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Assessment of the Water Balance of the Douni Watershed (Northwestern Côte d'Ivoire) Using the SWAT Model

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Abstract

Understanding the hydrological functioning of watersheds in sub-humid tropical regions is a key challenge for the sustainable management of water resources, particularly in contexts subject to significant human and climate pressures. This study assesses the hydrological water balance of the Douni watershed, located in northwestern Côte d'Ivoire, using the semi-distributed SWAT model. This modeling is based on hydroclimatic and discharge data covering the periods 1980-2020 and 1980-1996, respectively, as well as cartographic data (topographic, pedological, and land-use). Model calibration and validation were performed, respectively, on the periods from 1982 to 1987 and from 1988 to 1992 using the SUFI-2 algorithm. The performance obtained is considered satisfactory, with NSE values of 0.51 after calibration and 0.50 in validation, coefficients of determination (R^2) close to 0.52 and limited biases (PBIAS between −6.4% and +5.4%), as well as high P-factor (0.72) and low R-factor (0.53) values, reflecting a good reproduction of the seasonal dynamics of flows. The water balance shows that actual evapotranspiration dominates (62%), followed by surface runoff (28%), while infiltration (10%) and deep groundwater recharge (<1%) remain low. These results reflect the basin's high hydrological responsiveness, characterized by a predominance of surface and subsurface runoff and a low contribution to deep aquifer recharge. This provides clear guidance on how to mobilize water resources to meet various water needs. In this context, the choice of mobilizing surface water appears as a relevant option in the management of the Douni basin. In light of these results, the SWAT model could serve as a decision-making tool for the integrated and sustainable management of water resources in the Douni Basin (northwest Côte d'Ivoire).

Keywords

Evapotranspiration, Surface Runoff, Infiltration, Recharge, SWAT, Douni Watershed, Côte d'Ivoire

1. Introduction

Water resource management in West Africa is not merely a technical challenge; it is the socio-economic linchpin around which the daily lives of thousands of people revolve [1] [2]. In northwestern Côte d'Ivoire, this reality is particularly evident in the Douni Basin, a tributary of the Niger River, where rapid changes in the region are reshaping the water landscape.

Between the growing urbanization of the city of Odiénnée and its surrounding villages, the expansion of croplands, and the agricultural development goals driven by the implementation of a hydro-agricultural development project, the watershed is facing a profound transformation of its natural balance. These changes, combined with a climate characterized by highly seasonal rainfall patterns, are likely to alter water transfer processes across the basin. Yet, despite these challenges, the basin's hydrological functioning remains poorly documented to date, as no detailed quantitative study using integrated modeling has been conducted in this area.

This study aims to address this gap by applying the SWAT hydrological model to the Douni watershed to quantify its water balance. More than a simple simulation exercise, this work seeks to provide a better understanding of the hydrological functioning of bedrock basins in sub-humid zones, thereby offering a decision-making tool for the sustainable management of water resources in the context of increasing anthropogenic pressures.

2. Materials and Methods

2.1. Presentation of the Study Area

The Douni River basin is located in northwestern Côte d'Ivoire in the Denguélé region, between longitudes 7˚27' and 7˚45' W and latitudes 9˚21' and 9˚39' N (**Figure 1**). It is a sub-basin of the Baoulé River watershed, one of the main tributaries of the Niger River. The Douni Basin covers an area of 290 km^2 dotted with hills and plateaus overlooking peneplains at elevations ranging from 380 m to 780 m (**Figure 2**). The climate of the area is of the sub-humid tropical type, characterized by a dry season lasting from November to April and a rainy season extending from May to October, with peak rainfall frequently observed in August. Over the period from 1980 to 2020, the average annual precipitation is 1212 mm, with an average temperature of 29.1˚C (**Figure 3**). The basin is drained by the Douni River, from which it takes its name. The river originates near the village of Ziévasso and flows into the Baoulé River. The hydrological regime of the Douni basin is unimodal: it is characterized by a long dry season (December to June) and a wet season (July-November), with peak discharge values observed in August and October (Figure 4).

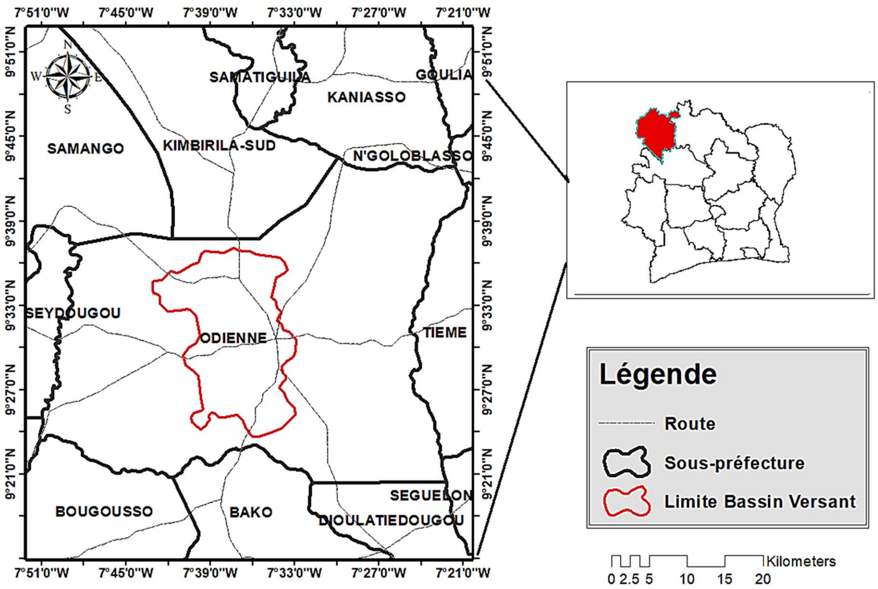

Figure 1. Location of the Douni watershed.

