Modelling the Hydrological Balance of the Okpara catchment at the Kaboua outlet in Benin

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INTRODUCTION

Rapid population growth associated with industrial development during the last few decades have increased 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 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 will become scarce natural resources which need to be quantified and managed more efficiently. During long time, this quantification was based on a strong assumption, that of climate stationarity which is now not realistic for West Africa where many ruptures of stationarity have been shown (Vissin, 2007). Therefore, an appropriate quantification of water resources at a watershed level should take into account climate variability. This is the main purpose of this study in which we quantify the different components of the hydrological balance in the Okpara-Kaboua catchment taking into account variability of topography, climate, soil, land use and agricultural practices.

MATERIAL AND METHODS

Study area

The study was conducted in the Okpara catchment at Kaboua outlet. It spreads over a total area of 9,461 Km^2 and is located between longitudes 2°31- 3°25 E and latitudes 8°13- 9°57 N. The catchment is characterised by a sudanian climate with 1100 mm as mean annual rainfall and 27° C as mean annual temperature.

SWAT model description

The SWAT model (Soil and Water Assessment Tool) 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). Model components include weather, hydrology, sedimentation, crop growth, nutrients cycling, pesticides dynamics and agricultural management. We used for this study SWAT 2003 model to assess the hydrologic balance in the Okpara-Kaboua basin and sediment yields with regard to the land use.

Hydrologic balance

The hydrologic balance is computed on the basis of the water balance equation:

$$SW_t = SW + \sum_{t=1}^{t} (R_{day} - Q_{surf} - Et_a - W_{seep} - Q_{gw})$$

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_{day} is the amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), Et_a is the amount of evapotranspiration on day i (mm H_2O), Wseep is the amount of water entering the vadose zone from the soil profile on day i (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

Erosion assessment

In this study, we measured soil loss in fields and we also assessed the amount of sediment which arrived at the outlet of the catchment in order to estimate the proportion of sediment loss in field which arrived at the outlet of the catchment.
Measurements of soil loss were performed from July to October 2009 in the sub-basin 19 (where there is the outlet of the catchment) by using sediment traps installed in three different soya plots: one trap in a plot of soya with ridges parallel to the slope, a second in a plot of soya with ridge perpendicular to the slope and a third one in a plot of soya that received flat ploughing. The amount of sediment that arrived at the outlet was estimated with the Modified Universal Soil Loss Equation (William, 1995).

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. 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. The coefficient of determination (R^2), Model Efficiency (ME) of Nash and Sutcliffe (1970) and Index of Agreement (IA) of Willmott (1981) were used to appreciate the model goodness.

RESULTS

Observed flow compared to simulated flow during the calibration period

The model goodness indicators obtained at a weekly period of time appeared significant with 0.89 as coefficient of determination, 0.81 as model efficiency and 0.96 as index of agreement. This indicated an appreciable adjustment between the observed and simulated flows.

Annual water balance

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

Table 4: Average annual basin values (2000 – 2004)

Components of water balance	Quantity (mm)	Proportion of the components related to the precipitation (%)
Precipitations	1113.7	100.00
Surface runoff	130.17	11.69
Lateral flow	3.22	0.29
Groundwater flow	165.20	14.83
Deep aquifer recharge	50.60	4.54
Shallow aquifer recharge	37.22	3.34
Transmission loss	2.82	0.25
Evapotranspiration	741.5	66.58
Potential evapotranspiration	2007.6	-
Change in soil water storage	-17.03	-1.53

From table 4, evapotranspiration was the primary mechanism by which water is removed from the Okpara-Kaboua catchment. It represented 66.58% of the total precipitation while the surface runoff and the groundwater flow approximated respectively 11.69% and 14.83% of the precipitation. The total aquifer recharge (groundwater flow, deep aquifer recharge and shallow aquifer recharge) was roughly 22.72% of the precipitation. The water volume annually produced in the catchment was about 4 billions m^3/a while the needs of its population was roughly 7 millions m^3/a based on the recommendation of FAO (20 litres of water/inhabitant/day).

