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Analysis of the Hydrological Budget using the J2000 Model in the Pendjari River Basin, West Africa

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Abstract

In a semi - arid region where water scarcity is a major problem, quantify the water balance variables is very essential for sustainable water management. In a condition where meteorological input data are often not available in a sufficient spatial and temporal resolution, simulating the water balance variables is a big challenge. This research assesses the water balance for the Pendjari River basin, a 23208 km² sub-basin of the Volta basin in West Africa. The main purpose of this study is to assess how much water is available in the Pendjari River basin in terms of blue water and green water. To assess the water balance variables the distributed hydrological model J2000 has been used. The model has been manually and automatically calibrated for the period 1982 – 1990 using 24 parameters and validated for the period 1998 – 2008. 17 of the parameters have been selected for regional sensitivity analysis. The performance of the model has been measured using objective functions: Root Mean Square Error, Percent Bias, Nash-Sutcliffe efficiency, Relative Nash-Sutcliffe efficiency and Coefficient of Determination. The findings of this study have indicated that 58.67% of annual rainfall represents the evapotranspiration, which is considered as the amount of green water used to support natural vegetation productivity and agricultural system. The total actual evapotranspiration is estimated at 87% of annual rainfall. 12.53 % of annual rainfall end up as surface runoff and 9.92% of annual rainfall represents the groundwater recharge rate. Approximately 21% of annual rainfall represents the water yield, which is devoted to blue water source in the Pendjari River basin. The meteorological simulations are globally acceptable and the hydro-meteorological component simulation has shown very good model performances in comparison with the observed discharge data, indicating the potential of J2000 model to reproduce the geographical environment of the Pendjari River basin.

Keywords: J2000; Green water; Blue water; Hydrological budget; Pendjari River

1. Introduction

The Pendjari River basin is one of the important basins in Benin. Originating in the Atacora Mountains in North West Bénin, the river flows over 420 km in Benin and cuts a gash in the Atacocra cliffs with a high average slope of 3.7m/km. Then, it bypasses the sandstone and jasper hills of the Pendjari National Park by describing a large loop. It flows following a SSW-NNE direction with a slope of 1.5 m/km until the Burkina Faso border, and then it turns towards Togo Republic following NE-SW direction which it conserves to cross Togo (Le Barbé et al., 1993) and join the Volta River in Ghana under the name of Oti River. The Pendjari River basin at Porga outlet is located in a semi-arid region of West Africa and it is shared between Benin Republic and Burkina Faso. It is one of the less studied basins in terms of hydrological process in Benin. For many years, there has been a lack of information about the baseline condition of different water balance components and how the rainfall is partitioned in green and blue water for a good planning water management in the basin. In order to bridge these gaps and understand the hydrological process, hydrological models are one of the available tools used to acquire precise information on the characteristics of the river basin (Tessema, 2011), which is essential for its water resource management.

Considering the Pendjari River basin as a mountainous physiographic unit and the number of rainfall gauge stations (10), this basin can be classified as a recording basin with a density of 2320.8 km2 per station, according to the classification of the World Meteorological Organization (1994) which has recommended a density of 2500 km2 per station in mountainous area. But looking at the geographical distribution of these rain gauge stations, they are not uniformly distributed in the basin; most of them are located around the basin. Thus, the quantification of the hydrological budget for this kind of basin should be done with certain accuracy, using a hydrological model which offers an appropriate basis parameterization with poor data availability like J2000 model (Wolf et al., 2009). For this purpose, a spatially distributed numerical catchment project, analysis of the hydrological budget using the J2000 model in the Pendjari River basin, has to be established.

The main purpose of this study is to assess how much water is available in the Pendjari River basin. In this paper blue water (runoff and groundwater) and green water (evapotranspiration) are quantified and mapped.

2. Materials and methods

2.1 Study area

The Pendjari River basin at Porga outlet is the Volta basin, part sharing between Benin Republic and Burkina Faso. It is located between latitudes 10° 05'- 12° 10' N and 0° 05' - 2° 05' E and covers an area of 23208 km2. 38.65 % of its area are located in Benin Republic, the remaining 61.35 % in Burkina Faso (Figure 1.). Also, about 55.4 % of the Pendjari River basin at Porga outlet surface is a protected area composed of Pendjari, Arly and W Packs. The climate is semi-arid, with one rainy season and one dry season. Rainfall period is from May to mid-October where the maximum of the precipitation is reached in August, whereas the stream flow at Porga outlet peaks in September. During the rainy season, the temperature is between 25 and 30 °C, with a maximal relative humidity of 97 percent in August. The following dry season (November - April) is a period where the temperature is raised and presents its maximum in March /April with value between 39 and 42 °C and the relative humidity is between 25 percent and 55 percent. The mean annual precipitation is between 950 mm 1294 mm (Barry et al. 2005). In brief, high fluctuations of rainfall and temperature are observed during the year and the average annual potential evapotranspiration at Fada N'Gourma and Natitingou are 1834.2 mm and 1477.3 mm, respectively. The vegetation is mainly a shrub savannah composed of *Combretum spp* and *Acacia gourmaensis Crossopteryx febrifuga* scattered everywhere (Idiéti 2012).

2.2 Data used

Table 1: Maps used for HRU delineation

Map layers	Original scale	Scale used	Data source
Elevation	90 m	150 m	SRTM[1]
Soil	1:500000	150 m	ORSTOM[2]
Geology	1:500000	150 m	OBRGM[3]
LULC maps (1990)	250 m	150 m	GLOWA[4]

Two major types of data have been used in this study and concern spatial data and hydro-meteorological data. The different spatial data used have concerned the digital elevation model (DEM), geological map, soil and land use maps. All these maps have been reclassified at 150 m resolution. Table 1 depicts the maps used in this study with their different characteristics. Observed daily hydro-meteorological data (precipitation, maximum and minimum temperature, relative humidity, sunshine duration, wind velocity and discharge) represent the climate input data required for J2000 modelling. The characteristics of these data are summarized in Table 2 and Figure 1 shows the geographical location of the weather and rain gauge stations.