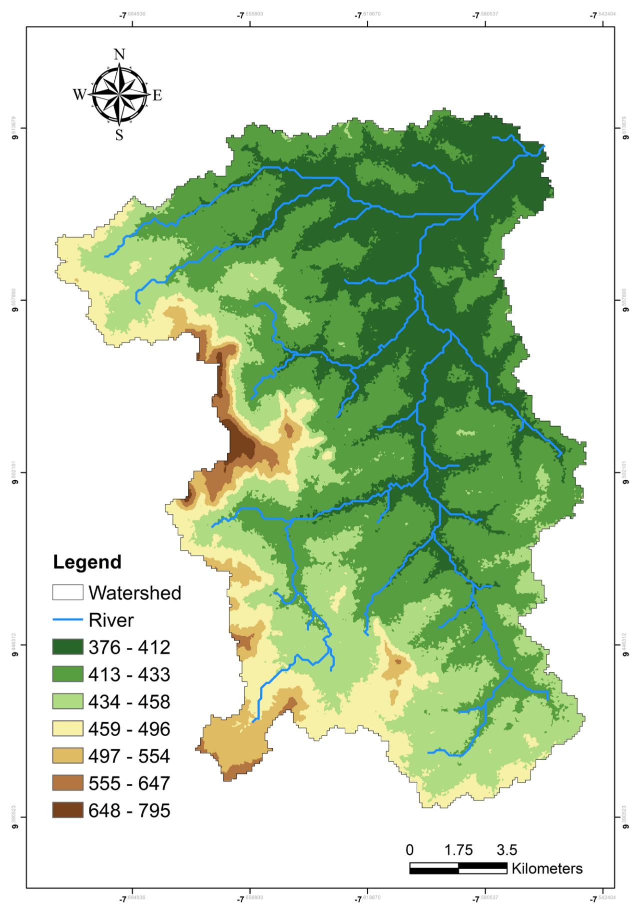

Figure 2. Topography and hydrological network.

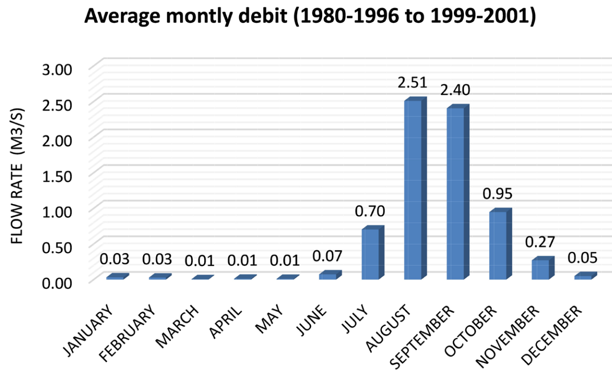

Figure 3. Hydrological regime of the Douni.

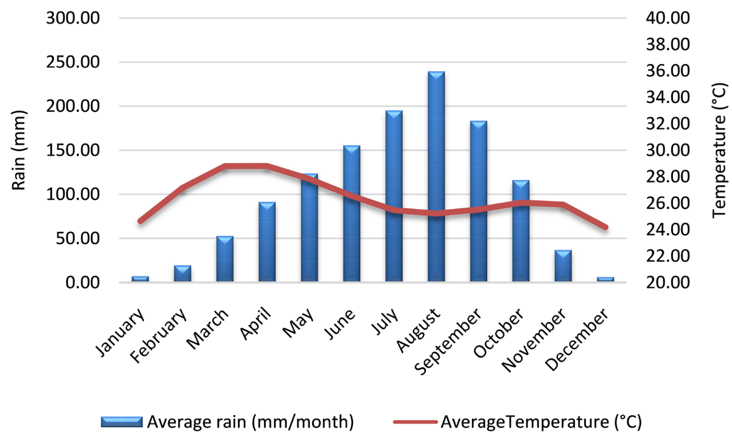

Figure 4. Odiennée ombrothermic diagram.

2.2. Materials

The data used to develop the SWAT model fall into two (02) categories: spatial data and point data.

