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Contribution of Agro-Hydrological Modeling in the Evaluation of Water Availability of an Ungauged Basin Reservoir in Côte d'Ivoire: Case of the Loka Reservoir in Bouaké

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Abstract

The city of Bouaké, the second biggest city of Côte d'Ivoire, experienced a water shortage in 2018 that lasted four months due to the drying up of the Loka reservoir, which supplies two-thirds of the city. The challenge of the Loka reservoir is that it is located in an ungauged basin where very few hydrological studies have been carried out, despite the recurrent problems of access to drinking water. In the purpose to better understand the phenomena that caused this temporary drying of the dam, the methodology implemented was based on agro-hydrological modeling with SWAT using a regionalization technique of a nearby watershed. The model performance was assessed using three statistical indices (the Nash-Sutcliffe coefficient (NS), the coefficient of determination (R^2) and the percentage of bias (PBIAS)) and the visual appreciation of hydrographs for monthly series. The statistical indices appear satisfactory with a NS and $R^2 \geq 0.6$ both for calibration and validation, and a PBIAS of −11.2 and −3.8 respectively for calibration and validation. The hydrological modeling of Loka basin has shown the impact of climate change already reported by some authors as well as anthropization. Thus, while the reservoir records a decrease in its water volume estimated at 384,604 m^3 each year, the water demand undergoes an increase of 122,033 m^3 per year.

Keywords

Loka Basin, Hydrological Modeling, SWAT, SUFI-2, Water Availability

1. Introduction

In constant interaction with all the elements of the biosphere, water is undoubtedly the non-substitutable substance, essential for life. Its management linked to that of other natural resources has motivated major international bodies to include it among the Millennium Development Goals [1]. In Côte d'Ivoire, the pressure on the availability of drinking water continues to grow due to the demography growth and uncertainties related to climate change [2] [3] [4] [5] [6]. Indeed, an unsuitable and insufficiently planned management has created during the first half of 2018 in various areas of the country, including Ferkessédougou, Niakaramandougou, Tiéningboué and Bouaké, disruptions in the drinking water supply [7]. In Bouaké, Côte d'Ivoire's second largest city, concerns about the management of drinking water are very real. Indeed, the populations of Bouaké city have been faced during almost four months in 2018, with an unprecedented water shortage. The Loka dam, which supplies two-thirds of the city with drinking water, has dried up. This drying up of the reservoir observed during the months of May, June and July 2018 has caused much tension. Among the factors indexed of this drying up are the Ivorian government through the Water Distribution Company in Côte d'Ivoire (SODECI), the climate change and the anthropization. In addition to these factors, the socio-political crisis that shook Côte d'Ivoire in 2011 has greatly affected the drinking water supply, due to the displacement of populations to Bouaké and its surroundings [8]. Yet this demographic growth, in addition to increasing the drinking water request [9], has exerted pressure on the natural environment through constant modification of the landscape for agricultural purposes, thus contributing to the emergence of bare soil [10]. Moreover, the increase in bare soil is a source of increased erosion [11]. In addition, it leads to a regular deposition of sediment in the reservoir during runoff on the watershed. These sediments, which for the most part carry pollutants, accumulate in the drinking water reservoir by gradually reducing its water storage capacity. Based on this observation, it seems more than urgent to set up a monitoring and decision support tool to prevent possible disruptions in the drinking water availability. Such management requires a more detailed knowledge of agro-hydrological processes involved in the water balance. Therefore, the main objective of this study is to understand the hydrological functioning of Loka reservoir used to supply Bouaké city drinking water in order to prevent future shortages of drinking water. To achieve this objective, the functionalities of SWAT model combined with Geographic Information Systems are used.

2. Material and Methods

2.1. Presentation of the Study Area

The Loka basin is located in the administrative region of Gbêkê, precisely the northwest of the Bouaké city. The Loka basin is a subbasin of Kossou Lake (**Figure 1**). It is geographically located between 07˚41 and 07˚48 North latitudes and between 05˚05 and 05˚15 of West longitudes. The Loka catchment, whose altitude varies between 199 m and 364 m drains an area of 133.21 km^2. That of Kossou drains an area of 32,671.82 km^2.

