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



Luc Ollivier Sintondji
University of Abomey-Calavi


Elliott Ronald Dossou-Yovo
Africa Rice Center (Africarice)

*International Journal of AgriScience Vol. 3(3): 182-197, March 2013* *www.inacj.com*
*ISSN: 2228-6322© International Academic Journals*

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

**Sintondji Luc O.*, Dossou-Yovo Elliott R., Agbossou Kossi E.**
*Laboratory of Hydraulics and Water Control, Faculty of Agronomic Sciences, University of Abomey-Calavi, Benin.*
**Author for correspondence (email: o_sintondji@yahoo.fr)*

Received December 2012; accepted in revised form February 2013

## ABSTRACT

Rapid population growth and industrial development create problems with water management that can lead to contamination and scarcity of water resources. The primary aim of the modeling in this study was to assess annual renewal rates of water resources and erosion rates in the Okpara catchment at the Kaboua outlet. The SWAT 2003 model was selected as the most appropriate for the purpose of this study; it was calibrated and validated for the study basin. Digital elevation model, daily climatic data for 1968-2007, soil and land use maps, physical characteristics of soil, physical parameters of crops were all incorporated in the model that divided the whole catchment in to sub-basins and Hydrological Responses Units (HRU). Calibration and validation of data demonstrated that precipitation in the watershed was 1,075.8 mm/a. Surface runoff was 106.6 mm/a (10% of precipitation), and the total recharge of aquifers was 225.4 mm/a (21% of precipitation). The actual rate of evapotranspiration was 759.8 mm/year (71% of precipitation). The total volume annually produced in the catchment was about 4 billions $m^3$; this amounted to more than 500 times the needs of the population, but paradoxically it still suffered from severe water scarcity. Regarding erosion, an average value of 7t/ha/year was obtained for the watershed with a maximum value for cropland (16.85t/ha/a) and the minimum value for bushed savannah (0.64t/ha/a). Moreover, agricultural practices most susceptible to reduce soil loss were those ridges perpendicular to a slope. Based on these results, some suggestions were made for more sustainable use of land and water resources in the catchment.

***Keywords*****:** *Erosion, Hydrological Balance, Modelling, Okpara, SWAT model*

## INTRODUCTION

Rapid population growth and industrial development during the last few decades have caused increasing pressure on land and water resources in most regions of the world (Abbott and Refsgaard 1996). Population growth increases the demand for domestic water consumption, agriculture and other uses particularly in countries that are heavily 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 by 2025 about 25% of the world's population will suffer from severe water scarcity. For Africa, some estimates suggest that the current amount of fresh water available per capita is only about a quarter of that in 1950 and that the supply of fresh water could become problematic especially in West Africa, a region that has experienced about 35 years of drought (Speth et al. 2002). In this context, Benin has recorded a 10% decrease in precipitation and a 40% decrease in surface water from 1955 to 1992 indicating that surface water resources decrease four times more rapidly than precipitation (Vissin 2007). Moreover, from 2001 to 2050, precipitation in Benin is set to decrease by 25-30% (Paeth et al. 2009). This may lead to drought for most surface water in the country. For these reasons, water resources will become a scarce natural resource and as such must be managed more efficiently.

According to the report of the Benin Water Ministry in 2009, Benin republic has a lot of water resources which, if well managed will help to meet the needs of its population in the medium and long terms. Unfortunately current overuse of water resources constitutes a serious threat that demands they be protected and preserved for future generations. In the particular case of the Okpara catchment at the Kaboua outlet where this study was conducted, one water hole was used by about 604 inhabitants, this was more than double the recommended standard of 250 inhabitants per waterhole. Due to population growth and multiple water use water resource managers face many problems such as pollution, mismanagement and scarcity (Vissin 2007). Sustainable water resource management requires the use of scientific data to accurately determine specifications for hydraulic structures and for a definition of the annual rate of water exploitation that needs to take into account the annual rate of water renewal. In this context, it is important to quantify the various components of the hydrological balance and the annual renewal of water resources. For a long time, this quantification has been based on the assumption of a stable climate. However, it is now apparent that this assumption is not realistic for West Africa. Climate analyses show ruptures in this stationary pattern throughout many areas of tropical Africa (Janicot and Fontaine 1993, Moron 1993) and particularly in Benin (Perard and Bokonon-ganta 1993, Boko and Adjovi 1994, Houndenou 1999, Vissin 2007).

Therefore, an appropriate quantification of water resources at watershed level should take into account climate variability but also spatial variability of the hydrological components. The main purpose of this paper was to 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. Results from this study will be useful to determine proper specifications for hydraulic constructions such as dams, wells and drilling and to avoid overexploitation of water resources.

## MATERIAL AND METHODS

### Study area

Located in West Africa, Benin has a dense hydrographic network, with river Oueme as its most important resource (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 9,461 $Km^2$ and is located between longitudes 2°31- 3°25 E and latitudes 8°13- 9°57 N. The Okpara-Kaboua catchment is characterised by a subequatorial climate in its southern area. But this climate has changed in recent years to a Sudanian climate, which is characteristic of 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°C and 30°C. The major soil types are tropical ferruginous soil, alluvial soil and raw mineral soil. The vegetation is dominated by bush land with much agricultural activity.

### Data

Data used in this study was supplied from:

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), derived the overland and channel slopes and lengths, the surface time of concentration, flow direction and other properties for each sub basin.

The digital land use/ land cover maps in a 300×300 m resolution of the catchment.

