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Hydrological Modeling of the Diamniadio Urban Area (PUD) Watersheds Using SWAT: Sensitivity Analysis, Calibration, and Validation Using Historical Data

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Abstract

This study presents a historical baseline analysis of the hydrological behavior of the Diamniadio Urban Area (PUD) using the SWAT model, coupled with SWAT-CUP for sensitivity analysis, calibration, and validation. The modeling covers the three watersheds that make up the PUD. The data used include the digital elevation model (DEM), the FAO soil map, land cover derived from 1992 Landsat images, and daily climate data covering the period 1981-2024. The 1992 land-use data were selected as a historical reference because they correspond to the available conditions closest to the observed discharge time series used for calibration and validation. The sensitivity analysis performed using the SUFI-2 algorithm shows that parameter CN2 is the most sensitive across all three watersheds. This result highlights the importance of surface runoff, land cover, and impervious surfaces, as well as the role of groundwater-related parameters in the hydrological response. Model performance was evaluated using the R^2, PBIAS, NSE, RSR, RMSE, p-factor, and r-factor metrics. The values obtained indicate generally satisfactory to excellent performance, with R^2 values ranging from 0.83 to 0.98 and NSE values ranging from 0.82 to 0.97. The SWAT model accurately reproduces the dynamics of regionalized runoff in WS1 and WS2. Despite satisfactory performance, WS3 has limited coverage of observations within the 95PPU uncertainty band and is therefore subject to greater uncertainty. Its results should be used as exploratory trends. The study thus provides a calibrated and validated historical hydrological database, with satisfactory performance for WS1 and WS2, but greater uncertainty for WS3.

Keywords

Hydrological Modeling, SWAT, SWAT-CUP, SUFI-2, Calibration, Validation, Diamniadio

1. Introduction

Population growth and urbanization are accelerating changes in hydrological processes, particularly by increasing impervious surfaces, reducing infiltration, and increasing surface runoff [1] [2]. The Diamniadio Urban Area (PUD), a strategic and rapidly evolving region, is directly affected by these dynamics. Thus, understanding its hydrological behavior is essential for stormwater management, flood prevention, and sustainable urban planning [3] [4].

To this end, hydrological modeling is an essential tool for analyzing the rainfall-runoff process and evaluating watershed responses. The SWAT model is widely used in hydrological studies to simulate various processes related to climate, hydrology, soils, and erosion [5] [6]. In this study, only the hydrological component of the SWAT model is considered to characterize runoff in the PUD. Additionally, SWAT-CUP is used to facilitate sensitivity analysis, calibration, validation, and uncertainty assessment [7].

Thus, this study aims to establish a baseline for the hydrological behavior of the watersheds that contribute to runoff in the PUD and to assess the uncertainty associated with the simulations. The year 1992 was selected as the baseline year due to the availability of a land-use map and regionalized discharge data from the Panthior station, which allow for calibration and validation. This modeling framework will subsequently be used to analyze, through scenario comparisons, the effects of changes in land cover between 1992 and a more recent period on hydrological processes.

2. Materials and Methods

2.1. Geographic Location of the Diamniadio Urban Area (PUD)

The Diamniadio Urban Pole (PUD), launched in 2014, is located in Senegal's Rufisque Department, about 30 kilometers east of Dakar. It spans the municipalities of Diamniadio, Bargny, Sendou, and Sébikhotane. It serves as the gateway to the capital, Dakar, and is situated at the intersection of National Highways 1 and 2. It is bounded to the north by the Niayes urban area, to the south by the Atlantic Ocean, to the east by the Diass urban area, and to the west by the Dakar metropolitan area [8] [9]. It is a priority government project aimed at creating a sustainable and resilient city, with the goal of relieving traffic congestion in Dakar. The

PUD covers an area of 1,644 hectares. It is divided into four districts and is expected to eventually accommodate 300,000 residents [8].

The project is based on public-private partnerships and is intended to serve as a showcase for a modern, forward-looking Senegal. The PUD is designed as a dense and compact city, an urban model for a new city based on sustainability and resilience. It is presented as [10] [11].

Figure 1 shows the geographic location of the PUD.

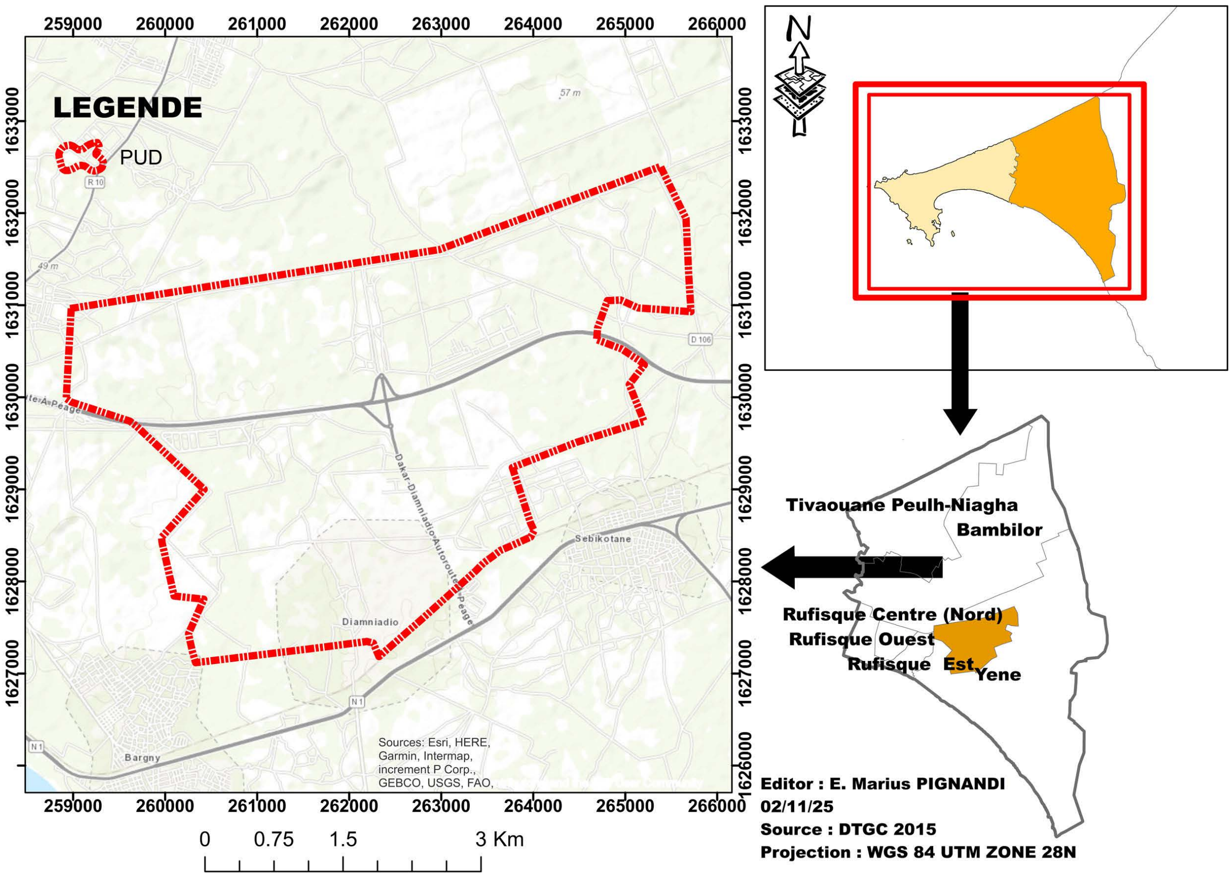

Figure 1. Geographic Location of the PUD.

The Diamniadio Urban Center is located in the coastal Sahelian climate zone, characterized by specific patterns of wind, precipitation, temperature, relative humidity, and sunshine [8]. According to ANACIM, average annual temperatures range from 21 to 28˚C. The highest average maximum temperature (28.65˚C) is observed in October, while the average minimum temperature (21.1˚C) is recorded in February. In Dakar, maximum temperatures are generally observed between September and October, and minimum temperatures between January and May. Between 1970 and 2021, the average annual rainfall in the Dakar region showed significant interannual variability, with values ranging from 116.7 mm to over 660 mm. The Diamniadio Urban Center (PUD) is subdivided into three (3) watersheds, as illustrated in Figure 2.