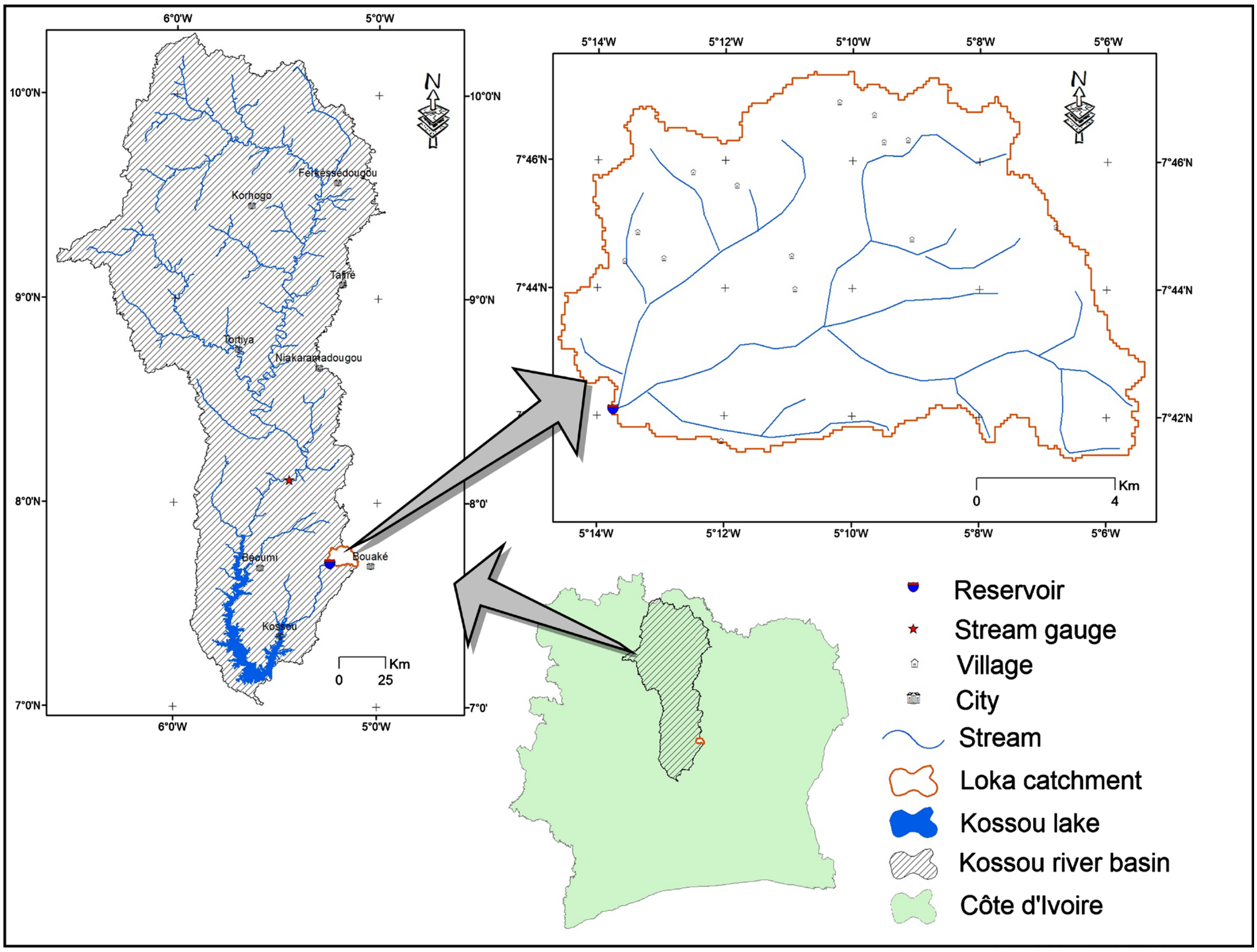

Figure 1. Presentation of Loka basin.

