Modelling the hydrological balance of the Okpara catchment at the Kaboua outlet in Benin

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Abstract

This modelling study was conducted in the Okpara catchment at the Kaboua outlet in Benin. The target idea is to assess the availability and annual renewal of the water resources. Aiming at this, the SWAT 2003 model, a semi-distributed watershed model with a GIS interface was selected, calibrated and validated for the study basin. After calibration and validation, it springs out that 1075.8 mm/year of precipitation fall in the watershed. The surface runoff is 106.6 mm/year (10% of precipitation) while the total recharge of aquifers is 225.4 mm/year (21% of precipitation). The actual evapotranspiration is 759.8 mm/year (71% of precipitation) and the change in soil water storage is -21,37mm/year. Regarding erosion, an average value of 7t/ha/year was obtained for the watershed with a maximum value for the croplands (16.85t/ha/a) and a minimum value for the bushed savannahs (0.64t/ha/a).

Keywords: Modelling, Hydrological Balance, Okpara catchment, SWAT model, Benin.

Modélisation du bilan hydrologique du bassin versant de l'Okpara à Kaboua au Bénin

Résumé

La présente étude de modélisation a été conduite dans le bassin versant de l'Okpara à l'exutoire de Kaboua au Bénin. L'objectif principal est d'évaluer la disponibilité et le renouvellement annuel des ressources en eau. Pour atteindre cet objectif, le modèle SWAT 2003, un modèle physique semi-distribué à interface GIS a été sélectionné, calé et validé pour le bassin d'étude. Après calibration et validation, il ressort qu'en moyenne 1075,8 mm de pluie est enregistré par année sur le bassin. L'écoulement de surface est de 106,6 mm/ an soit environ 10% des précipitations annuelles pendant que la recharge des aquifères est de 221,4mm/ an soit environ 21% des précipitations. L'évapotranspiration réelle est de 759,8mm/an (environ 71% des précipitations) et la variation du stock d'eau dans le sol de -21,37mm/an. En ce qui concerne l'érosion, une valeur moyenne de 7 tonnes/ha/an a été obtenue pour tout le bassin avec une valeur maximale dans les champs agricoles (16,85tonnes/ha/an) et une valeur minimale dans les savanes arbustives (0,64 tonnes/ha/an).

Mots clés : Modélisation, bilan hydrologique, bassin de l'Okpara, modèle SWAT, Bénin.

INTRODUCTION

The rapid population growth and the industrial development during the last few decades have caused an increasing pressure on land and water resources in almost all regions of the world (Abbott and Refsgaard, 1996). This phenomenon of population growth increases the demand of water for domestic, agricultural and other uses particularly in countries which are dependent on agriculture such as Benin (Sintondji, 2005). Fresh water has already become critically scarce in many regions of the world. It is anticipated that until 2025 about 25% of the world population will suffer from severe water scarcity. For Africa, some estimates suggest that already now the amount of fresh water available per capita is only about a quarter of that in 1950, and that fresh water supply could become problematic especially in West Africa, where about 35 years of drought have been observed (Speth et al., 2002). For these reasons, water resources have or will become scarce natural resources which must be managed more efficiently.
According to the report of Benin Water Ministry in 2009, Benin republic has many water resources which well managed will help to subdue the needs of the population in a mean and a long-dated. Unfortunately the current overuse of water resources constitutes a serious threat for their protection and preservation and in consequence for the survival of future generations. In the particular case of Okpara catchment at Kaboua outlet where this study is conducted, one waterhole is used by about 604 inhabitants which is more than the double of what is recommended by FAO: 250 inhabitants per waterhole. Due to population growth and multiple uses of water, the water resources managers will face some problems as pollution, mismanagement and scarcity (Vissin, 2007). A sustainable water resource management requires the use of scientific data for decision making. In this context, it is important to understand and to quantify the dynamic of water exchange between atmosphere, ecosystems and human activities. This is the main objective of this study. Of interests are the quantification of the annual renewal of water resources and sediment yield in the Okpara-Kaboua catchment taking into account climate variability, agricultural practises and land uses.