Climate data were obtained from two sources: Benin National Meteorology Direction (DMN) and French Project IRD (Institut de Recherche pour le Développement) gauged stations. These institutions had recorded data for rainfall, climatic parameters and stream runoff for several areas in the watershed over several years. For Okpara-Kaboua watershed, six (06) rainfall recorded data stations were used (Bembèrèkè, Nikki, Parakou, Tchaourou, Ouèssè and Savè), from which two (02) stations were considered as synoptic stations (Parakou and Savè).

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

For synoptic stations, the monthly average daily precipitation, its standard deviation and skew coefficient were calculated for 40 years as well as average daily maximum and minimum temperatures and dew point. Regarding solar radiation and wind, average monthly daily values were calculated for 30 years. At last, the other 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; probabilities of a wet day following a dry day and a wet day following a wet day for every month were obtained for a period of 10 years.

Data on discharge from the hydrometrical station of Kaboua (outlet of the watershed) were used for model calibration and validation.

The digitized soil map of the catchment on the scale of 1:200,000 was used.

**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 forecast the impact of land management practices on water, sediment and agricultural chemical yield in large, complex watersheds with varying soil, land use and management conditions over long periods of time.

Model components included weather, hydrology, sedimentation, crop growth, nutrient cycles, pesticide dynamics and agricultural management. The SWAT 2003 model was used in this study to assess the hydrologic balance in the Okpara-Kaboua basin, particularly which of spatial variation of runoff and sediment yield with regard to land use.

This SWAT model first partitions a watershed into sub basins that allow for consideration of land use and the impact of soil properties on hydrology. Then, the model subdivides the previous partitions in Hydrologic Response Units (HRU), which are lumped land areas within a sub basin and that have unique combinations of land cover, soil and management.

SWAT has been applied in several studies on basin scale involving assessment of water supply and nonpoint source pollution in the

United States. The results of SWAT application have been documented for hydrologic simulation in all river basins in the United States (Arnold et al. 1999). Several other studies have been done 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 2005, Bossa 2007, Awoye 2007, Ahouansou 2008) that indicate the strength of the SWAT model in simulating stream flow and sediment movement in large basins.

**Hydrologic balance**

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 below:

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

Where *SW*t is the final soil water content (mm H2O), *SW* is the initial soil water content on day *i* (mm H2O), *t* is the time (days), *Rday* is the amount of precipitation on day *i* (mm H2O), *Qsurf* is the amount of surface runoff on day *i* (mm H2O), *Eta* is the amount of evapotranspiration on day *i* (mm H2O), Wseep is the amount of water entering the vadose zone from the soil profile on day *i* (mm H2O), and *Qgw* is the amount of return flow on day *i* (mm H2O).

Hydrologic processes can be grouped in terms of five steps: precipitation, interception, surface runoff, soil and root zone infiltration, evapotranspiration and ground water flow (Sintondji 2005).

**Surface runoff**

Surface runoff occurs whenever the rate of water application to the ground surface exceeds the rate of infiltration. SWAT provides two methods for estimating surface runoff: the Soil Conservation Service (SCS) curve number procedure (SCS 1972) and the Green and Ampt's infiltration method (Green and Ampt 1911). The latter required intensive data compared to the SCS curve number method, which is simpler (Fontaine et al. 2002). The SCS curve number method was chosen to estimate the surface runoff because only data for daily rainfall were available. It is a commonly used method (Dingman 1994, Arnold et al. 1998, Lukman 2003, Sintondji 2005).

However, one should recognize that, at the difference of the Green-Ampt method, the SCS curve number just lumps canopy interception in the term for initial abstraction.

The SCS curve number main equation is:

$$Qsurf = \frac{(Rday - Ia)^2}{(Rday - Ia + S)}$$

Where Qsurf is the accumulated runoff (mm), *Rday* is the rainfall depth for the day (mm), *Ia* is the initial abstractions (surface storage, canopy interception, infiltration prior to runoff), and

*S* is the retention parameter.

The retention parameter (S) is function of Curve Number (CN) for the day:

$$S = 25.4\ (\frac{1000}{CN} - 10)$$

The CN are provided by the tables (SCS Engineering Division 1986) taking account of soil infiltration rate when thoroughly wetted (Ks), and slope adjustments (Williams 1995). The initial abstractions (Ia) is commonly approximated as 0.2xS (Neitsch 2001).

**Evapotranspiration**

Evapotranspiration is a collective term that includes all processes by which water at the earth's surface is converted to water vapor. This expression combines evaporation and transpiration. Evaporation refers to "evaporation from open water systems, like natural lakes and man-made pools and reservoirs, flowing streams, bare soil with water tables at or close to the land surface, and impervious surfaces like roofs and roads". Evaporation from vegetated land surfaces, forests and woodland, where evaporation is accompanied by transpiration is referred to as evapotranspiration (Shahin 2002).

Evaporation is ranked under the category of water loss defined as the difference between the total precipitation and the total runoff from a given area (Wisler and Brater 1957). An accurate estimation of evapotranspiration is critical in the assessment of water resources (Neitsch 2001).

