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Dynamics of Surface Conditions and Hydrological Functioning: The Case of the Ivorian River Basin Aghien Lagoon with the SWAT Model

Kansaye A. Daifourou[1,*], Noufé D. Djibril[1], Soro G. Emile[1], Dao Amidou[1], Kamagate Bamory[1], Gone D. Lanciné[1], Servat Eric[2], Mahe Gil[2]

[1]Geosciences and Environment Laboratory, Nangui Abrogoua University, Abidjan, Côte d'Ivoire
[2]UMR HydroSciences, IRD Université Montpellier 2, Montpellier, France
*Corresponding author: babson238@gmail.com

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Abstract In the Aghien lagoon hydrosystem, surface conditions are a major factor affecting hydrological processes. Changes in hydrological processes have a significant impact on the availability of water resources. The aim of this study is therefore to simulate the rainfall-discharge relationship in relation to demographic pressure and the dynamics of land use in the catchment area of the Aghien lagoon in southern Côte d'Ivoire. For this purpose, the SWAT model was calibrated and validated using daily time scale flow data at the outlet of the Djibi catchment for the reference year (1987) and gave satisfactory results (NSE ≥ 0.50, $R^2 \geq 0.50$ and PBIAS ≤ 10). An increase in surface runoff, water supply and evapotranspiration (5.61%), (0.15%) and (0.04%) associated with a decrease in lateral flow (Lat_Q), groundwater flow (Gw_Q), percolation (Perco) and potential evapotranspiration (ETP) (-19.20%), (-6.74%), (-0.15%) and (-0.14), were observed in 2020 compared with the reference year (1987). In a context of climate variability and change, the dynamics of the vegetation cover can provide information about changes in the major hydrological processes such as runoff, infiltration, *etc*. The increase in runoff and the decrease in infiltration observed can be linked to the dynamics of the plant cover, which has been replaced by crops and bare soil with a higher runoff capacity, thus partly explaining the increase in runoff and the decrease in infiltration.

Keywords: *Dynamics of surface conditions, hydrological functioning, Ivorian river, Aghien Lagoon, Swat Model*

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1. Introduction

Since the Neolithic period, changes in land use and occupation have been mainly attributable to pastoralism and agriculture. Today, in addition to agricultural activities, which have intensified, demographic growth, urbanisation through the expansion of urban areas, industrialization and mining are possible causes of changes in land use [1,2]. According to [3], changes in land use have a strong and rapid impact on the functioning of this vast Earth system, particularly its climate, but also on the water cycle, biodiversity and all ecosystem services, at both local and global scales. From an environmental point of view, the main consequences of changes in vegetation cover include the loss of biodiversity and ecosystem services, soil erosion, the risk of flooding and mudflows, increased greenhouse gas emissions and carbon depletion. According to [4], this phenomenon is recognised as one of the key factors affecting water resources. The Aghien lagoon, one of the largest freshwater reserves near the megalopolis of Abidjan, has been identified as a potential source of drinking water for the city. However, in recent years, the lagoon basin has seen a sharp deterioration in its plant cover as a result of intense human activities, particularly farming and livestock activities. Recent studies [5] have shown that the watershed of the Aghien lagoon is experiencing severe degradation of its vegetation cover, mainly as a result of the growth of the city of Abidjan and agro-pastoral activities. Hence the need, in the current context of global change, combining population densification, deforestation and climate variability and change, to understand the climatic and anthropogenic impacts on the water resources of this important lagoon hydrosystem. Quantifying the components of the hydrological system is a very difficult exercise because of the heterogeneity of the catchment areas (slope, soil, activities in the catchment area, etc.) and the inadequacy of measurement tools (climate stations, etc.). To deal with these difficulties, the hydrological sciences have seen the advent and development of new methods of approach such as hydrological modelling. Some of these hydrological models, known as distributed models, take into account the multifactorial relationship between natural conditions and the hydrological functioning of the catchment. Examples of models capable of taking these parameters into account include MODFLOW [6], TOPMODEL [7], SHE [8], MODCOU [9], SWAT [10], and MGBIPH [11], cited by [12]. Among these models, the SWAT model is currently considered to be one of the best models for simulating the impact of land use change on water quantity and quality. The SWAT model has been applied worldwide in different climatic contexts and for different land-use types [13,14,15,16,17,18,19,20]. Thus, in a context of climate variation and change, the SWAT model is used here to understand the impact of demographic pressure and changes in land use on the hydrological processes of the Aghien lagoon catchment.

