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Modeling physical flows in the Kasai sub basin , a particular case of the Congo River Basin in Central Africa by the Curve Number method.

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Abstract

Integrated Natural Resource Management (INRM) in the world requires a thorough understanding of all the components of renewable and non-renewable resources at a time when the problem of climate and environmental changes is incumbent upon us. Integrated Water Resources Management (IWRM) is part of it and watershed studies are the basis of it. Therefore, in order to help managers and decision makers in its governance and in good decision making, this research aims at building and calibrating a tool for surface water for a representative case study of large river basins such as the Kasai sub-basin, a particular case of the large Congo River basin located in Central Africa. It is one of the largest sub-basins in this region, with a large portion located in the Democratic Republic of Congo (DRC) and a small portion in the southwest bordering the northern part of the Republic of Angola. It occupies 28% of the entire greater Congo River basin and discharges a mean annual flow of about 9873 m^3/s into the Congo River. The location of this Kasai sub-basin south of the equator gives it a climate influenced by southern subtropical high pressure.

This research is based on the Curve Number (CN) method, implemented on SWAT and QGIS (QSWAT) software in the determination of water flows from physiographic, hydrometric and meteorological data measurements. These data are collected from international public databases (FAO software), satellite images (downloaded from the Cgiar.org website) and ground observations (hydrometric data for the period 2008-2013). The model constructed allowed the simulation of monthly flows with an overall coefficient of determination (R^2) evaluated at 0.9. It is shown that the most influential parameters on model performance are i) Curve Number (CN); ii) groundwater baseflow alpha (Alpha_BF.gw); iii) groundwater lag time (Gw_Delay); and iv) threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN.gw). The precipitation parameter has a large influence on the performance of this model due to its location in the equatorial torrid zone of central Africa.

Keywords: Surface water modeling, Kasai sub-basin, Curve Number, Calibration, IWRM.

1. Introduction

The issue of IWRM in the world is a big concept that requires a lot of attention from the leaders of international communities. Africa in general and the central region in particular, including our case of the Kasai sub-basin within the greater Congo River basin, is no exception to this concern. The Kasai River sub-basin corresponds essentially to areas of virgin equatorial forests in its northern part. In the south there are shrubby savannahs cut by forest galleries along the rivers.

These galleries widen as one move northward. The main river, the "Kasai", flows south-north down from the Angola plateaus, and at each level of the terraces that border the central basin, there are rapids and waterfalls. The direct confluence of rivers bearing the name of this sub-basin is the Congo River at an altitude of 272 m, the source of which is at an altitude of 1394 m (Wikipedia, 2021).