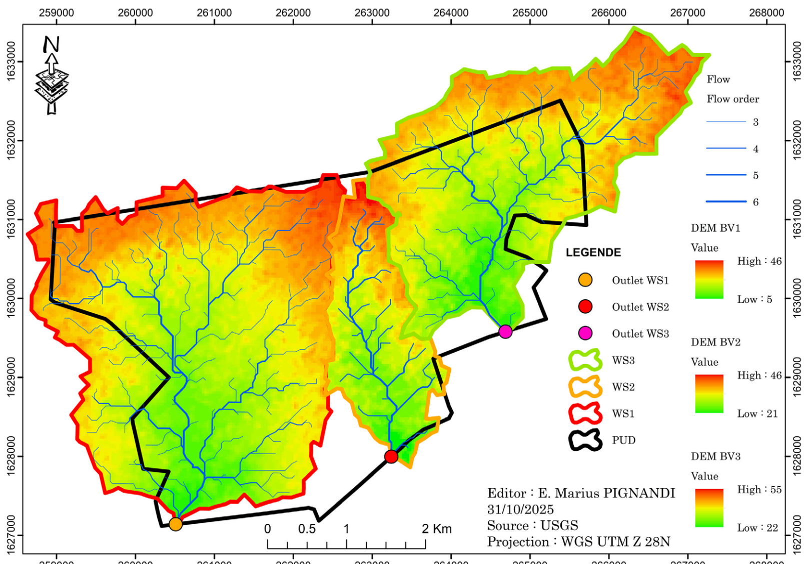

Figure 2. Digital elevation model of the PUD.

2.2. Brief Description of the SWAT Model

SWAT (Soil and Water Assessment Tool) is a physics-based semi-distributed model that simulates, in a simplified manner, the water cycle in a watershed at various time scales (hourly, daily, monthly, or annually). It was developed by the USDA-ARS. SWAT was designed to assess hydrological components-including water resources, sediment production, nutrients, and pesticides-under various scenarios and at different time scales. Its operation relies on a large number of [6]:

- input data: topography, soils, land use, management practices, precipitation, temperatures, sunshine, etc.;
- output data: streamflow, runoff volumes, soil moisture, sediment and nutrient fluxes, groundwater recharge, etc.

Figure 3 shows the hydrological structure of the SWAT model.

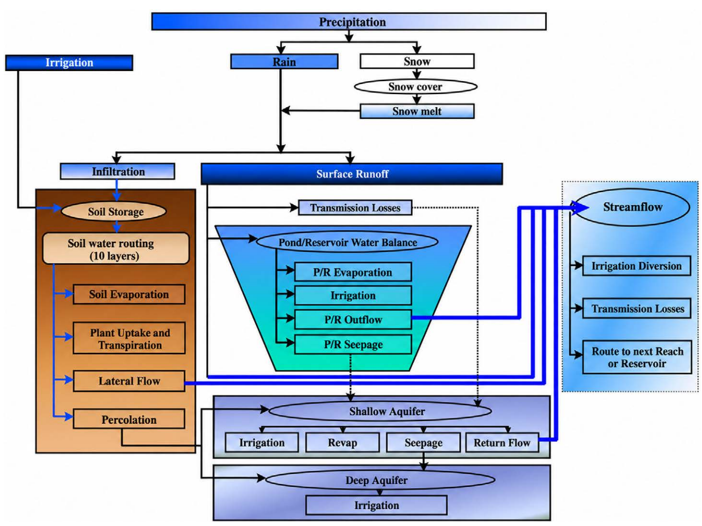

Figure 3. Hydrological structure of SWAT [6].

The SWAT model divides the watershed into several sub-watersheds, which are in turn subdivided into Hydrologic Response Units (HRUs) based on cropping practices, land use, and soil types. SWAT thus enables the estimation of hydrological components such as surface runoff, evapotranspiration, peak runoff discharge, sediment production, and groundwater flow [12].

The water balance simulated by SWAT is based on Equation (1) [13].

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

where SW_t is the soil water content at time t (mm), SW_o is the amount of water available to the plant in the soil at the initial time (mm), R_{day} is the precipitation at time i (mm), Q_{surf} is surface runoff at time i (mm), E_a is evapotranspiration at time i (mm), W_{seep} is percolation at time i (mm), and Q_{gw} is the base flow from the groundwater table at time i (mm).

The SWAT model simulates infiltration and surface runoff using two (2) methods: the Soil Conservation Service (SCS) Curve Number (CN) method and the method of Green and Ampt [14] [15]. For this study, the Curve Number method is used; its expression is given by Equation (2).

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} - 0.8S\right)} \quad (2)$$

where:

Q_{surf} : amount of runoff (mm);

R_{day} : daily precipitation (mm);

S: retention parameter (mm) defined by Equation (3).

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad (3)$$

where:

CN: Curve Number (Curve number for the day).

Furthermore, the amount of infiltrated water corresponds to the difference between precipitation and the amount of runoff. SWAT offers three methods for determining evapotranspiration, including the Penman-Monteith method (Equation 4), which was used in this study.

$$E_0 = \frac{1}{L_V} * \frac{\Delta * \left(H_{net} - G\right) + \left(\frac{\rho_{air} * C_P * e}{r_a}\right)}{\Delta * \gamma * \left(1 + \frac{r_c}{r_a}\right)} \quad (4)$$

where E_0 is the potential evapotranspiration (mm·day^{-1}), Δ is the slope of the vapor pressure curve at a given air temperature (kPa·˚C^{-1}), H_{net} is the net radiation (MJ·m^{-2}·day^{-1}), G is the heat flux transmitted to the ground (MJ·m^{-2}·day^{-1}), ρ_{air} is the density of air (kg·m^{-3}), C_p is the specific heat capacity of air (MJ·kg^{-1}·˚C^{-1}), e is the saturated vapor pressure of air or specific humidity (kPa), γ is the psychrometric constant (kPa·˚C^{-1}), r_c is the stomatal resistance (s·m^{-1}), r_a is the aerodynamic resistance (s·m^{-1}), and L_v is the latent heat of vaporization of water (MJ·kg^{-1}).

The SWAT model covers several areas of study, including climate, hydrology, erosion, crop growth, and water management and quality [16] [17]. In this study, only the hydrology component is considered. It was configured to directly provide monthly flow values in m^3/s. These values correspond to the monthly flows entered directly into SWAT-CUP without any additional processing. The model was set up using ArcSWAT 2012.10 7.26. The watersheds and hydrographic networks were delineated using the DTM, with a minimum threshold of 11.1 ha for watersheds WS1 and WS2 and a minimum threshold of 18.1 ha for watershed WS3.

2.3. Sensitivity Analysis of the SWAT Model

The sensitivity analysis, performed prior to calibration, involves determining which model parameters most influence the output data. It can be performed manually by changing one parameter at a time or automatically using SWAT-CUP. The parameters are then ranked in descending order of sensitivity, from the highest absolute value to the lowest. The procedure consists of six steps [14]:

- step 1: Use the default values for all parameters;
- step 2: Set all parameters except the one under study;
- step 3: Run the model with the minimum value of the parameter under study and save the output data;
- step 4: Run the model with the maximum value of the parameter under study and record the output data;
- step 5: Repeat steps 2 through 4 for all parameters under study;
- step 6: Use Equation 9 to calculate the sensitivity of each parameter for each term in the hydrologic balance.

$$P_{moy} = \frac{P_{\min} + P_{\max}}{2} \quad (5)$$

$$\Delta P = P_{\min} - P_{\max} \quad (6)$$

$$F_{moy} = \frac{F_{\min} + F_{\max}}{2} \quad (7)$$

$$\Delta F = F_{\min} - F_{\max} \quad (8)$$

$$|C_i| = \frac{P_{moy}}{F_{moy}} \frac{\Delta F}{\Delta P} \quad (9)$$

where i is the name of the parameter being tested, C_i is the sensitivity index of the parameter being tested, and each parameter has six sensitivity indices; P consists of two values ($P_{\min}$ and $P_{\max}$) for each parameter.

These minimum and maximum values are considered the input values for the parameter under test.