METHODOLOGY

Study area

Located in West Africa, Benin is watered by a dense hydrographic network with river Oueme as the most important (510 Km). This study was conducted in the Okpara catchment at the Kaboua outlet which is one of the Oueme river sub-basins. It spreads over a total area of 9461 Km^2 with an annual population rate of 3.5% giving a current estimation of 908438 inhabitants.It is located between longitudes 2°31- 3°25 E and latitudes 8°13- 9°57 N (figure 1). The Okpara-Kaboua catchment is characterised by a subequatorial climate in its south area. But since few years, this climate has changed to sudanian climate which characterises the centre and the north of the catchment with only one rainy season and one dry season. The mean annual rainfall is about 1100 mm. Annual temperature varies between 24 and 30°C. The major types of soil are tropical ferruginous soil, alluvial soil and raw mineral soil. The vegetation is dominated by bush land with high agricultural influence.

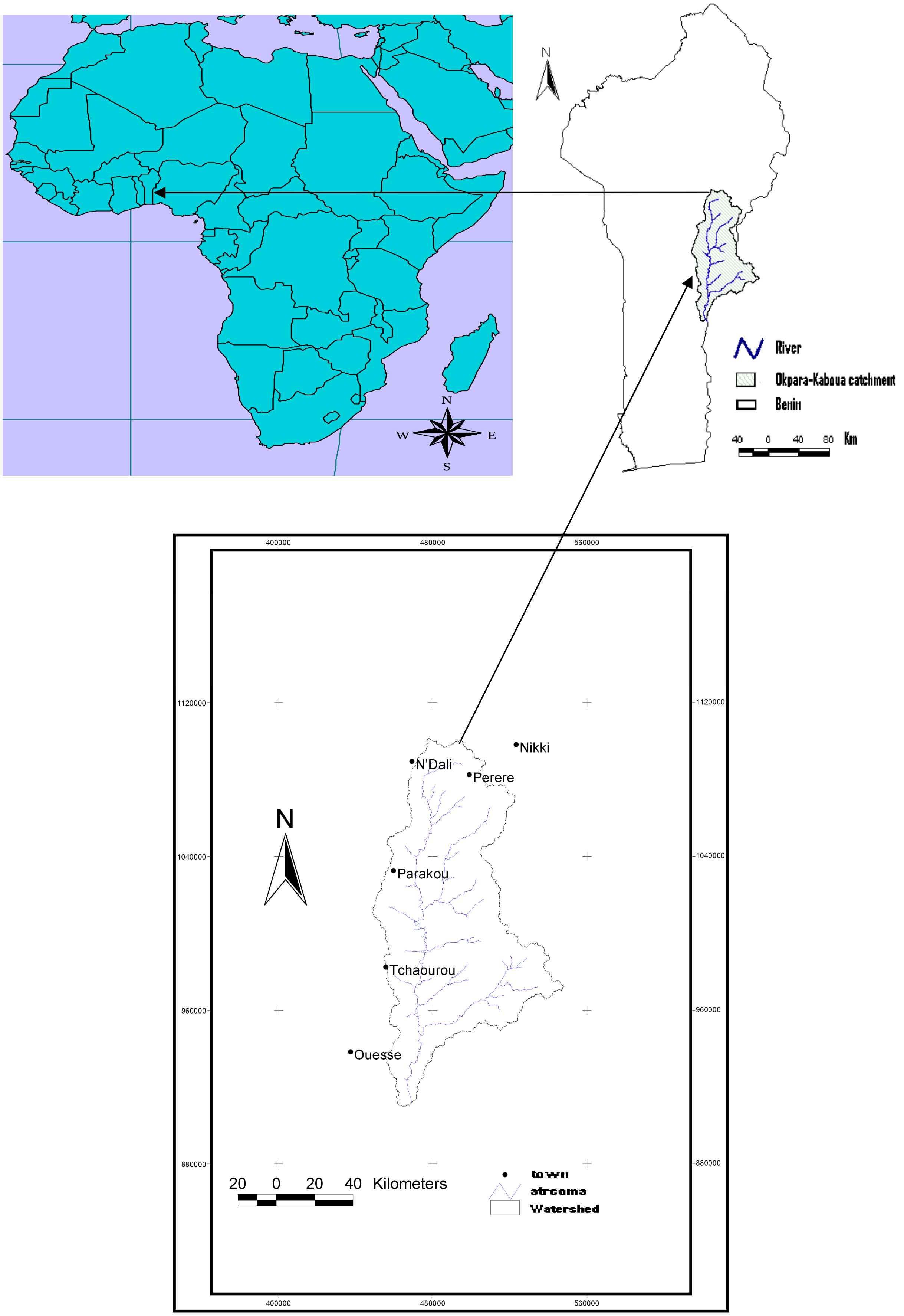

Figure 1: Okpara catchment at Kaboua outlet
Layout: E. Dossou-Yovo

Material and methods

Data

The data used during this study are:

- A Digital Elevation Model in a 90 m resolution data from the Shuttle Radar Topography Mission (SRTM) of the NASA. From the DEM, the model SWAT (Soil and Water Assessment Tool), which was used, derived the overland and channel slope and length; the surface time of concentration, flow direction and others properties for each sub basin.
- The digital land use/ land cover maps in a 300×300 m resolution of the catchment. Land use / land cover is one of the key parameters within the hydrological cycle and one of the inputs of the SWAT model.
- The climate data. They were obtained from two sources: Benin national meteorology Direction (DMN) and French Project IRD (ex-ORSTOM) gauged stations. These institutions have recorded data of rainfall, climatic parameters and stream runoff for several areas in the watershed for several years. For Okpara-Kaboua watershed, six (06) rainfall recorded data stations have been used (Bembèrèkè, Nikki, Parakou, Tchaourou, Ouèssè and Savè) from which two (02) stations are synoptic stations (Parakou and Savè).

  Apart from the climatic parameters related to rainfall, daily values of these two synoptic stations of maximum and minimum air temperatures, relative humidity, wind speed, solar radiation and their standards deviations have been used for the whole catchment.

  For the synoptic stations, the monthly average daily precipitation, its standard deviation and skew coefficient were calculated for 40 years as well as the average daily maximum and minimum temperatures and dew point. Regarding solar radiation and wind, their average monthly daily values were calculated for 30 years. At last, the others monthly parameters required by the model weather generator (relative humidity, the average number of days of precipitation for every month; the maximum 0.5 hour rainfall in the entire period of record for every month; the probabilities of wet day following a dry day and a wet day following a wet day for every month) were obtained for 10 years.
- The discharge data from the hydrometrical station of Kaboua (outlet of the watershed) were used for the model calibration and validation.
- The digitized soil map of the catchment on the scale of 1:200,000 was used. Soil is a key parameter of hydrological cycle and one of the inputs of the SWAT model.

SWAT model description

The SWAT model - Soil and Water Assessment Tool - (Arnold et al., 1998) is a semi-distributed watershed model with a GIS (Arc View) interface that outlines the sub basins and stream networks from a Digital Elevation Model (DEM) and calculates daily water balances from meteorological, soil and land-use data. SWAT is a hydrologic / water quality model developed by the United States Department of Agriculture- Agricultural Research Service (USDA- ARS) (Arnold et al., 1998). The model was developed to foresee the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long periods of time.

Model components include weather, hydrology, sedimentation, crop growth, nutrients cycling, pesticides dynamics and agricultural management. We use for this study SWAT 2003 model to assess the hydrologic balance in the Okpara-Kaboua basin, particularly spatial variation of runoff and sediment yields with regard to the land use.
Indeed, SWAT model first partitions a watershed into sub basins which allow accounting of land uses and soils properties impact on hydrology. Then, the model subdivides the previous partitions in Hydrologic Response Units (HRU) which are lumped land areas within the sub basin that are constituted of unique land cover, soil and management combinations.
SWAT has been applied in several basin scale studies involving assessment of water supply and nonpoint source pollution in the United States. Arnold *et al.* (1999) reported the results of SWAT application for hydrologic simulation in all river basins in the United States. Several other studies in other Continents (Europe, Africa, Asia) (e.g. Rosenthal *et al*., 1995; Bingner, 1996; Srinivasan *et al*., 1998, 2003; King *et al*., 1999; Santhi *et al*., 2001, 2005; Huisman et al., 2003; Sintondji et al., 2004; Pohlert et al., 2005; Sintondji, 2005; Bossa, 2007; Awoye, 2007; Ahouansou, 2008) indicate the strength of SWAT model in simulating streamflow and sediment movement in large basins.