2.3 Methods

Hydrological Response Units (HRU) represent the model entities of computing the hydrological process cycle. Thus, the existing hydrologic models built on this concept like J2000 model, one of the Integrated Land Management System (ILMS) models (Kralisch et al., 2012) is used to assess the hydrological budget of Pendjari basin.

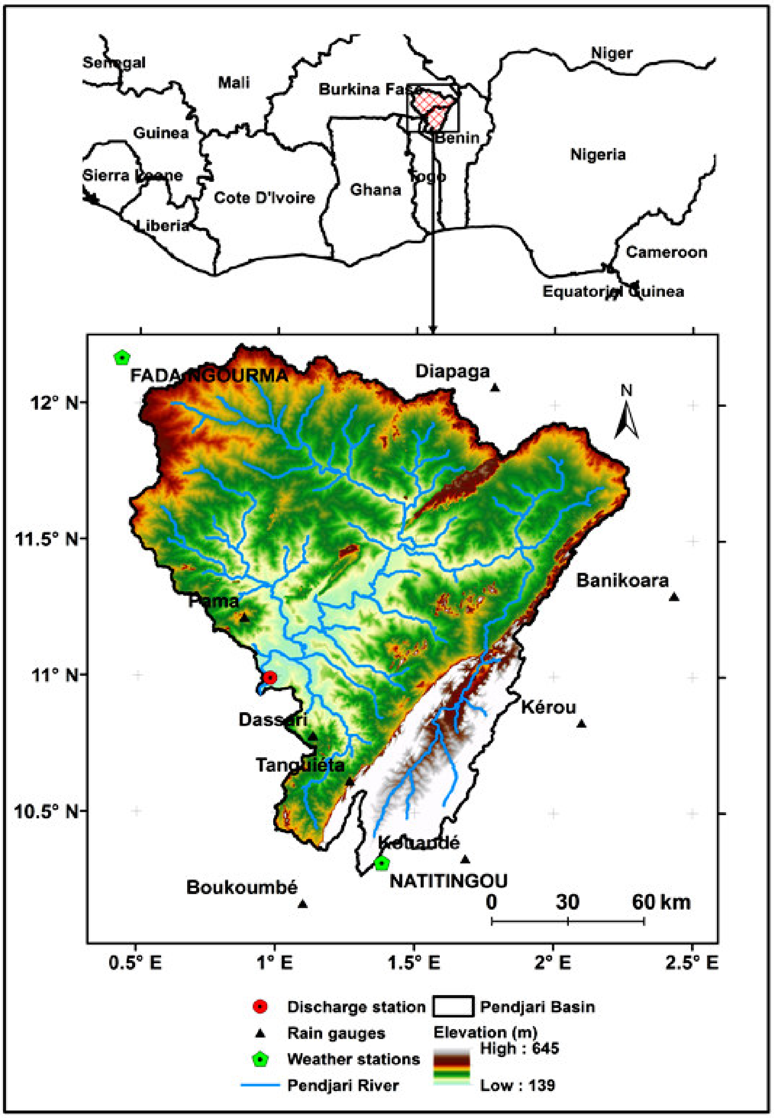

Figure.1: Geographycal location of Pendjari River basin

Table 2: Hydro meteorological data of Pendjari basin

Data	**Station**	**Country**	**Lat**	**Long**	**Elv (m)**	**Period**	**Years**	**Missing (%)**
Rainfall	Banikoara	Benin	11.30^{0}	2.43^{0}	310	1980-2008	29	0.30
	Boukoumbé	Benin	10.17^{0}	1.10^{0}	247	1980-2008	29	1.20
	Dassari	Benin	10.78^{0}	1.13^{0}	230	1980-2010	31	0.20
	Diapaga	Burkina F.	12.07^{0}	1.78^{0}	270	1980-2011	32	4.30
	Fada N'Gourma	Burkina F.	12.17^{0}	0.43^{0}	292	1980-2011	32	0.00
	Kérou	Benin	10.83^{0}	2.10^{0}	314	1980-2008	29	3.20
	Kouandé	Benin	10.33^{0}	1.68^{0}	442	1980-2008	29	5.00
	Natitingou	Benin	10.32^{0}	1.38^{0}	460	1980-2008	29	1.46
	Pama	Burkina F.	11.22^{0}	0.88^{0}	230	1980-2011	32	0.00
	Tanguieta	Benin	10.62^{0}	1.28^{0}	225	1980-2008	29	0.37
Max and Min temperature	Fada N'Gourma	Burkina F.	12.17^{0}	0.43^{0}	292	1980-2011	32	0.00
	Natitingou	Benin	10.32^{0}	1.38^{0}	460	1980-2008	29	0.00
Max and Min humidity	Fada N'Gourma	Burkina F.	12.17^{0}	0.43^{0}	292	1980-2011	32	0.00
	Natitingou	Benin	10.32^{0}	1.38^{0}	460	1980-2008	29	0.00
Wind velocity	Fada N'Gourma	Burkina F.	12.17^{0}	0.43^{0}	292	1980-2011	32	0.00
	Natitingou	Benin	10.32^{0}	1.38^{0}	460	1980-2008	29	2.52
Sunshine hours	Fada N'Gourma	Burkina F.	12.17^{0}	0.43^{0}	292	1980-2011	32	0.00
	Natitingou	Benin	10.32^{0}	1.38^{0}	460	1980-2008	29	0.00
Discharge	Porga	Benin	10.99^{0}	0.98^{0}	138	1980-2012	33	2.50

Lat : latitude ; Long : longitude ; Elv : Elevation. The weather data were from the meteorological offices of Benin Republic and Burkina Faso and the discharge data were from the General water Office of Benin

2.3.1 HRU Delineation

The HRUs were delineated using GRASS-HRU which is a GIS based program working under Quantum GIS (QGIS). The modeling entities delineation is based on the overlaying of the spatial data using the process developed by Pfennig and Wolf (2007). In this process, two concepts are combined namely topological connectivity (for the water and mass transport modelling in a specific surface area) and the process oriented regionalization concept in which a single HRU is an area of homogeneous topographic and physiographic environment. This HRU delineation approach aims to delineate the modelling entities based on a geo-morphological method. The real advantage of this HRU concept is the reduction of modeling entity's size without losing information. The model is run for each HRU and thereby produces the average value for the particular area (Nepal et al., 2012). Accordingly, the water balance components can be assessed in a small area as possible. This will contribute to a good application of the integrated watershed management approach. The spatial data presented in Table 1 are required for HRU delineation.