P_{moy}: corresponds to the average of the minimum and maximum values of each parameter to be tested;

ΔP: corresponds to the difference between the minimum and maximum values of each parameter to be tested;

F: consists of two values ($F_{\min}$ and $F_{\max}$) for each parameter;

$F_{\min}$ and $F_{\max}$ are the respective output values of $P_{\min}$ and $P_{\max}$;

F_{moy}: the average of $F_{\min}$ and $F_{\min}$;

ΔF: the difference between $F_{\min}$ and $F_{\max}$.

Table 1 presents the parameters typically considered in a sensitivity analysis.

Table 1. Parameters for sensitivity analysis [18].

Parameters	Description (unit)	Intervals (min-max)
Sols (sol)		
SOL_Z	Layer depth (mm)	0.1 - 3500
SOL_AWC	Available water capacity in the soil layer (mm/mm)	−0.45 - 0.2
SOL_BD	Moist bulk density (mg/m^3)	−0.1 - 0.1
SOL_CBN	Carbon dioxide content (%)	0.05 - 10
SOL_K	Hydraulic conductivity at saturation (mm/hr)	−0.4 - 0.4
Subbasin (sub)		
CH_Kl	Permeability of secondary channel banks (mm/hr)	0 - 100
CH_Nl	Manning's coefficient for secondary channels	0.01 - 0.12
HRU (hru)		
SLSUBBSN	Average slope length (m)	10 - 150
OV_N	Manning's coefficient for the entire hydrologic network	0.05 - 0.3
LAT_TIME	Travel time of the lateral flow (days)	0 - 180
CANMAX	Maximum canopy storage (mmH$_2$O)	0 - 20
ESCO	Soil evaporation factor as a function of depth	0.2 - 1
EPCO	Vegetation evaporation factor as a function of depth	0.2 - 1
SURLAG	Runoff delay coefficient (j)	1 - 12
Routing (rte)		
CH_N2	Manning's coefficient for main channels	0.02 - 0.15
CH_K2	Permeability of the banks of the main channels (mm/hr)	0 - 130
Groundwater (gw)		
GW DELAY	Aquifer recharge time (days)	5 - 250
ALPHA_BF	Discharge coefficient to the groundwater table (days)	0.1 - 0.95
GWQMIN	Threshold for groundwater contribution to base flow in the channel (mmH$_2$O)	0 - 1000
REVAP	Evaporation coefficient from the groundwater table	0.02 - 0.2
REVAPMN	Evaporation threshold from the groundwater table (mmH$_2$O)	0 - 300
RCHRG_DP	Percolation coefficient toward the deep aquifer	0 - 0.3
Management (mgt)		
CN2	SCS runoff curve number	−0.15 - 0.3

The parameters selected for calibration were chosen based on their hydrological relevance and the results of the global sensitivity analysis performed in SUFI-2. Their importance was assessed based on the absolute value of the t-stat and the p-value. A parameter with a high absolute t-stat value and a low p-value is considered more sensitive when the statistical significance threshold is set at 0.05 or less. This classification serves as the basis for prioritizing parameters during calibration.

2.4. Calibration and Validation of the SWAT Model

Calibration involves adjusting the parameters selected following the sensitivity analysis to achieve a better match between the simulated flow rates and the regionalized reference flow rates, using quality criteria. Since the three watersheds covered by the PUD do not have hydrometric stations at their outlets, the data series used for calibration were obtained by regionalizing the observed discharge rates in the neighboring Panthior watershed, using the DAR method described in Section I.6. Validation then allows us to assess the calibrated model's ability to reproduce hydrological behavior over an independent time period. Calibration can be performed manually or using SWAT-CUP [19]. In this study, the time periods were selected based on data availability. The simulation covers the period from 1981 to 2024. Calibration was performed using SWAT-CUP 2012 version 5.1.6 for the period 1986-1988 based on 36 regionalized monthly reference flows, and validation for the years 1991 and 1992 included 24 regionalized monthly reference flows. The period from 1981 to 1983 represents the model's warm-up phase (NYSKIP: 3). The years following 1992—specifically 1993-2024—are then used to analyze the simulated hydrological dynamics, including soil moisture, recharge, and so on. No monthly data are missing for the periods under consideration; therefore, no interpolation or data replacement procedures were applied. SWAT-CUP (Calibration and Uncertainty Procedures) is a standalone software program associated with SWAT that is used for calibration, validation, uncertainty analysis, and sensitivity analysis. It includes five algorithms: SUFI-2, PSO, GLUE, ParaSol, and MCMC [20]. In this study, the SUFI-2 algorithm was considered. The Nash-Shutckiffe criterion (NSE) was selected as the objective function and maximized during calibration. The procedure consisted of 5 successive iterations, each comprising 500 simulations for each watershed. The total number of simulations was 2,500 per watershed, or 7,500 simulations for the three watersheds. Each iteration involved a readjustment based on the results obtained, while adhering to the physically permissible limits in SWAT. Convergence was assessed based on the stabilization of the objective function and the factors p and r.

2.5. Model Performance Evaluation

Performance evaluation aims to verify the model's ability to accurately reproduce observations for its application. It is based on simulated results and several quality criteria presented in **Table 2** [21], [22].

Table 2. Criteria for evaluating the performance of the SWAT model [14].

Statistical criterion	Equation	Values	Classification	References
NSE	$1-\frac{\sum_{t=1}^{n}\left(Q_{obs}^{t}-Q_{sim}^{t}\right)^2}{\sum_{t=1}^{n}\left(Q_{obs}^{t}-\overline{Q_{obs}}\right)^2}$	0.75 < NSE ≤ 1 0.65 < NSE ≤ 0.75 0.5 < NSE ≤ 0.65 0.4 < NSE ≤ 0.50 NSE ≤ 0.50 0.50 ≤ NSE ≤ 0.70	Very good Good Satisfactory Acceptable Unsatisfactory Unacceptable	[23]
R^2	$\frac{\sum_{t=1}^{n}\left(\left(Q_{obs}^{t}-\overline{Q_{obs}}\right)\left(Q_{sim}^{t}-\overline{Q_{sim}}\right)\right)^2}{\sum_{t=1}^{n}\left(Q_{obs}^{t}-\overline{Q_{obs}}\right)^2 * \sum_{t=1}^{n}\left(Q_{sim}^{t}-\overline{Q_{sim}}\right)^2}$	$R^2 \geq 0.5$	Values greater than 0.5 are considered acceptable for the simulation of the model	[24]
PBIAS	$\frac{\sum_{t=1}^{n}\left(Q_{obs}^{t}-Q_{sim}^{t}\right)}{\sum_{t=1}^{n}\left(Q_{obs}^{t}\right)} * 100$	PBIAS < ±10 ±10 ≤ PBIAS < ±15 ±15 ≤ PBIAS < ±25 PBIAS ≥ ±25	Very Good Good Satisfactory Unsatisfactory	[25]
RMSE	$\sqrt{\frac{\sum_{t=1}^{n}\left(Q_{sim}^{t}-Q_{obs}^{t}\right)^2}{n}}$	Value less than half of the standard deviation	Satisfactory	[26]
RSR	$\sqrt{\frac{\sum_{t=1}^{n}\left(Q_{obs}^{t}-Q_{sim}^{t}\right)^2}{\sum_{t=1}^{n}\left(Q_{obs}^{t}-\overline{Q_{obs}}\right)^2}}$	0 ≤ RSR ≤ 0.50 0.50 ≤ RSR ≤ 0.60 0.60 ≤ RSR ≤ 0.70 RSR > 0.70	Very good Good Satisfactory Unsatisfactory	[27]

Q_{obs}^{t} : Observed; Q_{sim}^{t} : Simulated; $\overline{Q_{obs}}$: Observed mean; $\overline{Q_{sim}}$: Simulated mean.

Table 2 presents the following metrics:

- NSE: the Nash-Sutcliffe efficiency measure assesses the model's ability to reproduce the observed values;
- R^2: the coefficient of determination reflects the quality of the fit between the simulated and observed values;
- PBIAS: the percentage bias indicates the model's tendency to underestimate or overestimate the observed values (depending on the convention used, a positive PBIAS indicates an underestimation, and a negative PBIAS indicates an overestimation);
- RMSE: the root mean square error measures the average deviation between the simulated and observed values;
- RSR: The ratio of the RMSE to the standard deviation of the observations corresponds to the mean squared error normalized by the standard deviation of the observations.

