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International Journal Water Sciences and Environment Technologies
Vol. (vii), Issue. 4, December 2022, pp. 45-53
ISSN Online: 1737-9350; ISSN Print: 1737-6688, Open Access
www.jiste.org
Scientific Press International Limited
Received: 12 September 2022 / Revised: 25 October 2022 / Accepted: December 2022 / Published: December 2022

Case study of the modeling approach of the flows of the sub-catchment of Kisangani by the method of the curved numbers

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Abstract

Integrated water resources management (IWRM) in large basins requires a thorough understanding of all components of the water balance and the most realistic representation of biophysical processes that occur over time. In order to assist managers and decision makers, this research aims to build and calibrate a surface water tool for a representative case study of large river basins: the Kisangani sub-basin, a special 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). It occupies 24% of the entire greater Congo River basin and discharges a mean annual flow of approximately 20330 m^3/s into the Congo River in this city. The location of this Kisangani 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 software (QSWAT). Data are collected from international public databases, satellite images and ground observations (hydrometric data for the period 2008-2014). The constructed model was able to simulate monthly flows with an overall coefficient of determination (R^2) evaluated at 0.9 after calibration. It is shown that the most influential parameters on the performance of the model are: i) the curve number (CN); ii) the soil evaporation compensation factor (Esco .hru); iii) the Available Water Capacity of the soil layer (mm H2O/mm.) (Sol_AWC (...) soil and a test parameter to see the behavior of the model sensitivity the SFTMP.bn. We find that the precipitation parameter has a great influence on the performance of this model due to its location in the equatorial Torrid Zone of central Africa as in the case of other studies mentioned above.

Key Words*:* Surface water modeling, Kasai sub-basin, Curve Number, Calibration, IWRM.

Etude de cas de l'approche de modélisation des écoulements du sous-bassin versant de Kisangani par la méthode des nombres courbes

Résumé

La gestion intégrée des ressources en eau (GIRE) dans les grands bassins nécessite une compréhension approfondie de toutes les composantes du bilan hydrique et la représentation la plus réaliste des processus biophysiques qui se produisent au fil du temps. Afin d'aider les gestionnaires et les décideurs, cette recherche vise à construire et à calibrer un outil d'eau de surface pour un cas d'étude représentatif de grands bassins fluviaux : le sous-bassin de Kisangani, un cas particulier du grand bassin du fleuve Congo situé en Afrique centrale. C'est l'un des plus grands sous-bassins de cette région, avec une grande partie située en République démocratique du Congo (RDC). Il occupe 24% de l'ensemble du grand bassin du fleuve Congo et déverse un débit annuel moyen d'environ 20330 m^3 / s dans le fleuve Congo dans cette ville. La localisation de ce sous-bassin de Kisangani au sud de l'équateur lui confère un climat influencé par les hautes pressions subtropicales du sud. Cette recherche est basée sur la méthode Curve Number (CN), implémentée sur les logiciels SWAT et QGIS (QSWAT). Les données sont collectées à partir de bases de données publiques internationales, d'images satellitaires et d'observations au sol (données hydrométriques pour la période 2008-2014). Le modèle construit a permis de simuler des débits mensuels avec un coefficient de détermination global (R^2) évalué à 0,9 après calage. Il est montré que les paramètres les plus influents sur les performances du modèle sont : i) le numéro de courbe (CN) ; ii) le facteur de compensation de l'évaporation du sol (Esco .hru) ; iii) la capacité en eau disponible de la couche de sol (mm H2O/mm.) (Sol_AWC (...) sol et un paramètre de test pour voir le comportement de la sensibilité du modèle le SFTMP.bn. Nous constatons que le paramètre de précipitation a une grande influence sur les performances de ce modèle en raison de sa localisation dans la zone torride équatoriale de l'Afrique centrale comme dans le cas d'autres études mentionnées ci-dessus.

Mots clés : Modélisation des eaux de surface, sous-bassin du Kasaï, Curve Number, Calibration, IWRM.

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INTRODUCTION

The Kisangani sub-basin has the particularity of being exposed to equatorial climatic conditions with a distinct rainy season characterized by a proven equatorial rainfall regime. It requires a particular attention and a mode of management of its resources by its strategic position which constitutes the starting point of the navigability of the course of the Congo River towards the Capital Kinshasa. It is a route for the circulation of goods and people by supplying the far east of the country.
This type of watershed management is universally considered as a tool to provide precise elements of 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 anthropic influences on the hydrological cycle of a watershed (CREALP, 2019).

