Scientific Research Publishing

Open Journal of Modern Hydrology, 2026, 16(3), 229-246
https://www.scirp.org/journal/ojmh
ISSN Online: 2163-0496
ISSN Print: 2163-0461

Physically Based Hydrological Simulation of the Bia Transboundary Catchment (West Africa)

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How to cite this paper: Yao, B.A.F., Soro, G.E., Beniambie, F.M.C., Abo, N.K.E., Kansaye, A.D., Ba, B.T.A. and Goula, B.T.A. (2026) Physically Based Hydrological Simulation of the Bia Transboundary Catchment (West Africa). *Open Journal of Modern Hydrology*, **16**, 229-246.
https://doi.org/10.4236/ojmh.2026.163013

Received: February 11, 2026
Accepted: June 20, 2026
Published: June 23, 2026

Abstract

Understanding all the components of the water balance is essential for rational and sustainable management of water resources. However, direct assessment of several components of the water balance is very difficult and modelling is often necessary. The main objective of this study is to simulate the hydrological functioning of the Bia catchment upstream of lake Ayamé. To achieve this objective, this study is based on data processing (meteorological, hydrological and satellite data from 1982 to 2020) to describe the natural characteristics of the basin. Soil and Water Assessment Tool (SWAT) model implemented in Quantum Geographic Information System (Qgis) was used for the analysis and modelling of hydrological processes at catchment level. Analysis of satellite imagery reveals a significant decline of 46.10% in vegetation cover, with an increase in agricultural land, degraded forests, bare soil and built-up areas. This decline has affected the surface area of water bodies in the basin, with a 70.15% reduction over the period 1987-2017. SWAT model showed good performance (78% for calibration and 60% for validation) in reproducing the monthly flows of the river Bia at Bianoua. The annual balance shows high actual evapotranspiration (614.7 mm/year, or 66% of rainfall) in a basin that receives 921.3 mm/year of rainfall. Surface runoff accounts for 17.5% of rainfall and infiltration 16.7%. Volumes of precipitated water have suffered enormous losses due to high rates of actual evapotranspiration. Despite this, the balance remains acceptable across the basin, as rainfall exceeds actual evapotranspiration.

Keywords

Land-Cover, Runoff, SWAT Model, BIA Catchment, Côte d'Ivoire

1. Introduction

Despite significant progress in hydrological observation techniques, including remote sensing and geophysical methods, the functioning of catchment systems remains imperfectly understood due to the complexity of the interacting physical processes involved [1]. Catchments are dynamic systems whose hydrological responses are strongly influenced by climate variability and anthropogenic activities [2]. In particular, land-use changes and vegetation cover modifications significantly affect key hydrological processes such as infiltration, evapotranspiration, and surface runoff, thereby altering the overall water balance of the basin [3].

These transformations, combined with climate variability, generate complex hydrological responses that are often difficult to quantify due to the spatial and temporal heterogeneity of basin characteristics and hydraulic infrastructures [4]. Understanding these interactions has therefore become a major challenge for sustainable water resources management, particularly in regions where water systems support multiple socio-economic functions.

The transboundary Bia catchment, shared between Ghana and Côte d'Ivoire, represents a strategic water resource system. Its runoff feeds the Ayamé I and II hydroelectric dams and supports several key uses, including irrigation, fisheries, and drinking water supply for the town of Aboisso and surrounding areas. However, this basin is currently experiencing significant environmental pressures related to land-use changes, agricultural expansion, and artisanal gold mining [5]. Despite its socio-economic importance, the hydrological functioning of the Bia catchment remains poorly documented.

Hydrological modelling therefore provides a relevant framework for improving the understanding of basin processes and for analysing the impacts of environmental changes on water resources. In this context, the present study aims to analyse the hydrological functioning of the Bia catchment upstream of the Ayamé I & II reservoir. Specifically, the study first examines the dynamics of land-use and land-cover changes within the basin. It then evaluates the performance of the hydrological model in reproducing streamflow. Finally, the hydrological balance is assessed in order to better understand the distribution and variability of the main components of the water cycle.

2. Studie Area

The Bia basin is located in the Gulf of Guinea region and is shared by Ghana and Côte d'Ivoire (**Figure 1**). It lies between latitudes 05˚16'N and 07˚20'N and longitudes 4˚42'W and 2˚25'W. Elongated in shape, it covers an area of 9650 km^2, 2/3 of which lies within Ghanaian territory. It rises in Chemraso in northern Ghana and flows into the Aby lagoon in southern Côte d'Ivoire.