2.6. Data Collection and Sources

The data used include climate, topography, soil, hydrometric, and land-use data. The daily climate data, obtained from NASA, cover the period from 1981 to 2024 for the coordinate point 14.7329˚N and 17.2072˚W. These data, derived from

MERRA-2, correspond to the grid cell centered at 14.5˚N and 17.5˚W, with a native grid resolution of 0.5˚ latitude by 0.625˚ longitude. The data include precipitation, maximum and minimum temperatures, relative humidity, and wind speed; only solar radiation is associated with a 1˚ × 1˚ radiative cell centered at 14.5˚N and 17.5˚W, derived from the SRB and CERES radiative products. Solar radiation data are missing only for the period 1981-1983 and were estimated using the Hargreaves method (Equation (10)) [28].

$$R_S = k_{R_S} \sqrt{T_{\max} - T_{\min}} R_a \tag{10}$$

where R_S represents solar radiation (MJ m^{-2} day^{-1}), R_a represents extraterrestrial radiation (MJ m^{-2} day^{-1}), $T_{\max}$ and $T_{\min}$ represent the maximum and minimum temperatures (˚C), and k_{R_S} represents the adjustment coefficient. The adjustment coefficient is taken to be 0.19 since the PUD is located in a coastal region. Following the procedures used to determine the solar radiation data, the NASA POWER time series were not subject to any local bias correction due to the lack of a sufficiently complete ground-based meteorological time series. The absence of local correction and the spatial resolution of the data are considered sources of uncertainty. The topographic data consist of Digital Elevation Models (DEMs) derived from the USGS SRTM. The land-use data come from 1992 Landsat 4 - 5 TM C2 L2 satellite images, while the soil data are derived from the FAO's digital soil maps. Land cover was determined through unsupervised classification of the Landsat image, which was divided into 73,843 spatial units of pixels across 6 classes. Thematic accuracy was assessed using a confusion matrix based on 100 validation points, which yielded an overall accuracy of 91% and a Kappa coefficient of 0.84. These correspond to the Panthior hydrometric station in Bounga Bambara (code 1384099005), located at 14˚45'00"N, 17˚10'12"W, which monitors a watershed covering an area of 88.5 km^2 with observed discharge rates in m^3/s. Panthior station is not located at the outlets of the PUD basins. It belongs to a neighboring and hydrologically distinct basin. It is used as a reference due to the lack of flow measurements. The observed flows at Panthior were extrapolated to WS1, WS2, and WS3 using the drainage-area ratio (DAR) method. The Drainage-Area Ratio (DAR) method allows for the estimation of the discharge of an ungauged basin based on observations available in a neighboring basin, taking into account geographical proximity and comparable hydroclimatic conditions (Equation (11)) [29].

$$Q_{ref}(t) = Q_p(t) * \frac{A_i}{A_p} \tag{11}$$

where $Q_{ref}(t)$ is the regionalized reference discharge for basin i, $Q_p(t)$ is the observed monthly discharge, A_i is the area of the PUD basins, and A_p is the area of the Panthior basin. The time series obtained in this way preserve the temporal dynamics of the flows observed at Panthior, while their amplitudes are adjusted in proportion to the areas of the target basins. They are therefore referred to in this study as regionalized reference flows. The application of the DAR method assumes a relative homogeneity of specific discharge between the Panthior watershed and the PUD watersheds. Differences in area, slope, soil type, land use, and hydrological behavior nevertheless introduce uncertainty. The results therefore do not constitute an independent local hydrometric validation. The 1982 data were compiled but were not used in the performance criteria because they were from the start-up period.

All of the data used are presented in Table 3.

Table 3. Model input data.

Types	Resolution/période	Sources	Description
DEM (SRTM)	30 m × 30 m	https://earthexplorer.usgs.gov	Digital Elevation Model
Land cover	1992	https://earthexplorer.usgs.gov (Landsat 4-5 TM C2 L2)	Land cover
Soil data	1/5,000,000	https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/	Digital Soil Map v3.6
Daily climate data	1981-2024	https://power.larc.nasa.gov/data-access-viewer/	Precipitation, temperatures, relative humidity, solar radiation and wind speed
Observed hydrometric data	1982 1986, 1987, 1988, 1991, 1992	https://portal.grdc.bafg.de/ https://doi.org/10.23708/LXGXQ9	Monthly discharge data

In 1992, land cover in the PUD watersheds included water bodies, trees, flooded vegetation, croplands, bare soil, and savannas (Figure 4).

To integrate land-use data into SWAT, the classes were assigned the following codes: water bodies (WATR), trees (FRST), flooded vegetation (WETF), crops (AGRL), bare soil (BARR), and pastures (PAST).

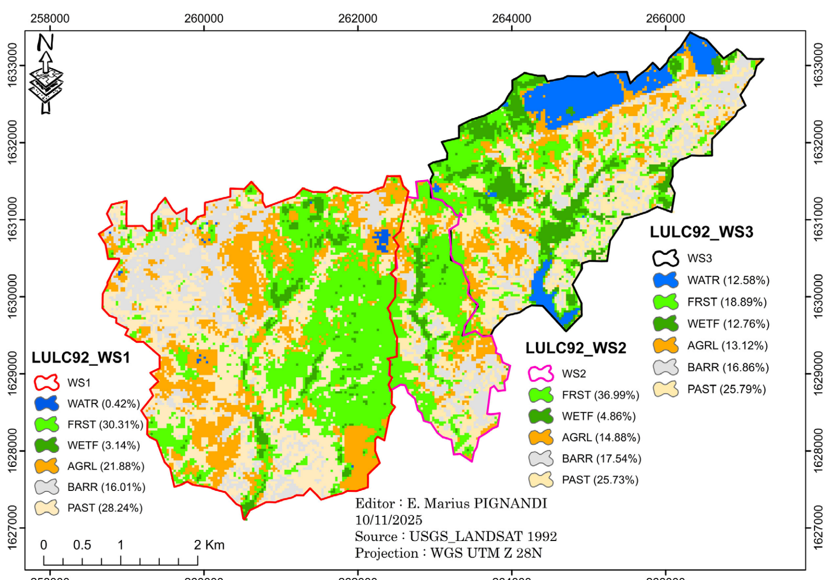

Figure 4. Land cover—1992.

The soils in the PUD watersheds consist mainly of Cambrian Lithosols with vertic characteristics and arenosols. They thus include expansive clay and sandy formations (**Figure 5**).

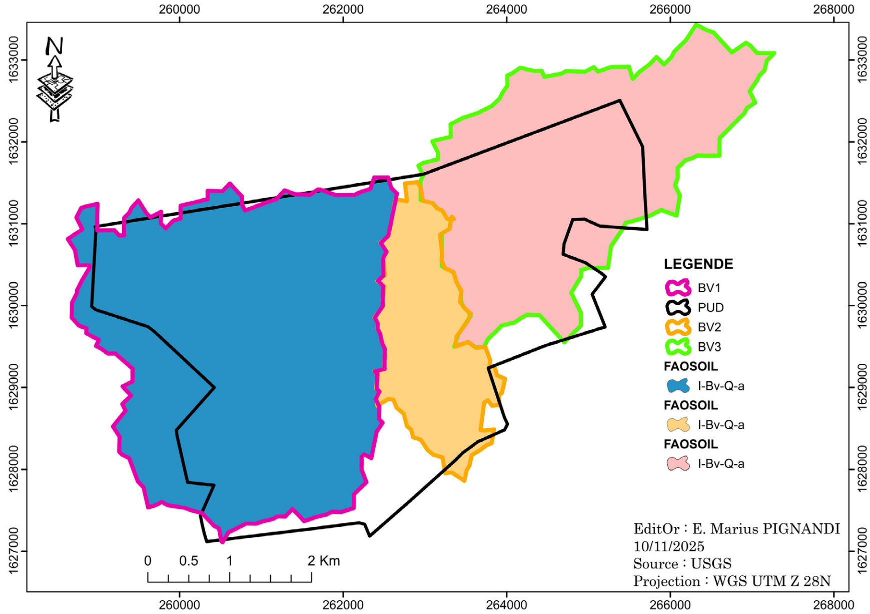

Figure 5. Soil types in the PUD.