**Evapotranspiration assessment**

Three methods of evapotranspiration (ET) were incorporated into SWAT: the Penman-Monteith method (Monteith 1965, Allen 1986, Allen et al. 1989), the Priestley-Taylor method (Priestley and Taylor 1972) and the Hargreaves method (Hargreaves et al. 1985). The Penman-Monteith method is the more complete, and as such was chosen for use in this study. It is as follows:

$$\lambda E = \frac{\Delta \cdot (H_{net} - G) + \rho_{air} \cdot C_p \cdot \left|e_z^0 - e_z\right| / r_a}{\Delta + \gamma \cdot (1 + r_c / r_a)}$$

Where λ*E* is the latent heat flux density (MJ $m^{-2}$ $d^{-1}$), E is the depth rate evaporation (mm $d^{-1}$), Δ is the slope of the saturation vapor pressure-temperature curve, *de/dT* (kPa °$C^{-1}$), $H_{net}$ is the net radiation (MJ $m^{-2}$ $d^{-1}$), G is the heat flux density to the ground (MJ m-2 d-1), $\rho_{air}$ is the air density (kg m-3), cp is the specific heat at constant pressure (MJ $kg^{-1}$ °$C^{-1}$), $e^o_z$ is the saturation vapour pressure of air at height *z* (kPa), $e_z$ is the water vapour pressure of air at height z (kPa), γ is the psychrometric constant (kPa°$C^{-1}$), $c_r$ is the plant canopy resistance (s $m^{-1}$), and $r_a$ is the diffusion resistance of the air layer (aerodynamic resistance) (s $m^{-1}$).

For well-watered plants under neutral atmospheric stability and assuming logarithmic wind profiles, the Penman-Monteith equation may be written as follows (Jensen et al. 1990):

$$\lambda E = \frac{\Delta \cdot (H_{net} - G) + \gamma.k1.(0.622.\lambda.\rho_{air} / P).\left|e_z^0 - e_z\right| / r_a}{\Delta + \gamma \cdot (1 + r_c / r_a)}$$

Where λ is the latent heat of vaporization (MJ $kg^{-1}$), $E_t$ is the maximum transpiration rate (mm $d^{-1}$), $k_1$ is a dimension coefficient needed to ensure that the two terms in the numerator have the same units (for *uz* (wind speed) in m $s^{-1}$, $k_1 = 8.64 \times 10^4$), and P is the atmospheric pressure (kPa).

**Soil water**

Water maintained in the soil profile after infiltration can flow under saturated or unsaturated conditions. In saturated soil, flow is driven by gravity and usually occurs in a downward direction. Unsaturated flow is caused by gradients that arise due to adjacent areas of high and low water content. Unsaturated flow may occur in any direction. SWAT directly simulates saturated flow if the water content is superior to the field capacity. The model records water contents of soil layers (min: 1 and max: 10) but assumes that the water is uniformly distributed within a given layer. Unsaturated flow between layers is indirectly modeled with the depth distribution of plant water uptake and the depth distribution of soil water evaporation. Water is allowed to percolate from one layer if the water content exceeds the field capacity for water content at that layer. The amount of water that moves from one layer to an underlying layer is calculated using storage routing methodology. The equation used to calculate the amount of water that percolates to the next layer was as follows:

$$W_{perc,ly} = SW_{ly,excess}\left(1 - e^{\left[\frac{-\Delta t}{TTperc}\right]}\right)$$

where $W_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm $H_2O$), $SW_{ly,excess}$ is the drainable volume of water in the soil layer on a given day (mm $H_2O$), $\Delta t$ is the length of the time step (hours), and $TT_{perc}$ is the travel time for percolation (hrs).

**Groundwater**

SWAT simulates two aquifers in each sub basin. The shallow aquifer (unconfined aquifer that contributes to flow in a main channel or reach of a sub basin) and the deep aquifer (confined aquifer). Water that enters the deep aquifer is assumed to contribute to stream flow somewhere outside of the watershed (Arnold et al. 1993). Water leaves groundwater storage either by discharge into rivers / lakes or by upward movement from the water table into the capillary fringe. It can also leave by seepage to the deep aquifer. The contribution of ground water to stream flow is simulated by creating a shallow aquifer storage that is recharged by percolation from the unsaturated zone and that discharges to the reach of the sub basin. The water balance for the shallow aquifer is:

$$aq_{sh,i} = aq_{sh,i-1} + W_{rchrg} - Q_{gw} - W_{revap} - W_{depp} - WU_{sa}$$

where $aq_{sh,i}$ is the shallow aquifer storage on day $i$ (mm$H_2O$), $aq_{sh,i-1}$ is the shallow aquifer storage on day $i$-1 (mm$H_2O$), $W_{rchrg}$ is the recharge entering the aquifer on day $i$ (mm $H_2O$), $Q_{gw}$ is the groundwater flow or base flow into the main channel on day $i$ (mm$H_2O$), $W_{revap}$ is the amount of water moving into the soil zone in response to water deficiencies on day $I$ (mm $H_2O$), $W_{deep}$ is the amount of water percolating from the shallow aquifer into the deep aquifer on day $i$ (mm $H_2O$) and $WU_{sa}$ is the amount of water used from the shallow aquifer (mm).

**Erosion assessment**

Soil erosion by water is important because loss of topsoil can greatly accelerate the deterioration of physical and chemical properties of soil and seriously affect soil fertility and affect crop production. Transported sediment can also reach the stream and increase turbidity and silting. In this study, soil loss in fields was measured and the amount of sediment which arrived at the outlet of the catchment was determined in order to estimate the proportion of sediment loss in a field at the outlet of the catchment.

Measurements of soil loss were taken from July to October 2009 in sub-basin 19 (at the outlet for the catchment) using sediment traps. These traps were installed in those fields with slope close to the average slope of the basin (3.5%). In total, three sediment traps (length 0.75 m, width 0.30 m and height 0.30 m) were 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 a ridge perpendicular to the slope and a third one in a plot of soya that maintained flat plugging.