2. Materials and Methods

2.1. Study Area

Located between longitudes 5°21' and 5°28' N, and latitudes 3°49' and 3°58' W (Figure 1), the Lagoon Aghien catchment area is a peri-urban catchment in the Abidjan district, covering an area of around 350 km². Divided between the city of Abidjan and the communes of Bingerville and Anyama, its southern part is heavily urbanised, encompassing the most densely populated districts of the commune of Abobo. The total population of the basin is around 1,200,000 [21]. Annual water inflows come mainly from the two tributaries located upstream of the basin, namely the Djbi and Bété rivers (Figure 1). The Aghien lagoon catchment is located in a region with a transitional equatorial climate. It is characterised by two wet periods (May to July and October to November) and two dry periods (December to April and August to September). The average annual rainfall in the study area is around 1,500 mm and the average annual air temperature ranges from 23˚C to 28.5˚C.

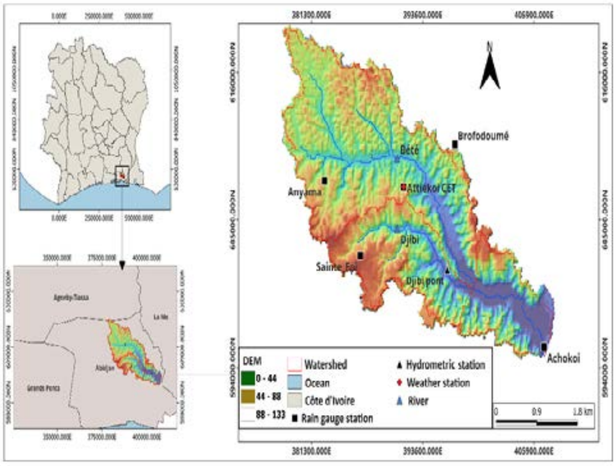


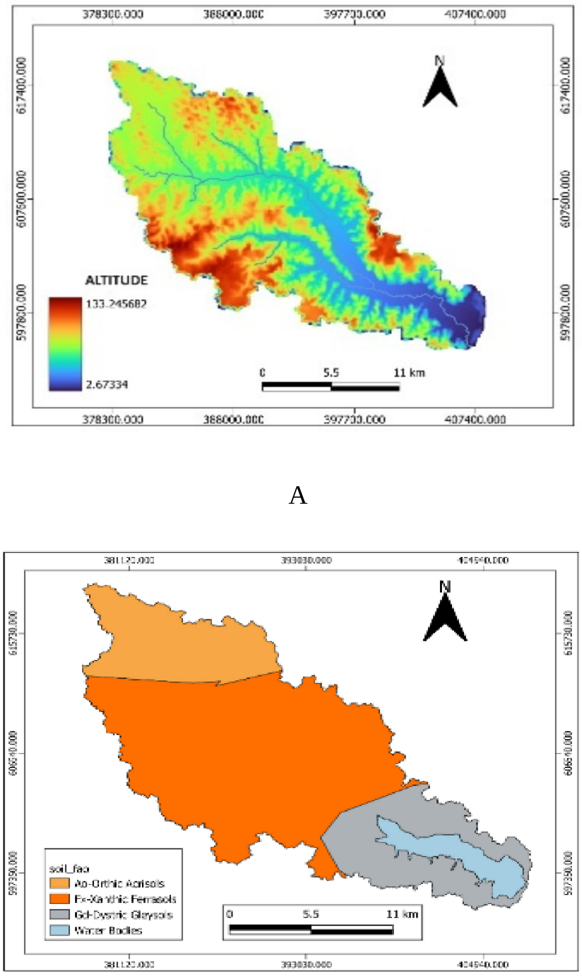
Figure 1. Geographical location of the Aghien lagoon

2.2. Data from Study

The data used in this study are essentially spatial and temporal. The temporal data consists of daily hydrometric and climatic data (rainfall, solar radiation, relative air humidity, wind speed, maximum and minimum air temperatures). As for spatial data, this is made up of satellite Land use and Land Cover, soil data (Figure 2b) and digital terrain model (DEM) data (Figure 2a). These data come from several sources (Table 1).