A total of 6923 HRU was delineated with varying sizes, ranging between 0.02 and 11.36 km2. These HRU were topologically connected for lateral routing of flows to simulate lateral water-transport processes between HRU. They were further connected to the nearby reach for reach routing. A specific protocol is that an HRU conveys water to adjacent HRU having lower elevations. This information is kept in each HRU parameter file, which is generated at the end of the HRU delineation process (Pfennig and Wolf, 2007). The HRU delineation process implemented in GRASS-HRU follows seven (07) steps, namely : physiographic data input and preparation; deriving slope and aspect, reclassification; flow accumulation plus direction, streams and sub basins; deriving basins based on outlet; generating data overlay, dissolving small areas; routing flow (HRU and reaches) and collecting HRU statistics. Detailed information on GRASS-HRU and the modelling entities delineation process can be found on http://ilms.uni-jena.de/ilmswiki/index.php/GRASS-HRU.

2.3.2 J2000 Modeling process

To assess the spatial distribution of the water balance component the hydrologic model J2000 was used. It is a distributed and physical-based model developed to simulate the hydrological processes as encapsulated process modules at meso and macro-scale catchment (Krause, 2002; Nepal et al., 2012) using long time series of daily hydro-meteorological data.

Conceptually, J2000 assumes that a fraction of the total precipitation is intercepted (Interception) by the plant canopy and returned to the atmosphere through evaporation without reaching the soil. The remaining precipitation (effective rainfall) reaches the soil. A significant part goes through surface runoff (RD1) and the rest infiltrates. Here also some of the infiltrated rainfall is either consumed by vegetation and transpired or directly evaporated from the soil surface (ET) and returns to the atmosphere. When the infiltrated water exceeds the middle pore storage (MPS) and large pore storage (LPS) capacity of the soil, the remaining flow can either percolate or recharge aquifers (Groundwater) or drain as interflow (RD2) or fast groundwater flow (RG1) and base flow (RG2) that reach the closest rivers or surface water bodies and contribute to the total runoff. Figure 2. illustrates the different pathways of water movement simulated by J2000.

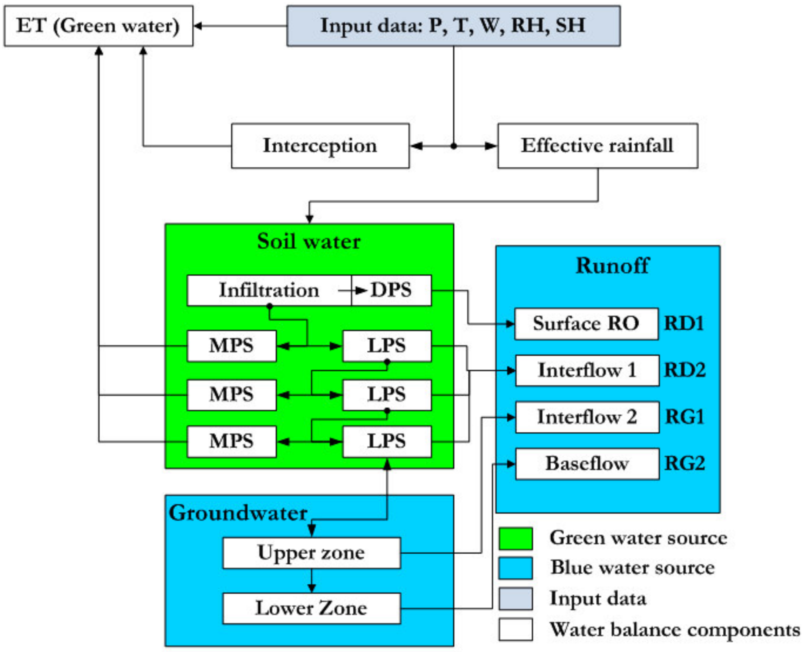

Figure 2: Principal layout of the J2000 model concept
Source: Adapted from Krause et al. (2009)

To reflect hydrological differences across a catchment, J2000 computes all water balance components for each HRU based on the HRU parameter file generated after the model entities (HRU) delineation process in GRASS-HRU. The J2000 model is composed of four modules, namely interception, soil-water, groundwater and routing.

Interception

$$Int_{\max}(mm) = \alpha \cdot LAI \quad (1)$$

In J2000 model, the amount of rainfall intercepted by vegetation cover is generated using the Equation (1). Int_{max} is the maximum interception capacity of each HUR; α is the interception coefficient of the leaf area index (LAI) for the vegetation type in each HRU. Leaf area index (LAI) of individual vegetation types is provided in the land-use parameter file throughout the year. Because LAI changes according to seasons, four different LAI types, based on the phenology period of each vegetation type, are proposed in land-use parameter file. In this study, LAI values for the study area were taken from the literature (Fang et al., 2013; Jarlan et al., 2008; Jin and Zhang, 2002).