The bottom of each sediment trap was perforated with very small holes to allow water to seep into the ground, protected by a fine mesh screen that retained sediment. The trap was inserted into a hole of the same size, so that the upper edges were flush with the ground in order not to affect cohesion of the soil. Sediment traps were installed at the lowest part of the plot precisely at the section that received all the water falling into the plot.

After each rainfall event, fresh weight of the trapped sediment was recorded for each plot using a spring balance. After drying the fresh soil samples in the sun, some samples were collected and placed in an oven in the laboratory. After measuring dry weight of the samples, the equivalent of sediment loss in each plot was determined in tons per hectare. This technique has been used to measure soil loss in fields with different crops (cotton, maize, yam) and tillage systems (lines, mounds), and in conditions of natural savannah (Junge 2004).

Measurements were not recorded for amounts of sediment to arrive at outlets, but estimates were made using the following Modified Universal Soil Loss Equation (William 1995).

$$Sed = 11.18\ (Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0,56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG$$

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), $K_{USLE}$ 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.

**Sub basins and Hydrological Response Unit (HRU) discretisation**

Several discretisation scenarios were performed with different thresholds for minimum draining areas defining a stream, land use and soil percentage to perform the HRU. Table 1 shows the final scenario used during this study for partitioning the Okpara-Kaboua watershed. It should be mentioned that an increase in the number of HRU makes it possible to take into account more types of land use and soil. Moreover, the maximum possible HRU evaluation obtainable from the SWAT 2003 model is 67; and this was achieved after the discretisation of the Okpara-Kaboua catchment.

**Model calibration and validation**

The time period from 1999-2007 was used for simulation in the model. The first year of the simulation was used as a model “warm-up”, for the first simulation period when the model’s conditions stabilized. The year 1999 was therefore omitted from final comparisons of final results. The results reported in this study for various simulations consisted of data for the time period from 2000-2004 for calibration and 2005-2007 for model validation.

To determine a base flow recession constant, a base flow automated digital filter program (Arnold et al. 1999, Arnold and William 1995) was used to separate the base flow and runoff portions of flow from the measured stream flow data obtained for the study area. Firstly, adjustment of surface runoff was simulated with the observed values and secondly for base flow.

A parameter sensitivity analysis was performed automatically for the possible ranges of each of the 27 parameters applied to the model; the following parameters were determined as the most sensitive for the Okpara-Kaboua catchment:

Sol_AWC (Soil Available Water Content)
CN2 (SCS runoff curve number for moisture condition)
Gwqmn (Threshold water depth in the shallow aquifer for flow (mm))
Rchrg_dp (Deep aquifer percolation fraction)
Sol_Z (Soil depth (mm))
Esco (Soil evaporation compensation factor)
Sol_K (Soil saturated hydraulic conductivity)
Gw_revap (Groundwater revap coefficient)
Slope (Average slope steepness)
Alpha_bf (Baseflow recession constant)
Gw_delay (Groundwater delay time)
Surlag (Surface runoff lag coefficient)
Revapmn (threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm $H_2O$))

These parameters were thus calibrated. Manual calibration was carried out based on a trial and error. Parameters were changed until the simulated runoff and base flow showed good agreement with the observed values. The setting values for the modified parameters that reproduced the hydrological components of the Okpara-Kaboua catchment with the best accuracy are presented in Table 2.

***Table 1.*** Okpara-Kaboua catchment discretisation

| Sub basin threshold [ha] | Number of sub basins | HRU threshold [%] land use/ soil | Number of HRU |
|---|---|---|---|
| 19.40 | 19 | 26/13 | 67 |

***Table 2***. Surface runoff and groundwater parameters calibrated

| Parameters | Initial value | Final value | Effect on the simulation |
|---|---|---|---|
| CN2 | 80 | 75 | Decrease the surface runoff |
| ESCO | 0.95 | 0.01 | Increase evapotranspiration |
| Gw_revap | 0.02 | 0.2 | Increase the water transfer from shallow aquifer to the root zone |
| Revapmn (mm) | 1.0 | 15 | Decrease the water transfer from shallow aquifer to the root zone |
| Rchrg_dp | 0.05 | 0.2 | Increase the deep aquifer recharge |
| Gwqmn (mm) | 0 | 10 | Increase shallow aquifer flow |
| Gw_delay (day) | - | 31 | Increase the lag between the time that water exits the soil profile and enters the shallow |
| Alpha_bf | - | 0.048 | Increase the response of the aquifer flow |
| Surlag | 4 | 1 | Decrease surface runoff time and decrease erosion rate |

**Evaluation of model goodness**

The coefficients used to appreciate the model goodness were the coefficient of determination ($R^2$), Model Efficiency (Nash and Sutcliffe 1970) and Index of Agreement (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 observed data that can be explained by the model. It ranged from 0.0 to 1.0 with higher values indicating better agreement.

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

With: *Oi*: observed data, *Pi*: simulated data $\bar{O}$ : observed mean, $\bar{P}$ : simulated mean, *N*: number of compared values.

Model Efficiency (ME) indicates how well the plot of an observed value versus a simulated value fits the 1:1 line. Estimation efficiency is commonly used in hydrologic model evaluation and is calculated through the equation beyond:

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

If the measured variable is simulated most accurately by the model, then ME = 1. If the coefficient is negative, the quality of the model's result is smaller than the average value of the measured variables. ME has a range of values from $-\infty$ to 1.

For evaluation of the quality of the discharges temporal reproduction, the Index of Agreement is used. Index of Agreement (*IA*) is calculated as:

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

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 is also sensitive to extreme values (Legates and McCabe 1999). For all of the 3 efficiency coefficients, value 1 represented complete agreement of measured and simulated values.