Table 1. Input data for the SWAT model

Data types	Data	Resolution	Sources acquisition dates
Spatial data	DEM	30×30 m	http://earthexplorer.usgs.gov/
	Soil	1: 5.000.000	FAO soil database
	Land use change (LUC)	30 m	1987, 2000, 2015 and 2020 [5]
Time data (2016-2020)	Rain	5	Aghien Project
	Temperature	1	
	Flow	1	



A

B

Figure 2. (a) DEM spatial data for the Aghien lagoon catchment area and (b) soil map

2.3. Description of the Hydrological Model Used

The SWAT model was developed by the Department of

Agriculture and the laboratories of the University of Texas A&M in the United States, with the aim of continuously simulating the impact of uses and developments on water transfers and the mobility of sediments, nutrients, pesticides and bacteria on a daily time scale. The SWAT model requires a Digital Terrain Model (DEM), a land-use map, a soil map and daily climate data (rainfall, maximum and minimum temperature, relative humidity and sunshine). Daily hydrometric data are used to calibrate and validate the model. The water balance equation used to simulate the SWAT hydrological cycle is as follows [22]:

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

With:

Swt: the final water content of the soil (mm);

Sw0: the initial water content of the soil on day **i** (mm);

t: time (days);

Rday: the amount of precipitation on day **i** (mm);

Qsurf: the amount of surface runoff on day **i** (mm);

Ea: the amount of evaporation on day **i** (mm);

Wseep: the amount of water entering the vadose zone from the soil profile on day **i** (mm);

Qgw: the amount of return flow over i days (mm).

2.4. Sensitivity Analysis and Assessment of the Model

2.4.1. Sensitivity Analysis of the Model

Table 2. Parameters tested in the sensitivity analysis.

Parameters	Description
CN2.mgt	SCS Curve Number
ALPHA_BF.gw	Base flow alpha factor
GW_DELAY.gw	Water transfer time to recharge the shallow aquifer from the bottom of the soil profile
GWQMN.gw	Threshold depth of water in the shallow aquifer required for flow to the river system to occur
GW_REVAP.gw	Groundwater re-evaporation coefficient
SOL_AWC().sol	Available water capacity of the soil layer
SOL_BD().sol	Apparent soil density used to determine the drainage porosity of the different soil horizons.
SOL_K().sol	Saturation hydraulic conductivity, which influences both the speed of percolation down the soil profile and the speed of lateral flow.
SURLAG.bsn	Surface runoff offset coefficient
EPCO.bsn	Plant removal compensation factor
CH_N2.rte	Maning coefficient for main channels
ALPHA_BNK.rte	Recession constant which characterises the flows between the water stored in the banks of watercourses and the hydrographic network.
HRU_SLP.hru	Main slope of the HRU
OV_N.hru	Overall Manning coefficient for the hydrographic network
SLSUBBSN.hru	Average slope length
ESCO.hru	Soil evaporation compensation factor
CH_K1.sub	Effective hydraulic conductivity in the alluvium of the tributary channel
CH_N1.sub	Maning coefficient for secondary channels
TRNSRCH.bsn	Fraction of the transmission losses of the main channel that penetrates the deep aquifer.
RCHRG_DP.gw	Fraction of water percolating to the deep aquifer

N.b: v_ means to replace the current value of the parameter by the given value, and r_ means to multiply the current value of the parameter by (1 + a given value)

Model sensitivity is the careful examination of the change in model output by changing an input parameter. The SWAT model tool, SWAT-CUP, uses sensitivity analysis to measure the average relative sensitivity of the best parameters [23,24]. A total of 20 parameters, shown in Table 2, were considered for this sensitivity analysis. These were chosen in accordance with the literature and knowledge of the catchment area under study.

