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Potential Impact of Climate Change on the Sediment Fluxes of a Watershed in West Africa: Cas of the Aghien Lagoon, Côte d'Ivoire

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Abstract

The semi-distributed SWAT (Soil and Water Assessment Tools) model was used in this study to model the sediment yield in the watershed of the Aghien lagoon with an area of 365 km^2, located in the north of the district of Abidjan (South-East from Côte d'Ivoire). A sensitivity and uncertainty analysis, as well as calibration of the SWAT model, was conducted using the Sequential Uncertainty Adjustment Procedure (SUFI-2) which is one of the programs interfaced with SWAT in the SWAT-Cup package (SWAT-Calibration-Uncertainty Programs). Five parameters of the SWAT model were found to be more sensitive to sediment fluxes. These have been modified (calibration) sparingly in order to improve the reproduction of observed sediments data. Two measures were used to assess the uncertainty analysis of the model: P-factor and R-factor. The R^2 and Nash-Sutcliffe (NS) coefficients of determination were used to assess the quality of the calibration. The P-factor obtained is 0.58 and the R-factor is 2.28. The NS and R^2 coefficients in calibration over the period from June 2014 to January 2015 are 0.51 and 0.86 respectively. These values indicate correct consideration of uncertainties by the model and satisfactory calibration of the SWAT model for solid fluxes. Then, the model was used to simulate the sediment fluxes at the horizons 2040 (2035-2056), 2060 (2057-2078) and 2080 (2079-2100) in order to assess the impact of climate change on sediments in the watershed of the Aghien lagoon. The results indicate that sediment fluxes could increase in the future under the RCP 4.5 and RCP 8.5 scenarios. With RCP 4.5, sediment fluxes would increase on average by 14.42%. They could increase by 17.95% on average under RCP 8.5.