The soil of the Loka watershed is a transition between savannas' ferruginous and forests' ferralitic soils. However, the basin is dominated by a ferruginous soil type with a sandy covering. As for the vegetation, it is composed of grassy savannah and trees. Climatically, the Loka basin is located in the transitional equatorial climate, more known as the Baoulean climate. Unfortunately, according to the conclusions of several authors including Ouedraogo [12], Ardoin [13], Goula *et al.* [14], Kouassi [15], Kouassi *et al.* [16], since 1965, rainfall in the basin has been decreasing. Demographically, Bouaké is the second largest city in Côte d'Ivoire. It records an annual growth rate of 0.95% with a population that has increased from 461,617 inhabitants in 1998 to 536,719 inhabitants in 2014 [8]. Among other factors of this strong demographic growth, the 2011 post-election crisis combined with the good forest cover of Bandama watershed [17] [18] [19] and [20]. With this high population density, the drinking water supply of Bouaké city is provided for 80% by surface water from three reservoirs (Kan, Gonfreville and Loka). The Loka reservoir provides two-thirds of Bouaké city and some surrounding village drinking water supply. Unfortunately, the latter experienced a drying up in 2018 during the months of May, June and July

(**Figure 2**).

2.2. Description and Implementation of the Model Used

The model used in this study is called SWAT "Soil and Water Assessment Tool" [21]. SWAT was developed by researchers at the United States Department of Agriculture (USDA) [20]. The choice of this model in this study is largely due to its ability to easily reproduce water cycle in a simplified manner in highly anthropized and ungauged watersheds [22]. It is also freely downloadable from the Internet and its open source code allows improvements through the vast scientific community that supports it. It also has several advantages, notably climate forecasting and impact simulation of planning scenarios. The SWAT agro-hydrological model is therefore a deterministic, physical, conceptual and semi-distributed model that operates on a continuous basis with a daily time step. The SWAT version used in this study is coupled with ArcGIS 10.0 GIS software. [18] in their work have summarized the implementation of SWAT model into 3 major successive phases.

2.2.1. Preprocessing Phase

The pre-processing phase consists of an adaptation of the standardized physiographic data for the entire American territory to the realities of Côte d'Ivoire. In others words, it consists in adding or adjusting certain parameters of the model source code (soil (usersoil), climate (userwgn)) [21] and agronomic (sowing and harvesting dates, fertilizer and nutrient inputs, tillage and cultural practices) [23] [5] to the realities of the Loka basin.

2.2.2. Processing Phase

Since the Loka basin is ungauged, the modeling of water flow to the Loka reservoir was based on one regionalization technique that is the spatial proximity. Indeed, studies reported in the scientific literature by [24] [25] [26] and [27]

Figure 2. Drainage of Loka reservoir in Bouaké in 2018.

have shown that among the three different methods of regionalizing hydrological model parameters (spatial proximity, physical similarity and linear regression), the spatial proximity approach leads to better results. The hypothesis that justifies this approach is that a spatially close gauged and ungauged basin should in theory have similar physical characteristics. Similarly, both basins should react in the same way to meteorological events [28]. Therefore, this phase was based on the Kossou Lake watershed in which the Loka River basin is located. The implementation of SWAT on the Kossou lake watershed requires a large number of files which are of two types (raster and point). Thus, the following data were entered in order in the model:

- the Digital Elevation Model (DTM) (established from Shuttle Radar Topography Mission (SRTM) images, with a spatial resolution of one arc per second; *i.e.* 30 m acquired via American site: http://earthexplorer.usgs.gov/);
- the location of hydrometric stations (the Marabadiassa hydrometric station located upstream of the Loka basin has monthly flow data for the period from 1981 to 2005, with gaps from 1997 to 2002. The streamflow data were made available by the National Drinking Water Office (ONEP) of the Human Hydraulics Department (DHH);
- the morphometric characteristics and the volumes of water withdrawn monthly from the reservoir from 1987 to 2019;
- the soil map established by FAO in 1995 with a spatial resolution of 10 km;
- the land use map with a spatial resolution of 30 m was obtained from Landsat 7 ETM+ images of 12/15/2005 via the site https://glovis.usgs.gov/;
- daily weather data from 1980 to 2006 (precipitation, temperatures (minimum and maximum) from the CRU website: http://www.cru.uea.ac.uk/~timm/data/index-table.