## RESULTS AND DISCUSSION

**Observed flow compared to simulated flow during the calibration period**

Figure 1 shows evaluations for weekly observed and simulated stream flow during the calibration period (2000-2004). The model goodness indicators were obtained at weekly intervals (Table 3) and 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 observed flow and simulated flow. Goodness indicators for weekly values (Table 3) indicated that observed and simulated flows matched well.

**Annual water balance**

Table 4 summarizes the annual basin values for water balance.

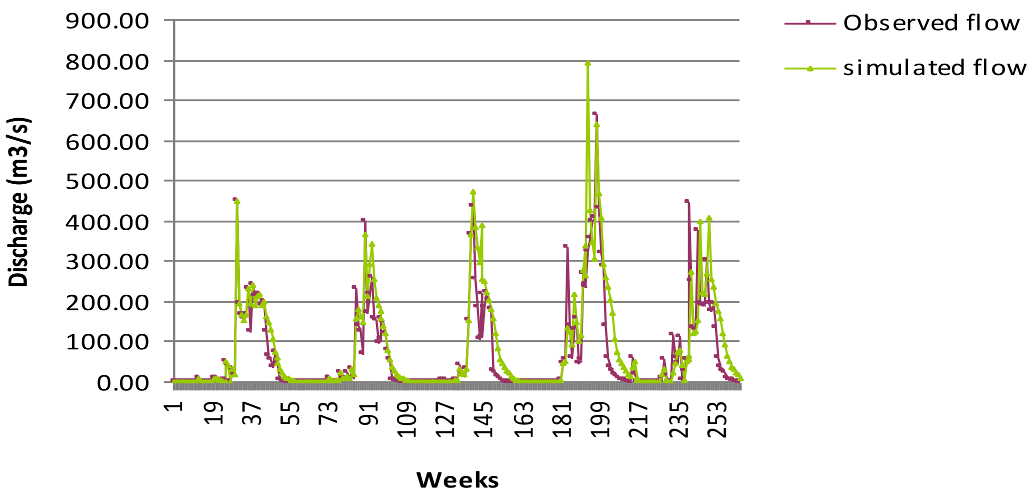


***Fig.1***. Comparison of the Okpara-Kaboua weekly stream flow for the calibration period

***Table 3.*** 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 |

***Table4.*** 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 |

Table 4 shows that evapotranspiration was the primary mechanism by which water was removed from the Okpara-Kaboua catchment. It represented 66.58% of the total precipitation, while percentages of precipitation for surface runoff and groundwater flow were 11.69% and 14.83% respectively. The total aquifer recharge (groundwater flow, deep aquifer recharge and shallow aquifer recharge) accounted for roughly 22.72% of precipitation. The water volume annually produced in the catchment was about 4 billions $m^3$/a while demand to meet the needs of its population was roughly 7 million $m^3$/a based on the recommendation of FAO (20 litres of water/inhabitant/day).

Similar results have been reported in other research (Dingman 1994, Sintondji 2005, Giertz et al. 2006). Evapotranspiration is about 62% of the precipitation that falls on the continent and it exceeds runoff in most continents except for Antarctica (Dingman 1994). The runoff coefficient was 11.1% and evapotranspiration was 67.3% in the Terou-Igbomakoro catchment (Sintondji 2005). Surface runoff varied from 9.5 to 18.7% in Aguima and Niaou catchments in 2002 and 2003 for annual precipitation levels between 1145 and 1230 mm (Giertz et al. 2006).

However, other research showed results contrary to the findings of this study. Surface runoff was 7.3% in the Zou-Atcherigbe catchment (Bossa 2007) and 7.8% in the Oueme-Save catchment (Ahouansou 2008). These values for surface runoff were lower than those recorded in this study, this may be explained by the fact that the Okpara-Kaboua catchment had undergone more deforestation to clear land for agricultural purposes than the two other catchments. Indeed, while agricultural land represented 66.11% of the Okpara-Kaboua catchment, it amounted to percentages of 38.24% and 42.10% of Oueme-Save and Zou-Atcherigbe catchments respectively. Therefore, the rapid creation of agricultural areas in the Okpara-Kaboua catchment compared to the other catchments led to loss of organic matter and increased surface runoff.

**Observed flow compared to simulated flow during the validation period**

During the validation period (2005-2007), the weekly observed and simulated flows matched well (Fig 2). Assessment of the model's predictions with the same model goodness indicators ($R^2$, ME, IA) was as high as those during the calibration period (Table 5).

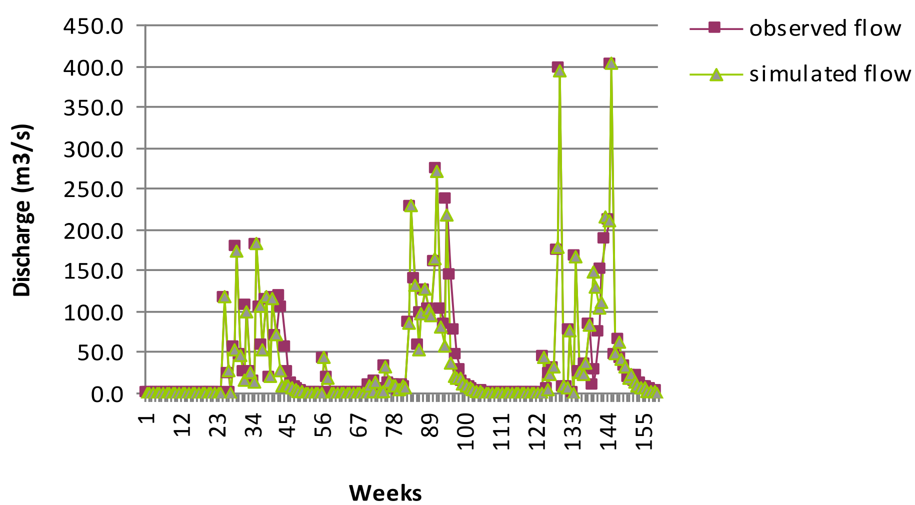


***Fig. 2.***Comparison of the Okpara-Kaboua weekly stream flow for the validation period

*Table 5.* 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 6 summarizes the annual basin values for water balance.