Slopes within the PUD are mostly gentle to moderate. The steepest slopes are found in watersheds 1 (WS1) and 3 (WS3), which are therefore more susceptible to runoff and erosion. In contrast, watershed 2 (WS2) is less steep than the other two. **Figure 6** shows the slopes of the PUD watersheds.

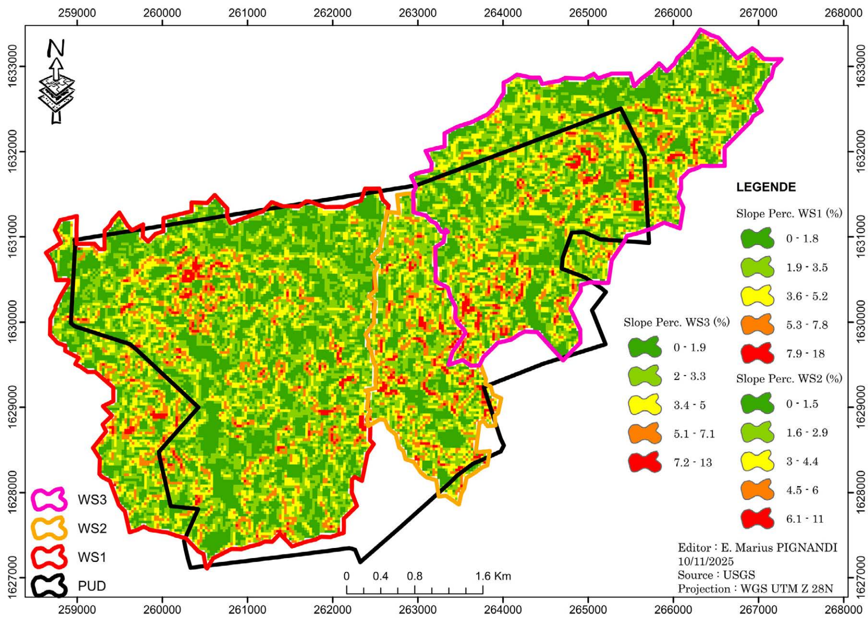

Figure 6. Slopes of the PUD's watersheds.

3. Results and Discussion

3.1. Results

The SWAT model can be used to study numerous processes, including hydrology, climate, soil erosion, crop growth, and water management and quality. In this study, only the hydrology component is considered. Figure 7 presents the main results of the SWAT simulation: watersheds and sub-watersheds, longest hydraulic paths, hydrographic networks, and outlets.

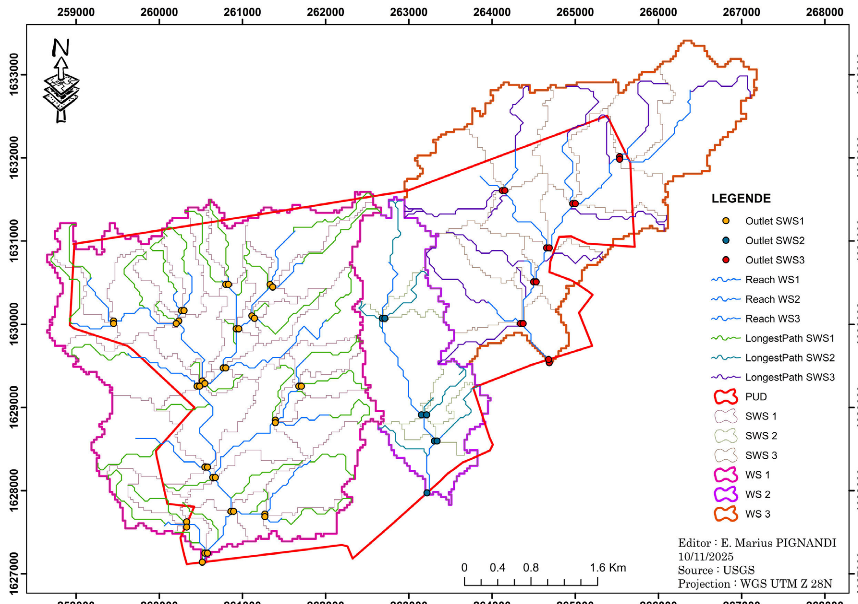

Figure 7. Characteristics of the PUD's watersheds obtained using SWAT.

The hydrological modeling performed using SWAT provides information on the three watersheds of the PUD, including the area of the sub-watersheds (SWS) and the hydrologic response unit (HRU) numbers. These results are presented in Table 4.

Table 4. SWAT results for the areas and HRU numbers of the PUD sub-watersheds.

WS 1									WS 2			WS 3		
SWS	Area (ha)	HRU No.	SWS	Area (ha)	HRU No.	SWS	Area (ha)	HRU No.	SWS	Area (ha)	HRU No.	SWS	Area (ha)	HRU No.
1	22.81	1	14	8.16	14	27	9.24	29	1	82.28	1	1	54.65	1
2	28.31	2	15	16.61	15	28	64.39	30	2	23.20	2	2	136.44	2
3	64.48	3	16	68.91	16	29	43.25	31	3	113.83	3	3	99.87	3
4	49.94	4	17	50.53	17	30	17.89	32	4	23.49	4	4	82.77	4
5	27.62	5	18	9.04	18	31	71.46	33	5	9.14	5	5	68.81	5
6	35.49	6	19	79.23	19	32	29.29	34	6	28.90	6	6	78.34	6
7	22.61	7	20	4.13	20	33	22.51	35	7	47.58	7	7	41.97	7

Continued

8	51.31	8	21	28.21	21	34	26.93	36				8	63.21	8
9	25.66	9	22	24.38	22	35	10.12	37				9	42.47	9
10	48.27	10	23	9.34	23	36	24.48					10	41.78	10
11	0.88	11	24	50.92	24	37	0.88					11	81.39	11
12	43.74	12	25	88.27	27							12	8.85	12
13	15.33	13	26	64.39	28							13	51.90	13
Total						**37**	**1259.02**	**37**	**7**	**328.42**	**7**	**13**	**852.45**	**13**

The areas of WS1, WS2, and WS3 are 1259.02 ha, 328.42 ha, and 852.45 ha, respectively, for a total of 2439.89 ha, which exceeds the 1644 ha specified in the PUD. This discrepancy is due to the inclusion of certain upstream portions of the watersheds located outside the PUD that contribute to runoff. The watersheds were modeled in their entirety to preserve hydrological continuity. Using the areas of the various watersheds, it is possible to determine the conversion factors for the flow rates of the Panthior River relative to those of the PUD watersheds. Table 5 shows the conversion factors for the Panthior River's flow rates.

Table 5. Conversion factors for the Panthior River's flow rates.

Bassins versants	Superficie Ai (km²)	Rapport A_i/A_P	Relation de transposition
WS1	12.5902	0.1423	$Q_{ref}(t) = 0.1423 * Q_p(t)$
WS2	3.2842	0.0371	$Q_{ref}(t) = 0.0371 * Q_p(t)$
WS3	8.5245	0.0963	$Q_{ref}(t) = 0.0963 * Q_p(t)$

The results of the sensitivity analysis, calibration, and validation are presented in the following sections.

3.1.1. Sensitivity Analysis

Sensitivity analysis helps identify the most influential model parameters prior to calibration. In this study, six parameters (soil, sub, hru, rte, gw, and mgt) were selected for sensitivity analysis. The SUFI-2 algorithm was used in SWAT-CUP for each of the three watersheds. The SUFI-2 algorithm was used in SWAT-CUP, with approximately 500 simulations for each of the three watersheds. For each parameter, SUFI-2 provides a t-statistic and p-value, as shown in Table 6. A high absolute value of t indicates high sensitivity, while a low p-value indicates statistically significant sensitivity. The results show that CN2 is the most influential parameter for all three watersheds. Other parameters, notably ALPHA_BN for Watershed 1 (WS1), ESCO, REVAP, CH_N2, and SOL_BD for Watershed 2 (WS2), as well as GWQMN, GW_REVAP, REVAPMN, ESCO, CH_N1, ALPHA_BNK, and GW_DELAY for Watershed 3 (WS3), also exhibit significant sensitivity. The prefix "V" indicates that the initial value of the parameter is replaced by a new one, while "R" corresponds to a relative change in the value. Figures 8-10 present the results of the overall sensitivity analysis of the SWAT-CUP parameters for watersheds WS1, WS2, and WS3.