The spatial data used in our study include the Digital Elevation Model (DEM), the soil classification map, and the land-use maps. The DEM for the study area was downloaded from the USGS website https://earthexplorer.usgs.gov/ and then imported into ArcGIS software. After verification, the DTM was projected into the UTM system – WGS 84, zone 29 North, which corresponds to the location of the study area. The DTM of the study area was extracted using the clipping operation along its boundaries. To account for the dynamics of soil evolution, a soil dynamics study was conducted using Landsat satellite images from January 16, 1995, January 1, 2005, January 7, 2015, and January 2, 2025. These images, with a spatial resolution of 30 meters, originate from scene 198/053. Their analysis and processing using supervised classification algorithms (Random Forest, SVM, or Maximum Likelihood) according to the flowchart illustrated in the **Figure 5**, allowed for the creation of land cover maps for the following years: 1995, 2005, 2015, and 2025 (**Figures 6-9**). Regarding pedology, all data on the physicochemical characteristics of the soil in the Douni watershed were extracted from the Digital Soil Map of the World and Derived Soil Properties database, Version 3.6, developed by FAO/UNESCO [3]. The resulting watershed map consists of highly desaturated ferrallitic soil (Af5) or ferralsol (97%) and acrisol (Ao60).

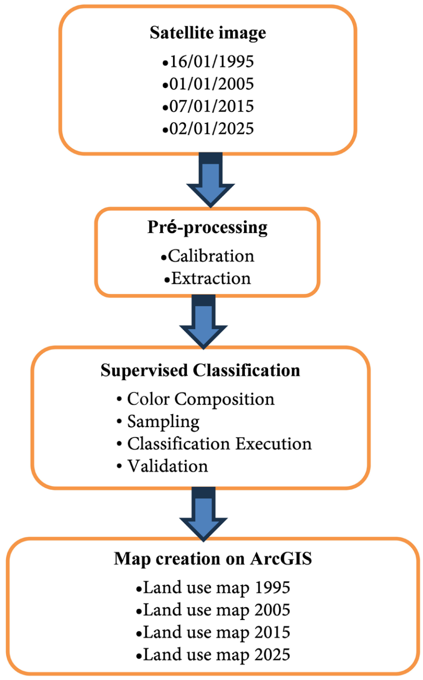

Figure 5. Land use analysis flowchart.

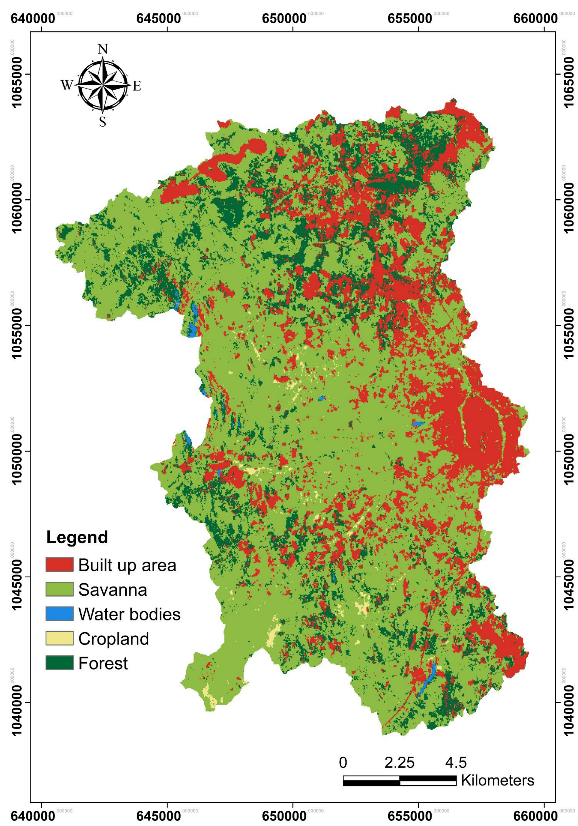

Figure 6. Land use map (1995).

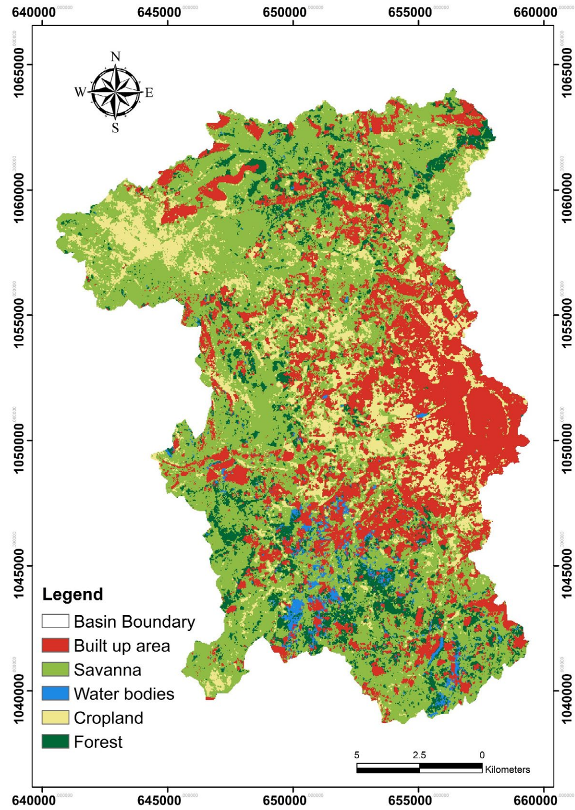

Figure 7. Land use map (2005).