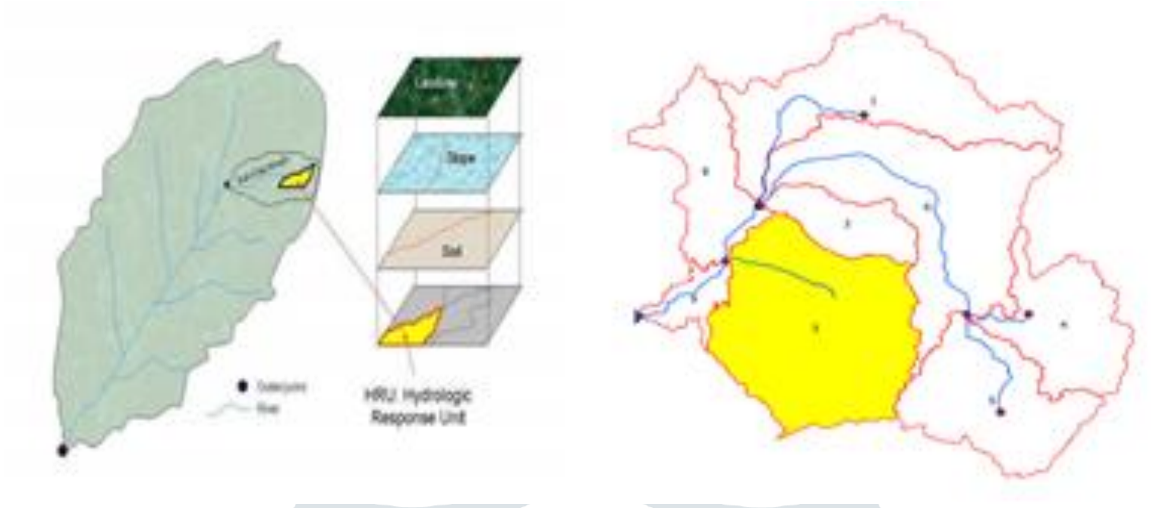

Figure 1. Location of the Kasai sub-basin in the great Congo River basin

This type of management is universally considered as a tool to provide accurate knowledge on the manifestations of climate variability and its relationship with water resources (Ardoin Bardin, 2004).It is indeed appropriate to adopt a good integrated management strategy, passing through hydrological modeling that also facilitates the analysis of meteorological scenarios and allows the study of the impacts of climate change and / or anthropogenic influences on the hydrological cycle of a watershed (CREALP, 2019). The hydrologic model chosen for our case study is SWAT, which is an acronym for Soil and Water Assessment Tool. It is a watershed assessment tool developed by researchers at the United States Department of Agriculture (USDA) (Arnold et al. 1993; Arnold et al. 1998). Other applications have been made on the Ganges, the longest river in India (Shivhare et al., Engineering, 2018) and also taking into account the characterization of large areas grouping the major African watersheds (SCHUOL ET AL.2008). And finally, by having this hydrological model of the Kasai sub-basin, it will be possible to carry out good feasibility studies of various projects especially in the context of agriculture because this region supplies the Capital Kinshasa in commodity and constitutes through the Kasai River a navigable route to reach the Congo River. Furthermore, to understand the problem of the evolution of the Congo River estuary and the erosion of the coastal flank at its mouth towards the Atlantic Ocean.

2. Materials and methods

Implementation of the SWAT Model by: (1) Automatic delimitation of the watershed (spatial discretization) - from the DTM ,(2) Creation of HRUs: Result of crossing land use, Soil type and slope maps, (3) Integration of climatic data, (4) Choice of calculation methods (runoff, ETP...) and data update, (5) Simulation over a period of 30 years (1979-2014 with 5 years start-up period), (6) Automatic calibration (monthly time step) -SWAT-CUP-SUFI algorithm27,(7)Visualization of results / calculation reports / static and dynamic maps8 Exploitation of results and export. The chosen method is that of Curve Numbers, allowing to estimate the runoff and which can be adjusted according to the hydric state of the ground and the tool used is that of the Qswat model which has a specification of its "Open Source" character opening the field of adaptation of the model to the possible specificities of the studied environment. From the point of view of its representation, this computerized management tool includes a database (spatial and attributes), a geographic information system (GIS), an interface database and a mechanistic simulation model. The modeling can be separated into two parts: a sub-basin component that performs water balances on each sub-basin, which are then integrated over the entire basin, and a transfer component that performs the transfer of water in the networks to the outlet.

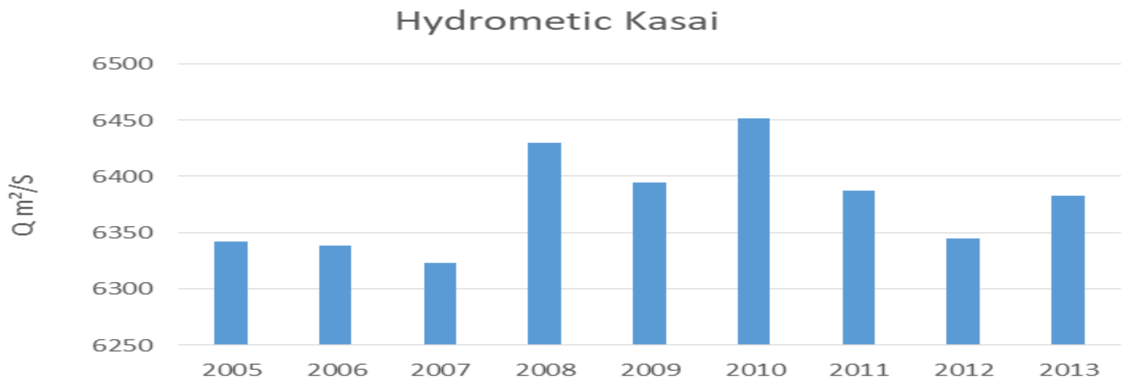

Figure 1. Representation of hydrometric data from the Kasai sub-basin (2005-2013).

