Model Efficiency (ME)[20] and the Agreement Index (IA) of Willmott[21] were used to appreciate the fitness of the model.

The R^2 indicates the proportion of the total variance of the observed data explained by the model. Its value range between 0.0 and 1.0 where the high value indicates a best relationship between the observed and simulated data.

$$R^2 = \left\{ \frac{\sum_{i=1}^{N}\left(O_i - \bar{O}\right)\left(P_i - \bar{P}\right)}{\left[\sum_{i=1}^{N}\left(O_i - \bar{O}\right)^2\right]^{0.5}\left[\sum_{i=1}^{N}\left(P_i - \bar{P}\right)^2\right]^{0.5}} \right\}^2 \quad (3)$$

With O_i: observed flow, Pi: simulated flow, $\bar{O}$: mean of observed flow, $\bar{P}$ mean of simulated flow.

ME, indicates how well the plot of observed versus simulated value fits the 1:1 line. This coefficient is recommended in hydrological modelling and is calculated as:

$$ME = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}\left(O_i - \bar{O}\right)^2} \quad (4)$$

Where: Oi is the observed data, Pi the computed by the model, $\bar{O}$ is average of the observed data, N is the number of the compared values. ME = 1 means that the model simulates accurately the flow. If ME is negative, the model result values are lower than the observed variables. ME is between -∞ and 1.

To assess the temporal reproduction of the observed flow, the IA is used.

From Willmott [21], IAis assessed as:

$$IA = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}\left(\left|P_i - \bar{O}\right| + \left|O_i - \bar{O}\right|\right)^2} \quad (5)$$

The IA is ranged between 0 and 1, the higher values correspond to a better agreement between the modeled values and the observed. It is very sensitive to the extreme values[21]. For the three goodness coefficients, the value 1 represents the best goodness[22].

Results and discussion

Figure-5 displays the simulated and observed flows for the calibration time period from 2001 to 2003. After the graphic we have the average discharges and the modelling evaluation factors (Table-1).

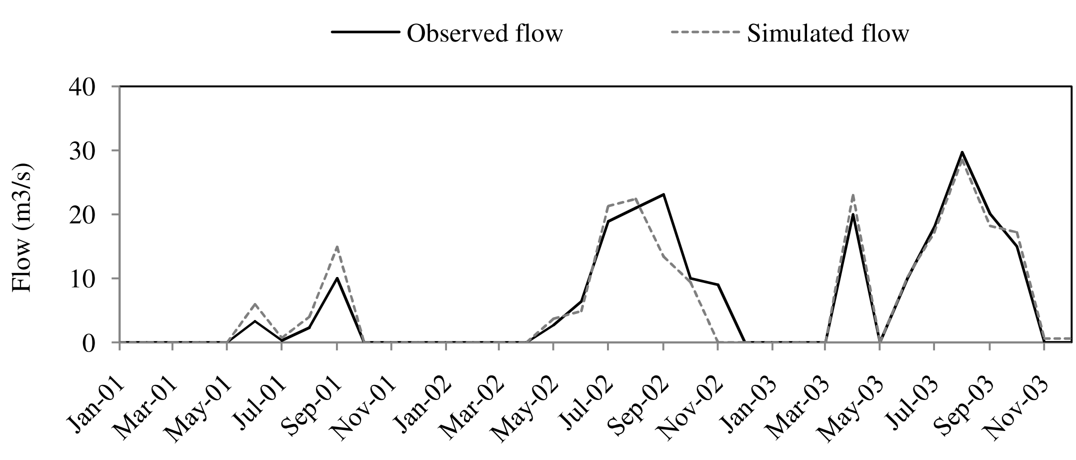

Figure-5: Comparison of Couffo-Lanta monthly discharge during the calibration time.

Table-1: Model goodness indicators.

Monthly average (m^3/s)		Goodness coefficients		
Observed flow	Simulated flow	R²	ME	IA
6.61	5.54	0.8	0.77	0.94

The high values of the evaluation on a monthly scale coefficients show that the measured and observed flows are adjusted.

Annual water balance: The average annual water balance in the basin is synthesizes in Table-2.

Table-2: Annual values of hydrological balance (2001-2003).

Water balance components	Values (mm)
Annual rainfall	1110
Evapotranspiration	800
Potential Evapotranspiration	1148
Production of water (runoff+lateral flow+ underground flow +recharge of groundwater flow deep aquifers and shallow)	281
Change in soil water storage	29

Table-2 shows that the share of rainfall that contributes to evapotranspiration is 72% and that contributes to the total water production from the basin is 25%. From the analysis of these results, it appears that most of the precipitations return to the atmosphere as soil, lakes, rivers evaporation. and plants transpiration.