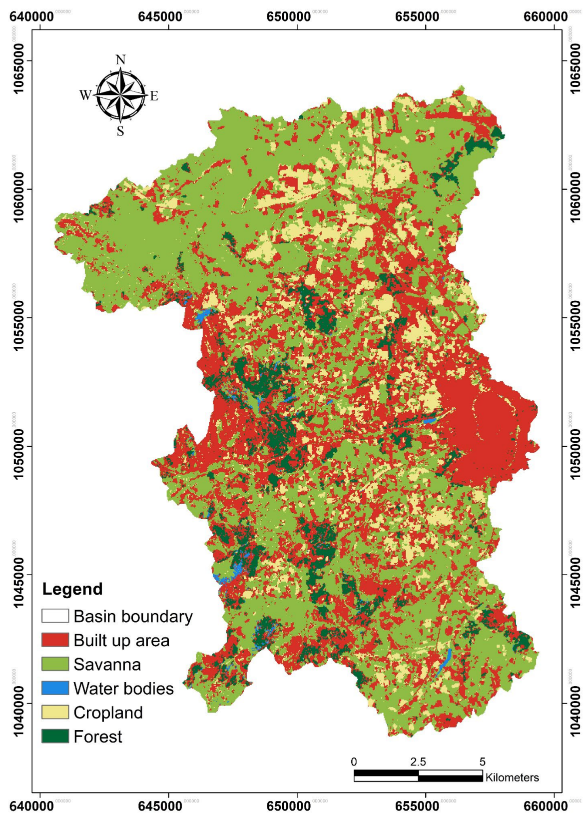

Figure 8. Land use map (2015).

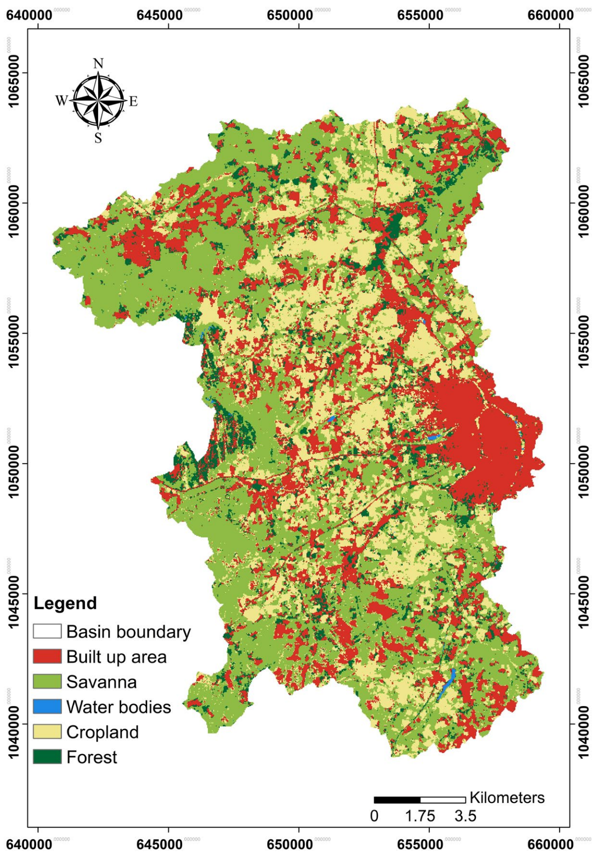

Figure 9. Land use map (2025).

The climate data required for hydrological modeling include daily precipitation data and daily minimum and maximum temperatures recorded from 1980 to 2020. These data come from the local weather station in the city of Odienné (latitude: 9.5000, longitude: −7.5667, elevation: 434 m). The data relating to solar radiation, relative humidity and wind speed were generated by SWAT. In addition, flow data obtained from the Hydrology Department for the period from 1980 to 1996 are included.

2.3. Method

Introduction to the SWAT Model

The Soil and Water Assessment Tool (SWAT) is open-source software developed by the Department of Agriculture and the laboratories at Texas A&M University in the United States. SWAT is a semi-distributed model designed to simulate the hydrological cycle, sediment transport, and nutrient transport at the watershed scale. It operates on time steps ranging from daily to decadal. According to its official website (http://swat.tamu.edu/), SWAT is a watershed- or river basin-scale model used to simulate the quality and quantity of surface and groundwater and predict the environmental impact of land use, land management practices, and climate change. SWAT is one of the world's most widely used hydrological and environmental models for simulating the impacts of land management practices, land-use changes, and climate variability on water resources [4]. As described by the Food and Agriculture Organization of the United Nations (FAO), SWAT is a river basin-scale model developed to quantify the effects of land management practices in large and complex watersheds and to assess water quality, including nonpoint source pollution issues [5]. It has proven its reliability in studies of a wide variety of watersheds ranging in size from a few square kilometers to thousands of square kilometers. In the U.S., SWAT has been applied to the Mississippi River basin (3,000,000 km^2) and the Maumee River basin (16,000 km^2); in France, to the Garonne basin (55,000 km^2); in Africa to the Nakhla basin (110.8 km^2) in Morocco and in Côte d'Ivoire to the Upper Bandama basin along the Korhogo-Badikaha road (9688 km^2) and the Buyo watershed (over 24,500 km^2). In its operation, SWAT divides the watershed into sub-watersheds, which are themselves subdivided into Hydrologic Response Units (HRUs) [6]. HRUs are homogeneous areas with the same soil types, slopes, and vegetation, serving as the basic units for calculating the water cycle. For each HRU, the model applies a water balance equation that subtracts losses (evapotranspiration, runoff, infiltration) from precipitation to determine soil water storage. The balance equation applied in the SWAT model is [7]:

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right)$$

where:

t: is the time in days;

SW_t (mm): the soil moisture content at time t;

SW_0 (mm): the soil moisture content at the initial time;

R_{day} (mm): the precipitation at time i;

W_{seep} (mm): the amount of precipitation infiltrated into the soil from the surface at time i;

Q_{surf} (mm): the amount of precipitation available for runoff at time i;

Q_{gw} (mm): the base flow from the groundwater table at time i;

E_a (mm): evapotranspiration at time i.

Figure 10 below shows the schematic representation of the hydrological cycle in the SWAT software.

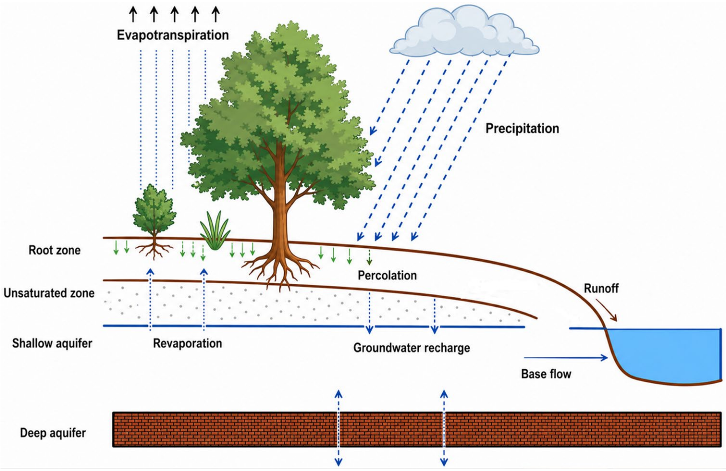

Figure 10. Schematic representation of the hydrological cycle (Source: [8]).

Implementation of the SWAT model

To carry out this work, the Digital Elevation Model (DEM), the soil classification map, and the land use map in raster format were converted, taking care to project them into the same coordinate system (UTM-WGS 84 Zone 29) corresponding to the basin's location. The integration of these spatial data into the model was carried out sequentially: the Digital Elevation Model was incorporated first, followed by the pedological data, and then the land use maps. The slope class was calculated directly within the model using the Digital Elevation Model. This was followed by the creation of Hydrologic Response Units (HRUs) using the HRU Analysis tab by cross-referencing the land use, soil, and slope layers. The data integration process concluded with the inclusion of meteorological data (precipitation and temperature).

After entering all the required data, an initial simulation was conducted. The initial results obtained were used to support the calibration phase of the developed model.

The calibration phase ensures that the model is capable of reproducing the hydrological behavior of the study area. The SWAT model includes a large number of parameters that must be varied during the calibration phase. Since each parameter has five algorithms: SUFI2 [9], GLUE [10], ParaSol [11], MCMC [12], and PSO [13], each of which allows for the creation of a list of sensitive parameters and the execution of the calibration.

As part of this study, sensitivity analysis and calibration were performed using the SUFI 2 algorithm, which is recognized for its robustness in exploring uncertainties and identifying optimal parameter combinations [14].

During calibration, the model's performance was evaluated using the Nash-Sutcliffe coefficient (NSE), the coefficient of determination (R^2), and the PBIAS index, in accordance with the criteria recommended in the literature by Moriasi *et al.* (2007) [15]. The calibration phase covers the period from 1982 to 1987. The model calibrated in this manner served as the basis for the validation phase.

The validation aims to demonstrate that the calibrated model is capable of reproducing the hydrological behavior of the Douni basin over a time period different from that used for calibration (1982-1987). The period selected for validation spans from 1988 to 1992, a total of four years. During this final phase, the performance criteria (NSE, PBIAS, and R^2) were also evaluated in accordance with the criteria of Moriasi *et al.* (2007) [15].

Once the model was calibrated and validated, simulations were conducted to establish the watershed's water balance. To this end, three 10-year periods were considered: 1990-2000, 2000-2010, and 2010-2020. Land-use data were selected for these three periods in accordance with the SWAT philosophy, which is based on a distributed and physically based representation of processes.

3. Results and Discussion

Spatial Discretization

Processing the 30 m resolution DEM using Arcswat software enabled the creation of the slope map and the regeneration of the hydrographic network. This step proved highly successful, as the generated hydrographic network closely follows the existing watercourse. Overlaying the soil map, the slope map, and the land cover maps using the Dominant algorithm allowed for the creation of thirty-five (35) sub-basins and Hydrological Response Units (HRUs), as shown in **Figure 11**.