Table 6. t-statistics and p-values for the parameters following the sensitivity analysis.

WS 1			WS 2			WS 3		
Parameters	t-Stat	p-Value	Parameters	t-Stat	p-Value	Parameters	t-Stat	p-Value
V_GWQMN.gw	−0.07	0.95	V_SURLAG.bsn	−0.01	0.99	V_ALPHA_BF.gw	0.37	0.72
R_SOL_BD(..).sol	−0.18	0.86	V_EPCO.hru	0.06	0.95	R_SOL_BD(..).sol	0.66	0.51
V_SURLAG.bsn	0.20	0.84	V_ALPHA_BNK.rte	0.08	0.94	V_SURLAG.bsn	0.72	0.47
V_GW_DELAY.gw	0.31	0.76	V_CH_K2.rte	−0.10	0.92	V_RCHRG_DP.gw	1.12	0.26
V_ALPHA_BF.gw	−0.36	0.72	R_SOL_AWC(..).sol	−0.31	0.76	V_OV_N.hru	1.15	0.25
V_CH_K1.sub	0.37	0.71	V_REVAPMN.gw	−0.61	0.54	R_SOL_K(..).sol	1.39	0.16
R_SOL_K(..).sol	−0.53	0.60	V_OV_N.hru	−0.75	0.45	V_CH_N2.rte	1.44	0.15
V_GW_REVAP.gw	−0.58	0.57	V_ALPHA_BF.gw	0.96	0.34	V_CANMX.hru	1.53	0.13
V_CH_K2.rte	−0.60	0.55	V_CH_N1.sub	−0.99	0.33	V_CH_K1.sub	−1.57	0.12
V_CANMX.hru	0.62	0.54	V_CANMX.hru	−1.13	0.26	V_EPCO.hru	−1.72	0.09
R_SOL_AWC(..).sol	1.20	0.24	R_SOL_K(..).sol	−1.44	0.15	V_CH_K2.rte	1.76	0.08
V_RCHRG_DP.gw	1.22	0.23	V_RCHRG_DP.gw	−1.44	0.15	R_SOL_AWC(..).sol	−2.36	0.02
V_OV_N.hru	1.31	0.20	V_GW_DELAY.gw	−1.78	0.08	V_GW_DELAY.gw	−2.84	0.00
V_CH_N2.rte	−1.36	0.18	V_CH_K1.sub	−2.48	0.02	V_ALPHA_BNK.rte	−3.03	0.00
V_ESCO.hru	1.53	0.14	V_GWQMN.gw	−2.78	0.01	V_CH_N1.sub	3.03	0.00
V_CH_N1.sub	−1.67	0.11	R_SOL_BD(..).sol	3.06	0.00	V_ESCO.hru	3.54	0.00
V_REVAPMN.gw	−1.73	0.09	V_CH_N2.rte	3.08	0.00	V_REVAPMN.gw	5.99	0.00
V_EPCO.hru	−1.94	0.06	V_GW_REVAP.gw	−3.41	0.00	V_GW_REVAP.gw	−6.45	0.00
V_ALPHA_BNK.rte	2.17	0.04	V_ESCO.hru	3.61	0.00	V_GWQMN.gw	−7.67	0.00
R_CN2.mgt	5.39	0.00	R_CN2.mgt	4.77	0.00	R_CN2.mgt	19.89	0.00

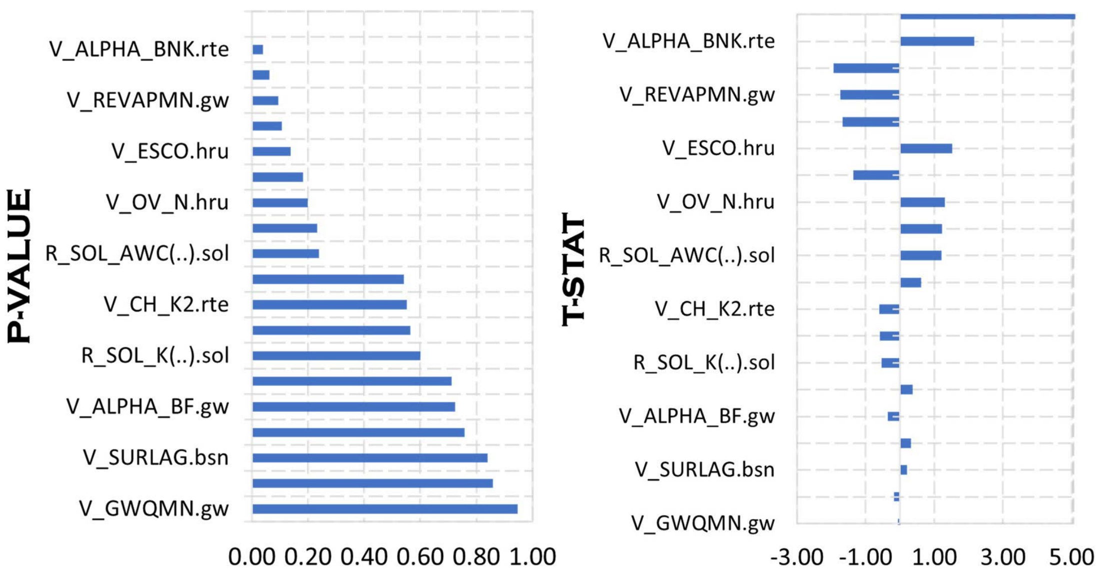

Figure 8. t-statistics and p-values for the sensitive parameters of WS1.

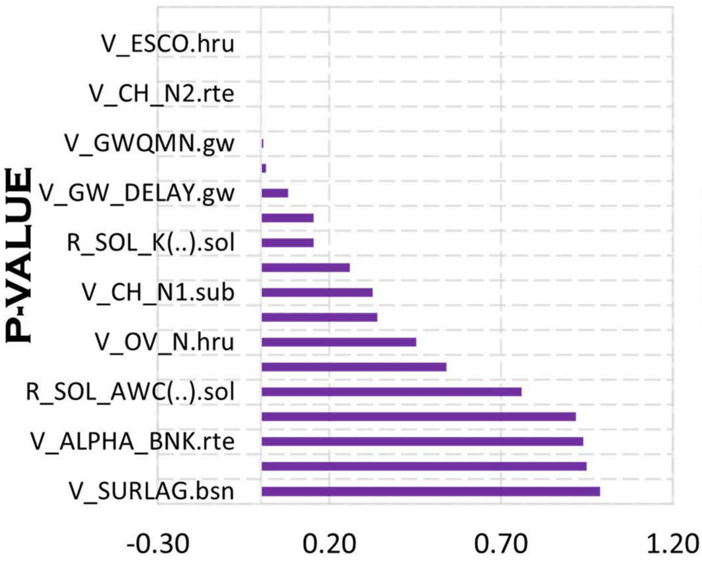

Figure 9. t-statistics and p-values for the sensitive parameters of WS2.