In order to take into account the heterogeneity of the basin, SWAT has divided the basin into several Hydrological Response Units (HRU). Note that a HRU is the result of the intersection of three unique elements (land use, soil and slope) in a subbasin. Also, in order to increase the accuracy of the model, the several HRUs option in each subbasin was chosen. The last adjustments of this phase concerned the calculation of potential evapotranspiration (PET), water flow and runoff. The PET was defined using the Penman-Monteith equation, water flow by the variable storage method and runoff by the Curve Number (CN) method. Neitsch *et al.* [29] propose a very detailed description (phenomena, processes and equations) of agro-hydrological modeling with SWAT in the user manual.

2.2.3. Post-Processing

The last adjustments of this phase concerned the calculation of potential SWAT is a complex model with many parameters that make it difficult to optimize. Indeed, it includes 629 parameters on which it is possible to adjust to have a good performance of model [5] [30]. In addition to these parameters, several uncertainties may arise during the SWAT model implementation. These uncertainties contribute to reduce its optimization. Therefore, a sensitivity and uncertainty analysis is required. To identify the parameters and quantify the uncertainties, the SUFI-2 (Sequential Uncertainty Fitting version-2) algorithm of the SWAT-CUP (SWAT-Calibration and Uncertainty Program) software of [31] was used. Note that SWAT-CUP which is increasingly used by the SWAT community is an external software tool allowing SWAT users to realize automatic calibration with more comfort and efficiency [32]. In SWAT-CUP, SUFI-2 uses the Latin-One-At-a-Time (LH-OAT) Hypercube method [33] as a method for sampling sensitive parameters. The LH-OAT method involves changing one parameter at a time, while the other parameters are left untouched To avoid sampling all 629 parameters, the sensitivity analysis was based on the literature on the use of SWAT model in Côte d'Ivoire by [5] [11] [18] [20] [30] [34] [35] [36]. At the uncertainties level, two variables were used to quantify their inclusion by SUFI-2 algorithm [37] [38]. These are notably the P-factor, which represents the degree to which all uncertainties have been taken into account (namely the percentage of measured data framed by 95% uncertainty prediction (95PPU)) and the R-factor, which is the thickness of the 95PPU band. The P-factor and the R-factor both vary from 0 to 1; with 1 as optimum for P-factor and 0 as optimum for R-factor in regards to water flows [31] [39]. Furthermore, to be able to realistically reproduce the Loka reservoir water flows, SWAT needs observed hydrometric data series. According to the application [40] index calculated on the basis of the Marabadiassa station water flows (situated on the Kossou lake watershed), the years 1983-1985, 1987, 1988 and 1991 correspond to dry years, while the years 1995-1997 and 2002-2004, correspond to wet years. Thus, the observed hydrometric data were dived into a calibration period (1983 to 1991) and a validation period (1995 to 2004). Three years (1980-1982) were used for model warming. Several criteria are used in the literature to gauge the goodness of the stream flow simulations. These criteria can be either visual or quadratic. The visual criterion consists in looking at the similarities between the observed and simulated hydrographs. As for the quadratic criteria, also called "objective function", they are expressed in statistical equations. In this study, three statistical criteria widely used in most studies with SWAT model were used. These are the Nash-Sutcliffe coefficient "NS" (Equation (1)), the coefficient of determination "R^2" (Equation (2)) and the percentage of bias "PBIAS" (Equation (3)).

$$\mathrm{NS} = 1 - \frac{\sum_{i=1}\left(Q_m - Q_s\right)^2}{\sum_{i=1}\left(Q_m - \bar{Q}_m\right)^2} \tag{1}$$

$$\mathrm{R}^2 = \frac{\left[\sum_{i=1}\left(Q_m - \bar{Q}_m\right)\left(Q_s - \bar{Q}_s\right)\right]^2}{\sum_{i=1}\left(Q_m - \bar{Q}_m\right)^2 \sum_{i=1}\left(Q_s - \bar{Q}_s\right)^2} \tag{2}$$

$$\mathrm{PBIAS}(\%) = 100 \times \frac{\sum_{i=1}^{n}\left(Q_m - Q_s\right)}{\sum_{i=1}^{n} Q_m} \tag{3}$$

With Q_m = observed flow, Q_s = simulated flow, $\bar{Q}_m$ = average of measured flows and $\bar{Q}_s$ = average of simulated flows.