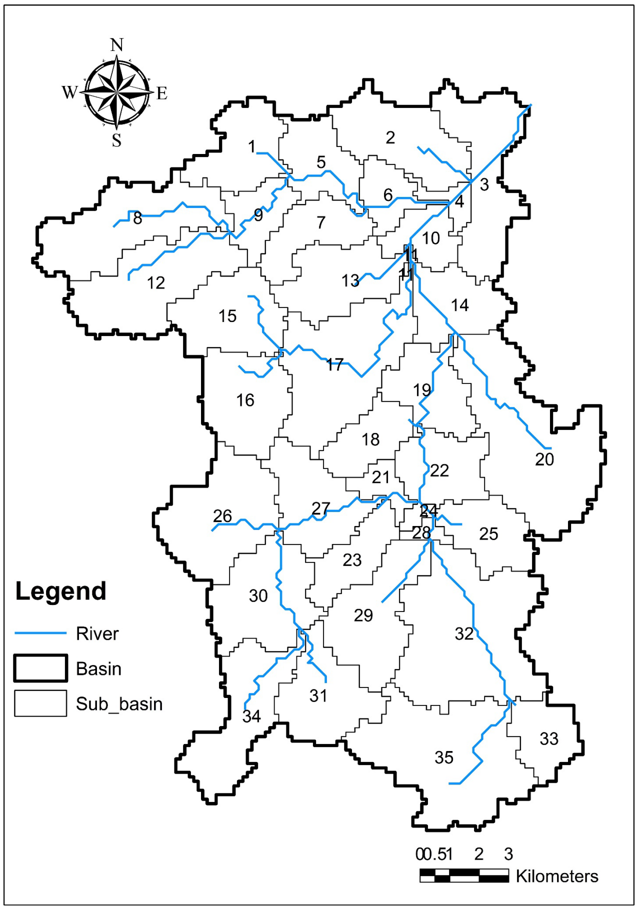

Figure 11. Map of sub-basins and Hydrological Response Units.

Sensitivity Analysis and Model Calibration

The sensitivity analysis identified five (05) parameters deemed highly sensitive (**Table 1**). The presence of CN2 (Curve Number), Alpha_BF (baseflow recession factor), and SOL_AWC (soil available water capacity) in the list of the most sensitive parameters highlights a close link between surface processes and the dynamics of the shallow aquifer. The parameter RCHRG_DP, which tops the list of the most sensitive parameters, highlights a significant interaction between shallow groundwater and the deep groundwater system. Its high sensitivity, coupled with a deep recharge value that is virtually zero (0.6% of the balance), indicates that deep groundwater flows contribute only marginally to the basin's hydrological regime. This suggests a system where water transfers are primarily surface and lateral, limiting multi-year storage capacity in deep aquifers.

Table 1. Parameters considered highly sensitive.

Parameter_Name	Description	Change Method	Adjusted Value
1: R__RCHRG_DP.gw	Fraction of deep aquifer recharge	Relative	−0.672986
2: R__CN2.mgt	Curve Number (Moisture Condition II)	Relative	40.032588
3: V__ALPHA_BF.gw	Base flow recession factor	Replacement	−0.932311
4: R__CH_W2.rte	Average width of main channel (m)	Relative	−0.511558
5: R__SOL_AWC(..).sol	Available soil water capacity (mm/mm)	addition	0.208515

Figure 12 shows a comparison of observed and simulated discharge rates during the model calibration phase for the period from 1982 to 1987. It revealed a generally satisfactory agreement between the two (02) discharge curves. The calculated performance criteria yield values of NSE = 0.51, R^2 = 0.51, and PBIAS = +5.4%. These are considered satisfactory according to the scales of Moriasi *et al.* (2007) [15]. The obtained NSE value indicates that the model explains slightly more than half of the observed variability in discharge. This assessment is supported by the coefficient of determination (R^2 = 0.51), which reflects a reasonable correlation between the simulated and observed series. The positive relative bias obtained (PBIAS = 5.4%) indicates a slight overall underestimation of the simulated discharge values [16], which is evident in the flood hydrograph generated by SWAT (**Figure 12**). The P-factor (0.72) and R-factor (0.53) obtained during the calibration of the SWAT model with the SUFI-2 algorithm indicate an overall satisfactory performance of the model. This means that 72% of the observed flows are correctly bounded by the simulations, thus demonstrating good consideration of uncertainties related to the parameters and input data [9]. This value is considered acceptable for watersheds with limited hydrometeorological data [14]. The low value of the R-factor obtained indicates that the prediction interval remains relatively narrow, thus reflecting a low dispersion of the simulated results around the observations. The R-factor is considered satisfactory in hydrological modeling if its value is less than 1.5 [14]. The value obtained therefore shows that the calibrated parameters allow for the reproduction of flows with reasonable accuracy.

The combination of a high p-factor (0.72) and a low R-factor (0.53) reflects a good compromise between observation coverage and simulation accuracy. These results confirm the quality of the SWAT model calibration and reinforce the reliability of the statistical performance obtained (NSE = 0.51; R^2 = 0.51; PBIAS = 5.4%), thus demonstrating that the model satisfactorily reproduces the hydrological behavior of the studied watershed.