The Curve Numbers method aims to estimate the flow of the basin and not only that from surface runoff (Romain Lardy, note on Curve Numbers, 2013). Furthermore, by considering the flow as surface runoff, it is then implicitly considered to come solely from Hortoniens runoff, which would take place over the entire modeled area and be the dominant surface runoff process (Garen and Moore, 2005). Note, however, that for the SWAT model, when calculating the value of CN as a function of soil water content, if the soil is saturated, then the coefficient is 99, indicating the existence of flow through soil saturation (Neitsch et al., 2009). Its implementation in the SWAT tool by integrating the daily dynamics including one method integrating the soil water content admitting the value of CN of 99 in the case of saturated soil and the other based on the potential evapotranspiration of plants, the retention coefficient. Moreover, by integrating the effect of the slope, it is possible to adjust the CN. This slope also affects the flow velocities of overhead and underground streams.

3. Results

The present study develops from a combination of physiographic (DTM, soil types, land use, meteorology) and hydrometric input data, a SWAT model to reproduce the hydrological functioning of our Kasai sub-catchment conditioned by calibration parameters and the most sensitive indices to ensure its performance. For the most appropriate spatial discretization and best subsequent analyses, we performed 27 spatial breakdowns of our sub-catchment, corresponding to average HRU areas ranging from 1 km² to 8886 km².The identical combination obtained by crossing the sub-catchment breakdown, land use and pedology is supposed to produce a similar hydrological response (HRU) in each sub-catchment. A total of 748 HRUs were identified in our Kasai sub watershed. Given these results, the Curve Number method seems so crucial in this case study.

In view of these results, we admit that this ability to reproduce without calibration is an indicator of the quality of our input data according to our objective. This application without calibration of the SWAT model for our case gives satisfactory results (R^2= 0. 57) for a monthly time step, respectively 9873 m³/S as average of the observed flows whose linear equation is:

$$Y=40.028x - 188892 \quad (1).$$

We could not try to reproduce this variability of hydrological functioning on a daily scale given our objective. But nevertheless, we will try in what follows and leave the way open to those who want to realize them.

Parameter Name	t-Stat	P-Value
3 : V_GW_DELAY.gw	-0.18524183	0.853231895
4 : V_GWQMN.gw	0.824003766	0.410944119
1 : R_CN2.mgt	4.76243129	0.000003725
2 : V_ALPHA_BF.gw	22.43357862	0

Figure 2. global sensitivity analysis parameters of the model.

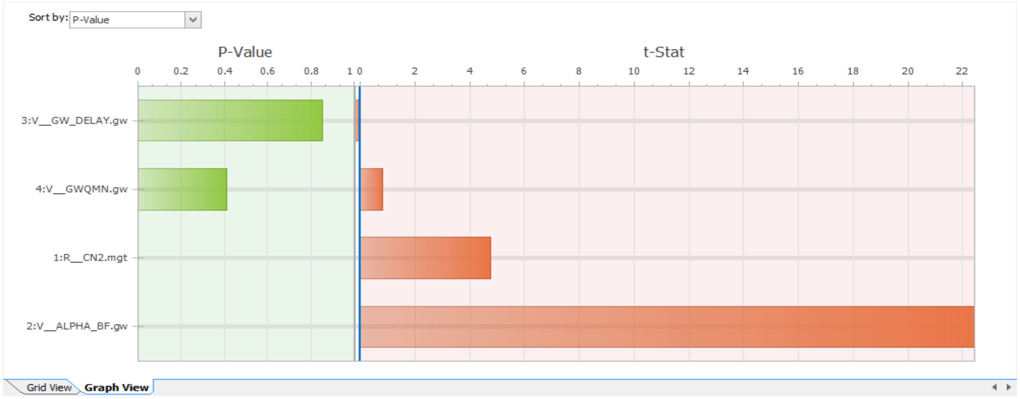

Figure 3. Graph of the most sensitive parameters of the model.