Soil water

Soil water is the principal module in the J2000 modelling system. It indicates the essential position of soil, acting as a regulation and distribution system, influencing nearly all processes of the hydrological cycle (Krause, 2002). Effective rainfall constitutes the inputs for soil water module. In J2000 model an empirical approach is used to calculate infiltration by taking into account the actual soil moisture. If infiltration rate is less than the rainfall rate, water is stored as depression storage (DPS) at the soil surface; the excess is treated as surface runoff (RD1) and routed to the next HRU. The soil zone of each HRU is considered as two storage areas according to the specific soil pore volumes. Thus, infiltrated water is distributed between MPS and LPS according to the actual MPS' water saturation. The first one represents the pores with a diameter 0.2–50 mm where water is held against gravity but can be consumed through plant transpiration. When water reaches the MPS capacity, it considered as soil field capacity. LPS represents the macro pores (>50 mm), which cannot hold water against gravity. The Equations 2 and 3 are used to compute the amount of water enters the middle pores and large pores.

$$MPS_{in}(mm) = Inf_{act} \cdot \left[1 - \exp\left(\frac{-1 \cdot soilDistMP\ SLPS}{satMPS}\right)\right] \quad (2)$$

$$LPS_{in}(mm) = Inf_{act} - MPS_{in} \quad (3)$$

Where: MPS_{in} and LPS_{in} represent respectively the middle and large pores' inflows, Inf_{act} is actual infiltration, *satMPS* is actual water saturation in MPS and *soilDistMPSLPS* a calibration parameter.

LPS' water is separated into lateral flow considered as Interflow 1 (RD2) which is routed to the next HRU or connected to a stream (Equation 4) and vertical flow (percolation) depending on the slope (Equation 5). Percolation is treated as input of groundwater module.

$$Intflow \ (mm) = Slope_{weight} \cdot Q_{LPS} \quad (4)$$

$$Percolation \ (mm) = (1 - Slope_{weight}) \cdot Q_{LPS} \quad (5)$$

All soil properties, regarding soil water-holding capacity, are provided in a soil-parameter file. Details information on different equations of soil module are available in (Nepal, 2012) and http://ilms.uni-jena.de/J2000

Groundwater

Two geological units are identified in J2000 model for each HRU: the upper groundwater storage (RG1) in the loose material with high permeability and short retention time and the lower groundwater storage (RG2) in the matrix, fissures and ravines of bedrock with low permeability and long retention time. Therefore, two basic runoff components are generated depending on the slope of the response unit, the fast one from the upper groundwater storage and the slow one from the lower groundwater storage. Groundwater contribution to the total runoff is carried out in the form of a linear-outflow function using storage retention coefficients for the storage. These coefficients (kRG1, kRG2) are a factor of the current storage volume (actRG1 and actRG2) used for the calculation of the groundwater outflow (outRG1 and outRG2) that contribute to the total runoff (Equation 6, 7). Also, a certain amount of upper groundwater storage is conveyed into capillary rise in J2000 model.

$$outRG1 \ (mm) = \frac{1}{gwRG1Fact \cdot kRG1} \cdot actRG1 \quad (6)$$

$$outRG2 \ (mm) = \frac{1}{gwRG2Fact \cdot kRG2} \cdot actRG2 \quad (7)$$

Where: *outRG1* and *outRG2* are groundwater outflow that contribute to total runoff; *gwRG1Fact* and *gwRG2Fact* are calibration parameters; *kRG1*and *kRG2* storage retention coefficients of upper and lower groundwater respectively; *actRG1* and *actRG2* are the actual groundwater storage in upper and lower zone in the geological unit of each HRU.

Routing

HRU Routing and Reach Routing constitute the two routing components considered in J2000 model. The first one concerns water transfer between HRU from the upper areas until the receiving stream according to the topological connectivity. The second routing component (most important one) describes flow processes in the reach network by using the commonly applied kinematic wave approach and the computation of velocity according to Manning and Strickler (Krause, 2002; Nepal et al., 2012). Here, the individual reaches receive water from neighboring HRU and upstream reaches and the user has to estimate a routing coefficient.

2.3.3 Modeling procedure

The modeling procedure applied in this study was mainly model setup, model calibration and validation, water balance elements quantification and analysis. The model setup has concerned the input of the hydro-climatic data and the different parameter files into J2000 model as it is recommended. Five different parameter files are requested to run the model; there are named HRU parameter file, reach parameter file, hydrogeology parameter file, land use parameter file and soil parameter file.

The first two parameter files (HRU and reach) are automatically generated during the HRU delineation process in GRASS-HRU. Thus, based on the spatial data, the HRU parameter file contains information on the elevation, coordinates, area, slope, aspect, drainage type, flow-length, land-use type, hydrogeology, soil type and topological connectivity for each HRU. In the reach parameter file the length (m), slope (percent), mean width (m), connectivity between reach and reach roughness according to Manning-Strickler are stored. Based on the geological information the maximum storage capacities of RG1 and RG2 are estimated and the storage coefficient values (RG1_k and RG2_k) are used as a general recession co-efficient of two storages. These parameters are stored in the hydrogeology parameter file. The land use parameter file stores information about the land surface albedo, surface resistance for water saturated soil of each month, leaf area index for the four quarters of the vegetation periods, effective vegetation height for the four quarters of the vegetation periods, the maximum root depth and the sealed grade to check infiltration. In this study these information were derived from literature (Fang et al., 2013; Jarlan et al., 2008; Jin and Zhang, 2002) and a field visit, according to the different land use classes. Finally, the soil parameter file stores information on soil thickness; maximum and minimum permeability coefficient of the soil; the depth of the horizon above the horizon with the smallest permeability coefficient; air capacity representing excess water in a LPS; useable field capacity representing a MPS and; useable field capacity per decimeter of profile depth. These parameters were obtained from soil investigations to parameterize the soil map. The soil parameters measured through the soil investigation are the saturated hydraulic conductivity, texture and organic matter. The texture information gathered from the soil survey was used to depict the characteristics of the soil water retention curve and it was provided as input data to the software component Rosetta inside 'HYDRUS 1D4' to understand the soil pedotransfer function in three different hypothetical pressure scenarios (0 mbar, 60 mbar and 15,000 mbar) which help to estimate the LPS and MPS of each soil type.