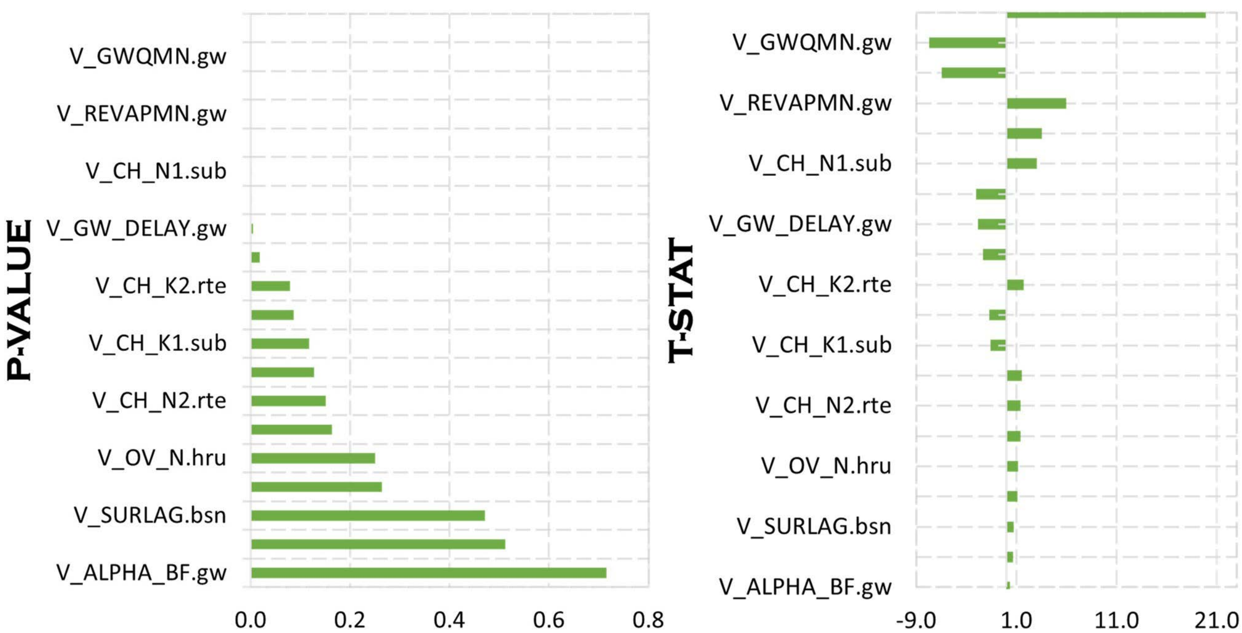

Figure 10. t-statistics and p-values for the sensitive parameters of WS3.

3.1.2. Model Calibration and Validation

Following the sensitivity analysis, the model was calibrated using SWAT-CUP based on observed discharge data from 1986 to 1988. Approximately 2500 simulations were conducted to adjust twenty parameters in order to reduce the discrepancies between observed and simulated discharges and achieve satisfactory performance. The final values of the calibrated parameters are presented in Table 7.

These values were then used to verify the model's performance over an independent period. The validation thus covers the period 1991-1992. The performance results obtained during calibration and validation are presented in Table 8. Performance was evaluated using the NSE, R^2, PBIAS, RSR, RMSE, p-factor, and r-factor metrics. The NSE assesses the overall quality of the simulation, while R^2 measures the consistency between observed and simulated flows. PBIAS indicates the model's tendency to overestimate or underestimate flows. The RSR evaluates the normalized residual errors, and the RSME measures the mean error between simulated and observed discharge values. The p and r factors are used to assess calibration uncertainties in SWAT-CUP. For a calibration to be considered satisfactory, the p factor must be as close to 1 as possible, and the r factor as low as possible.

Table 7. Parameter values after calibration with SWAT-CUP.

Parameters	**WS1**			**WS2**			**WS3**		
	Adjusted value	Minimum value	Maximum value	Adjusted value	Minimum value	Maximum value	Adjusted value	Minimum value	Maximum value
R_CN2.mgt	0.111	−0.15	0.15	0.122	−0.15	0.15	0.21525	−0.15	0.15
V_ALPHA_BF.gw	0.443	0.1	0.8	0.496	0.1	0.8	0.41675	0.1	0.8
V_GW_DELAY.gw	177.400	30	250	231.300	30	250	19.795	30	250
V_GWQMN.gw	770.000	0	1000	505.000	0	1000	117.300003	0	1000
V_GW_REVAP.gw	0.076	0.02	0.15	0.065	0.02	0.15	0.06147	0.02	0.15
V_REVAPMN.gw	135.000	0	300	115.500	0	300	42.300003	0	300
V_RCHRG_DP.gw	0.285	0	0.3	0.122	0	0.3	0.1882	0	0.3
V_SURLAG.bsn	11.450	1	12	10.405	1	12	2.749	1	12
V_ESCO.hru	0.976	0.2	1	0.948	0.2	1	0.85775	0.2	1
V_EPCO.hru	0.640	0.2	1	0.372	0.2	1	0.5925	0.2	1
V_OV_N.hru	0.098	0.05	0.3	0.081	0.05	0.3	0.19225	0.05	0.3
V_CANMX.hru	15.400	0	20	18.900	0	20	0.98	0	20
R_SOL_AWC(..).sol	0.036	−0.2	0.2	0.098	−0.2	0.2	−0.42025	−0.2	0.2
R_SOL_K(..).sol	−0.392	−0.4	0.4	0.140	−0.4	0.4	0.0962	−0.4	0.4
R_SOL_BD(..).sol	0.086	−0.1	0.1	−0.053	−0.1	0.1	0.0126	−0.1	0.1
V_CH_N2.rte	0.079	0.02	0.12	0.102	0.02	0.12	0.04353	0.02	0.12
V_CH_K2.rte	126.100	0	130	95.550	0	130	9.889999	0	130
V_ALPHA_BNK.rte	0.210	0	1	0.055	0	1	0.091	0	1
V_CH_N1.sub	0.038	0.01	0.12	0.033	0.01	0.12	0.11857	0.01	0.12
V_CH_K1.sub	47.000	0	100	12.500	0	100	47.049999	0	100

Table 8. Statistical performance criteria for calibration and validation.

Criteria	WS1				WS2				WS3			
	Calibration		Validation		Calibration		Calibration		Calibration		Validation	
	Value	Analysis	Value	Analysis	Value	Analysis	Value	Analysis	Value	Analysis	Value	Analysis
NSE	0.94	*Very good performance*	0.94	*Very good performance*	0.82	*Good to very performance*	0.97	*Excellent performance*	0.82	*Good to very performance*	0.90	*Very good performance*
R^2	0.94	*Very strong correlation*	0.96	*Excellent correlation*	0.83	*Good correlation*	0.98	*Excellent correlation*	0.85	*Good correlation*	0.92	*Very strong correlation*
PBIAS	7.0%	*Low bias, slight underestimation*	11.9%	*Acceptable bias, moderate underestimation*	−6.1%	*Low bias, slight underestimation*	7.9%	*Low bias, slight underestima tion*	21.2%	*Fairly high bias, significant*	9.2%	*Low bias, slight underestima tion*
RSR	0.24	*Very good performance*	0.25	*Very good performance*	0.43	*Good performance*	0.17	*Excellent performance*	0.42	*Good performance*	0.32	*Very good performance*
RMSE	0.0266	*Low error*	0.0089	*Very low error*	0.0122	*Low error*	0.0041	*Very low*	0.045 8	*Moderate error*	0.0118	*Low error*
r-factor	0.68	*Acceptable uncertainty*	0.97	*Moderate uncertainty*	0.76	*Acceptable uncertainty*	0.44	*Low and satisfactory uncertainty*	0.4	*Low uncertainty*	0.57	*Acceptable uncertainty*
p-factor	0.83	*Good coverage of observations*	1	*Excellent coverage of observations*	0.89	*Very good coverage of observations*	0.92	*Very good coverage of observations*	0.39	*Insufficient coverage of observations*	0.42	*Insufficient coverage of observations*

The calibration and validation results obtained with SWAT-CUP, as well as the 95PPU uncertainty envelope, are presented in **Figure 11** for WS1, in **Figure 12** for WS2, and in **Figure 13** for WS3.