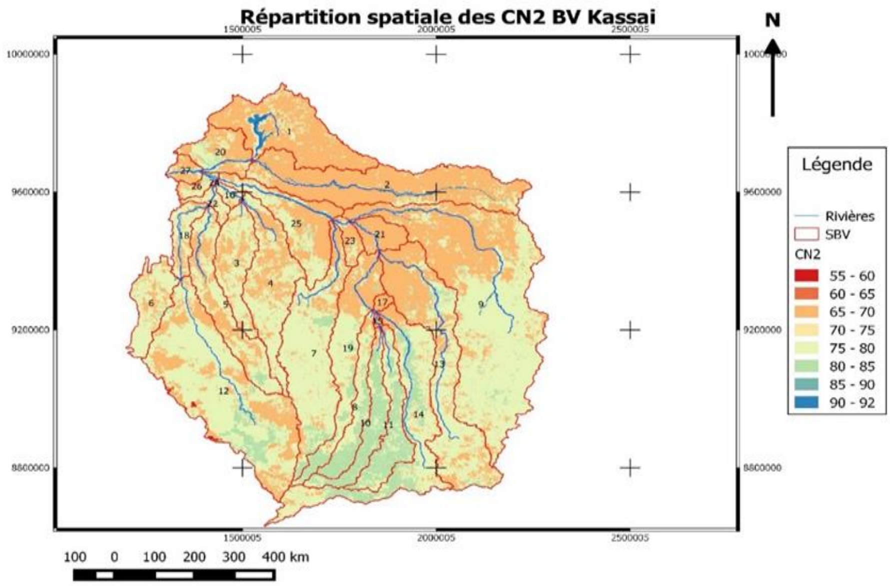

Figure 4 : Representation of the spatial distribution of curves numbers on the whole Kasai Watershed.

4. Discussions

The Kasai sub-basin offers several potential energy, biomass and agricultural products that can be exploited. Unfortunately, at this stage, all of this potential lacks good management and monitoring in time and space. Integrated water resources management (IWRM) with the SWAT model seems to be the most effective way to systematically inventory and monitor this sub-area of the greater Congo River basin.

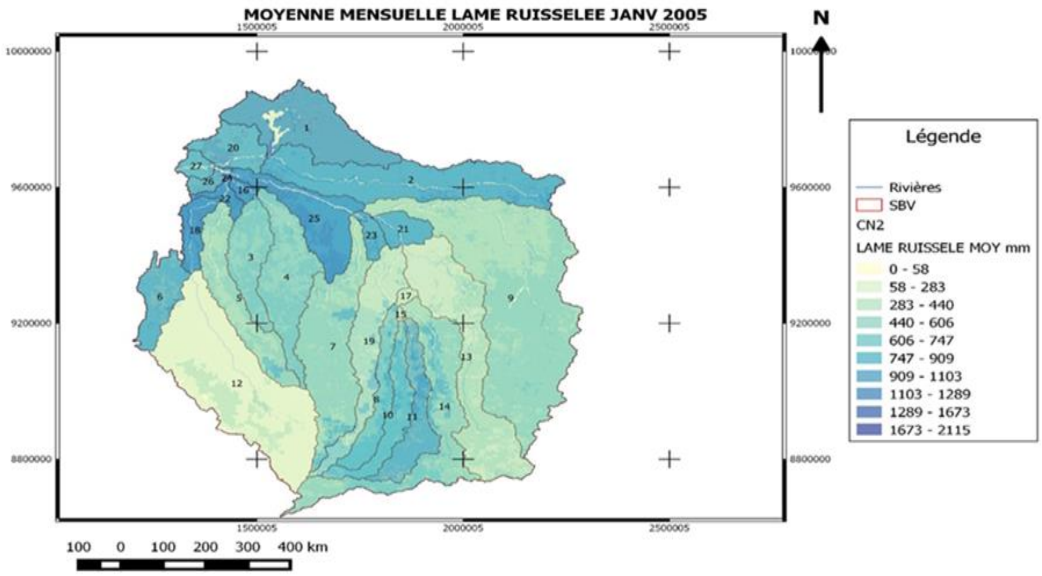

Figure 5: Representation of the spatial distribution of the average rainfall runoff over the entire Kasai Watershed.

The results of the sensitivity analysis for this case study of the Kasai sub-basin confirm the quality of our input data used, which ideally represent (optimize) the reality on the ground (fig.2). The most sensitive parameters are related to the basic input data, including surface runoff, soil water, groundwater, channel water conveyance, and actual and potential evaporation (Fig. 3).