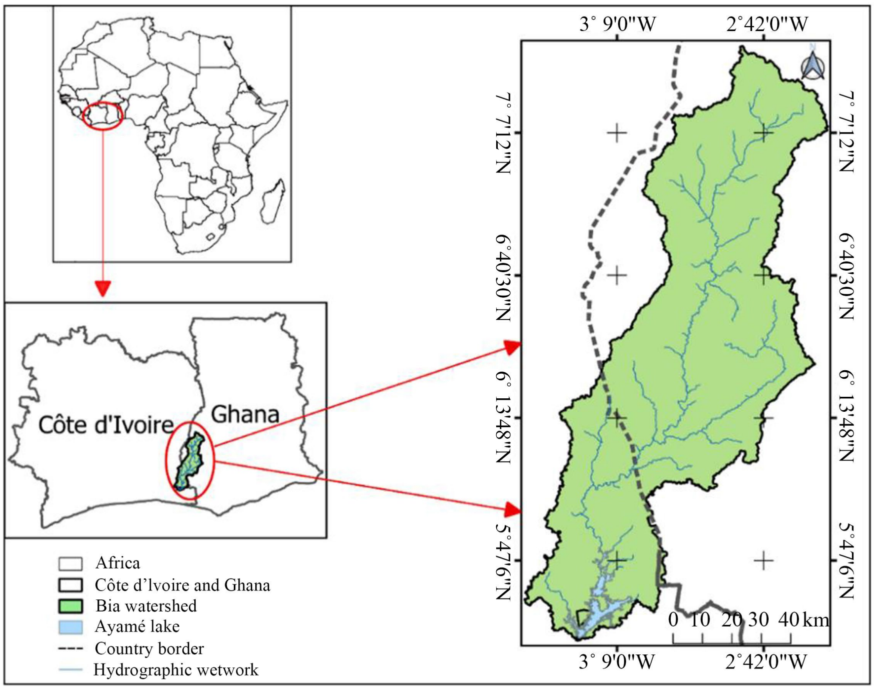

Figure 1. Geographical location of the Bia catchment area.

3. Data

To run the SWAT (Soil and Water Assessment Tool) model, several temporal and spatial datasets were required. These included time series of climatic variables (1982-2020), such as precipitation, maximum and minimum air temperatures, as well as spatial datasets including land use (1987 and 2020), soil characteristics, and topographic data derived from a Digital Elevation Model (DEM). In addition, streamflow time series were used for model calibration and validation. These datasets were obtained from various sources. Details regarding data types, spatial resolution, and data sources are summarized in **Table 1**.

Table 1. Summary of data and sources.

Data types	Data	Resolution	Source
Spatial data	DEM	30 × 30 m	https://www.usgs.gov/products/maps/overview
	Soil	1:5.000.000	https://data.apps.fao.org/?lang=fr
	Land-use (1987 & 2017)	300 m	https://www.esa-landcovercci.org
Temporal data (1982-2020)	Rainfall	four stations	SODEXAM
	Temperature	three stations	
	Flow	Trois stations	Hydrology Direction

4. Methodology

4.1. Land Use Maps and Dynamics

Processing satellites images to obtain a land cover/land use map requires a few different steps, summarized in the diagram below (**Figure 2**).

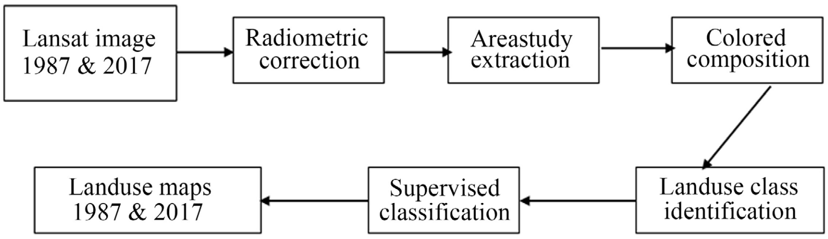

Figure 2. steps processing satellites images to obtain a land cover/land use map.

The dynamics of land cover were assessed by spatio-temporal variations in the areas of the land cover classes between 1987 and 2017. The rate of change (Tc) in land cover between these dates was calculated for each land cover class using the following formula [6]:

$$Tc = 100 \times \left(\frac{A_2 - A_1}{A_1} \right) \tag{1}$$

A_1 and A_2 are, respectively, the initial and final areas of the land use class.

The average annual rate of change for each land use class was calculated using the following formula:

$$r = \left(\frac{100}{t_2 - t_1} \right) * \ln \frac{A_2}{A_1} \tag{2}$$

r: Annual growth rate of class i; A_1: area of class i at time t_1; A_2: area of class i at time t_2.

The simulation of the water balance in this study will only be carried out using the 1987 land use map.

4.2. Climate Data Filling

The missing daily rainfall values were filled using ARC2 (Africa Rainfall Climatology version 2) data (for stations in Côte d'Ivoire) and NASA (National Aeronautics and Space Administration) data (for stations in Ghana). Before using ARC2 or NASA data in this work, the correlation between these data and the observed data was established over the common's periods for stations with missing data. The correlation coefficients were found to vary between 0.68 and 0.90.

4.3. Description of SWAT Model

The SWAT model is a watershed hydrological model developed by the United States Department of Agriculture in the 1990s and incorporated into the Geographic Information System (GIS) platform. It was designed to predict the effects of weather, different land-use patterns, and soil conditions on river runoff [7].