Hydrologic balance

Sintondji (2005) mentioned that simulation of the hydrology of a watershed can be separated in two major components: the land phase of the hydrologic cycle and the routing phase (movement through the channel network) of the hydrologic cycle. At the first phase the hydrologic cycle is computed on the basis of the water balance equation:

$$SW_t = SW + \sum_{t=1}^{t} (R_i - Q_i - Et_i - P_i - Qr_i)$$

Where SW_t is the final soil water content (mm H_2O), SW is the initial soil water content on day *i* (mm H_2O), *t* is the time (days), R_i is the amount of precipitation on day *i* (mm H_2O), Q_i is the amount of surface runoff on day *i* (mm H_2O), Et_i is the amount of evapotranspiration on day *i* (mm H_2O), *Pi* is the amount of water entering the vadose zone from the soil profile on day *i* (mm H_2O), and Q_{ri} is the amount of return flow on day *i* (mm H_2O).
The hydrologic processes can be grouped in five steps: precipitation, interception, surface runoff, soil and root zone infiltration, evapotranspiration and ground water flow (Sintondji, 2005).
Surface runoff was estimated by the curves number method (SCS, 1972), that depends on precipitation, interception, slope, saturated hydraulic conductivity and infiltration rate. The water contained in the soil was valued by the method of routing with storage (Sloan and Moore, 1984). The actual evapotranspiration was quantified by Penman's method (1956).

Erosion assessment

We measured the sediment loss in the sub-basin 19 (the outlet of the catchment) in *Glycine max* farms with different agricultural practises (rows parallel to hill slope, rows perpendicular to hill slope and in the case of flat ploughing). Every two weeks, the sediment transported weight was measured. For the sediment loss simulation, we use the modified universal soil loss equation (William, 1975).

$$Sed = 11,18\ (Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0,56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE}\ .\ CFRG$$

Where *Sed* is the sediment yield on a given day (metric tons), Q_{surf} is the surface runoff volume (mm H_2O/ha), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of the HRU (ha),

K_{USLE} is the USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm)), C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor and *CFRG* is the coarse fragment factor.

Model calibration and validation

The time period from 1999 – 2007 was used for model simulation. The first year of the simulation was used as a model "warm-up", for the first simulation, period when model conditions stabilized. This year was therefore omitted from final result comparisons. The results reported in this study for various simulations consist of data for the time period from 2000 – 2004 for calibration and 2005-2007 for the model validation.
To derive the baseflow recession constant, a baseflow automated digital filter program (Arnold *et al.*, 1999; Arnold & William, 1995) was used to separate the baseflow and runoff portions of flow from measured stream flow data obtained for the study area. We first adjust the surface runoff simulated with the observed values and secondly the baseflow.

Evaluation of model goodness

The coefficients used to appreciate the model goodness were coefficient of determination (R^2), Model Efficiency (ME) of Nash & Sutcliffe (1970) and Index of Agreement (IA) of Willmott (1981).
The R^2 value is the square of the Pearson's product-moment correlation coefficient and describes the proportion of the total variance in the observed data that can be explained by the model. It is ranged from 0.0 to 1.0 with higher values indicating better agreement.

$$R^2 = \left[\frac{\sum_{i=1}^{N} (O_i - \overline{O})(P_I - \overline{P})}{\left[\sum_{i=1}^{N} (O_i - \overline{O})^2\right]^{0,5} \left[\sum_{i=1}^{N} (P_i - \overline{P})^2\right]^{0,5}} \right]^2$$

With: O_i: Observed data, P_i: simulated data, $\overline{O}$: Observed mean,
$\overline{P}$: simulated mean, N: Number of compared values.

Model efficiency, according to Nash and Sutcliffe, indicates how well the plot of observed versus simulated value fits the 1:1 line. Estimation efficiency is commonly used in hydrologic model evaluation and is calculated through the equation beyond:

$$ME = 1 - \frac{\sum_{i-1}^{N} (O_i - P_i)^2}{\sum_{i=1}^{N} (O_i - \overline{O})^2}$$

If the measured variable is simulated most accurately by the model, then ME = 1. If the coefficient is negative, the quality of the model results is smaller than the average value of the measured variables. ME has a range of values from $-\infty$ to 1.
For the evaluation of the quality of the discharges temporal reproduction, the Index of Agreement is used. Index of Agreement (*IA*) according to Willmott (1981) is calculated as:

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

It varies from 0 to 1, with higher values indicating better agreement between the model and observations, similar to the interpretation of the coefficient of determination R^2. It represents a decided improvement over the coefficient of determination, but also is sensitive to the extreme values (Legates & McCabe, 1999).
For all of the 3 efficiency coefficients, the value 1 represents the complete agreement of the measured and simulated values.