Table 6 shows that evapotranspiration (74.96% of the precipitation) was the primary mechanism by which water was removed from the watershed during the calibration period. Surface runoff was about 8% of the precipitation and percentages of precipitation for groundwater flow and total aquifer recharge were 12.40% and 19.07% respectively.

Results of calibration and for the validation period both 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 for cropland (16.85 t /ha/a) and the minimum value for bush savannah (0.64 t/ ha/a). Regarding the spatial variation of erosion in the study catchment, it appeared that sub-basins 5, 9 and 10, which were located in the district of Tchaourou and covered the localities of Yerimarou, Tchatchou and Tandou were the most sensitive to erosion (figure 3).

Some authors found lower values for sediment loading: 4.4 t/ha in Oueme-Save catchment (Ahouansou 2008) and 4.3 t/ha in Zou-Atcherigbe catchment (Bossa 2007). The higher values obtained in catchment of this study were certainly due to higher amounts of surface runoff as a consequence of higher intensity of deforestation for agricultural purposes in the area.

Concerning sediment transported through the traps; 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 ploughed land (figure 4). The lowest values for transported sediment were obtained from the site where rows were perpendicular to the slope. The effectiveness of this technique was due to the fact that, arranged perpendicularly to the slope, these ridges reduced streaming and favored the infiltration of water. On the contrary, on sites where ridges were parallel to the slope or where there was no ridge (flat ploughing), water during streaming did not face any obstacles so its speed and thus power of erosion increased according to slope length, which led to high sediment loss.

***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 |

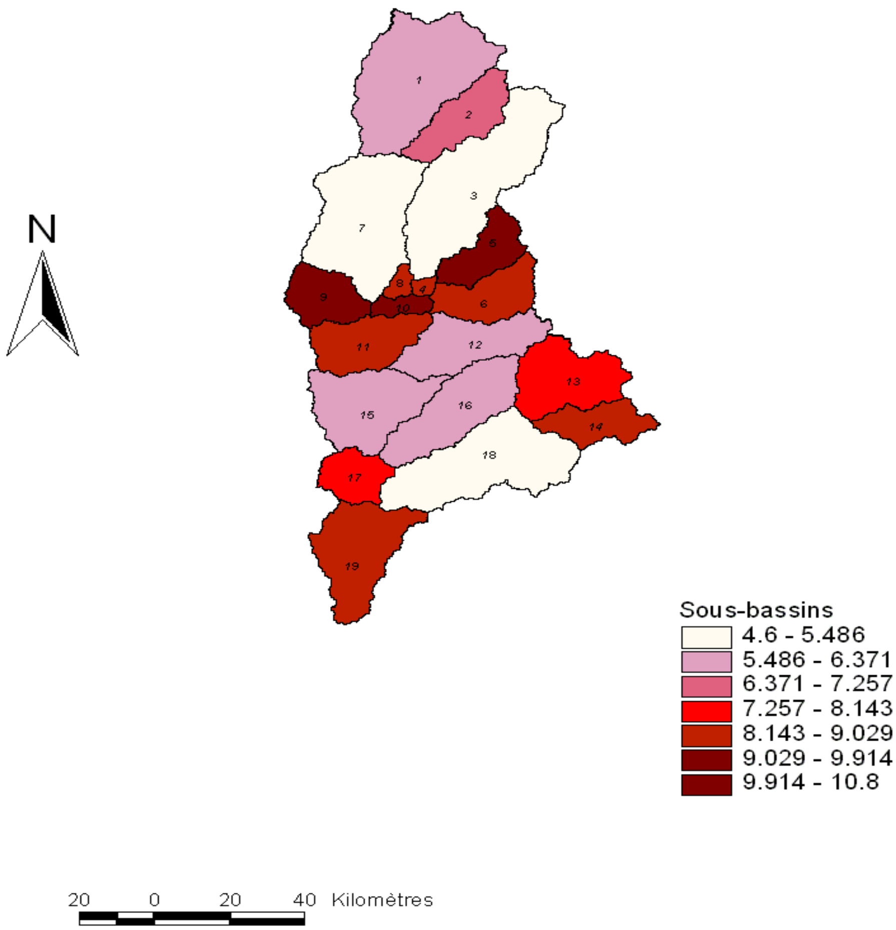


***Fig. 3.*** Average erosion rate per year per sub basin during calibration period (2000-2004)

Some measurements indicated 23 tones/ha, 10 tones/ha and 17 tones/ha in three fields of cotton where agricultural practices were ridge parallel to the slope, ridge perpendicular to the slope and flat ploughing respectively (Bossa 2007). These values, which are higher than those of this study, may be explained by the fact that measurements in this study were taken in soya fields while those of Bossa (2007) were taken in cotton fields. Indeed, soya plants have a high leaf area index and basal leaves (Schori et al. 2003) and are thus categorized as cover plants as are bean and peanut. These plants protected the soil's surface with their litter or vegetative cover and reduced sediment loss from streaming (Roose 1994).