After the model was set up, it was manually and automatically calibrated for the period 1980 – 1990 and validated for the period 1998 – 2008. The first two years, 1980 and 1981, are considered as the warm up period. For the model calibration, 24 calibration parameters were used. 17 of these parameters were selected for regional sensitivity analysis. The model input parameters were automatically calibrated using random sampling method, where the values of the parameters were chosen within the range provided. The model performance was measured using objective functions: Root Mean Square Error (RMSE), Percent Bias (PBIAS), Nash-Sutcliffe efficiency (NSE), Relative Nash-Sutcliffe efficiency (rNSE) and Coefficient of Determination (R2), as a quality measure between simulated and observed discharge.

3. Results

3.1 Hydro meteorological conditions

By using the inverse distance weighting (IDW) and vertical (regression) variation, as regionalization approach, the hydrological model J2000 has been able to simulate the annual variations of the hydro meteorological parameters.

Figure 3 and Figure 4 show the average monthly rainfall, discharge, actual (AcET) and potential (PET) evapotranspirations simulated by J2000 model. Observing the Fig.3., climate in Pendjari basin is characterized by only one rainy season that peaks in August with annual average of 1032 mm, whereas the peak of the simulated discharge it is observed in September with an average value of 65.35 mm. In addition, Fig.4. shows the variations of AcET and PET within a year, where the months from Jun to September represent the moment of high evapotranspiration. Also, the water demand from the atmosphere is very important from February to Jun.

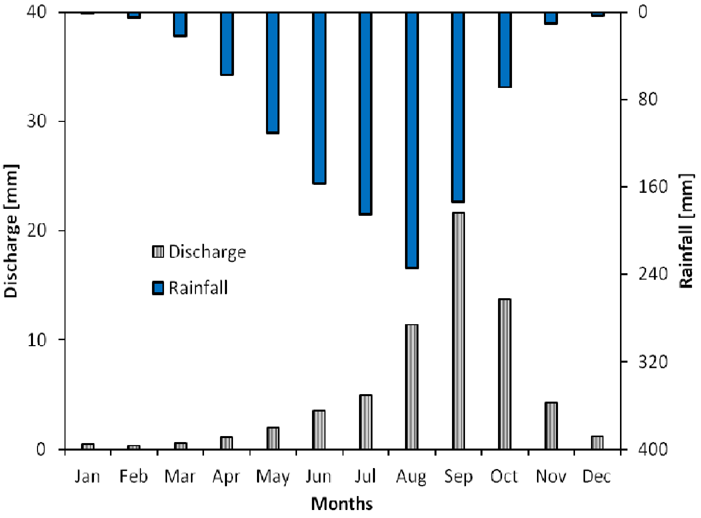

Figure 3: Average monthly simulated rainfall and discharge

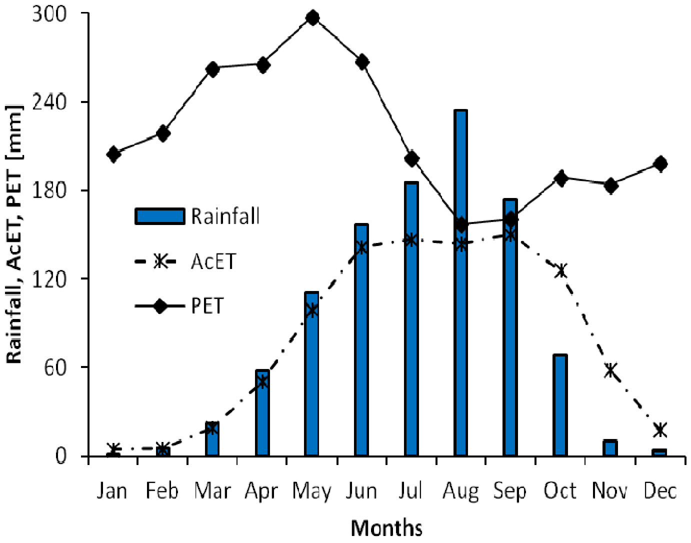

Figure 4: Average monthly simulated rainfall, AcET and ETP.

Even though the maximum of the rain falls from July to September, the atmosphere water demand is not satisfied. This indicates the semi-aridity of the region. This result shows that the IDW method for precipitation and other climate parameters simulation is quite good and indicates that the J2000 model reproduction of the hydro meteorological condition of the Pendjari River basin is fairly accurate.

3.2 Model sensitivity analysis

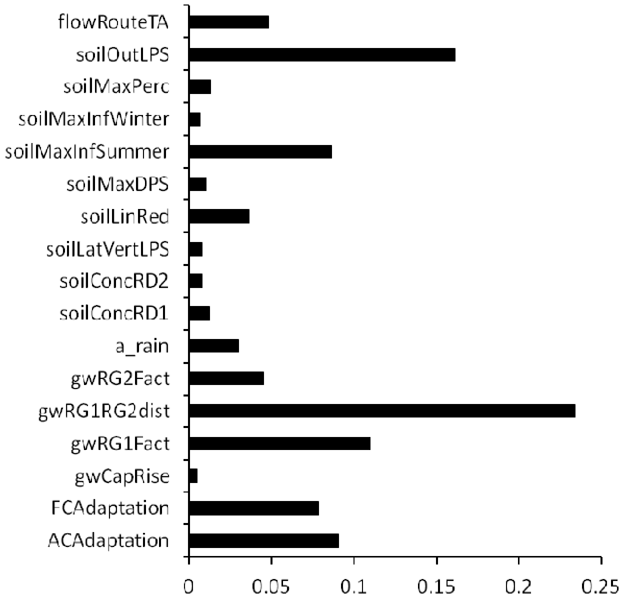

Figure 5: Sensitivity of Parameters with NSE

To avoid the risk of major errors in the model outputs, Regional Sensitivity Analysis (RSA), also called generalized sensitivity analysis, was used to assess the parameters that have strong influence on model outputs and in what ways or what extent. Thus, during the calibration process using the "trial-and-error" method 17 parameters out of 24 were found to be more sensitive. The Monte Carlo analysis performed on the all 17 parameters, after 7397 simulations using the NSE objective function, reveals that the “gwRG1RG2dist” is the most sensitive parameter and it has explained about 24% of the variation in model results followed by “soilOutLPS” which explained about 16% of the model outputs (Figure 5).