The SWAT model uses the water balance equation for simulation as follows:

$$SW_t = SW_o + \sum\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \tag{3}$$

where SW_t is the final soil moisture content, mm; SW_0 is the initial soil moisture content of the ith day, mm; t is the time, days; R_{day} is the precipitation of the ith day, mm; Q_{surf} is the surface runoff of day i, mm; E_a indicates the amount of evapotranspiration on day i, mm; W_{seep} indicates the amount of water entering the vadoze zone from the soil profile on day i, mm; and Q_{gw} indicates the return flow amount on day i, mm.

Figure 3 shows the summary of the implementation of the SWAT model in Bia watershed at Bianoua.

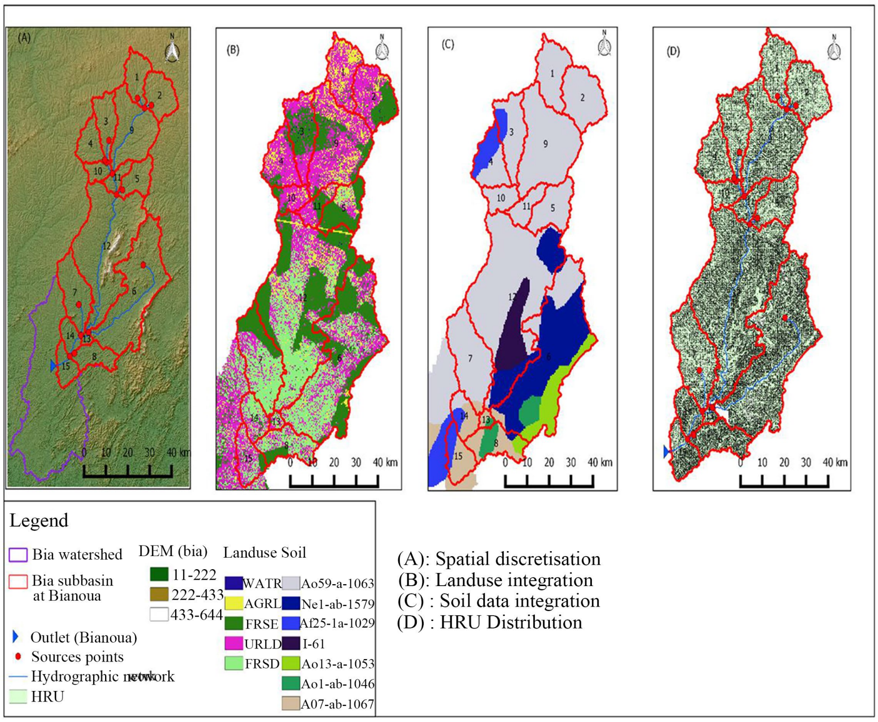

Figure 3. Summary of SWAT implementation on the Bia.

4.4. Sensitivity Analysis and Calibration-Validation

4.4.1. Sensitivity Analysis

Model parameters exert the highest influence on model calibration and predictions. The models respond in a different way to different parameters, and as a result, the outputs become different. Model sensitivity is scrutiny of the change in model output per change in a parameter of input. Sensitivity analysis is one version of the SWAT model tool to show the mean relative sensitivity of the best parameters through SWAT-CUP [8] [9].

4.4.2. SWAT Model Calibration and Validation

Model calibration is the adjustment of model parameters, within the recommended ranges, to optimize the simulated output so that it matches with the observed data. Calibration allows the provision of different parameters for the adjustment during operation. Validation is the process of testing the calibrated parameters with an independent set of observed data without further changes to parameters [8] [9]. Flow data collected at the gauging station of Bianoua was used to do calibration and validation. The Sequential Uncertainty Fitting version two (SUFI-2) algorithm set in SWAT-CUP 2012 was used during model calibration and validation [10]. The model evaluating decision factors as shown in **Table 2**.

Table 2. Model evaluation thresholds [11].

Performance rating	Flow		
Verry good	0.75 NSE ≤ 1	PBIAS ≤ ±10%	$R^2 \geq 0.80$
Good	0.65 NSE ≤ 0.75	PBIAS ≤ ±15%	$R^2 \geq 0.70$
Satisfactory	0.5 NSE ≤ 0.65	PBIAS ≤ ±25%	$R^2 \geq 0.5$
Unsatisfactory	NSE ≤ 0.5	PBIAS ≥ ±25%	$R^2 \leq 0.5$