Keywords

Abidjan, Aghien, Calibration, Climate Change, Côte d'Ivoire, Sediment, SUFI-2,

SWAT

1. Introduction

The fresh water available on the earth's surface represents a low percentage, around 0.76% [1]. Despite this low availability, it has always been an essential element in human societies. Great civilization flourished when it was abundant, secured its access, or died out because of its absence. Today, human activities are subjecting resources to increasing pressure, until posing real problems of availability [2]. The uses of water for drinking water supply (DWS), industrial or agricultural needs, have led to unsustainable management of water resources. As proof, the availability of water per inhabitant has steadily decreased over the past decades, with significant inequality between the countries of the north and those of the south [2]. Côte d'Ivoire, like these countries, is facing this decline in the availability of its water resources under the pressures of climate change, human activities and population growth. For illustrative purposes, the Abidjan groundwater which serves as a drinking water supply for the Abidjan population is currently under strong pressure and can no longer meet the water needs of the populations of the Autonomous District of Abidjan. Indeed, a deficit of 58 million m^3/year of water must be mobilized to meet the pressing needs of this constantly growing population. The Ivorian government, therefore, considered exploiting the Aghien lagoon to make up for this deficit. The Aghien lagoon watershed, with an approximate area of 365 km^2, is located in the South-East of the Côte d'Ivoire, precisely in the north of the district of Abidjan. The Mé, Djbi and Bété rivers are the main tributaries of the Aghien lagoon (Figure 1). The Aghien lagoon has great potential for a set of uses. Indeed, it constitutes a living space for the riparian populations, a buffer zone between the continent and the ocean and a water reserve for the addiction of drinking water and agriculture in the medium and long term. It was therefore retained by the Ivorian authorities as an alternative resource to make up for the water deficit estimated at 58 million m^3/year in the economic capital Abidjan [3]. In order to help Ivorian decision-makers to develop policies for better management of this lagoon in a context of climate change, a study on its quantitative availability was carried out by [4]. According to this study, the flow of the Aghien lagoon would decrease on average from 10% (RCP 4.5) to 17% (RCP 8.5) in the future. In this same dynamic of helping decision-makers to effectively manage the Aghien lagoon, a study on its qualitative availability in this context of climate change is discussed in this paper. The objective of this paper is to assess the potential impact of climate change on sediment yield in the watershed of the Aghien lagoon using the SWAT (Soil and Water Assessment Tools) hydrological model coupled with six (6) climate models of the CORDEX-Africa project.
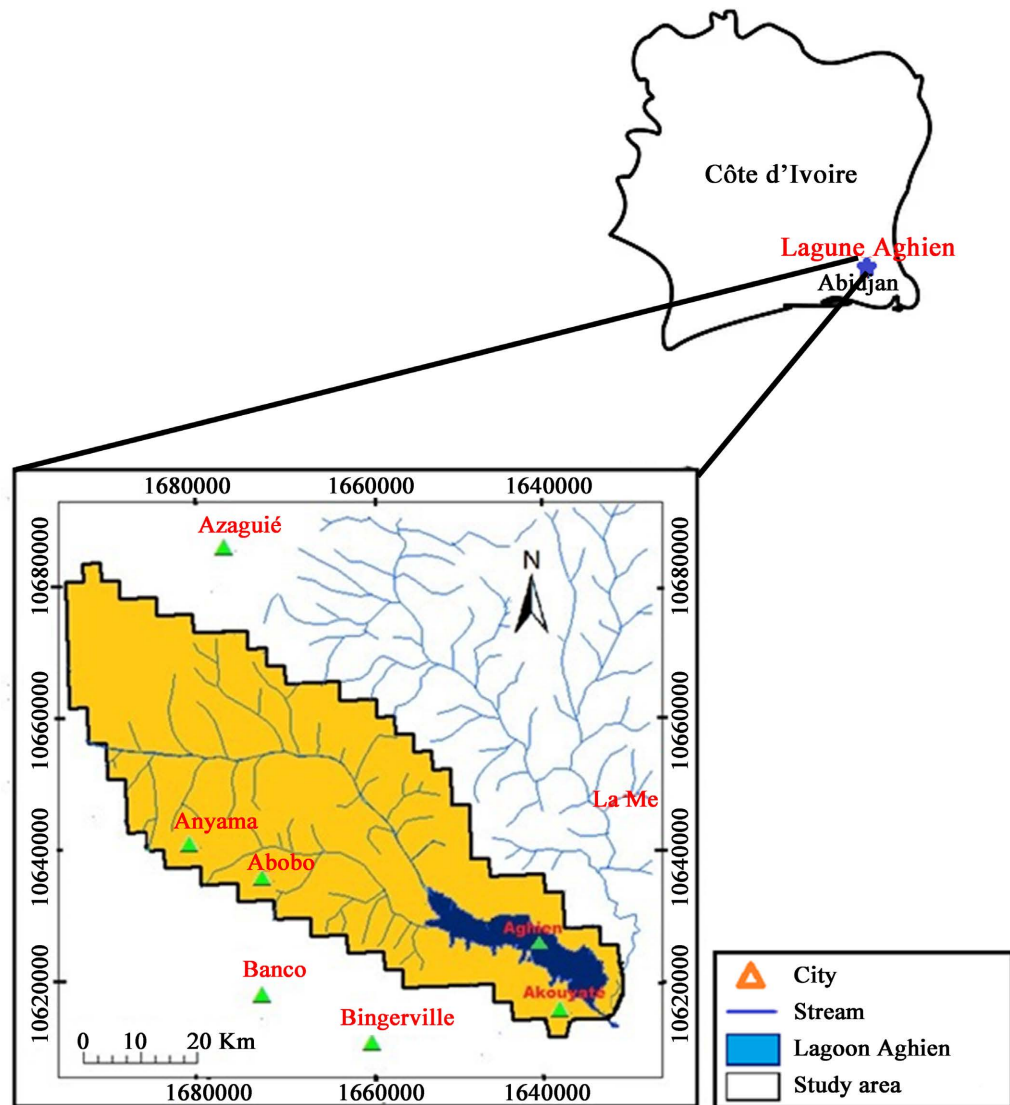
Figure 1. Location of the watershed of the Aghien lagoon.