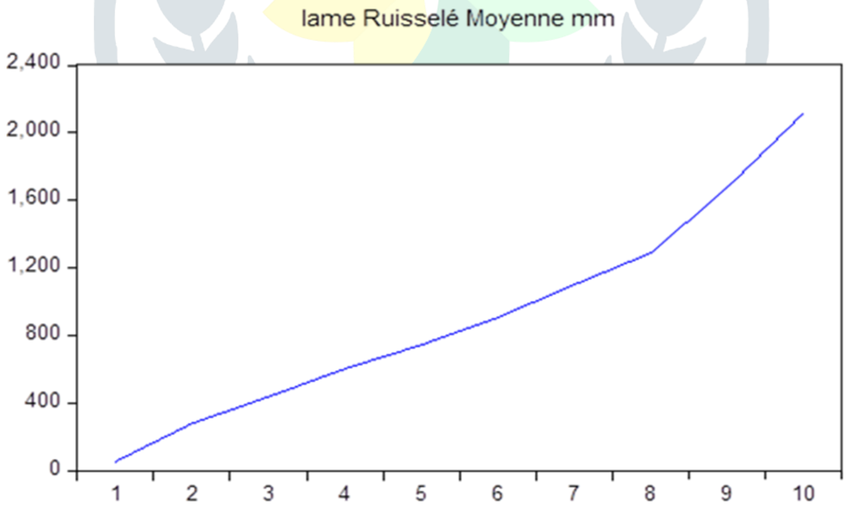

Figure 6 : Representation graphic of the spatial distribution of the average rainfall runoff over the entire Kasai Watershed.

Given our objectives, the first parameter is R_CN2.mgt which estimates runoff adjusted for soil water status. These runoff fluxes are driven by Hortonian runoff, which occurs when the precipitation rate exceeds the infiltration rate, due to soil saturation, and shallow subsurface runoff, which can recharge surface runoff. In our case study, we had to make a spatial distribution in eight classes ranging from the value of 92 to 55 (fig.4).

The second parameter Alpha_BF.gw which is a factor that determines the groundwater base flow. These first two parameters are crucial for our evaluation of peak flows. The last two groundwater-related parameters are V_GW_DELAY.gw, which determines the aquifer recharge delay, i.e., the time between when water leaves the ground and when it enters the shallow aquifer, and A_GWQMN. gw, which determines the threshold of groundwater contribution to the channel or base flow, i.e., the amount of water that remains in the aquifer without ever emptying; all these parameters were chosen according to the elements characterizing the sub-watershed under study and our objectives.

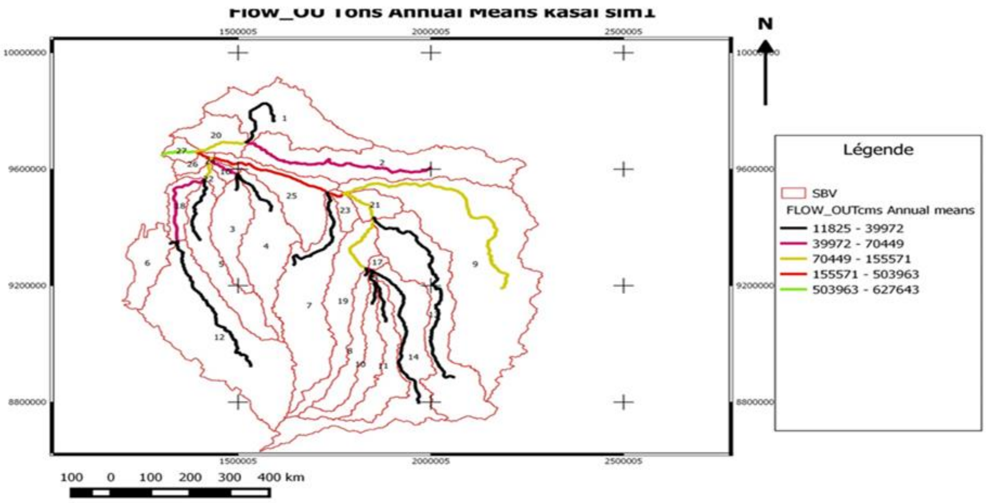

Figure 7 Representation of the spatial distribution of the average rainfall runoff over the entire Kasai Watershed.