5. Results

5.1. Soil Surface Condition in the Bia Watershed

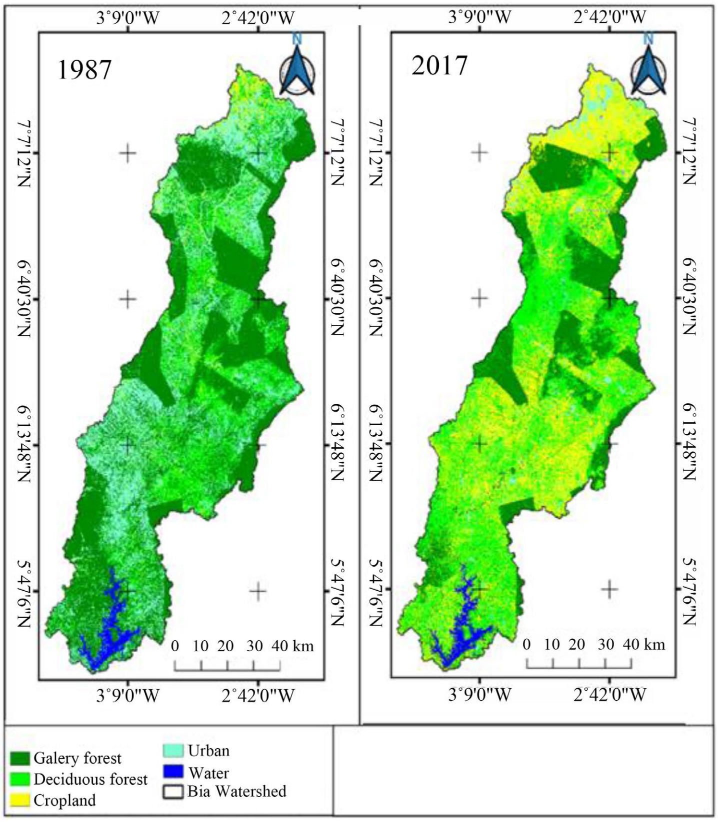

Figure 4. Land use map of the Bia catchment for the years 1987 and 2017.

The main land use classes are deciduous forest, gallery forest, cropland, urban, and water. These different classes have seen a variation in their surface areas at the level of each sub-basin from 1987 to 2017 (**Figure 4**).

The land cover maps (**Figure 4**) show that in 1987, gallery forest represented 54.99%, deciduous forest 6.55%, cropland 3%, urban 10.87%, and water 24.59% of the total area of Bia basin.

In 2017, gallery forest represented 29.64%, cropland increased to 16.77%, deciduous forest 19.76%, water 7.34% and urban 26.5% of the total area of the Bia basin.

The rate of change (Tc) and average annual rate of change (r) show that in 30 years, the gallery forest and water class has seen their area shrink by 46.10% and 70.15%, *i.e.*, an annual loss of 2.06% and 4.03% respectively (**Table 3**). As for the cropland, urban, water, and deciduous forest classes, their areas have increased by between 143.79% and 459%, *i.e.*, annual gains of between 2.97% and 5.74% depending on the class (**Table 3**). Despite this, a few pockets of vegetation (dense forests) still exist in the basin, thanks to the presence of parks and reserves (**Figure 7**).

Table 3. Evolution of the different land use classes and overall changes in the Bia basin.

Watershed	Land-use class	Area (Km^2)		Rate (%)		Dynamic (%)	
		1987	**2017**	**1987**	**2017**	**TC**	**r**
Bia (9650 km^2)	**Cropland**	289.5	1618.30	3	16.77	459.00	5.74
	Deciduous forest	632.07	1906.84	6.55	19.76	201.68	3.68
	Gallery forest	5306.53	2860.26	54.99	29.64	−46.10	−2.06
	Urban	1048.95	2557.25	10.87	26.5	143.79	2.97
	Water	2372.93	708.31	24.59	7.34	−70.15	−4.03

5.2. Evaluation of SWAT Model Performance

5.2.1. Sensitivity Analysis of the Hydrological Model

The results of the sensitivity analysis of the Bia basin at Bianoua (**Table 4**), carried out by successive iterations, made it possible to identify the predominant influence of certain parameters (7/14) on the flows production. The most influential parameters have p-values < 0.1. The small number of sensitive parameters to be calibrated is a real challenge since each parameter change must have a physical meaning and requires knowledge of how the catchment functions. These parameters are: the effective hydraulic conductivity in the alluvium of the main channel (CH_K2), The Manning Coefficient ‘n’ of the main channel (CH_N2), river water return coefficient (ALPHA_BNK), Minimum water depth for water to be transferred from the shallow aquifer to the watercourse (GWQMN), Fraction of the water in the soil that percolates downwards and joins the deep water table (RCHRG_DP), Available water storage capacity of the soil layer (SOL_AWC) and Coefficient allowing the transfer of water from the aquifer to the overlying unsaturated soil horizons (GW_REVAP).

Table 4. Lists of parameters by orders of sensitivity.

Order of Sensitivity	Parameter Name	t-Stat	P-Value
1	V__CH_K2.rte	−43.54	0.00
2	V__CH_N2.rte	−4.72	0.00
3	V__ALPHA_BNK.rte	3.51	0.00
4	A__GWQMN.gw	−3.07	0.00
5	R__RCHRG_DP.gw	−2.95	0.00
6	R__SOL_AWC(..).sol	2.06	0.04
7	A__GW_REVAP.gw	1.82	0.07
8	R__SOL_K(..).sol	−0.83	0.41
9	R__CH_N1.sub	0.73	0.47
10	R__CH_K1.sub	−0.71	0.48
11	V__SFTMP.bsn	0.57	0.57
12	A__ESCO.hru	−0.35	0.73
13	R__CN2.mgt	0.04	0.97
14	V__REVAPMN.gw	0.00	1.00

5.2.2. Calibration Et Validation

After calibration of the most sensitive parameters, analysis of the NSE and R^2 statistical indices shows that the flow simulations are good (**Table 5**). For the period used for calibration (1985-1990), the values for NSE and R^2 were 0.78 and 0.80 respectively for monthly flows at the Bianoua station. The indices evaluated on a monthly scale for the validation period (2000-2005) are 0.60 and 0.64 for NSE and R^2 at the same station.