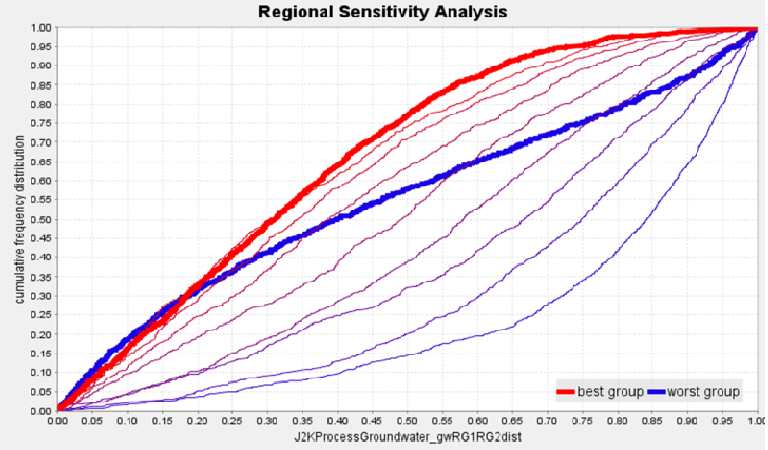

Figure 6: Regional Sensitivity Analysis of “*gwRG1RG2dist”* parameter with NSE

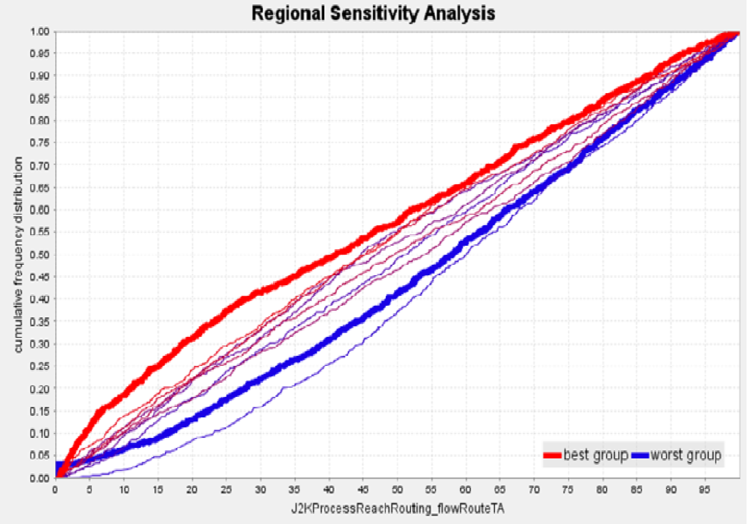

Figure 7 Regional Sensitivity Analysis of “*flowRouteAT”* parameter with NSE

Based on the likelihoods normalization of each parameter during the simulations, their cumulative frequency of distribution is calculated and plotted. Thus, the Figure 6 and Figure 7 show, respectively, how the model performance is sufficiently sensitive to “gwRG1RG2dist” parameter with a large difference between the cumulative frequency distributions (Nepal et al., 2012) and the low sensitivity of “flowRouteTA” parameter on the model output.

3.3 Discharge dynamics (calibration and validation)

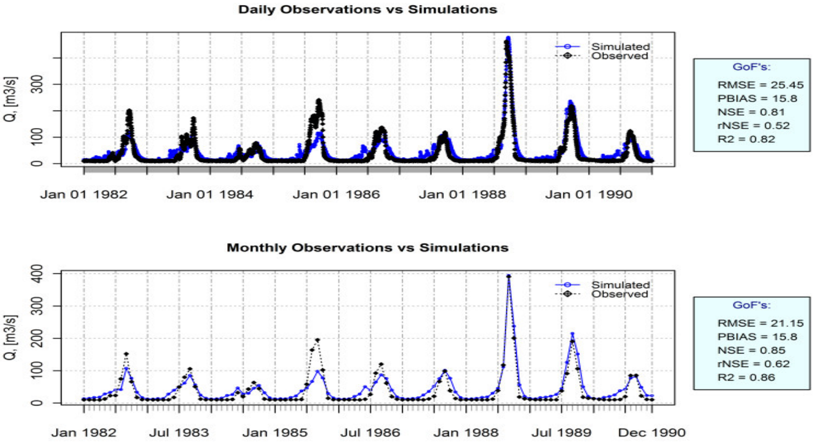

Figure 8: Observed and simulated discharge during the calibration period (1982–1990)

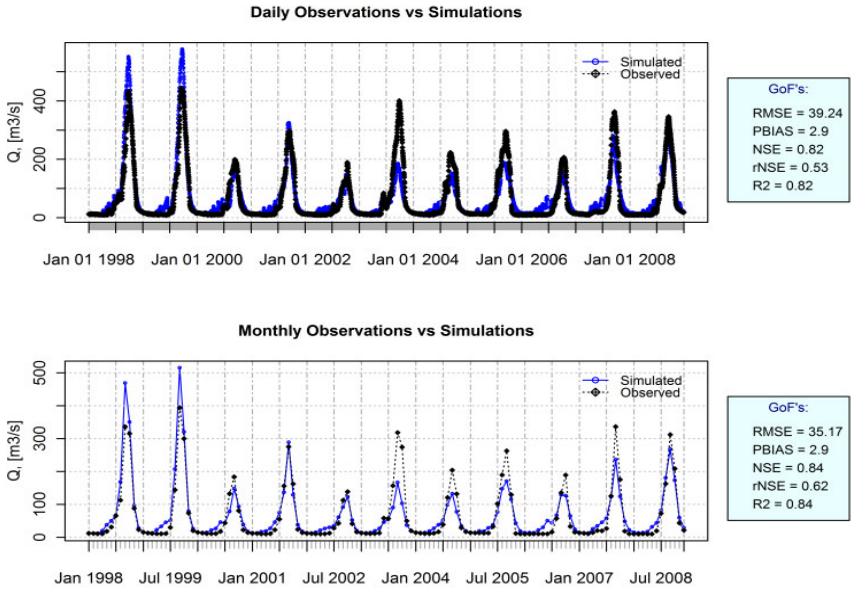

Figure 9: Observed and simulated discharge during the validation period (1998–2008)