2. Data and Methods

2.1. Data

The data used are described in the manuscript of [5]. These are: the digital Elevation model (DEM) data, the soil map and soil type data, the land use data of the Aghien lagoon watershed, meteorological data (precipitation, temperatures) from the period 1951 to 1998 and future climate data from 6 CORDEX-AFRIQUE climate models for the RCP4.5 and RCP8.5 scenarios. These six (6) climate models are ISPL-CM5, HADGEM2, MIROC, MPI, CNRM and EC-EARTH. The delta method was required to correct for the bias of the six climate models [4]. All of these data were used to set up the hydrological SWAT model and to project the future flow [4]. Monthly sediment measurement data was also required. These measurements were taken (11 sampling points) at Anyama, Abobo debacardère, Akandjé, Aghien and Akouyaté (**Figure 2**). The surface
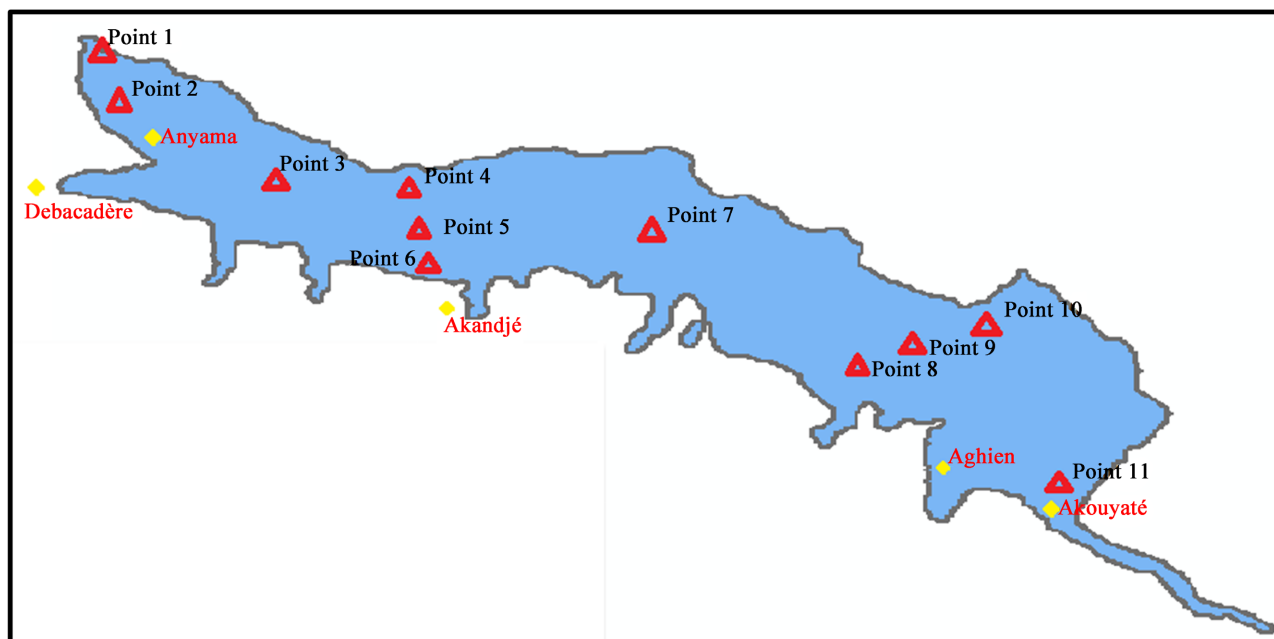
Figure 2. Sampling stations distribution (Institut Pasteur-June 2014-January 2015).

immersion sampling method was used to collect this data. Sampling was done once every three days on average. These sediment data were provided by the Institut Pasteur of Côte d'Ivoire. It's a public industrial and commercial establishment. His missions are research, training, diagnosis and epidemiological monotoring. These data covering the period from June 2014 to January 2015 and were therefore collected as part of the project to set up a permanent monitoring system for the Aghien lagoon.