Table 5. SWAT model performance criteria result.

	NSE	R^2
Calibration	0.78	0.80
Validation	0.60	0.64

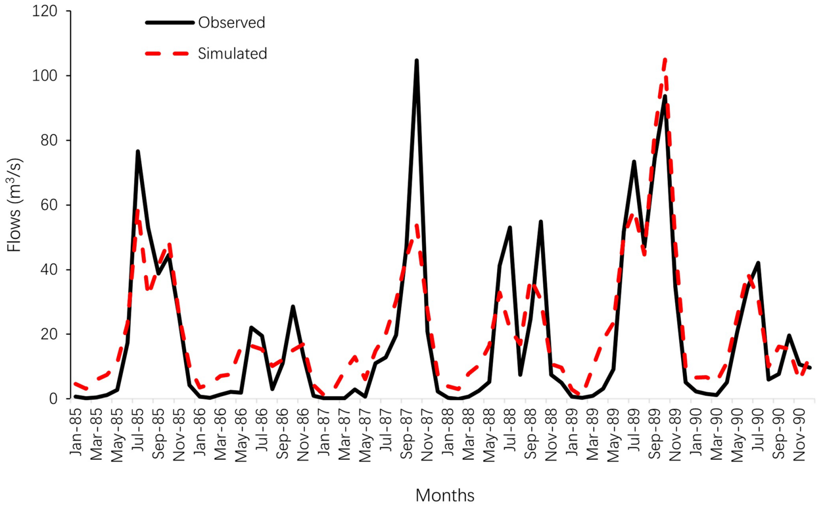

Figure 5. Hydrographs of observed and simulated flows for the calibration period.

The analysis of the hydrographs (calibration and validation) confirms that they were carried out on the basis of the performance criteria, where good performance was obtained. **Figure 5** and **Figure 6** shows perfect synchronisation between the simulated and observed flows during calibration and validation.

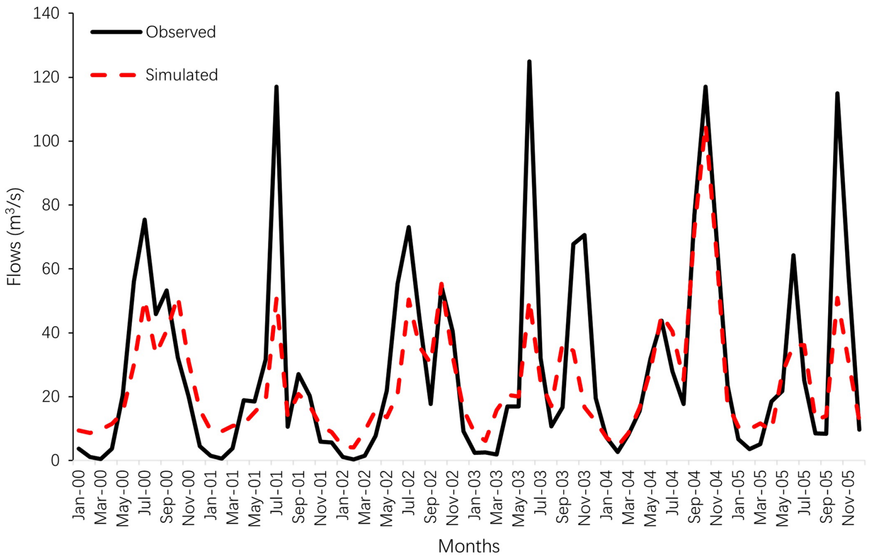

Figure 6. Hydrographs of observed and simulated flows for the validation period.

5.3. Water Balance Analysis of the Bia

By analyzing the various components of the water balance, it is possible to refine the diagnosis of how the model is working and identify areas for improvement.

5.3.1. Monthly Water Balance

The average monthly climate balance shows four seasons (**Figure 7**):

- two short wet seasons lasting only 1 month: June and September;
- a short two-month dry season (July to August);
- a long dry season lasting eight months (from October to May), during which evaporative demand is high.

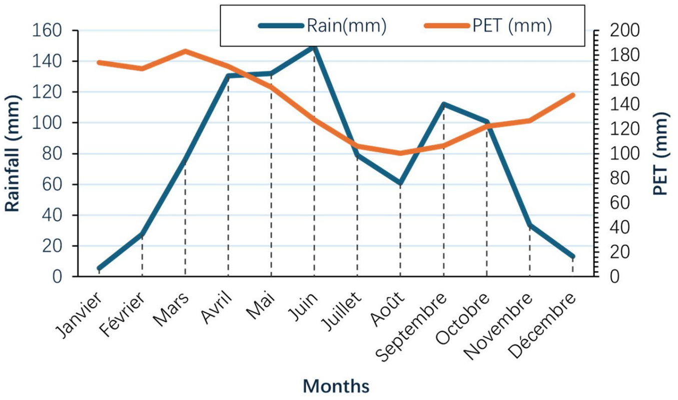

Figure 7. Seasonal variation in the average monthly balance of climatic parameters (1982-2020) in the Bia catchment area.