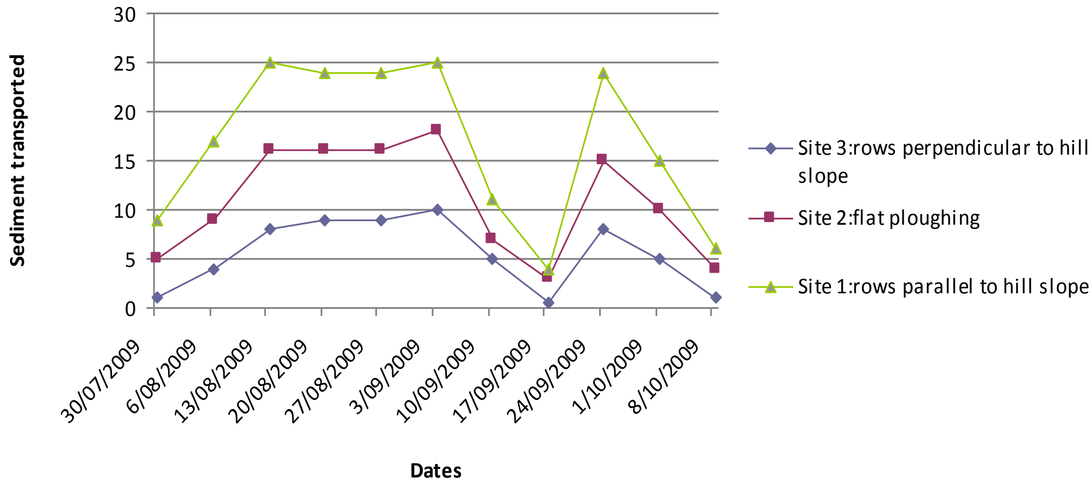


***Fig.4.*** Sediment transported for different agricultural practice (t/ha). Period: August – October. (2009)

## CONCLUSION

The physical semi-distributed model SWAT helped to assess the state of water resources in the Okpara-Kaboua catchment. These results could be used for future projections and as a basis to make decisions concerning hydraulic buildings. The annual surface water was about 1 billion $m^3$/year. To benefit from this resource, water reservoirs should be built for agricultural, pastoral and industrial activities. Stored water for domestic consumption should be treated to reduce human suffering from a lack of water and related illnesses. The availability of aquifer water was also important (3 billion $m^3$/year). So modern wells with larger diameters equipped with locking a device, drilling should be done to use water from aquifers. As the erosion rate was high in agricultural sub-basins and was damaging to the environment, it is suggested that dykes are built in those areas as well as micro-dams, hedges, appropriate agricultural practises such as planting crops that reduce the transportation of sediment. Finally, it is suggested that further studies should be done to model solute and sediment transportation and to assess the impact of climate change and land use dynamics on water resources in the study catchment.

## ACKNOWLEDGMENTS

This work was supported by the Netherlands's Project for the Institutional Reinforcement of Higher Education.

## REFERENCES

Abbott MB, Refsgaard JC (1996) Distributed Hydrological Modelling. Kluwer Academic Publishers, The Netherlands

Ahouansou M (2008) Modélisation du fonctionnement hydrologique dans le bassin versant de l'Ouémé à Savè : contribution à la Gestion Intégrée des Ressources en Eau. Dissertation, University of Abomey-Calavi

Allen R (1986) A Penman for all seasons. J. Irrig. and Drain. Engrg. 112(4): 348-368

Allen R, Jensen M, Wright J, Burman R (1989) Operational estimates of evapotranspiration. Agronomy Journal 81: 650-662

Arnold J, Allen P, Bernhardt G (1993) A comprehensive surface-groundwater flow model. Journal of Hydrology 142:47-69

Arnold J, Srinivasan R, Muttiah R, Allen P (1999) Continental scale simulation of hydrologic balance. Journal of The American Water Resources Association 35(5): 1037-1051

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

Arnold JG, Williams JR (1995) SWRRB- A watershed scale model for soil and water resources management. In: Singh V (ed) Computer Models of Watershed Hydrology. Water Resources Publications, Colorado, USA, pp 847–908

Awoye H (2007) Modélisation du bilan hydrologique dans le bassin du Klou au Centre-Bénin : contribution à l'utilisation durable des ressources en eau. Dissertation, University of Abomey-Calavi

Bingner R.L (1996) Runoff simulated from the Goodwin creek watershed using SWAT. Trans. ASAE 39(1): 85-90

Boko M, Adjovi L (1994) Recherche des tendances dans les séries pluviométriques du Bénin méridional. Implications agroclimatiques. Publications de l'Association Internationale de Climatologie 7: 294-304

Bossa A (2007) Modélisation du bilan hydrologique dans le bassin du zou a l'exutoire d'Atchérigbé: contribution a l'utilisation durable des ressources en eau. Dissertation, University of Abomey-Calavi

Dingman SL (1994) Physical hydrology. Prentice-Hall. Englewood Cliffs, NJ, 575p.