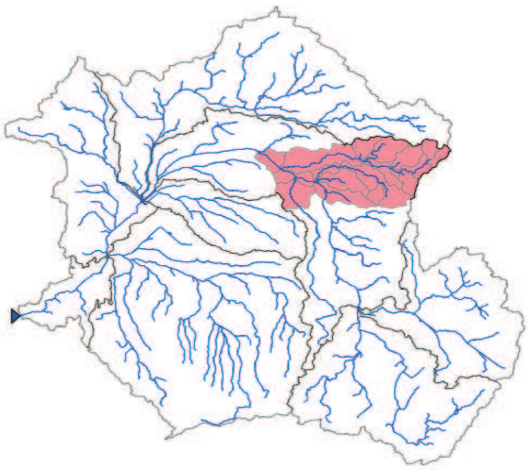

Figure. 1: Representation of the Kisangani sub-basin in the greater Congo River basin

This Kisangani sub-basin (in red) is part of the Lualaba sub-basin (Upper Congo) belonging to the Great Congo River Basin located in Central Africa. It is also one of the largest sub-basins in this region and the only one that constitutes the hinge between the southern and northern hemispheres of the Great Congo River Basin, most of which is located only in the Democratic Republic of Congo (DRC). It occupies 24% of the entire great Congo River basin and its location astride the equator shows that this great Congo River basin has a bimodal regime. The Kisangani sub-basin which is the subject of our study is located in the eastern part of the whole Congo River Basin and DRC, occupying only 7.35% of its surface.

MATÉRIELS AND METHODS

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 soil 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.
The Modelling can be separated into two parts: a sub-basin component which carries out water balances on each sub-basin, which are then integrated on the whole basin, and a transfer component which carries out the transfer of water in the networks towards the outlet. 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 Hortonian 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. This sub-basin is only a special case for its modeling and a practical case as a whole. The calibrated simulation model therefore provides a solid basis for building an integrated surface water management tool for the Kisangani sub-basin.

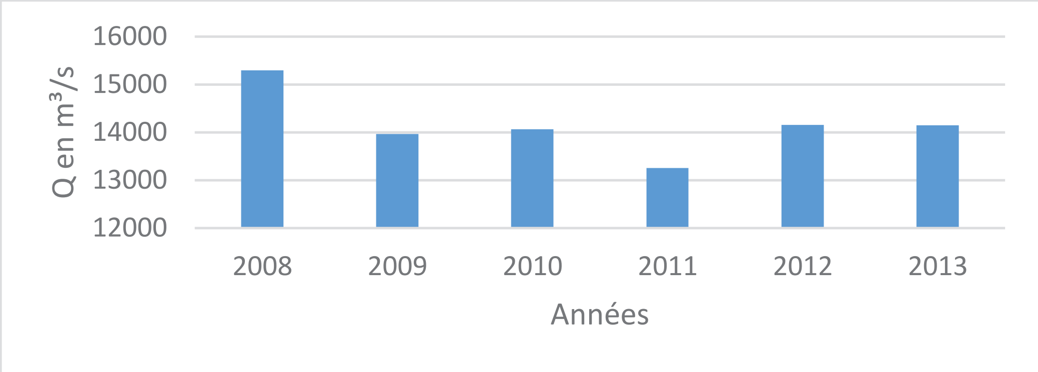

Figure. 2: Representation of the hydrographic flows of Kisangani sub-basin.

We used the physiographic data defined in Table 7 below. This is a suite of data sets from the greater Congo River basin

Table 1: Table of physiographic data used in this Kisangani sub-basin case.