NS varies from −∞ to 1. NS is considered "good" when it is ≥0.5 and "very good" above 0.75 [41]. R^2 varies from 0 to 1. An R^2 value greater than 0.5 would reflect good agreement between observed and simulated data [42]. PBIAIS is between ±25% [43]. The optimal PBIAS value (zero) indicates a perfect simulation of the model [32]. A positive PBIAS indicates an underestimation of the model while a negative PBIAS demonstrates an overestimation of the model [31] [41].

3. Results and Discussion

The implementation of SWAT model made it possible to discretize 251 subbasins for a minimum threshold of 75 km^2. The model was simulated for a period of 29 years over the period 1978 to 2005. The ability of SWAT model to restore water flows from the Loka reservoir is based on the examination of the performance values reflected by the static tests and the similarity of the observed and simulated hydrographs.

3.1. Sensitivity Analysis

The sensitivity analysis applied to the 14 hydrological parameters showed 9 parameters sensitive to the simulation of water flows from the Marabadiassa hydrometric station. The global sensitivity of these 9 parameters and their readjusted values are summarized in **Table 1**.

According to Abbaspour [31] [39], more the higher absolute value of t-stat and P-value close to zero (0), and more the sensitivity of the parameter is important. Thus, the global sensitivity analysis of the SWAT model showed, in decreasing order, that the most sensitive parameters were the groundwater drying coefficient (ALPHA_BF), the effective hydraulic conductivity of the main channels (CH_K2), the initial "SCS" runoff curve number for the moisture condition II (CN2), the maximum canopy storage (CANMX), the available water capacity of the soil layer (SOL_AWC), soil evaporation compensation factor (ESCO),

Table 1. Global sensitivity and adjusted model parameters.

Ranking	Parameter Name	t-Stat	P-Value	Initial value	Final calibrated Value
1	ALPHA_BF.gw	8.915	0.000	0.048	0.50
2	CH_K2.rte	4.653	0.000	0.0	230.83
3	CN2.mgt	−2.385	0.017	74 - 92	−0.44%
4	CANMX.hru	2.168	0.031	0.0	99.33
5	SOL_AWC.sol	−1.886	0.061	0.093 - 0.175	+0.28%
6	ESCO.hru	0.951	0.342	0.0	0.31
7	CH_N2.rte	0.732	0.464	0.014	0.05
8	GW_DELAY.gw	0.697	0.486	31.0	390.25
9	GWQMN.gw	−0.590	0.953	0.0	4050.57

Manning's roughness coefficient (CH_N2) of the main channels, the time for groundwater transiting through the surface water table to reach the stream (GW_DELAY), and the threshold depth of water in the shallow aquifer required for return flow to occur (GWQMIN). All of these sensitive parameters have also been identified as sensitive parameters by many authors including [5] [18] [20] [30] [34] [36] [45] [46] [47] [48].

3.2. Objective Function

The best performance criteria were obtained after 4 iterations of 500 simulations. The analysis of the statistical indices (**Table 2**) shows that the stream flow simulation is satisfactory. Indeed, the performance of the model obtained in calibration as well as validation respects the conditions of Van Liew *et al.* [49] and Moriasi *et al.* [43]. Moreover, the performance remains very close to the work of Schuol *et al.* [37] and [30].

Figure 3 graphically illustrates the evolution of statistical criteria at the Marabadiassa station (subbasin 191).

Table 2. Statistical criteria for model performance.