5.3.2. Annual Water Balance

1) Distribution of water balance parameters

The annual water balance (**Figure 8**) over the period (1982-2020) shows that on average 30.6% of the rainfall received by the Bia catchment feeds the watercourses, of which approximately 17.5% is direct runoff (surface runoff), 0.542% lateral runoff, 11.8% groundwater and then rejoins the watercourses and only 0.76% recharges the groundwater. On the other hand, approximately 69.61% of rainfall returns to the atmosphere through evaporation from the storage basin and watercourses and through (actual) evapotranspiration.

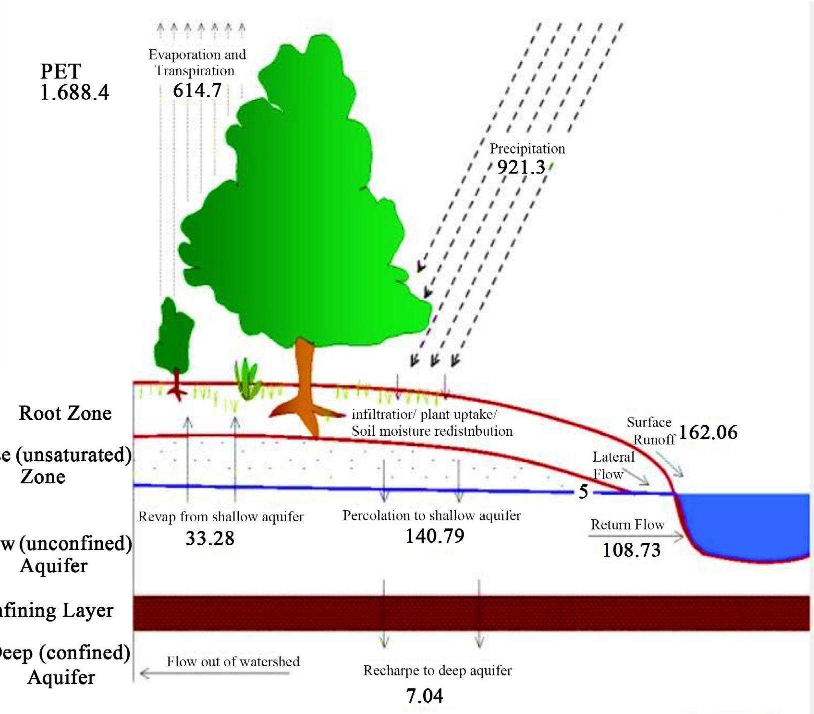

Figure 8. Conceptual balance for the Bia catchment area (1982-2020).

2) Spatio-temporal assessment of water balance parameters

Spatial and temporal trends in rainfall over the entire catchment area over the period 1982-2020 are shown in **Figure 9(b)**. It shows rainfall amounts ranging from 840 to 930 mm. Heavy rainfall is concentrated in the southern part of the catchment, with amounts of up to 930 mm, decreasing away from the south to 840 mm in the north. The spatio-temporal evolution of surface runoff is shown in **Figure 9(a)**. Runoff varies between 90 and 210 mm depending on the sub-basin. Over the reference period (1982-2020), the model indicates a higher runoff in the central and northern central areas than in the other areas of the basin. **Figure 9(c)** shows the spatial and temporal evolution of the ETR, which varies between 546-690 mm depending on the sub-basin. It is high (580 - 690 mm) in the south and extreme north and medium (546 - 580 mm) from the centre to the centre-north of the basin. Percolation (**Figure 9(d)**) varies between 50 - 190 mm depending on the sub-basin. It is high (170 - 190 mm) in the centre and centre-north (sub-basins

3, 5, 11 and 12), low (130 - 170 mm) in sub-basins 4, 7, 9 and 10 and average in the other sub-basins.