Dataset	Associated physical reality	Origin
Digital terrain model(DTM)	Topography, hydrographic network	Produced by a raster image upload in the Cgiar.org site.
Météorological	Précipitations, les températures, solar radiation, humidity relative, Wind speeds	Observed city stations and those downloaded from Global Weather Data for Swat (GWD)
Land cover	A supervised classification into different dominant classes	Obtained by downloading from FAO soft
Soil Type	Pédology	

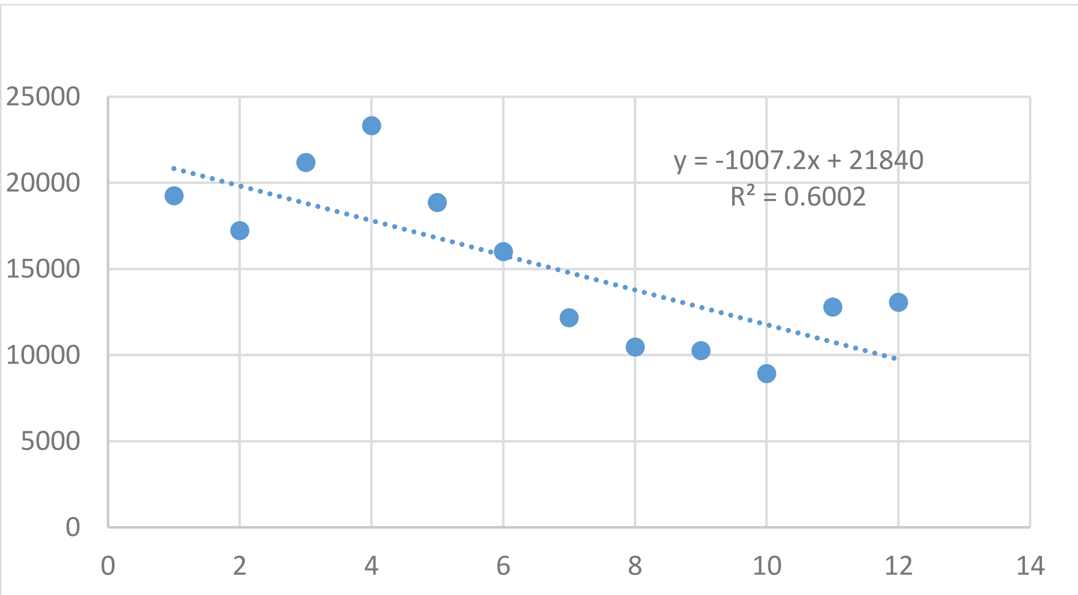

Figure.3: representation of the linear flow of the river in the Kisangani sub-basin

RESULTATS

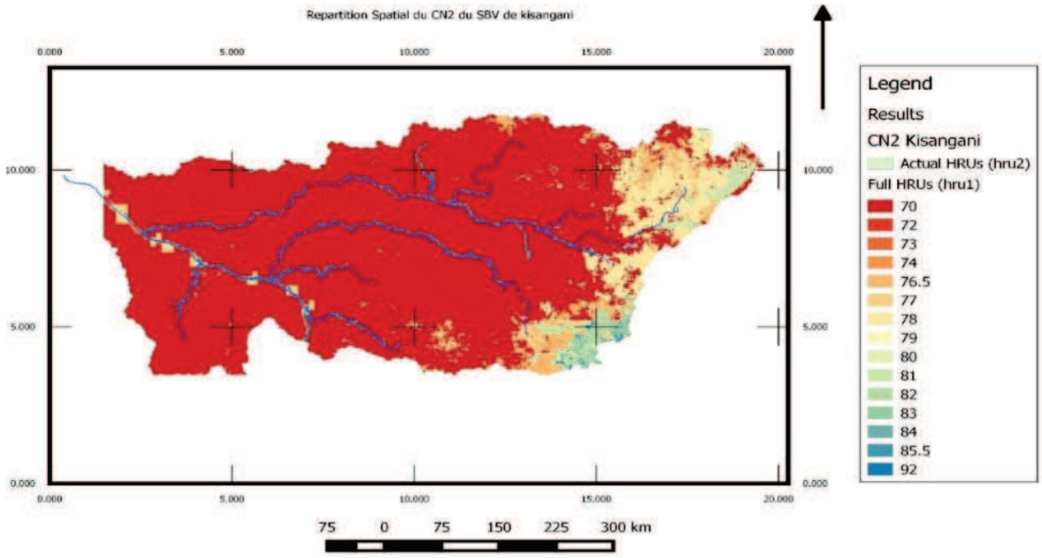

Figure.4: Representation of the spatial distribution of CN2 in the Kisangani sub-basin.

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 Kisangani sub-catchment conditioned by calibration parameters and the most sensitive indices to ensure its performance.