J2000 model has been calibrated using discharge data for the period 1982 - 1990. Next, the model was validated using discharge data from the period 1998 - 2008. Figure 8 shows daily and monthly observed and simulated stream flow for the calibration period 1982 – 1990 with the model efficiency coefficients. The values for goodness-of-fit (RMSE, PBIAS, NSE, rNSE and R^2), obtained during the calibration period, are all acceptable. For instance, the NSE and R^2 are about 0.81 and 0.82, respectively, for daily discharge simulation with a slight overestimation of the low flow.

The statistical indicators of the validation period (1998 – 2008) were also very acceptable for daily and monthly stream flow simulation. It has been also observed a slight overestimation of the low flow during the validation. Fig.9. shows daily and monthly observed and simulated discharge for the validation period with the model efficiency coefficients.

In short, the comparison between daily observed and simulated discharge for calibration and validation periods indicated that J2000 was able to capture and reproduce the average flows and seasonal variations in Pendjari basin. Predictions on daily and monthly discharge were accurate (NSE = 0.81, 0.85 and PBIAS = 15.8%) (Table 3) (Moriasi et al. 2007); also, validation performance statistics (1998 - 2008) can be considered highly accurate for daily and monthly simulation (NSE = 0.82, 0.84 and PBIAS = 2.9%). This may be partly related to the difference in the accuracy of climatic datasets for the validation period. Table 4 presents the calibrated parameters with their final values.

Table 3: Model evaluation for daily and monthly simulations

Statistics	Daily simulation		Monthly simulation	
	Calibration	Validation	Calibration	Validation
RMSE	25.45	39.24	21.15	35.15
PBIAS	15.80	2.90	15.80	2.90
NSE	0.81	0.82	0.85	0.84
rNSE	0.52	0.53	0.62	0.62
R^2	0.82	0.82	0.86	0.84

RMSE: Root mean square error (range = −∞/+∞, optimum 0); PBIAS: Percentage Bias (< 10%: very good; 10% to 15%: good; 15% to 25%: Faire) ; NSE: Nash-Sutcliffe efficiency (range = −∞/1, optimum 1); rNSE: Relative Nash-Sutcliffe efficiency (range = −∞/1, optimum 1); regression coefficient (R^2) (range = 0–1, optimum 1)

3.4 Water balance in Pendjari Basin

Table 5 shows the annual summary of the daily outputs provided by J2000 model. The largest fraction of annual rainfall (86.94%) returns to the atmosphere through canopy interception (28.27%) and evapotranspiration (58.67%). This amount of the evapotranspired water can be considered as green water flow which is used to support primary productivity of natural vegetation and farmland production since in the study area there is no application of irrigation (Willaarts et al. 2012). The fraction of rainfall, which does not regain the atmosphere represents the blue water flow, which is composed of surface runoff (12.53%) and groundwater recharge

(9.92%). The total annual blue water flow production or water yield in the Pendjari River basin is estimated at 21.45% of annual rainfall. Comparing the results of calibration and validation, it is clear that the model validation confirms the reliability of J2000 to generate green and blue water flow in the Pendjari River basin (Table 5).

4. Discussion

The accuracy in interpolating spatial rainfall depends on the rain gauges density (Dirks et al., 1998) and their uniform distribution. Within a context of West Africa, one of the difficulties faced by hydrologist is the availability of climate data. In addition to the data scarcity, the rain gauges are too scattered. Since, hydrological response models are sensitive to input volume at the watershed scale (Nicótina et al. 2008), an appropriate interpolation method which can accurately reproduce continuous spatial rainfall is required. This is particularly true in mountainous areas, where rainfalls are more difficult to forecast due to complex topography (Ly et al., 2013). However, the J2000 hydrological model is able to handle the rain-dominated conditions of the Pendjari River basin. The model accuracy in pluvial settings is principally determined by the IDW method used.

Table 4: Calibrated parameters for Pendjari basin

Parameters	Description	Final value	Range
Initialising module			
FCAdaptation	Multiplier for field capacity	1.9059	0 - 10
ACAdaptation	Multiplier for air capacity	8.23	0 - 10
initRG1	Initial storage relative to maximum storage for groundwater component RG1	0.01	0 - 1
initRG2	Initial storage relative to maximum storage for groundwater component RG2	0.01	0 - 1
Interception module			
a_rain	Maximum storage capacity per LAI for rain (mm)	0.6067	0 - 10
Soil water module			
SoilMaxDPS	Maximum depression storage capacity (mm)	3.6504	0 - 10
SoilPolRed	Potential reduction coefficient for actual Evapotranspiration computation	5.0	0 - 10
SoilLinRed	Linear reduction coefficient for actual Evapotranspiration computation	0.3531	0 - 10
SoilMaxInfSummer	Maximum infiltration in summer (mm)	108.083	0 - 200
SoilMaxInfWinter	Maximum infiltration in winter (mm)	181.138	0 - 200
SoilImpGT80	Relative infiltration for impervious area greater 80% sealing	0.25	0 - 1
SoilImpLT80	Relative infiltration for impervious area less 80% sealing	0.6	0 - 1
SoilDistMPSLPS	Middle pore storage & large pore storage distribution coefficient	0.4	0 - 10
SoilDiffMPSLPS	Middle pore storage & large pore storage diffusion coefficient	0.68	0 - 10
SoilOutLPS	Outflow coefficient for large pore storage	0.5006	0 - 10
SoilLatVertLPS	Lateral-vertical distribution coefficient	1.0457	0 - 10
SoilMaxPerc	Maximum percolation rate (mm)	1.0457	0 - 1000
SoilConcRD1	Recession coefficient for overland flow	0.3044	0 - 10
SoilConcRD2	Recession coefficient for interflow	9.9334	0 - 10
Groundwater module			
gwRG1RG2dist	RG1-RG2 distribution coefficient	0.7518	0 - 1
gwRG1Fact	Adaptation for RG1 outflow	0.5718	0 - 10
gwRG2Fact	Adaptation for RG2 outflow	1.3034	0 - 10
gwCapRise	Capillarity rise coefficient	0.1716	0 - 1
Reach routing module			
flowRouteAT	Flood routing coefficient	3.0553	0 - 100