Period	P-factor	R-factor	R^2	NS	PBIAS
Calibration	0.83	0.98	0.68	0.66	−11.2
Validation	0.81	1.08	0.59	0.59	−3.8

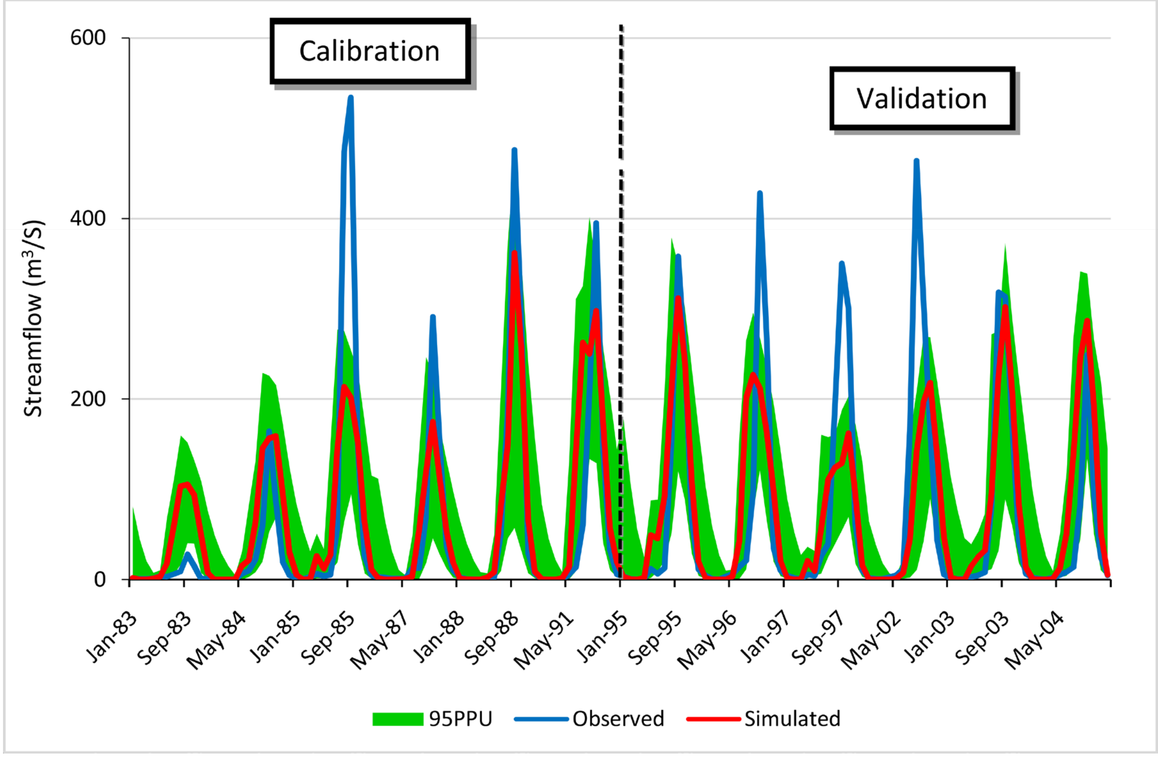

Figure 3. Observed and simulated hydrograph for the Marabadiassa station (left calibration period and right validation period).

The visual analysis of the hydrographs generally shows good synchronism between observed and simulated stream flows with however, a slight underestimation of peak floods in both periods. Several reasons can explain these trends of underestimation of flows. Indeed, the model was fed by different sources of data according to their availability and quality [50]. According to [51] [52], SWAT model is extremely sensitive to the quality of soil data, land use, as well as the preprocessing procedures adopted for geographically distributed data. Yet, the soil map and soil data used for the modeling were obtained from the FAO regional database. The latter does not accurately represent the basin soil characteristics. In addition to the soil map, the small-scale of landuse map does not define the different crops and land uses clearly enough. Other than the detail of the different types of crops, there are several small hydro-agricultural dams upstream of the basin, which were not taken into account during the implementation. The presence of these reservoirs upstream of the watershed changes the spatial availability of the water resource [20]. Other drawbacks of SWAT that could justify the dephasing of hydrographs are linked to the spatial distribution of climate stations [20] [30] and to unobservable data, notably the empiricism of SWAT model [53].