RESULTS

Observed flow compared to simulated flow during the calibration period

Figure 2 shows the weekly observed and simulated stream flows during the calibration period (2000-2004). This figure is followed by the mean flow value and the model goodness indicators (table 1).

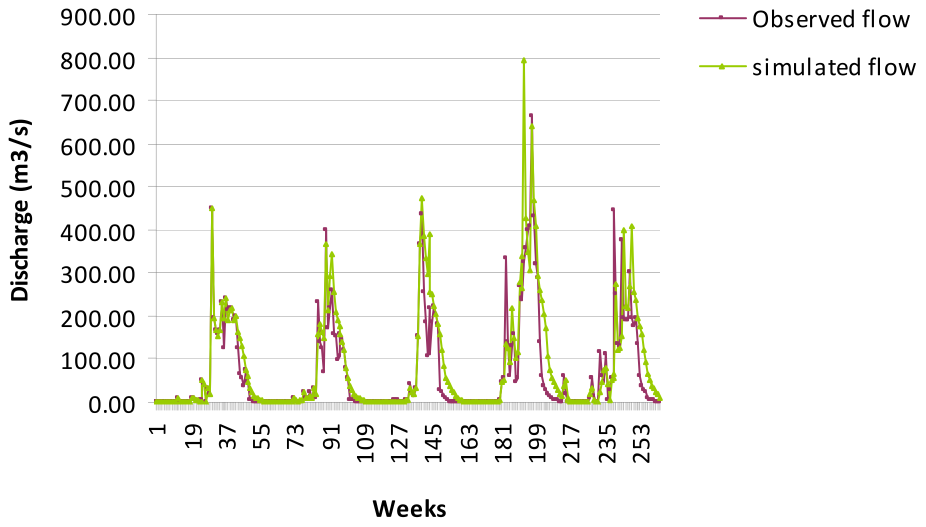

Figure 2: Comparison of the Okpara-Kaboua weekly stream flow

Table 1: Model goodness indicators for the calibration period

Weekly average (m^3/s)		Model goodness indicators		
Observed flow	Simulated flow	R^2	ME	IA
72.38	85.44	0.89	0.81	0.96

The high values of model goodness indicators at the weekly scale (table 1) attest that observed and simulated flows matched well.

Annual water balance

Table 2 summarizes the annual basin values for the water balance.

Table 2: Average annual basin values (2000 – 2004)

Components of water balance	Quantity (mm)
Precipitations	1113.7
Surface runoff	130.17
Lateral flow	3.22
Groundwater flow	165.20
Deep aquifer recharge	50.60
Shallow aquifer recharge	37.22
Transmission loss	2.82
Evapotranspiration	741.5
Potential evapotranspiration	2007.6
Change in soil water storage	-17.03

Evapotranspiration is the primary mechanism by which water is removed from a watershed. From table 2, runoff coefficient is equal to 11.70%, evapotranspiration coefficient is equal to 66.58% and total aquifer recharge coefficient is 22.72 %.
Dingman (1994) estimated that about 62% of the precipitation that falls on the continent is evapotranspired. Evapotranspiration exceeds runoff in most watersheds and in all continents except Antarctica. Sintondji (2005) estimated that runoff coefficient is equal to 11.1% and evapotranspiration is equal to 67.3% in Terou-Igbomakoro catchment. Amoussou (2005) found that potential evapotranspiration exceeds precipitation in Couffo catchment during the period from 1968 to 2000. Giertz et al. (2006) estimated that surface runoff varies from 9.5 to 18.7% in Aguima and Niaou catchments in 2002 and 2003 for annual precipitations comprise between 1145 and 1230 mm. Ahouansou (2008) and Bossa (2007) respectively found in the Oueme-Save and Zou-Atcherigbe catchments 7.8% and 7.3% as surface runoff. The values fund by Ahouansou (2008) and Bossa (2007) are higher than ours. Taking into account the results of those authors about the land use in the précised catchments, it appears that the Okpara-Kaboua catchment is more submitted to deforestation for agricultural purposes. In fact, the rapid creation of agricultural areas leads to the lost of organic matter and increases the surface runoff, the erosion rate and the sediment loading (FAO, 1998).

Observed flow compared to simulated flow during the validation period

During the validation period (2005-2007), the weekly observed and simulated flows matched also well (Fig 3). The assessment of the model prediction with the same model goodness indicators (R^2, ME, IA), is as high as during the calibration period (table 4).