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. The assessment of the model prediction with the same model goodness indicators (R^2=0.86, ME=0.80, IA=0.95) was as high as during the calibration period.

Annual water balance during validation period

Table 6 summarizes the annual basin values for the water balance.

Table 6: Average annual basin values for the validation period (2005-2007)

Components of water balance	Quantity (mm)	Proportion of the components related to the precipitation (%)
Precipitations	1037.9	100.00
Surface runoff	82.96	8.00
Lateral flow	2.58	0.25
Groundwater flow	128.66	12.40
Deep aquifer recharge	39.5	3.81
Shallow aquifer recharge	29.67	2.86
Transmission loss	2.24	0.22
Evapotranspiration	778.0	74.96
Potential evapotranspiration	2020.6	-
Change in soil water storage	-25.71	-2.48

From table 6, evapotranspiration (74.96% of the precipitation) was the primary mechanism by which water was removed from the watershed as remarked during the calibration period. The surface runoff was about 8% of the precipitation while the groundwater flow and the total aquifer recharge were respectively 12.40% and 19.07% of the precipitation. Both the results of the calibration and the validation period showed that groundwater flow was more important than surface runoff in the Okpara-Kaboua catchment.

Sediment loading

The average annual value of 7t/ha/a was obtained for the watershed during the calibration period. This value differed from one sub-basin to another and from one land use to another. The maximum value was recorded on croplands (16.85 t /ha/a) and the minimum value on bush savannah (0.64 t/ha/a). Regarding the spatial variation of erosion in the study catchment, it appeared that the sub-basins 5, 9 and 10 which were in the district of Tchaourou and which covered the localities of Yerimarou, Tchatchou and Tandou were the most sensitive to erosion (figure 3).

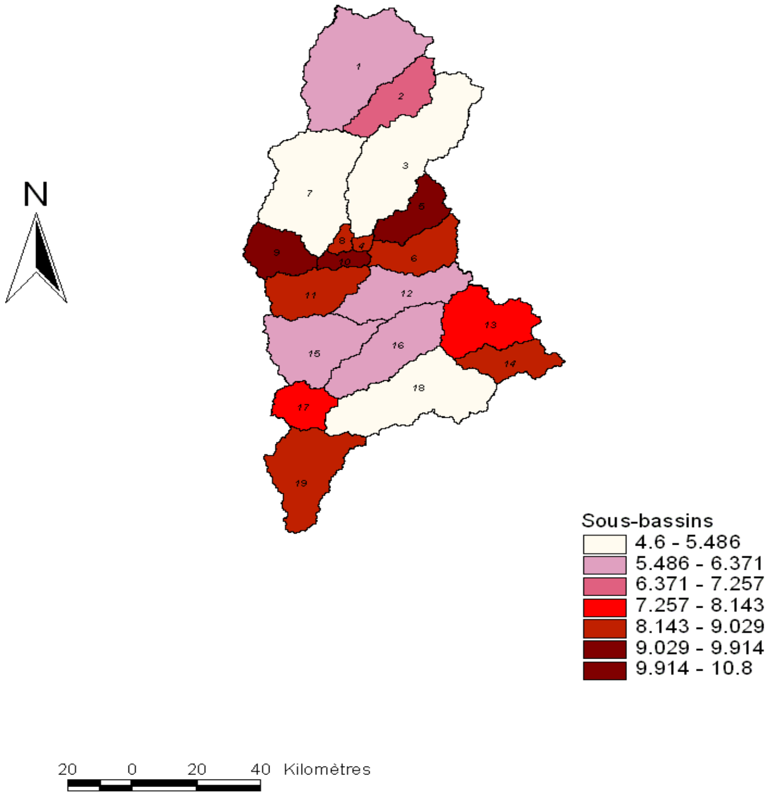

Figure 3: Average erosion rate per year per sub basin during calibration period (2000-2004)

Concerning the sediment transported, it appeared that average values of 16.36, 5.84 and 11 tonnes per hectare were obtained respectively on rows parallel to hill slope, rows perpendicular to hill slope and in the case of flat ploughing (figure 4). The lowest values of sediment transported were obtained from the site where the rows were perpendicular to the slope. The effectiveness of this technique is due to the fact that, arranged perpendicularly to the slope, these ridges reduced the streaming and favored the infiltration of water. On the contrary, in the sites where the ridges were parallel to the slope or where there was no ridge (flat ploughing), water during its streaming did not face any obstacle and its speed and erosivity increased with the slope's length leading to high sediment loss.