These results are similar to those obtained by Amoussou[23] who found that 80% of rains were evaporated in the same basin and those of Awoye[18] on the Klou basin in Zou at the same latitudes of the country, where 68.9% of the rainfall was evaporated. Actual evapotranspiration water is higher than runoff in many cases in the world except Antarctica and the potential evapotranspiration exceeds rainfall generally over the period from 1968 to 2000 on the watershed Couffo[23].

These results are also confirmed in the Couffoat Lanta watershed. Observed flow of Couffo catchment compared to simulated flow during the validation period (2004-2005). The observed rates and simulated monthly time during the validation period starting from 1 January 2004 to 31 December 2005 are presented in Figure-6 and the evaluation coefficients in Table-3.

Table-3: Model goodness indicators.

Monthly average (m3/s)		Goodness Coefficients		
Observed flow	Simulated flow	R²	ME	IA
5.54	4.04	0.77	0.76	0.93

The high values of the evaluation, on a monthly scale, coefficients show that flows (observed / simulated) are adjusted.

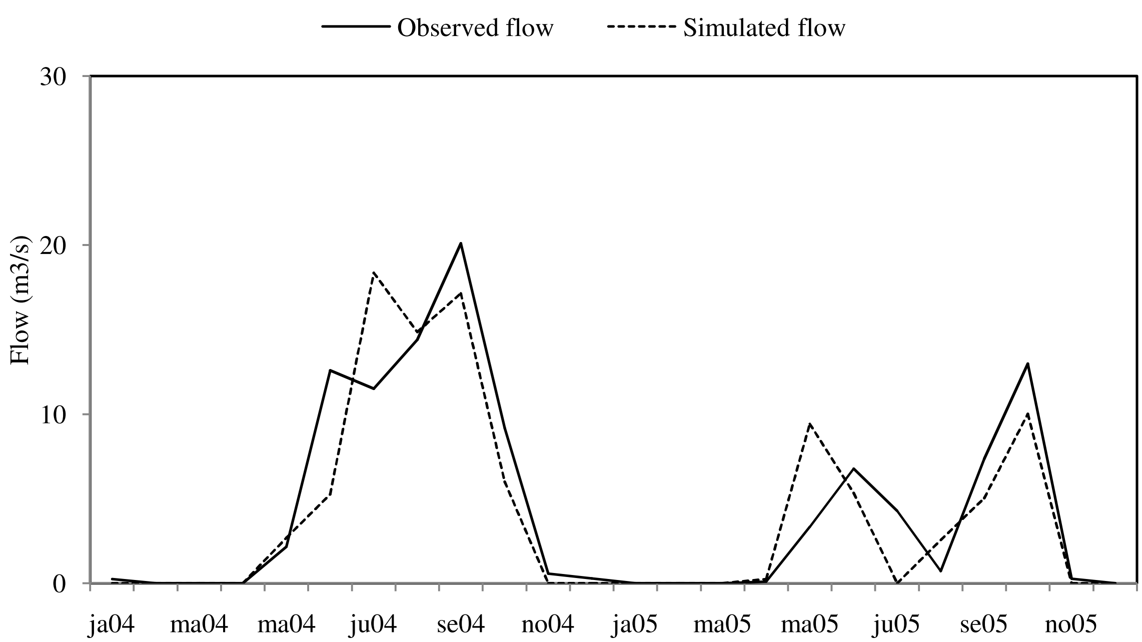

Figure 6: Comparison of Couffo-Lanta monthly discharge during the validation time.

Table 4: Annual values of hydrological balance (2004-2005).

Water balance components	Values (mm)
Annual rainfall	1177
Evapotranspiration	829
Potential Evapotranspiration	1158
Production of water (runoff + lateral flow + underground flow +recharge of groundwater deep aquifers and shallow)	324
Change in soil water storage	24

Table-4 shows that the share of rainfall that contributes to evapotranspiration is 70% and that contributes to the basin water production is 27%. It appears, as during the period of the model calibration, that the greatest proportion of annual precipitation is lost through evapotranspiration.

Sediment loading: From Figure-7, the erosion phenomenonis more pronounced in the localities as Atomè, Monsourou, Djidja, Lonkly and Lanta. Indeed, the simulated soil losses are on average of 1.45 tons $ha^{-1}yr^{-1}$ in these sub-basins. Most of the lands of these sub-basins is used for agricultural purposes. The lowest erosion values are observed in the sub-basins 8; 10 and 11 where the loss average land rises to 0.16 tons $ha^{-1}yr^{-1}$.