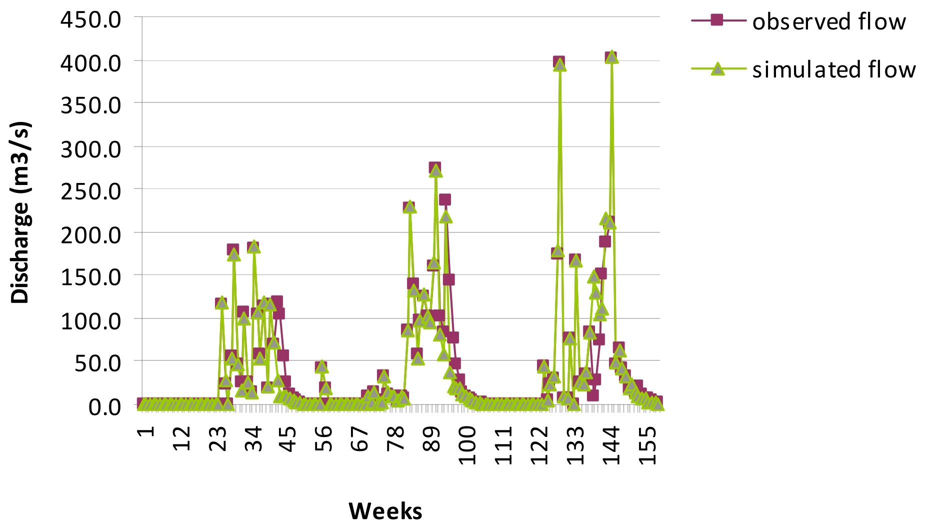

Figure 3: Comparison of the Okpara-Kaboua weekly stream flow

Table 3: Model goodness indicators for the validation period

Weekly average (m^3/s)		Model goodness indicators		
Observed flow	Simulated flow	R^2	ME	IA
50.3	60.6	0.86	0.80	0.95

Annual water balance during validation period

Table 4 summarizes the annual basin values for the water balance.

Table 4: Average annual basin values for the validation period (2005-2007)

Components of water balance	Quantity (mm)
Precipitations	1037.9
Surface runoff	82.96
Lateral flow	2.58
Groundwater flow	128.66
Deep aquifer recharge	39.5
Shallow aquifer recharge	29.67
Transmission loss	2.24
Evapotranspiration	778.0
Potential evapotranspiration	2020.6
Change in soil water storage	-25.71

From table 4, runoff coefficient is equal to 8% and evapotranspiration coefficient is equal to 75%. Evapotranspiration is the primary mechanism by which water is removed from a watershed as remarked during the calibration period.

Sediment loading

The average annual value of 7t/ha/a is obtained for the watershed during the calibration period. This value differs from one sub-basin to another and from one land use to another. The maximum value is recorded on croplands (16.85 t /ha/a) and the minimum value is recorded on bush savannah (0.64 t/ ha/a). Figure 4 shows that erosion is more observed in sub-basins 5, 9 and 10 which cover the cities of Yerimarou, Tchatchou and Tandou.