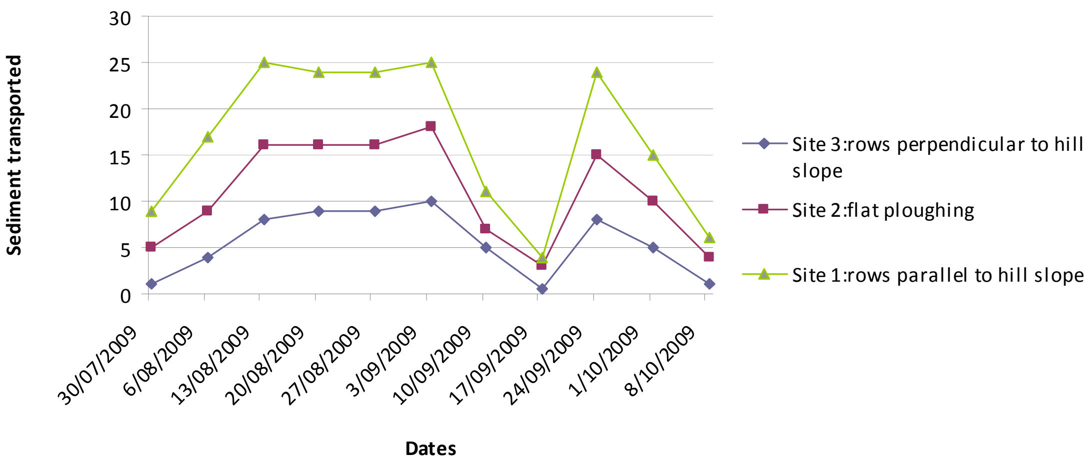

Figure 4: Sediment transported for different agricultural practice. Period: August – October. (2009)

CONCLUSION

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

Arnold J, Srinivasan R, Muttiah R, Williams J (1998) Large area hydrologic modeling and assessment. Part I: Model development. J. American Water Resources Association, 34 (1), p. 73-89.

Nash J.E, Sutcliffe J.V (1970) River flow forecasting through conceptual models part I– a discussion of principles. Journal of Hydrology 10, p. 282 – 290.

Paeth H, Born K, Heuer O (2009) Human activity and future climate. Impetus Atlas of Benin. 13-14p.

Sintondji L (2005) Modelling the rainfall-runoff process in the Upper Ouémé catchment (Terou in Benin republic) in a context of global change: extrapolation from the local to the regional scale. PhD Thesis in Hydrology and Environmental management of the Mathematics and the Natural Sciences Faculty of the University of Bonn. Shaker Verlag GmbH. P.O. Box 101818. D-52018 Aachen Germany.

Speth P, Diekkrüger B, Christoph M (2002) IMEPTUS West Africa–An integrated approach to the efficient management of scarce water resources in West Africa. In: GSF (Hrsg.): German Programme on Global Change in the Hydrological Cycle (Phase I, 2000-2003), Status Report.

Vissin E. W (2007) Impact de la variabilité et de la dynamique des états de surface du bassin versant du fleuve Niger. Thèse de doctorat, Université de Bourgogne, CRC, Dijon, 310 p.

Williams J.R (1995) Chapter 25. The EPIC Model. In Computer Models of Watershed Hydrology. Water Resources Publications. Highlands Ranch, CO. p. 909-1000.

Willmott C.J (1981) On the validation of models. Physical Geography 1, S. 184 – 194.