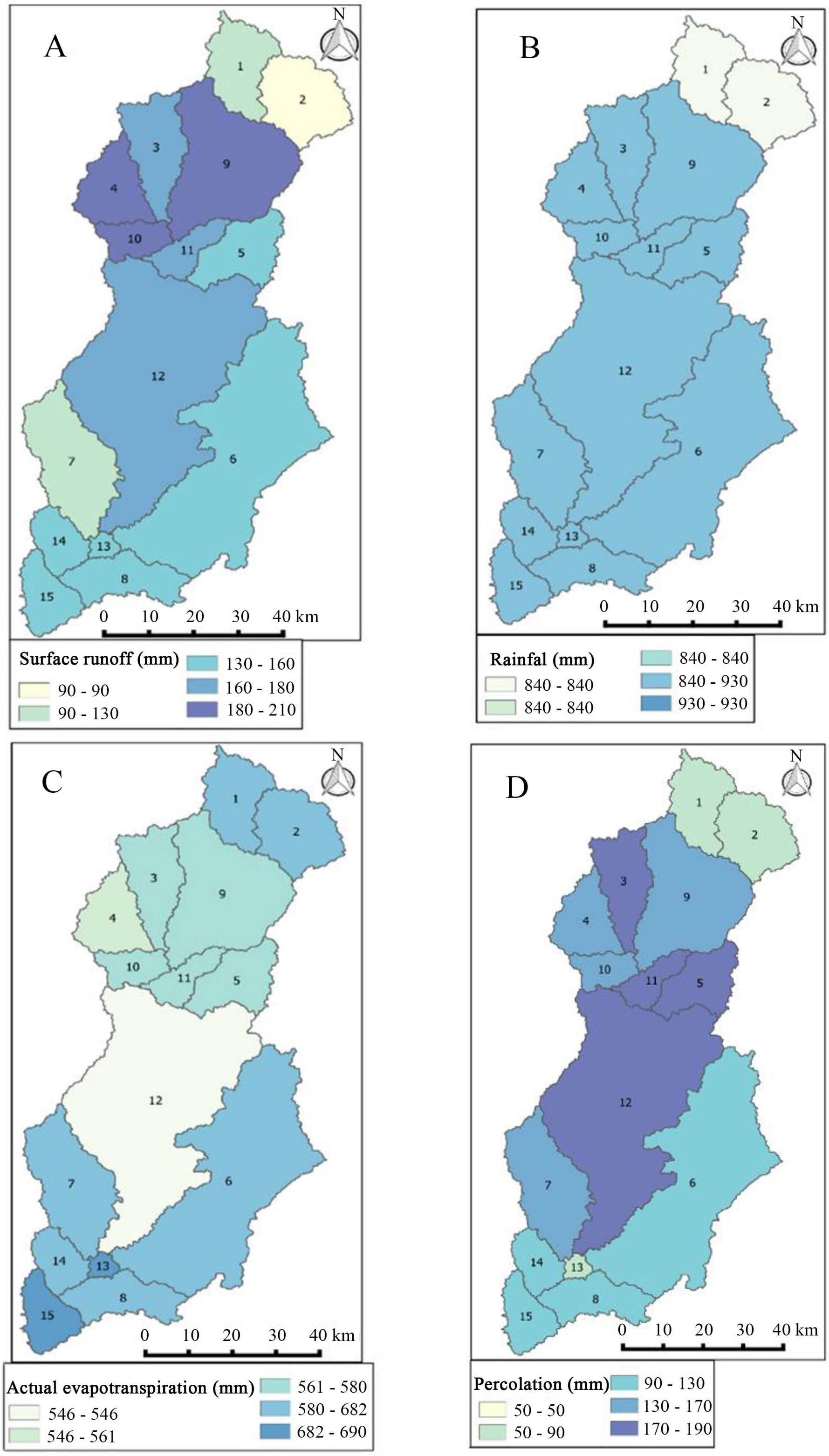

Figure 9. Spatio-temporal distribution of Bia water balance parameters (1982-2020).

6. Discussion

6.1. Land Use Dynamics

Statistics on the various land-use categories from 1987 to 2017 show a 46.10% decline in the area of dense forest, representing an annual loss of 2.06%. This decline in forest cover has been offset by an increase in agricultural areas (459.00% of its total area, representing an annual increase of 5.74%), degraded forests (201.68% of the total area, representing an annual increase of 3.68%), and bare land and built-up areas (143.79% of the total area, representing an annual increase of 2.97%). This finding is consistent with the work of [12] on land-use dynamics in the Davo watershed. It shows that forest cover declined from 65.60% to 25.70% of the total watershed area between 1986 and 2014. These findings are also consistent with the work of certain researchers in West Africa [9] [13]-[17], each of which reveals a decline in vegetation cover in favor of mosaics of croplands, fallow lands, and built-up areas.

It should be noted that this decline in vegetation cover has repercussions on the basin's water resources, resulting in a sharp decrease in the area of water-retaining surfaces (70.15% of its total area, representing an annual loss of 4.03% between 1987 and 2017). All these changes in land-use classes affect the hydrological behavior of the Bia basin through reduced rainfall, decreased infiltration, and increased evapotranspiration, runoff, and erosion (which will lead to problems of siltation, sedimentation, and sand accumulation). This same observation is made by [18] and [19] regarding, respectively, land-use dynamics and water resources in the Zou River watershed at the Domè outlet in Benin, and the ecological control of the water cycle's response to climate variability in deserts.

6.2. Model Performance

During calibration, a Nash value of around 78% was obtained, indicating very good performance in terms of calibrating the hydrological model. Similarly, at the validation stage, despite a drop in the Nash value (60%), the model's ability to simulate flows remains satisfactory on the basis of the performance criteria used in this study.