This application without calibration of the SWAT model for our case gives satisfactory results (R^2= 0.6) for a monthly time step, respectively 7930,13 m³/S as average of the observed flows whose linear equation is:

$$Y = -1007.2x + 2184040 \quad (1).$$

We could not try to reproduce this variability of the hydrological operation 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.

We realized the delimitation of this sub-basin of Kisangani by using the digital terrain model which was used to draw the paths and directions of flow in an open source geographic information system (QGIS).

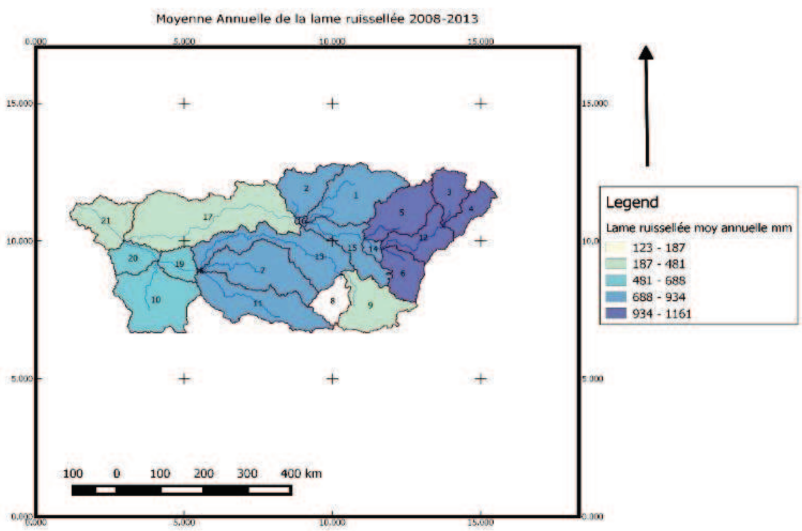

Figure.5: Representation of the spatial distribution of the results of the average annual runoff in the Kisangani sub-basin.

For the most appropriate spatial discretization and best subsequent analyses, we performed 21 spatial cuttings of this sub-catchment ranging from 21 km² at the smallest to 41038 km² at the largest. The identical combination obtained by crossing the sub-catchment cutting, land use and Pédology assumes a similar hydrological response (HRU) in each sub-catchment. A total of 738 HRU were identified in our Kisangani sub-catchment.
The curves numbers method with its CN index is spatially distributed in this sub-basin in a range of 92 to 70.This is explained by the types of soils and land uses in this eastern area of the country with the presence of two lakes Edward and Albert in the range of 83 to 81, the source or resource of the great Nile River. The average height of the runoff is also distributed over the entire area with high heights of 1161 to 934 mm and a minimum of 187-123 mm.
In view of these results, we accept that this ability to reproduce without calibration is an indicator of the quality of our input data according to our objective.

Sensitivity analysis tool

We analyze it with SWAT-CUP (SWAT Calibration and Un certainty Procedures) which is a calibration program for SWAT models. For our case, the choice of the calibration method is the SUFI-2 procedure (Sequential Uncertainty Fitting).
In SUFI-2, the identification of sensitive parameters is done using the t-stat and P-value indicators. A parameter is more sensitive when it has a high absolute value of t-stat and a value of P-value close to zero.

Tools for evaluating the performance of the model

The SWAT model's performance is first evaluated graphically by the Nash-Sutcliffe Efficiency (NSE) which is an objective function that indicates to what extent the variation of the observations corresponds to the variation of the simulated values. It determines the magnitude of the residual variance (or "noise") compared to the measured data variance. This evaluation of the fit of the simulated data to the observed data is done by a value ranging from - ∞ to 1. The closer the NSE is to 1, the better the modeling. Its équation is as flows:

Équation 1 . Equation's Nash - Sutcliffe

$$NSE = 1 - \frac{\sum (O - S)^2}{\sum (O - \overline{O})^2}$$

Then by the coefficient of determination R². It represents the proportion of variance explained in the total variance of the observations. Its value varies from 0 (null model) to 1 (perfect model), with results considered satisfactory when it exceeds 0.5:

Équation 2. . Equation's Determination

$$R^2 = \frac{\left[\sum (O - \overline{O}).(S - \overline{S})\right]^2}{\left[\sum (O - \overline{O})\right].\left[\sum (S - \overline{S})\right]^2}$$

With 0 the observed values;Ō the average of the observed values;S the simulated values and Ṡ the average of the simulated values.