2.4.2. Performance

The Djibi station was selected for model calibration, to assess the dominant flow parameters, using the SWAT Calibration and Uncertainty Procedures (SWAT-CUP) tool with the Sequential Uncertainty Fitting (SUFI-2) program algorithm [25]. The SWAT-CUP model was calibrated using daily data from May 2017 to October 2017. Calibration is a process that assesses the goodness of fit between observed and simulated data, in order to obtain optimal values of representative functions such as Nash-Sutcliffe efficiency (NSE), coefficient of determination (R^2) and percentage bias (PBIAS). For PBIAS, the most optimal value is zero, while for R^2 and NSE, it is 1. The value of R^2 is between 0 and 1; the value closest to 1 indicates the best results, while a value greater than 0.5 is within an acceptable range.

After calibration, the model was validated over the period October 2017 to June 2018. The performance of the model was evaluated during the calibration-validation process using the decision factors of [26], as shown in Table 3.

Table 3. Model evaluation thresholds [26]

Performance rating	Flow		
Very good	$0.75 \le NSE \le 1$	PBIAS ≤ ±10%	$R^2 \ge 0.80$
Good	$0.65 \le NSE \le 0.75$	PBIAS ≤ ±15%	$R^2 \ge 0.70$
Satisfactory	$0.5 \le NSE \le 0.65$	PBIAS ≤ ±25%	$R^2 \ge 0.5$
No Satisfactory	$NSE \le 0.5$	PBIAS ≥ ±25	$R^2 \le 0.5$

2.4.3 Assessing the Impact of Changes in Land Use on Hydrological Response

To assess the impact of Land Use (LUC) on the hydrological response, the parameters derived from the calibration were used to simulate the hydrological balance of the basin using the land use map of the year (1987) over the climatic period from 2016 to 2020. The balance resulting from this last simulation, chosen as a reference, is compared with the balance from three other new simulations carried out, using the land-use maps for 2000, 2015 and 2020; the same values of the calibrated parameters from the reference period are used together. This method has already been used by many authors [27,28,16,29,30].

3. Results

3.1. Transformation of the Environment As an Indicator of Anthropogenic and Climatic Pressure on the Basin

Monitoring surface conditions (natural vegetation, cultivated soils, bare soils and water bodies) is an initial approach to taking account of the impact of climate and environmental change on hydrology. In this study, Landsat TM satellite images from 1987, ETM+ from 2000 and OLI from 2015 and 2020 were interpreted to obtain seven land cover classes: residential-high density, residential-low density, agricultural land-row crops, rubber trees, palm trees, wetland forest and water (Figure 3). A diachronic analysis of land use between 1987 and 2020 shows an increase in human activity in the Aghien catchment (Figure 3). Table 4 gives an idea of this anthropisation based on the percentage change in the surface area of the different land cover classes. Between 1987 and 2020, perennial rubber (24.3%) and oil palm (8.87%) crops, wetland forest (0.29%) and water reservoirs (-0.05%) were reduced in favour of food crops and fallow land, and concentrated and dispersed habitats, which increased by 22%, 496.74 and 77.26% respectively.

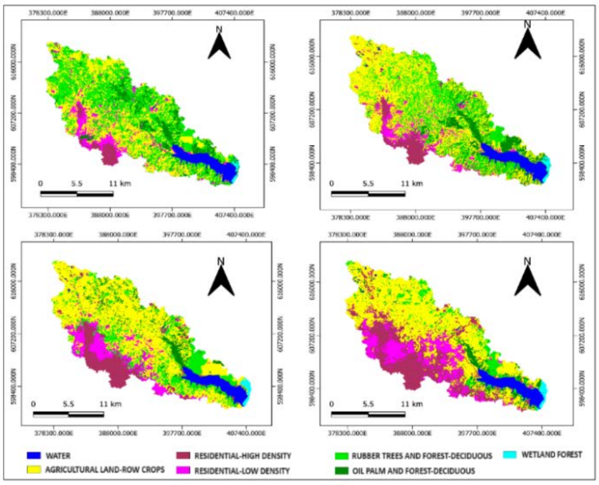


Figure 3. Land use maps for 1987, 2000, 2015 And 2020

Table 4. Statistical evolution of land use types from 1987 to 2020 in the Aghien catchment area