In general, the highest rates of soil erosion in the fields can be explained as a consequence of mechanical destruction of the soil and vegetation cover: the biological activity (density earthworms) decreases; which reduces macroporosity. Furthermore, the lower permeability of the surface that results due to surface flows and increased erosion of the soil. Awoye[18] got on the watershed of Zou at Klou, 4.3 tons $ha^{-1}yr^{-1}$and Sintondjiet*al.*[24]. got at Ouémé at Savè, 4.4 tons ha^{-1} yr^{-1}. This value of soil losses in Couffo catchment is rather low compared to those obtained by above authors and can be explained by the degradation of vegetation cover due to human activities in the sub-basin Couffo which have led to a reduction of infiltration by the porosity they generate and facilitate rapid drainage of water.

Dynamics of land cover during the period 1995 – 2006in the basin of Couffo at Lanta outlet. From the analysis of land use maps of 1995 and 2006, gallery forests, savannahs, rock surface and water bodies have regressed in the Couffo catchment at the Lanta outlet. Overall, 2218.4 ha of gallery forests, 3362.8 ha of surface rock and water bodies were lost during the period 1995-2006. On the contrary, croplands and settlements areas increased in the catchment during the same period, leading to the conclusion that natural formations are regressing due to human activities (agriculture and urbanization) in the catchment. These observations are consistent with those of Amoussou[23] who mentioned uncontrolled exploitation of forest ecosystems for agriculture and urbanization. The frequently mentioned causes are population growth (2.32% between 2000 and 2005) and reduced rainfall (15% to 30% after the 1970s). In summary, the basin had experienced a general decline in forests and savannah in 50 years and a very progression of cultivated land and / or fallow and residential areas.

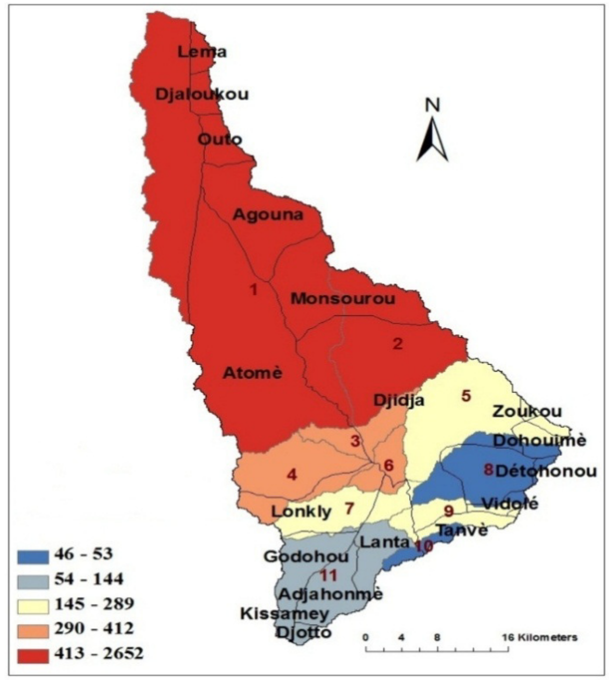

Figure-7: sediment loss ($kg.yr^{-1}$) per sub basin during calibration period.

Conclusion

The running of agro-hydrological model SWAT in the Couffo basin at Lanta outlet required a good knowledge of Geographic Information Systems (GIS), which allowed the treatment and management of all data used in the physical characterization of the basin and input for the model. This study shows that the productivity of the basin's hydro systems varies in space and time due to local conditions (soils and climate). The total volume of water produced amounted to5 billionm^3/year. The result is that all water resource utilization projects should reflect this spatial and temporal variability of the resource. Given the fact that some sub-basins have significant hydraulic potential, it is recommended the construction of water reservoirs and micro-dams in these sub-basins. The stored water through these canals will be processed and used to supply drinking water for people and livestock. As erosion is important in the sub basin dominated by agricultural practices, it is indicating that that activity is damaging the environment. Then, we suggest the application of soil and water conservation techniques to reduce the land degradation and soil loss. This would also contribute actively to the consolidation efforts and reduce water borne diseases in these communities. It is also desirable that future studies are conducted to calibrates oil loss, agricultural pollutants and estimate climate change and vegetation cover dynamics influence on the basin water.

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