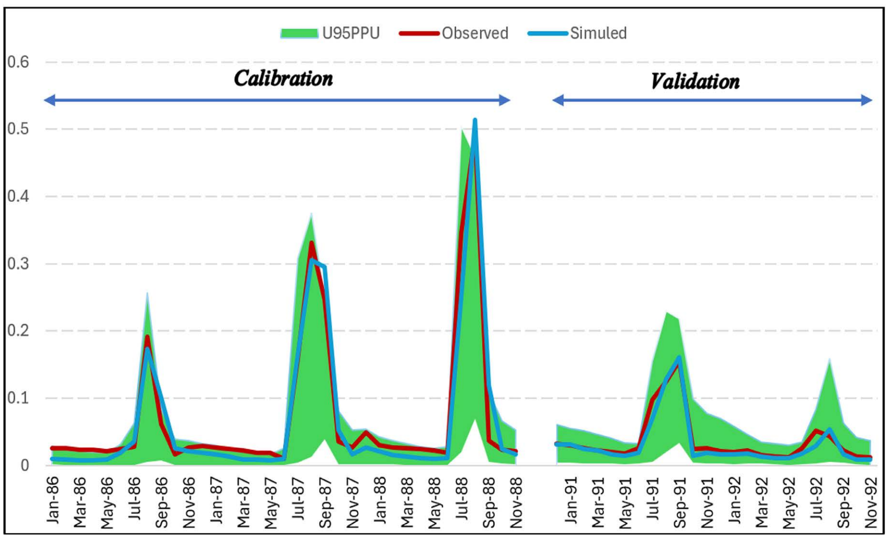

Figure 11. Comparison of regionalized and simulated reference discharge rates with the 95PPU Uncertainty Band—calibration and validation of WS1.

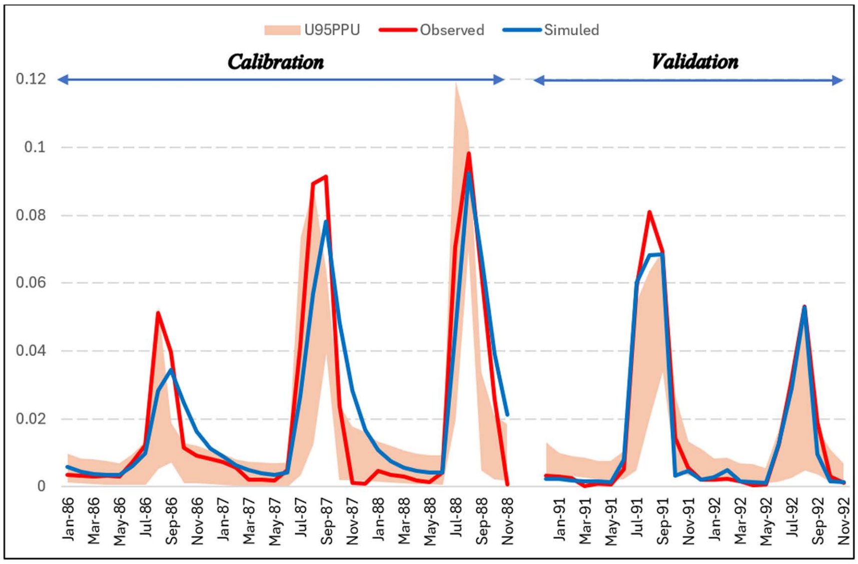

Figure 12. Comparison of regionalized and simulated reference discharge rates with the 95PPU uncertainty band—calibration and validation of WS2.

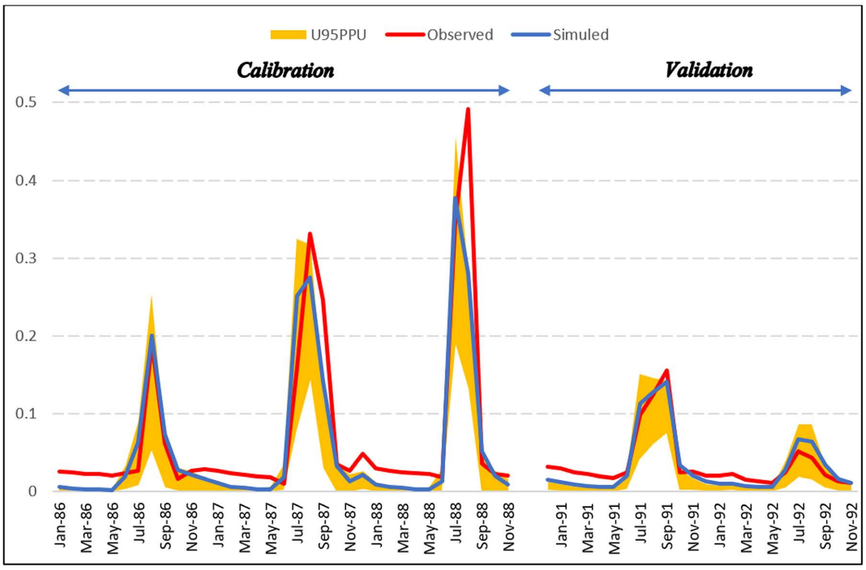

Figure 13. Comparison of regionalized and simulated reference discharge rates with the 95PPU uncertainty band—calibration and validation of WS3.

3.2. Discussion

The results from the hydrological modeling of the PUD using SWAT indicate that the model generally reproduces the hydrological behavior of the three studied watersheds well. The analysis is based on the delineation of watersheds and sub-watersheds, hydrographic networks, and hydrological response units.

The sensitivity analysis conducted using SWAT-CUP/SUFI-2 shows that parameter CN2 is the most sensitive across the three watersheds. This result is consistent with several SWAT applications in West Africa, notably in the Pra and White Volta basins in Ghana [30] and the Sherigu basin straddling Ghana and

Burkina Faso [31]. This result highlights the importance of surface runoff, land use, and impervious surfaces in the PUD's hydrological response. Other parameters related to groundwater, soils, evapotranspiration, and channels also influence the results, depending on the watershed.

The model's performance ranges from satisfactory to excellent. The NSE values range from 0.82 to 0.97, while the R^2 values range from 0.83 to 0.98, indicating good agreement between simulated and observed discharge values. The low RSR and RMSE values also indicate that simulation errors remain limited [21].

WS1 exhibits good stability between calibration and validation, while WS2 achieves its best performance during validation. The WS3 also shows good results; however, its p-factor indicates that the 95PPU uncertainty band does not adequately represent the predictive uncertainty. The low coverage may be related to uncertainties associated with the regionalization of Panthior discharge rates, the lack of direct observations at the outlets, and the parameter ranges used. These results do not support the conclusion that the model has been validated for WS3. Thus, the watershed requires further adjustment of its sensitive parameters [32].

Overall, the SWAT model proves to be suitable for simulating the hydrological behavior of the PUD. The results allow for an examination of the influence of urbanization and impervious surfaces on runoff. Despite the satisfactory performance achieved, the model remains subject to uncertainties related to the quality and availability of observed rainfall data. Nevertheless, it can serve as a decision-support tool for stormwater management and sustainable planning of the PUD.

4. Conclusion

The results of the modeling show that the SWAT model accurately represents the hydrological behavior of the three watersheds in the PUD. The sensitivity analysis highlights the predominance of parameter CN2, underscoring the importance of surface runoff, land use, and impervious surfaces in hydrological behavior. The sensitivity of other parameters related to groundwater, evapotranspiration, and soil properties indicates that hydrological behavior varies from one watershed to another. This variability confirms the value of a spatialized, watershed-based approach. The calibration and validation models demonstrate good statistical performance, characterized by high NSE and R^2 values as well as low RSR and RMSE values. The model serves as a historical baseline due to the satisfactory performance of WS1 and WS2, which demonstrate good stability between calibration and validation. WS3, however, remains uncertain due to the limited coverage of reference data by the 95PPU band and therefore cannot be considered fully validated. Applying the WS1 and WS2 models to recent land-use data will allow for the assessment of potential changes in hydrological processes in a subsequent study, while only WS3 will enable the identification of exploratory trends. It requires further adjustments to these parameters. In the absence of recent observed discharge data, the results will be considered hydrological scenarios. Ultimately, the study confirms the value of the SWAT model for analyzing the effects of urbanization on runoff and for contributing to the sustainable management of stormwater in the PUD.

Author Contributions

Conceptualization, Pignandi, E.M., and Ndao, S.; methodology, Pignandi, E.M. and Sambou, L.E.V. ; software, formal analysis, investigation, data curation and visualization, Pignandi, E.M., Sambou, L.E.V., Ndiaye C., Mendy, C.M.; validation, Pignandi, E.M., Sambou, L.E.V., Ndao, S. and Mendy, C.M.; writing—original draft preparation, Pignandi, E.M.; writing—review and editing, Sambou, L.E.V., Ndiaye, C., Mendy, C.M. and Ndao, S.; supervision, Sambou, L.E.V., Ndiaye, C., Mendy, C.M. and Ndao, S. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

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

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