In the light of the results presented, it appears that during calibration and validation, the SWAT model gives a better estimate of flows. These results are approved by several authors throughout the world, who tested it for catchments of various sizes and with different geological contexts [20]-[22]. In the Ivorian context, [9] have demonstrated the robustness of the model in simulating the hydrological balance of the Cavally River catchment at Toulepleu. This observation was also made by [23] [24] in their studies on assessing the performance of the SWAT agrohydrological model in reproducing the hydrological functioning of the Nakhla catchment (Morocco) and on the application of the SAWT model to estimate the water balance in the Aghien lagoon (south-east of Côte d'Ivoire), respectively. It has also been used for studies of the impacts of climate change on water resources [25] [26] on the Aghien lagoon, the Lake Buyo catchment area and water resources in Burgundy, respectively. [27] and [28] applied it to simulate the impact of crops on water quality in the Cache River catchment in Arkansas and the Moine catchment, respectively. The hydrological model used in this study produced satisfactory results in terms of simulating runoff.

6.3. Water Balance

The balance shows that ETR is the most dominant parameter in the basin, with a value of 614.7 mm/year, or 66% of rainfall. The importance of this term in the catchment is due to very high soil transpiration combined with low plant transpiration. All these factors are linked to the exposure of the soil due to agriculture and the destruction of the forest cover, as well as to the high temperature (an average of 26˚C) throughout the catchment. The results of this study are in the same order of magnitude as those obtained by [23], and [29] for the Nakhla basins (Morocco), Baya and Comoé respectively. An analysis of rainfall in the Bia catchment shows an abundance of rainfall in the south of the basin, leading to a decrease in rainfall from south to north. A similar observation on the same basin was made by [30]. According to [31], the abundance of rainfall in the southern part of the basin is favoured by the fact that the eastern and western sectors of the coastline are more perpendicular to the monsoon winds. Furthermore, according to [32], the decrease in rainfall from south to north could be explained by the continentalization effect, due to the depletion of water in the air carrying precipitation as it moves northwards through the basin. The high runoff observed in the center and center-north of the basin is explained by the presence of steep slopes and rapidly receding vegetation cover, which encourage significant surface runoff. In the south of the basin, runoff is less significant because of the gentle slopes and dense vegetation. The same observation was made by [26] in their study of rainfall and runoff in the context of climate change in the Lake Buyo catchment. As for infiltration, this represents the fraction of rainfall that is supposed to recharge the groundwater. It is estimated at 145.79 mm/year (16.712% of rainfall) for the basin. This value fits in well with the ratio observed in most studies carried out in other parts of Côte d'Ivoire [29] [33]-[35]. The recharge values estimated in these studies are generally between 10% and 30% of rainfall. It should also be noted that groundwater recharge is proportional to rainfall in the basin [9]. In fact, groundwater recharge decreases from forest regions (where rainfall is more abundant) to savannah regions [29]. The balance is acceptable throughout the basin, as rainfall exceeds evaporative demand (614.7 mm/year). This contrasts with what [30], states in his work on the same basin, which stipulated that the balance was in deficit over the 1971-2009 period.

7. Conclusions

The main objective of this study was to simulate the hydrological functioning of the Bia catchment upstream of Lake Ayamé. To achieve this objective, three specifics goals were defined. The first was to examine the dynamics of land-use and land-cover changes within the basin, the second was to evaluate the performance of the hydrological model in reproducing streamflow within the basin and the third was to analyze the main components of the basin's hydrological balance under past conditions. To accomplish these objectives, this study used meteorological, hydrological and satellite data from 1982 to 2020. GIS was used to develop spatial databases and perform spatial analyses, while the SWAT model was employed for hydrological simulations. The analysis of land cover dynamics reveals a sharp decline of 46.10% in the area of vegetation cover, representing an annual loss of 2.06%. This has occurred at the expense of an increase in agricultural areas, degraded forests and bare land and built-up areas. This decline has impacted the aera of water in the basin with 70.15% of reduction in their surface during the period 1987-2017. The model performance results (78% for calibration and 60% for validation) indicate that the hydrological model is suitable for streamflow simulation in the basin. The simulated hydrographs show that the model satisfactorily reproduces the observed flows at the basin outlet. The annual water balance indicates high actual evapotranspiration (614.7 $\text{mm}\cdot\text{yr}^{-1}$) in a basin receiving an average precipitation of 921.3 $\text{mm}\cdot\text{yr}^{-1}$. Runoff represents approximately 17.5% of total precipitation, while percolation accounts for about 16.7%. Overall, the water balance remains consistent across the basin, as precipitation exceeds evaporative demand.

This study should be extended to assess the potential impacts of climate change and land-use changes on water resources in the Bia catchment.

Consent to Participate

All authors confirmed their participation and approved submitting the final manuscript.

Consent to Publish

All authors have consented to the publication of this manuscript.

Availability of Data and Materials

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that there is no known conflict of interest that may have influenced the work reported in the submitted manuscript.

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Highlights

- Application of the SWAT hydrological model to simulate runoff.
- Assessing the components of the water balance in Bia Catchment.
- Understanding the hydrological functioning of Bia catchment.

Graphical Abstract