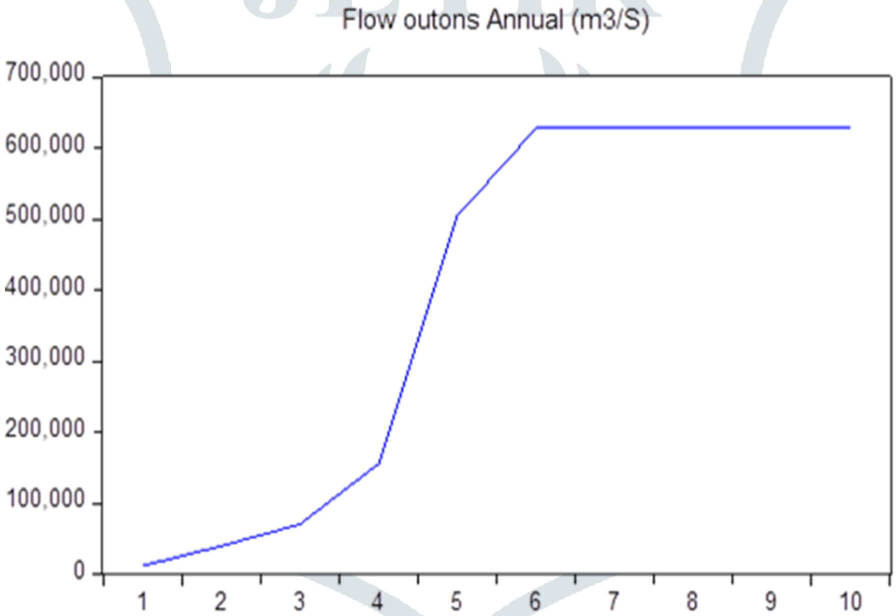

Figure 8. Representation graphic of the spatial distribution of the average rainfall runoff over the entire Kasai Watershed.

Covariance Analysis: Ordinary
Date: 11/16/22 Time: 16:07
Sample: 1 10
Included observations: 10

Correlation Probability Observations	CLASSE_CN2	FLOW_OUTONS_ANNUAL__M3_S_	LAME_RUISSELE_MOYENNE_MM
CLASSE_CN2	1.000000 ----- 10		
FLOW_OUTONS_ANNUAL__M3_S_	0.785334 0.0071 10	1.000000 ----- 10	
LAME_RUISSELE_MOYENNE_MM	0.814916 0.0041 10	0.829980 0.0030 10	1.000000 ----- 10

Figure 9. Graph representing the test of covariance of the results of the runoff and runoff quantities according to the curves numbers.

The SWAT-CUP tool allowed us to calibrate our model. The sensitivity study led us to the selection of the following parameters: In "relative" mode: CN2, Alpha_BF.gw and in "replacement" mode: GW_DELAY, GWQMN. We ran the model for 4 years with 200 simulations (fig.10). This number, although high, was essential to have optimal values of the parameters, better performance of the model and to see that the variations of the performance indices were more or less reliable. After the calibration of the most sensitive parameters, the analysis of the statistical indices NSE and R^2 shows that the flow simulations are satisfactory at the period used for the calibration with respective values of 0.88 and 0.9. The digital terrain model is used to plot the paths and flow directions in an open source geographic information system (QGIS).