	LUC (%)				Relative Change (%)			
Land use	LU_1987	LU_2000	LU_2015	LU_2020	1987-2000	2000-2015	2015-2020	1987-2020
WATR	5,67	5,83	5,35	5,62	2,9	-8,2	5,1	-0,80
URHD	3,93	6,81	10,34	23,46	73,1	51,9	127	496,74
AGRR	35,42	37,28	46,79	43,22	5,3	25,5	-7,6	22,02
URLD	7,99	9,50	12,56	14,17	18,8	32,4	12,8	77,26
WETF	1,24	0,83	0,90	0,95	-33,2	9	5,7	-23,04
OILP	13,67	8,35	6,93	4,80	-39	-17	-30,7	-64,89
RUBR	32,08	31,40	17,13	7,78	-2,10	-45,5	-54,6	-75,77

3.2. Sensitivity Analysis

Table 5 shows the results of the sensitivity analysis performed by SWAT_Cup. Here, a high absolute value of t-stat and a low value of p-value are attributed to the most sensitive parameters. The 10 most sensitive parameters in the flow simulation are respectively TRNSRCH, CH_K1, ALPHA_BF, GW_DELAY, CH_N2, EPCO, SOL_K, HRU_SLP, CN2, SLSUBBSN.

Table 5. Sensitivity analysis performed by SWAT_Cup

Parameter Name	T-Stat	P-Value
7: R_SOL_BD (..).sol	-0.08	0.94
9: V_SURLAG.bsn	-0.12	0.90
16 : V_ESCO.hru	0.20	0.84
12 : V_ALPHA_BNK.rte	0.21	0.84
18 : V_CH_N1.sub	-0.28	0.78
4: V_GWQMN.gw	-0.50	0.62
5: V_GW_REVAP.gw	-0.74	0.46
6: R_SOL_AWC(..).sol	-0.85	0.40
14: R_OV_N.hru	-1.27	0.21
20: V_RCHRG_DP.gw	-1.65	0.10
2: V_ALPHA_BF.gw	-2.02	0.04
10 : V_EPCO.bsn	-2.03	0.04
3: R_GW_DELAY.gw	2.08	0.04
1 : V_CN2.mgt	2.30	0.02
19 : V_TRNSRCH.bsn	2.68	0.01
8: R_SOL_K(..).sol	-2.75	0.01
17: V_CH_K1.sub	3.07	0.00
13: V_HRU_SLP.hru	-5.03	0.00
11: V_CH_N2.rte	11.57	0.00
15: V_SLSUBBSN.hru	19.29	0.00

3.1. Calibration and validation of the SWAT Model

After calibration of the most sensitive parameters (Table 5), analysis of the statistical indices NSE, R² and Pbias shows that the flow simulation at the outlet (Djibi station) is satisfactory. At calibration, the performance index values evaluated on a daily scale are 0.61, 0.61 and 1, respectively for R^2, NSE and Pbias. They are estimated at 0.57, 0.57 and 1.7 respectively for R^2, NSE and Pbiais at validation.

Table 6. Model performance statistics for daily flow simulations at the Djibi outlet

Variable	Calibration	Validation
R2	0.61	0.57
NSE	0.61	0.57
PBIAS	1	1.7

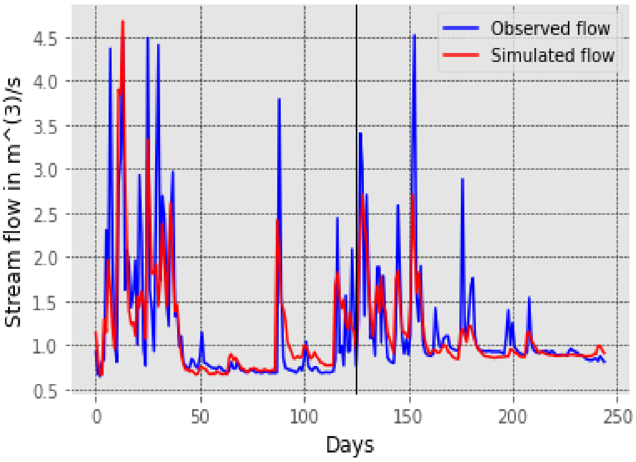


Figure 4. Simulated and observed daily flows during calibration and validation

Analysis of the hydrograph (Figure 4) shows good synchronisation between the simulated and observed lows, despite underestimation of the peaks during the two stages of model performance evaluation. Table 6 above shows the results obtained after calculation of the performance criteria during the different calibration and validation periods.