Table 5: Annual values of the water balance components

Water balance components		**Rainfall**	**Total Actual ET**		**Surface Runoff**	**Ground water**	**Water yield**	**Stock**
			Interception	**ET**				
Calibration	mm/year	923.34	265.73	536.47	110.75	72.86	183.60	-62.42
	Rainfall partition (%)	100	28.78	58.10	12.00	7.89	19.88	-6.76
Validation	mm/year	1079.19	299.57	639.43	141.11	107.39	248.50	-108.31
	Rainfall partition (%)	100	27.76	59.25	13.07	9.95	23.03	-10.04
Average	mm/year	1001.26	282.65	587.95	125.93	90.13	216.05	-85.36
	Rainfall partition (%)	100	28.27	58.67	12.53	9.92	21.45	-8.40

Even though, Dirks et al. (1998) have recommended IDW method for rainfall interpolation using spatially dense rain gauge networks, this method applied in this study, provided acceptable results regarding the modelling outputs. Thus, by using this approach, the average annual rainfall is estimated between 835.69 and 1210.21 mm considering the calibration (1982–1990) and validation (1998–2008) periods. This finding is closed with the results of Barry et al. (2005) that found the annual average rainfall in the northern section of the Oti River basin, between 1000 and 1200 mm while the Benin section of the basin or Pendjari River basin receives annually 1100 mm for the period 1961–1990. Furthermore, these results are close to the findings of Idiéti (2012) that found the average annual rainfall between 900–1200 mm in the Benin section of the Pendjari River basin after regionalised rainfall data using thirteen rain gauge station data for the period 1961–2006.

In addition, the annual AcET estimated by the model was between 724.86 mm and 1004.55 mm. These results support the findings of Ediéti (2012) and Oguntunde et al. (2006) that found the annual AcET in the range of 954.4 mm – 1131mm and 690 mm – 1148 mm, respectively. Similarly, the annual ETP simulated by the model was 2610.88 mm. This result was slightly different comparing to Barry et al. (2005) and Oguntunde et al. (2006), that estimated the annual PET to 2540 mm (Pan Evaporation) and 2136 mm (Penman-Monteith method) for the northern part of Volta basin, respectively. This slightly overestimation of the ETP may due to the location which is just a portion of the northern part of Volta basin, and also the period considered in this study which is different from the one used by these authors. In short, the simulation of precipitation and other climate parameters by the IDW method has produced acceptable results. Thus, the hydrological process and water budget can be analyzed with certain accuracy in the study area.

Analyzing the hydrological budget in the Pendjari River basin, about 87% of the total annual rainfall turns into green water (interception and evapotranspiration) and 67% of this amount is used for primary productivity of natural vegetation and agricultural ecosystems (Willaarts et al. 2012). This rate of green water consumption is similar to Andreini et al. (2000) who estimated the actual ET at 91% of the total rainfall, in Volta basin. Also Martin (2006) estimated ET rate in the range of 70-87% of the total rainfall in the White Volta basin, which is approximately in the same climatic zone with the Pendjari River basin. The important amount of the intercepted water observed (28.27% of the total annual rainfall) might be explained by the portion of the basin (55.4% of the total area) is a protected area composed of Pendjari, Arly and W National Parks where important biomass are observed.

In the Pendjari basin, the annual water yield (surface runoff and groundwater) is estimated at 21.45% of annual rainfall. Approximately 12.53% of annual rainfall consists of runoff, while 9.92% of annual rainfall represents groundwater recharge. These findings are similar to Martin (2006) who estimated the groundwater recharge, as a percentage of the total rainfall, in the range of 2% - 13% and the surface runoff between 11% - 23% of the total rainfall in the White Volta catchment.

4. Conclusion

The distributed hydrological model J2000 was adapted to the Pendjari River basin. The results of the hydrological simulations driven by measuring discharge flow for the required weather input data reveal that for the calibration and validation periods, the temporal variation of the overall stream flow could be simulated accurately considering the weak data availability and the non uniform distribution of the rain gauges. The total runoff simulation tends toward overestimating of measured discharge flow during the low flow period. This issue is due may be to the parameters in groundwater module that well adjusted or the type of equations used. Despite this tendency the outcomes of the coupled meteorological-hydrological simulations indicate that the hydrograph curves can be reproduced accurately. The stream flow is overestimated with acceptable magnitude. Globally, the hydrological model J2000 is fairly well adapted in simulating the climate and hydrological data at basin scale. The model efficiencies of the simulations driven by observations and by hydrological model output are comparable. It is therefore clear that the regionalization of meteorological data was fairly well performed and has been able to produce the required meteorological data for hydrological simulations. This model has the potential to simulate the spatial and temporal changes of water balance variables and estimate their values. The outputs of this study can serve as baseline information for water resources management in the Pendjari River basin.

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