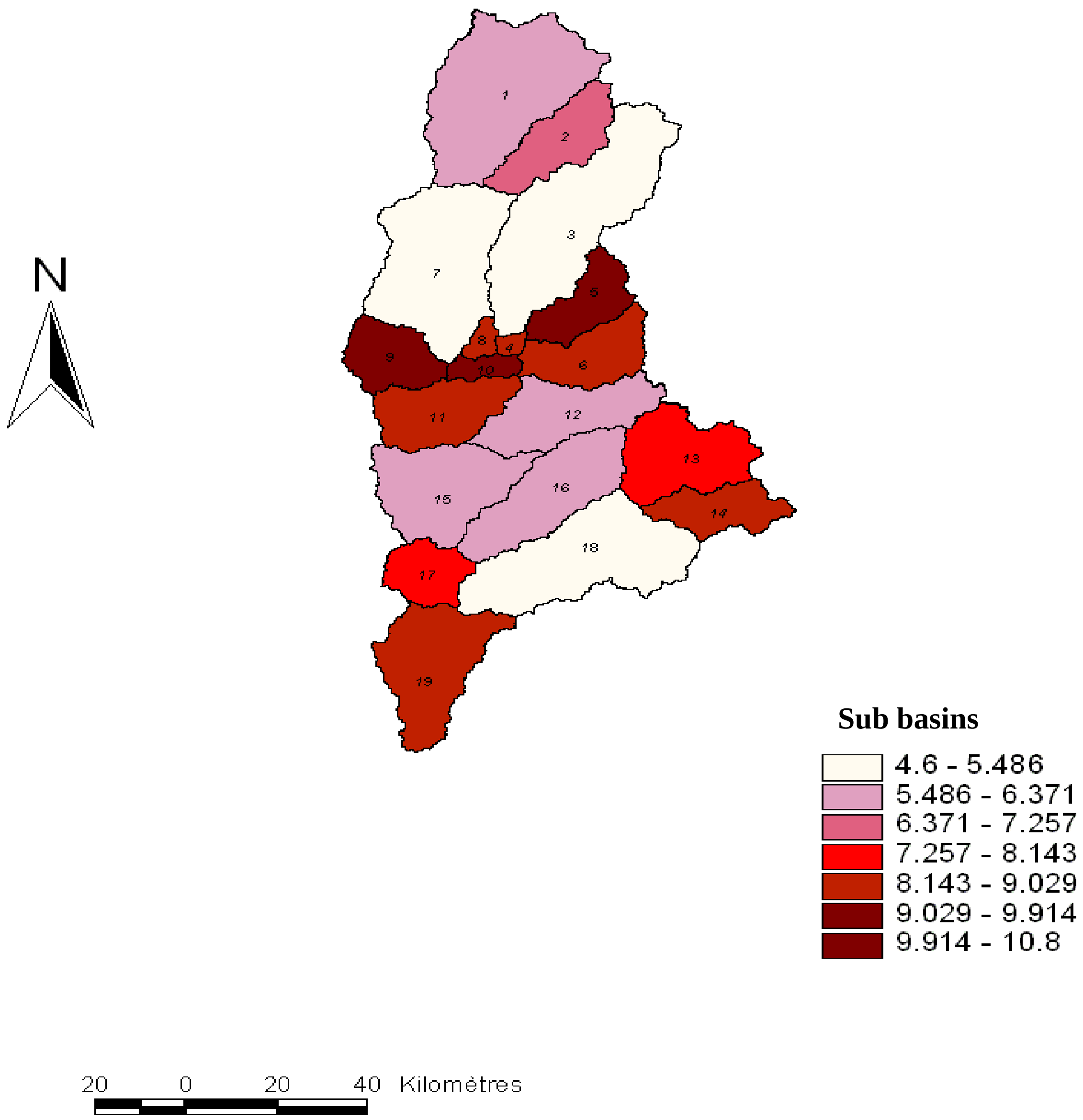

Figure 4: Average erosion rate per year per sub basin during calibration period (2000-2004)

Ahouansou (2008) and Bossa (2007) found respectively in Oueme-Save and Zou-Atcherigbe catchments: 4.4 and 4.3 t/ha for sediment loading. Our values that are higher than theirs are certainly due to the higher surface runoff observed in our study catchment. This higher value of surface run off as we explained before is due to the higher intensity of deforestation for agricultural purposes in our study catchment.

Regarding erosion, figure 5 shows that an average values of 16.36, 5.84 and 11 tonnes per hectare were respectively obtained on rows parallel to hill slope, rows perpendicular to hill slope and in the case of flat ploughing.