Analysis of the hydrographs shows that the model accurately captures the seasonal dynamics of runoff, with a good representation of the timing of rises and falls in water levels associated with rainfall events. Flood peaks are generally well-timed, although their magnitude is occasionally overestimated or underestimated.

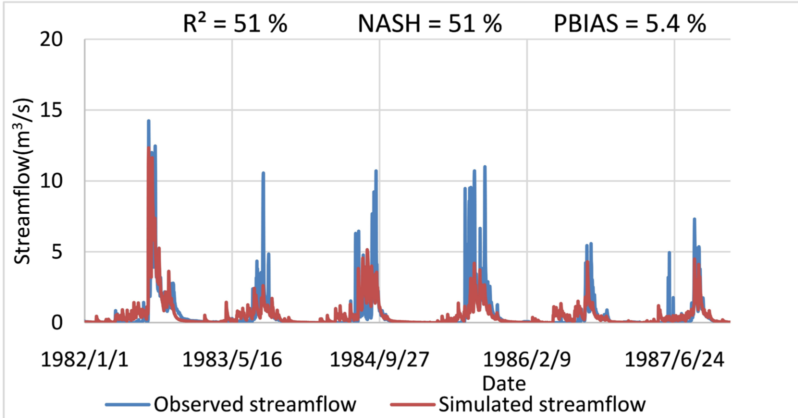

Figure 12. Hydrological chart for the Douni River during the calibration period (1982-1987).

Model validation

The performance of the model during the validation phase (1988-1993) is illustrated in **Figure 13** by comparing observed and simulated discharge values. A good overall fit is observed in the reproduction of seasonal flow cycles. The validation performance, deemed satisfactory, is comparable to that observed during calibration, with an NSE value of 0.50, a slightly higher coefficient of determination ($R^2 = 0.52$), and a PBIAS value of −6.4%. These results indicate that the model maintains a stable ability to reproduce flow dynamics without significant degradation in performance. The validation hydrographs confirm this through the accurate reproduction of seasonal trends and the sequence of rising and falling water levels.

However, as in the calibration phase, the most notable discrepancies occur during major floods, for which the model tends to smooth out extreme values. The relative bias calculated during the validation phase (PBIAS = −6.4%) indicates a slight overall overestimation of simulated discharges. This value nevertheless remains within a satisfactory range, confirming the absence of significant model drift over an independent period. The reversal of the sign of PBIAS between the calibration and validation phases suggests moderate sensitivity of the model to interannual hydro-climatic conditions, without calling into question its overall stability.

Although the NSE value is at the lower end of what is considered satisfactory, it is acceptable in our context due to the low density of the rainfall network and the age of the discharge data. These data limitations are common in sub-Saharan Africa and do not affect the validity of the overall water balance trends.

The performance obtained in the Douni basin (NSE = 0.51 and 0.50; $R^2 = 0.51$ and 0.52; PBIAS = +5.4% and −6.4% respectively in calibration and validation) is lower than that reported in several recent studies in Africa. Guug *et al.* (2020) [17] obtained NSE values of 0.74 in calibration and 0.79 in validation in the Sherigu basin, in Ghana and Burkina Faso, associated with R^2 values of 0.80 and 0.81. Similarly, in the upper Bandama basin, in Côte d'Ivoire, Ouédé (2024) [18] obtained NSE and R^2 values of 0.69 and 0.70 respectively in calibration and 77%

in validation.

This does not call into question the robustness of the SWAT model calibrated and validated on the Douni basin, whose performance parameters, in addition to conforming to the criteria of Moriasi *et al.* (2007) [15], remain comparable to those of the Luvuvhu watershed in South Africa. On this sparsely instrumented basin like that of Thavhana *et al.* (2018) [19] obtained with the SWAT model, in calibration NSE = 0.66; R^2 = 0.63; PBIAS = +16.3%, and in validation NSE = 0.66 and 0.48; and 0.52; and 19.90%.

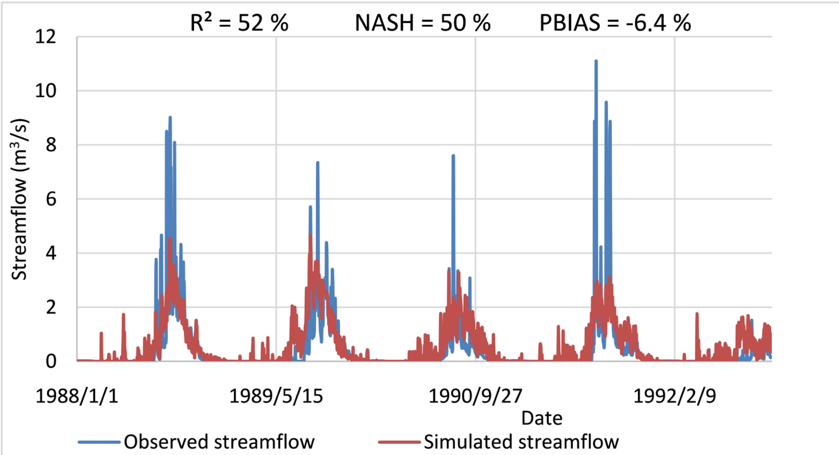

Figure 13. Hydrological chart of the Douni River for the validation period (1988-1992).