Sensitivity Analysis and Calibration.

Parameter sensitivity analysis is a method of identifying changes in output variables based on changes in model parameters.We relied on the SWAT-CUP variable parameter approach by choosing SUFI-2 as our type of calibration method by pulling out the most sensitive parameter indicators t-stat and P-value. This algorithm was developed for parameter optimization so that all uncertainties (parameter, conceptual model, input, etc.) are mapped onto the parameter ranges, which are calibrated to set most of the measured data within the 95% prediction uncertainty.

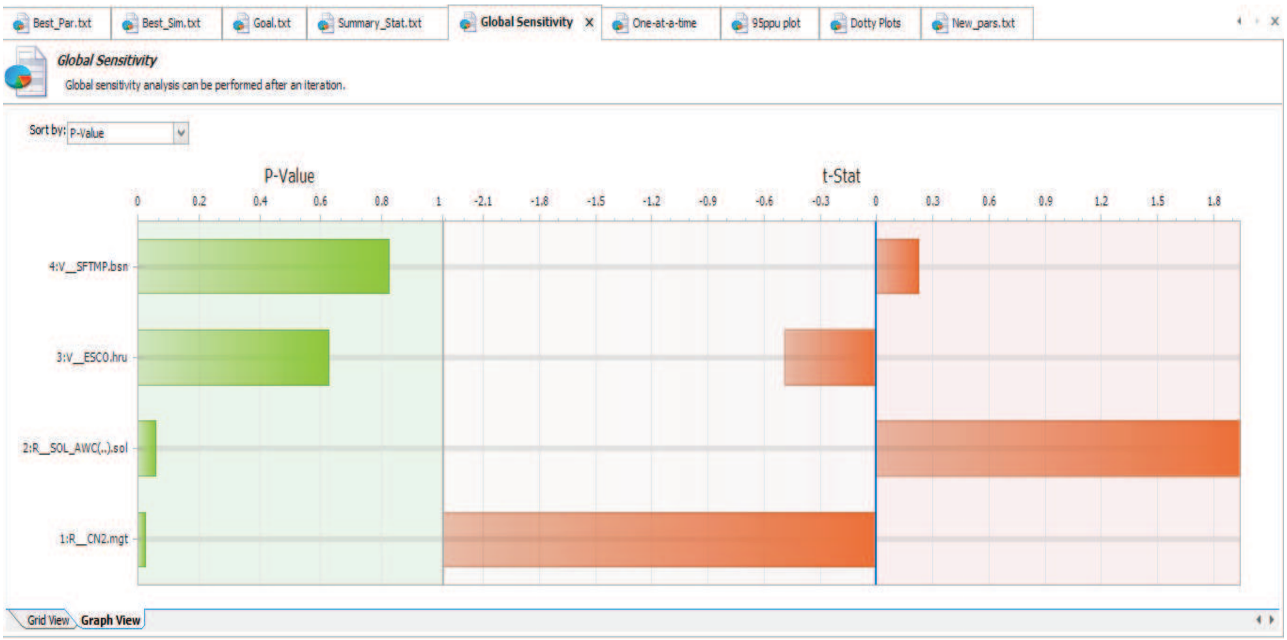

Figure.6: Figure of the index table of the most sensitive parameters.

In our case of study, the period from 1979 to 2010 consisted in establishing a comparison of the observed data and downloaded on GWD given the vastness of our watershed and the great unavailability of acquisition of meteorological information from different stations.

This operation led us to be able to make an amplification of the meteorological data by creating a grid of the GWD stations on all the extent of our Watershed. This phase constituted our first test way to assure us of our meteorological data leading us in the continuation of our process of study. The period of 2005 - 2008 is the one of the starting up of the model (Warm up period) and of 2008 - 2014 is the one of our automatic calibration at the monthly scale.

```
Goal_type= Nash_Sutcliff   No_sims= 50   Best_sim_no= 14   Best_goal = 9.999224e-001

Parameter_Name          Fitted_Value   Min_value    Max_value
1:R__CN2.mgt            -0.176016      -0.395842    0.003842
2:R__SOL_AWC(..).sol    0.490027       0.064988     0.603012
3:V__ESCO.hru           0.845734       0.750189     0.917811
4:V__SFTMP.bsn          -3.533839      -4.780385    1.780386


  -0.176016   0.490027   0.845734   -3.533839

r__CN2.mgt              -0.176016
r__SOL_AWC(1).sol       0.490027
v__ESCO.hru             0.845734
v__SFTMP.bsn            -3.533839
```

Figure.7: Representation of the values of the best parameters after 50 simulations.