3.3. Determination of Water Flows in the Reservoir

Due to the political crises in Côte d'Ivoire, the data of water withdrawn from Loka reservoir cover the period from 1987 to 1997. Thus, the hydrological simulations carried out over this period (1983 to 1997) allowed to reconstitute the various contributions in the Loka reservoir. The average monthly inflow to the reservoir is 0.78 m^3/s, *i.e.* a water level of 15.30 mm per month. **Figure 4** shows the evolution of the interannual average water flow in the Loka reservoir, as well as water quantities extracted from the reservoir for drinking water supply.

The visual analysis shows that the Loka reservoir, with a maximum capacity of 3000.104 m^3 and an area of 187.5 km^2, is experiencing a decrease of water volume

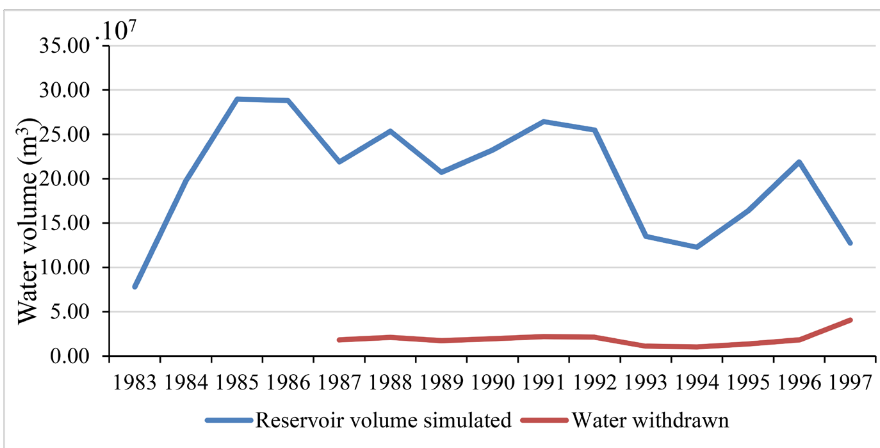

Figure 4. Evolution of the adequacy between the water needs and availability in the Loka reservoir.

estimated at 384,604.167 m^3/year; *i.e.* a decrease of 2.26% per year. Unlike the volume of water in the reservoir, the demand for water undergoes an increase of 2%; that is, a volume of 122,033.3 m^3 per year. Hydrological modeling of the Loka basin has shown the impact of climate change as well as anthropization. Indeed, the decrease of Loka reservoir inflows during the period from 1983 to 2018 (drying year) is related to the drop in rainfall.

Yet this decrease in rainfall had been reported in the work of [13] [14] [54] and [55]. In addition, the action of anthropization has been reinforced by the various crises in Côte d'Ivoire, which have made the Bouaké city a pole of attraction for indigenous and non-indigenous populations of West African sub-region.

4. Conclusion

The work of this study focuses on the assessment of the water availability of the Loka reservoir in Bouaké, face to the uncertainty posed by climate change and anthropization. To better characterize the Loka reservoir, the methodology used was based essentially on agro-hydrological modeling with SWAT. This was based on the performance evaluation criteria of a gauged watershed located near the Loka reservoir. The statistical criteria of the model give satisfactory values of model with an NS of 0.66, an R^2 of 0.68 and a PBIAS of −11.2 for the calibration, and an NS and R^2 of 0.59, and a PBIAS of −3.8 for the validation. From this study, it appears that the average volume of water in the reservoir decreases by 384,604.167 m^3 each year. This decrease is partly due to climatic hazards. In addition, the impact of anthropization should not be overlooked, because while the volume of water in the reservoir decreases, the drinking water needs increase. Studies on hydro-climatic variability previously carried out by a number of researchers have shown a drop in rainfall in the study area. It therefore attests the 2% drop of annual rainfall observed noticed since a few years. To improve the results of this study, it would be desirable to carry out a more detailed study of the soil physico-chemical characteristics. Likewise, to avoid a repetition of the water shortage, a coupling of SWAT model to climate model would be ideal.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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