Table 7. The annual water balance components and percentage of change according to land use maps for 1987, 2000

Components of the water balance	Years				Change in (%)		
	1987	2000	2015	2020	1987-2000	1987-2015	1987-2020
Surf_Q	644.54	653.99	656.74	680.73	1.85	1.89	5.61
Lat_Q	26.90	26.72	23.720	21.75	-0.74	-11.89	-19.20
Gw_Q	246.87	243.51	244.84	230.24	-1.36	-0.82	-6.74
Wyld	1120.5	1123.8	1125.9	1122.2	0.29	0.49	0.15
Perco	477.66	471.66	474.25	447.41	-1.26	-0.71	-6.33
Et	446.9	444.6	443.8	447.1	-0.51	-0.69	0.04
Pet	849.80	848.60	846.80	848.60	-0.14	-0.35	-0. 14

3.3. Transformation of surface conditions and hydrological response on a basin scale.

Figure 5 and Table 7 above present the results after simulation on three land use maps (1987, 2000, 2015 and 2020). Between 1987 and 2020, surface runoff (Surf_Q) and water supply show an increase in rate of change with percentage of 1.85% and 0.29% respectively. Between these two land use dates, a decrease was observed in processes such as lateral flow (Lat_Q), groundwater flow (Gw_Q), percolation (Perco), evapotranspiration (Et), and potential evapotranspiration (Etp), with percentages of change in the order of (-0.74%), (-1.36%), (-1.26%), (-0.51) and (-0.14) respectively. Between 1987 and 2015 the trend was observed, the variation was marked by a decrease in five processes: (Lat_Q), (Gw_Q), (Perco), (Et) and (Etp). With a decrease of -11.89%, the lateral flow (Lat_Q) is the process with the most pronounced variation. The processes showing an increase are surface runoff (1.89%) and water yield (0.49%). Between 1987 and 2020, a decrease is observed in the same hydrological processes, with increases in water yield and surface runoff of 5.61% and 0.15% respectively.

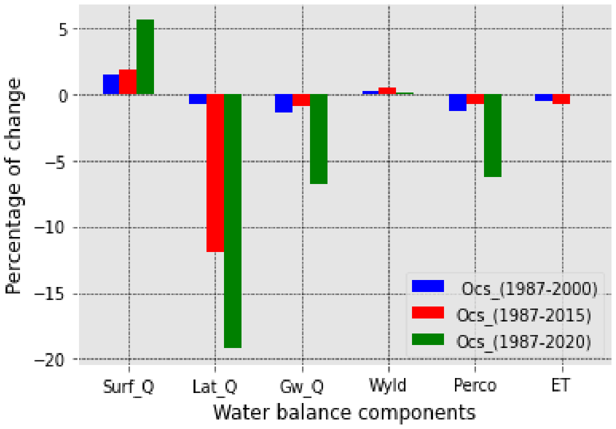


Figure 5. Percentage of changes on the annual water balance components according to Land Use maps (1987, 2000, 2015 and 2020)