Water Balance

Table 2 shows the quantitative distribution of the components of the annual water balance at the watershed scale. For an average annual precipitation of 1212 mm, the model reveals a highly structured hydrological flow pattern, influenced by the watershed's climatic, pedological, and vegetation characteristics. In fact, a significant portion of precipitation is consumed by actual evapotranspiration (AET), estimated at 750 mm, or approximately 62% of annual rainfall. Surface runoff, estimated at 342 mm, accounts for nearly 28% of annual precipitation. Infiltration through the unsaturated zone, estimated at 121.8 mm (10% of annual precipitation), remains relatively modest compared to the total volume of precipitation. Recharge of the deep aquifer, meanwhile, is very low (7.3 mm, or less than 1% of annual precipitation).

The predominance of ETR values in the basin can be explained by the severity of the dry season, which lasts from November to April (6 months). Temperatures during this dry season are high, with averages estimated at around 30˚C. These conditions boost transpiration from the vegetation cover, which consisted of 15% forest and 60% savanna in 1995, compared to 9% forest and 43% savanna in 2025. This high ETR rate confirms what several authors, notably Gassman *et al.* (2007) [20] and Mahé *et al.* (2011) [21], have already highlighted for sub-humid zones: the atmosphere remains the primary "consumer" of water. Also, ETR rates between 60% and 80% depending on the state of the vegetation cover, were obtained in studies by Ouédé (2024) [18] and Sintondji *et al.* (2010) [22], respectively on the Upper Bandama (Côte d'Ivoire) and on the Ouémé watershed (Benin).

The fact that 28% of inflow is captured by surface runoff indicates that the watershed responds almost immediately to heavy rainfall events. Beyond slope, it is the soil surface condition and changes in land use that appear to act here as true catalysts for runoff. This rapid transfer to the outlet unfortunately occurs at the expense of infiltration and deep recharge. The low deep recharge observed here is consistent with the findings of Goula *et al.* (2006) on watersheds in northern Côte d'Ivoire, who note that the clayey nature of lateritic soils and high evaporation rates drastically limit deep infiltration in favor of surface runoff. Estimated at approximately 1%, the recharge value remains similar to that obtained by Ouédé (2024) [18] on the Upper Bandama basin. On the Sherigu basin (Ghana/Burkina Faso), Guug *et al.* (2020) [17] also quantified a deep recharge of around 1% using the SWAT model.

These results may suggest a weak connection between the deep aquifers and the surface waters of the basins. The stream remains fed by water from the shallow aquifer, as evidenced by the flow observed even in the absence of rain. The deep aquifer remains only weakly fed by the shallow aquifer. This type of configuration is characteristic of systems where deep groundwater is "disconnected" from surface flows [14].

Table 2. Annual water balance components of the Douni watershed simulated using the SWAT model.

Hydrological balance component	Value (mm / year)
Precipitation	1212
Actual evapotranspiration	750
Surface runoff	342
Infiltration	121.8
Deep groundwater recharge	7.3

4. Conclusions

The application of the SWAT model to the Douni watershed successfully simulated the hydrological behavior of this sub-basin of the Baoulé basin. The performance results, both during the calibration phase (NSE = 0.51; R^2 = 0.51, PBIAS = +5.4% P-factor = 0.72 and R-factor = 0.53) and during the validation phase (NSE = 0.50; R^2 = 0.52, and PBIAS = −6.4%), confirm the model's ability to reproduce seasonal flow dynamics, despite a tendency to smooth out peak flows during major floods. The evaluation of the water balance highlights the predominance of actual evapotranspiration, which accounts for 62% of annual precipitation (*i.e.*, 750 mm). Surface runoff accounts for 28% of the inflow. Conversely, infiltration remains modest (10%), and recharge of the deep aquifer is virtually nil, accounting for less than 1% of total precipitation. This configuration indicates a poor connection between surface flows and deep aquifers, suggesting that low-flow support in the Douni River relies primarily on shallow aquifers. However, this interpretation should be considered with caution, as it relies on the results of a model calibrated and validated solely using observed flow data. The lack of piezometric data prevents independent validation of the simulated processes related to exchanges between surface water and aquifers. In this context, the results obtained nevertheless constitute a decision-making tool for water resource management in the Douni watershed. They suggest that utilizing surface water resources could be a relevant option under the currently simulated conditions, without excluding the potential of deep aquifers, whose functioning remains to be better characterized.

Looking ahead, strengthening hydrometric monitoring, expanding the meteorological measurement network, and deepening hydrodynamic knowledge of the basin's soils would improve the model's performance. Data from these future systems, coupled in the SWAT model with climate change and land-use scenarios, would enable the anticipation of water stress risks for the city of Odienné and its surroundings in the coming years.

Conflicts of Interest

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

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