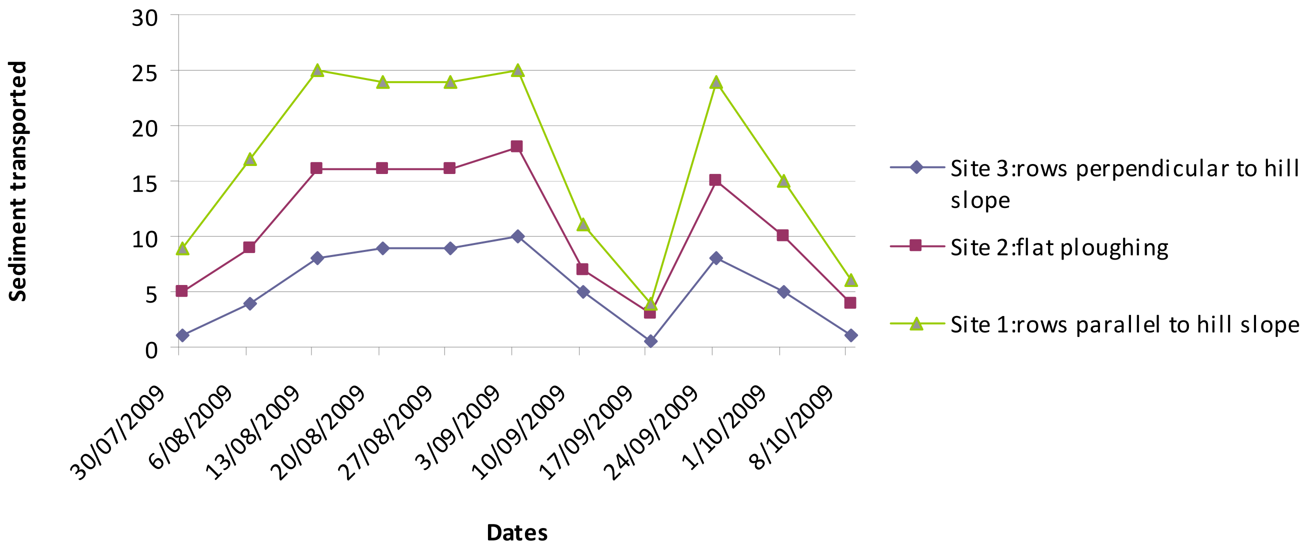

Figure 5: Sediment transported for different agricultural practice.

Period: August – October. (2009)

Regarding suspended sediment (figure 6), it rises with the discharge and varies from 0.067 to 0.17 g/l with an average of 0.11 g/l. These values are similar to those found by Sintondji (2005), Awoye (2007), Bossa (2007) respectively in Terou-Igbomakoro, Klou, Zou-Atcherigbe catchments.

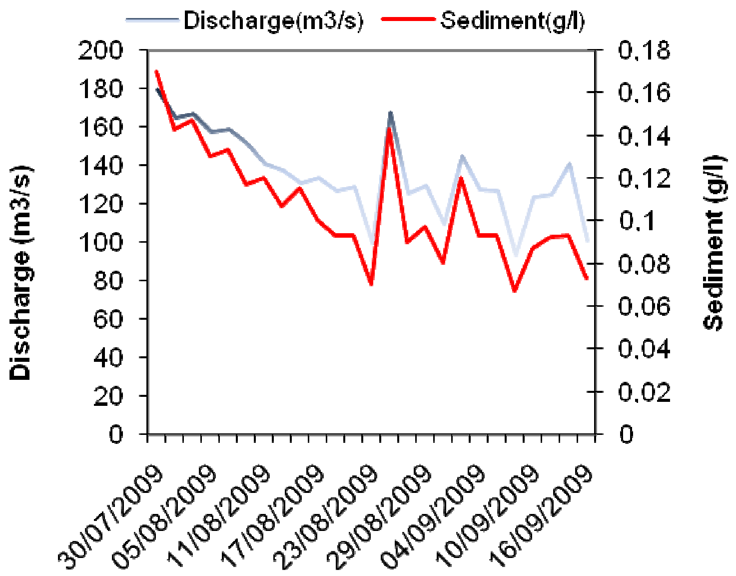

Figure 6 : Suspended sediment at the outlet of the catchment. Period: July to October.(2009)

CONCLUSION

The physical semi-distributed model SWAT helps to assess the water resources in the Okpara-Kaboua catchment. These results could be used for future projection and as basic to take decisions in order to set up hydraulic buildings. The annual surface water is about 1 billion m^3/year. To take benefit from this resource, water reservoirs must be built for agricultural, pastoral and industrial activities. Water stored must be treated for drinking needs and that will reduce the rate of people who is actually suffering from the lack of water and illness related. The availability of aquifer water is also important (3 billion m^3/year). So modern wells with larger diameters equipped with locking device, drilling must be built for aquifers water use. As the erosion rate is high in agricultural sub-basins and is damaging environment, we suggest in those areas the building of dykes, micro-dams, hedges, appropriate agricultural practises, crops association to reduce the sediment transported. In the end, we suggest that further studies should be done to model solute and sediment transport and to assess the impact of climate change and land use dynamic on water resources in the study catchment.

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TABLES WITH CAPTIONS

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FIGURES CAPTIONS

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Figure 5: Sediment transported for different agricultural practice. Period: August – October (2009)

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