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We performed 50 simulations although the number seems so small but is part of the test experiments. The parameters gave us information about the sensitivity of our model and the best simulation n°14 with adjusted parameter values for calibration and simulation.

Figure.8: Summary representation of the statistics of the values of the indices of the parameters of the simulation.

Global Sensitivity

Global sensitivity analysis can be performed after an iteration.

Parameter Name	t-Stat	P-Value
4:V__SFTMP.bsn	0.222531293	0.824907274
3:V__ESCO.hru	-0.490363222	0.626259451
2:R__SOL_AWC(..).sol	1.941004943	0.058536661
1:R__CN2.mgt	-2.311245840	0.025455938

Figure.9: Table of global sensitivity parameters

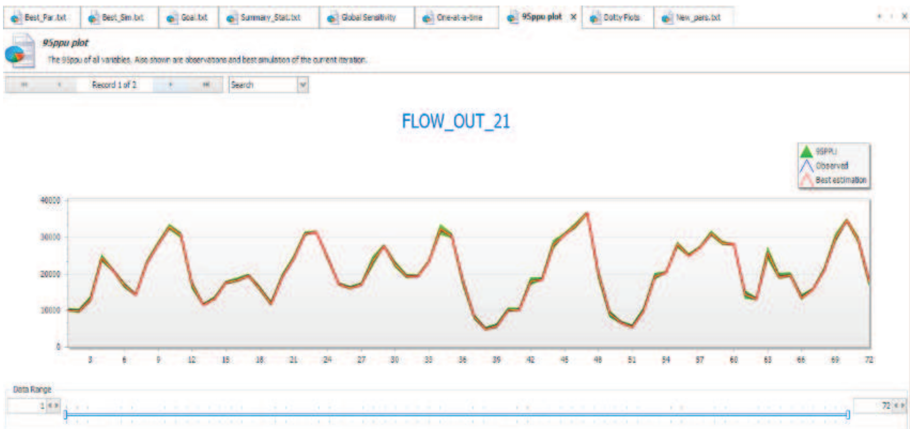

Figure.10: Representation of the simulation with SWA-CUP of the Kisangani Basin.

DISCUSSION AND CONCLUSION

Our conclusions are based on our objectives for the Congo River Basin, which was to show the availability of SWAT to perform analysis and modeling operations given its large size and the opportunities

The sensitivity analysis for this Kisangani sub-basin case study confirms the quality of our input data used, which ideally represents (optimizes) the reality on the ground

The most sensitive parameters are related to baseline inputs, including surface runoff, soil water, groundwater, channel delivery, and actual and potential evaporation.

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 i) the curve number (CN); ii) the Available Water Capacity of the soil layer (mm H2O/mm.) (Sol_ AWC (...) and "replacement" mode; iii) the soil evaporation compensation factor (Esco .hru); iv) soil and a test parameter to see the behavior of the model sensitivity the SFTMP.bn.

For the most appropriate spatial discretization and the best subsequent analyses, we performed 27 spatial breakdowns of our sub-watershed, corresponding to average HRU areas ranging from 1 km² to 8886 km².

A total of 738 HRUs were identified in our Kisangani subwatershed. Given these results, the Curve Number method seems so crucial in this case study.

In short, the Curve Number method implemented in SWAT can provide useful information for the successful implementation of integrated water resources management in the Kisangani sub-basin.

Finally, these steps have contributed to prove that despite the complexity and the immensity of the studied environment, the restriction in the acquisition of observed data, the obtained results prove that the SWAT hydrological model provides information of the different interactive and complex natural processes in a sub-watershed. It is a robust tool in its operation and its capacity to achieve a good integrated management of water and soil resources that will lead to a good sustainable exploitation of the biophysical characteristics of the Kisangani sub-basin and the surrounding areas .

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