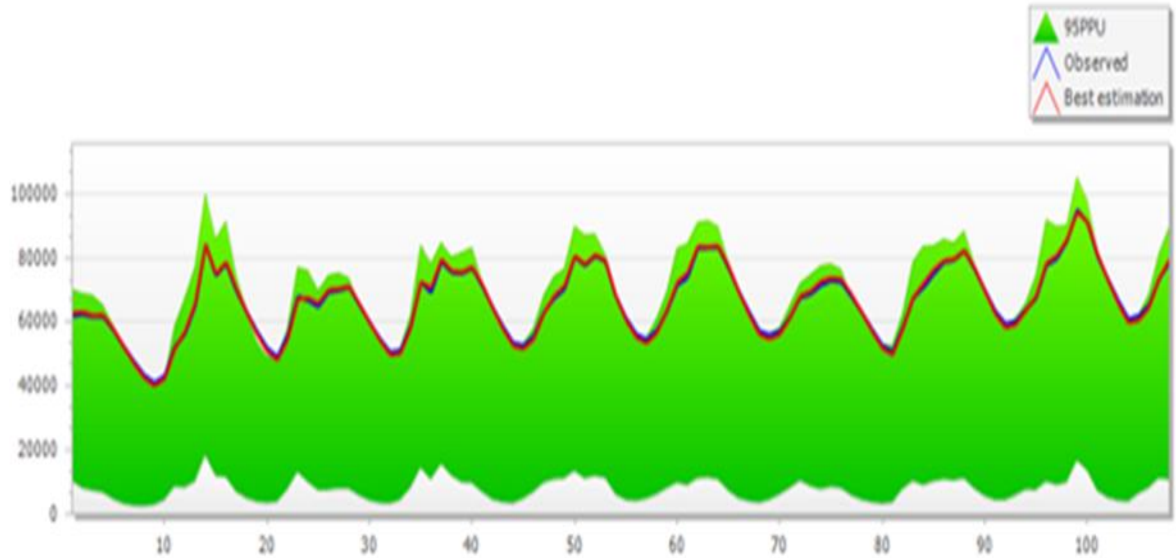

Figure 10. Graphical representation of the Kasai Basin model simulation with swat-cup.

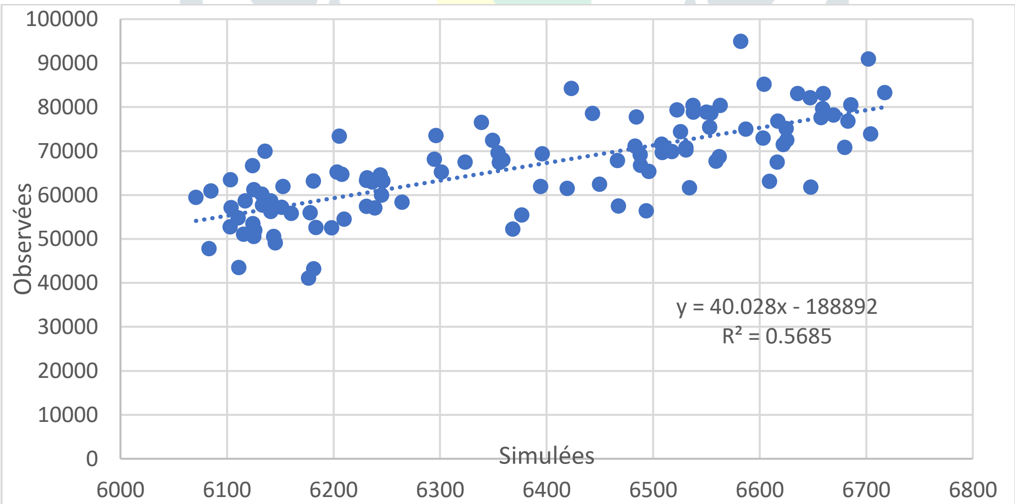

Figure 11. Correlation of simulated and calculated flows of the Kasai sub-basin.

5. Conclusions

Our objective was to model the flows of the Kasai sub-basin with SWAT in order to perform analysis and comparison between the observed flows, with an emphasis on the Curve Number method, given its large size and the opportunities it offers for good management of its hydrological resources. Subsequently, we were able to eventually use data downloaded from the Global Weather Data for Swat (GWD) to populate batch sets of meteorological data in support of the observed data which are in most cases difficult to obtain. Using observed climate data from the four cities of the Democratic Republic of Congo covering the period from 1979 to 2010 and observed flows in the city of Kinshasa from 2010 to 2014, we first conducted a comparison of the reliability of the meteorological data with that of the Global Weather Data for Swat (GWD). The results were satisfactory and reassured us that a gridded intensification of climate data stations over the entire sub-watershed could be considered. A graphical comparison of observed and simulated flows during the pre- and post-calibration period allowed us to assess the overall capacity of the model to satisfactorily reproduce the flow series on a monthly scale. Given the diversity of physiographic data in this Kasai sub-basin, it would be quite possible to improve the results by sub-discretizing the calibration and simulation HRUs. This sub-discretization should also be based on topography, land use classes, and a good improvement of the longer series of observed flow data for calibration. Also, for a better adaptation of the SWAT model, several iterations of the calibration period in a targeted objective, is to take into account the temporal uncertainties of the operation of the hydrological model to those of the climates that prove to be crucial and necessary. Finally, these steps have contributed to prove that despite the complexity and the immensity of the studied environment, the restriction in the acquisition of the observed data, the obtained results prove that the hydrological model SWAT provides information of the different interactive and complex natural processes in a sub-catchment. It is a robust tool in its operation exploitation of the biophysical characteristics of the Kasai sub-basin and surrounding areas. In short, the Curve Number method implemented in SWAT can provide useful information for the successful implementation of integrated water resources management in the Kasai sub-basin.

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