Fontaine TA, Cruickshank TS, Arnold JG, Hotchkiss RH (2002) Development of snowfall snowmelt routine for mountainous terrain for the soil and water assessment tool (SWAT). Journal of hydrology 262: 209-223

Giertz S, Diekkrüger B, Jaeger A, Schopp M (2006) An interdisciplinary scenario analysis to assess the water availability and consumption in the Upper Ouémé catchment in Benin, Adv. Geosci. 9: 3-13

Green W, Ampt A (1911) Studies on soil physics, 1. The flow of air and water through soils. Journal of Agricultural Sciences 4:11-24

Hargreaves GL, Hargreaves GH, Riley J.P (1985) Agricultural benefits for Senegal River Basin. J. Irrig. and Drain. Engrg. 111(2):113-124

Houndenou C (1999) Variabilité climatique et maïsiculture en milieu tropical humide. L'exemple du Bénin, diagnostic et modélisation. Doctorate thesis, University of Bourgogne

Huisman JA, Breuer L, Frede H-G (2003) Spatial consistency of automatically calibrated SWAT simulations in the Dill catchment and three of its sub-catchments. DBG-Mitteilungen 102(2): 653-654

Janicot S, Fontaine B (1993) L'évolution des idées sur la variabilité interannuelle récente des précipitations en Afrique de l'Ouest. La Météorologie série 8(1) : 28-53

Jensen ME, Burman RD, Allen RG (1990) Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practice No. 70, New York, 332 p.

Junge B, (2004) Die Böden des oberen Ouémé-Einzugsgebietes in Benin/Westafrika- Pedologie, Klassifizierung, Nutzung und Degradierung – PhD thesis, University of Bonn

King KW, Bingner RL, Arnold JG (1999) Comparison of Green-Ampt and curve number methods on Goodwin Creek watershed using SWAT. Transactions of the American Society of Agricultural Engineers 42(4): 919-925

Legates DR, McCabe GJ (1999) Evaluating the use of goodness-of-fit measures in hydrologic and hydroclimatic model validation. Water Resources Research 35:233-241

Lukman AP (2003) Regional impact of climate change and variability of water resources (Case study, lake Naivasha basin , Kenya). Dissertation, International Institute for Aerospace Survey and Earth Science, Enschede, The Netherlands

Monteith, JL 1965. Evaporation and environment. In: G.E. Fogg (ed.) Symposium of the Society for Experimental Biology. The State and Movement of Water in Living Organisms, vol 19. Academic Press, Inc., New York, pp 205-234

Moron V (1993) Variabilité des précipitations en Afrique tropicale au nord de l'Equateur (1933-1990) et relation avec les températures de surface océaniques et de la dynamique de l'atmosphère. Doctorate thesis, University of Bourgogne

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models part I– a discussion of principles. Journal of Hydrology 10: 282-290

Neitsch S.L, Arnold J.G, Kiniry J.R, Williams J.R (2001) Soil and Water Assessment Tool Theoretical Documentation Version 2000. Agricultural Research Service. Tempel, Texas.

Paeth H, Born K, Heuer O (2009) Human activity and future climate. In: Judex M, Röhrig J, Schulz O, Thamm H-P (ed) Impetus Atlas of Benin, 3rd edn. Department of Geography, University of Bonn, Germany, pp 13-14

Perard J, Bokonon-Ganta E. B (1993) Variabilité pluvieuse et mutations socio-économiques dans le Haut-Borgou (Nord-Bénin). Association Internationale de Climatologie 6: 509-518

Priestley CHB, Taylor RJ (1972) On the assessment of surface heat flux and evaporation using large scale parameters. Mon. Weather Rev. 100: 82-92.

Roose E (1994) Introduction à la gestion conservatoire de l'eau, de la biomasse et de la fertilité des sols (GCES). Bulletin pédologique de la FAO 70

Rosenthal WD, Srinivasan R, Arnold JG (1995) Alternative river management using a linked GIS-hydrology model. Transactions of the American Society of Agricultural Engineers 38(3): 783-790

Santhi C, Arnold JG, Williams JR, Dugas WA, Srinivasan R, Hauck LM (2001) Validation of the SWAT model on a large river basin with point and non point sources. Journal of the American Water Resources Association 37(5): 1169-1188

Santhi C, Muttiah RS, Arnold JG, Srinivasan R (2005) A GIS-Based Regional Planning Tool for Irrigation Demand Assessment and Savings Using SWAT. Transactions of the American Society Agricultural Engineers 48(1): 137-147

Schori A, Charles R, Peter D (2003) Soja: sélection, agronomie et production en Suisse. Revue suisse Agric. 35 (2): 69-76

Shahin M (2002) Hydrology and water resources of Africa. Kluwer Academic Publishers, The Netherlands

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, University of Bonn

Soil Conservation Service (1972) Hydrology In The Service (ed) SCS National Engineering Handbook, section 4 U.S. Govt. Print. Off. Washington, DC

Soil Conservation Service Engineering Division (1986) Urban hydrology for small watersheds. U.S. Department of Agriculture, Technical Release 55

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. Available via: http://www.uni-koeln.de/globaler-wandel/impetus/oeffentliches/sonst/abstracts.pdf

Srinivasan R, Jacobs J, Angerer J, Vitale J, Kaitho R, Stuth J, Clarke N. (2003) Exploring the Potential Impact of Reforestation on the Hydrology of the Upper Tana River Catchment and the Masinga Dam, Kenya. Draft. Available via www-ssl.tamu.edu/pdfFiles/research/tana_report_2004.pdf

Srinivasan R, Ramanarayanan TS, Arnold JG, Bednarz, ST (1998) Large area hydrologic modelling and assessment, Part II. Model application. Journal of the American Water Resources Association 34(1): 91-101

Vissin EW (2007) Impact de la variabilité et de la dynamique des états de surface du bassin versant du fleuve Niger. Doctorate thesis, University of Bourgogne

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

Willmott CJ (1981) On the validation of models. Physical Geography 2: 184-194

Wisler CO, Brater EF (1957) Hydrology. John Wiley and Sons, New York. Chapman and Hall, London