4. Discussion

4.1. Evaluation of Model Performance

During the calibration phase, the performance indices R^2, NSE and Pbiais had values of 0.61, 0.61 and 1 respectively. During the validation phase, these same indices had values of 0.57,0.57 and 1.7 respectively. Both the calibration and validation results are fairly satisfactory, since according to [26,31] and [32] values of R and NSE greater than 0.5 and Pbiais less than ±20% are considered acceptable. These results are similar to the values found in some studies in several regions with different climatic and physiographic conditions. In Côte d'Ivoire, [33]. used the SWAT model to simulate water flow in the Lake Buyo catchment. During their studies, statistical index values of 0.89 for R2 and 0.87 for NSE showed that there is a good correlation between observed and simulated monthly discharge over the calibration period. In their studies, [34] gave similar results for the Mé catchment and the Aghien lagoon. Also, in other regions of the world, several authors [35,36,37] have demonstrated the effectiveness of the SWAT model in simulating runoff. With a satisfactory performance, the capacity of the SWAT model to reproduce the flow within the basin has been demonstrated even if the values of the performance criteria show a certain limit of the model to reproduce the flows under our conditions. For some, this limitation may be linked to the time step used in the simulations, and for others to the accuracy of the hydrometeorological and physiographic data. Concerning the physiographic data, according to some authors [38,39] the SWAT model is very sensitive to the quality of the data, particularly the soil and land use data.

4.2. Impact of Changes in Land Use on Hydrological Functioning

The impact of changes in land use on the hydrological functioning of the basin studied was assessed by inserting into the calibrated model the classified LUC maps of 1987, 2000, 2015 and 2020. A decrease was observed in lateral flow (Lat_Q), groundwater flow (Gw_Q), percolation (Perco) and potential evapotranspiration (Etp), with percentage variations of the order of -19.20%, -6.74%, -0.15% and -0.14, in parallel with an increase in evapotranspiration (Et), surface runoff (Surf_Q) and water yield (Wyld) with values of 5.61%, 0.04% and 0.15% respectively. Indeed, the increase in runoff and the decrease in percolation can be explained by the expansion of cultivated land and urbanised areas: these consequences of the degradation of natural vegetation cover in this study between 1987 and 2020, are confirmed by numerous studies in several regions. In Côte d'Ivoire, our results are in line with those of [40] on the Boubo watershed. In their studies, these authors noted an increase (+2.49%) in the water level drained after the vegetation cover had been degraded in favour of agricultural areas between 1990 and 2001. The results of [41] also confirm our findings, with an increase in the water level after simulation of the water balance using a land-use scenario marked by an increase in urban and agricultural areas. At the borders of Côte d'Ivoire in the Bonsa catchment in Ghana, our results are consistent with those of [42] who observed an increase in surface runoff following an increase in urban areas and agricultural land. However, our results differ from those of [43] in the Oti sub-catchment, where an increase in agricultural and urban areas led to a decrease in surface runoff. Further away from the Ivorian borders, in East Africa, [44] in the course of their studies in the Upper Gilgel Abbay catchment area in Ethiopia, observed an increase in surface runoff and average annual water input of 6% and 1.8%, respectively, over the period 1986 to 2003 following an increase in cultivated land and a decrease in forests and shrubs. Also in the same region, [45] on the Kasiry catchment also found an increase in surface runoff after an increase in agricultural land. As indicated, a decrease was observed in certain terms of the hydrological balance, such as percolation, groundwater flow and lateral flow. In fact, this decrease is simply the consequence of the reduction in soil infiltration, which is similar to the increase in runoff. This chain of cause and effect is linked to the sealing of surfaces due to the increase in the surface area of certain land-use classes, such as urban and agricultural areas. Concerning the potential evapotranspiration (Etp), the decrease in this process is mainly due to the decrease in forest areas, [46] on the Owabi catchment have obtained similar results.

5. Conclusion

In this study, the impact of land use change on the hydrological cycle processes within the Lagune Aghien catchment was assessed. The SWAT hydrological model was used to simulate the terms of the hydrological balance within the catchment over the climatic period from 2016 to 2020, using land-use maps for the years 1987, 2000, 2015 and 2020. The analysis of the hydrograph and statistical indices shows that the SWAT model has a satisfactory capacity to reproduce the flow within the Aghien lagoon catchment, despite an underestimation of the extremes.

The changes in land use from 1987 to 2020 show that the expansion of urban and agricultural areas has led to an increase in evapotranspiration (Et), surface runoff and water yield (Wyld) and a parallel decrease in lateral flow (Lat_Q), groundwater flow (Gw_Q), percolation (Perco) and potential evapotranspiration (Etp).

These study results can be beneficial to authorities, decision-makers and planners for the sustainable management of water resources in the face of environmental change.

Declaration of Interests

Authors have declared that no competing interests exist.

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