2.2. Methods

SWAT-CUP (SWAT Calibration Uncertainty Procedures) is a platform that brings together different calibration and uncertainty analysis procedures for the SWAT model. SWAT-CUP brings together three procedures: Generalized Likelihood Uncertainty Estimation (GLUE [6], "Parameter Solutions" (ParaSol [7], Sequential Uncertainty Fitting (SUFI-2 [8]). This package is used because of its adaptation to SWAT projects, its ergonomic interface, its processing speed and its features which allow to create graphs or compare the different results between them. The SUFI-2 procedure proposes about ten objective-functions to optimize the calibration of the model, among these the Nash-Sutcliffe criteria and the coefficient of determination R2 which are the two objective-functions most used in this field [9]. These two statistical parameters are used to measure the performance of the model. Table 1 below presents the criteria for evaluating the performance of the SWAT model. Several iterations are required to update the parameter sets. Within the SUFI-2 program, all the parameters of the model are entered as well as their minimum and maximum potential values having a real physical meaning, in order not to obtain outliers. Thus, the parameters vary

randomly between minimum and maximum values, simulation after simulation, decreasing the magnitude of the uncertainty, and focusing on the last "best" set of parameters.

For the SWAT model uncertainty analysis, two bands are compared: the 95PPU for model simulation and the band representing the measured data plus its error. Two indices called "P-factor" and "R-factor" are used for the analysis of the uncertainties of the SWAT model [12]. The P-factor is the fraction of the measured data (plus its error) in the 95PPU band interval and ranges from 0 to 1, where 1 indicates 100% of the measured data within the model prediction uncertainty (1 indicates a perfect model simulation considering the uncertainty). The quantity (1 - P-factor) could therefore be called the model error. A P-factor value greater than 0.7 or 0.75 could be adequate for this factor according to [12]. This of course depends on the scale of the project and the adequacy of the input data and calibration. The R factor, on the other hand, is the ratio of the average width of the 95PPU band and the standard deviation of the measured variable. An R-factor value of less than 1.5, still depending on the scale of the project, would be desirable for this clue [8]. These two clues are used to judge the strength of calibration and validation. Bigger P-factor can be obtained at the expense of a bigger R-factor. Therefore, there is often a balance between the two factors. In the final iteration, when the acceptable values of R-factor and P-factor are reached, the parameter ranges are taken as calibrated parameters.

2.3. Calibration and Validation of SWAT Model

The calibration is carried out on the flow initially over the period 1960-1981 [5]. The Nash-Sutcliffe (NSE) and R^2 determination coefficients in calibration (1960-1969) are 0.807 and 0.809, respectively. In validation (1970-1981) NSE = 0.59 and R^2 = 0.64. These values are greater than the guide value (0.5). According to [10] coefficients of NSE and R^2 greater than 0.5 are acceptable and demonstrates the good performance of the SWAT model in reproducing the discharge. Thus, in view of values of the NSE and R^2 coefficients obtained in calibration and validation, the SWAT model reproduced the discharge fairly faithfully [5]. Then, in a second step, the calibration was carried out on the sediments flows. In order to improve the reproduction of the observed point sediment data, the most sensitive model quality parameters (Table 2) for the simulation of sediment transport, eleven (11) according to the literature, have been modify. During this

Table 1. Criteria for evaluating the performance of the commonly used SWAT model [10] [11].

Performance evaluation	Nash (NSE)	R^2
Very good	0.75 < NS < 1.00	0.75 < R^2 < 1.00
Good	0.65 < NS < 0.75	0.65 < R^2 < 0.75
Satisfying	0.50 < NS < 0.65	0.50 < R^2 < 0.65
Not satisfying	NS < 0.50	R^2 < 0.50

Table 2. Most sensitive sediment transport modeling (SWAT) parameters (11).

Parameters	Description of Parameters	Range of value
SLSUBBSN	Average slope length	10 - 150
HRU_SLP	Average slope steepness	0 - 1
USLE_C	Soil occupation and conservation factor	0.001 - 0.5
RSDIN	Initial residue cover	0 - 10,000
BIOMIX	Biological mixing efficiency	0 - 1
CH_COV	Channel cover factor	0.04 - 0.6
SPEXP	Exponent for the transport of sediments in the channel	1 - 1.5
USLE_P	Anti-erosion practices factor	0.1 - 0.9
CH_EROD	Channel erodibility factor	0 - 0.3
SPCON	Channel sediment routing parameter	0.002 - 0.005
USLE_K	USLE soil erodibility factor	−0.3 - 0.3

phase, calibration took place in two steps. First, a sensitivity analysis selects the most sensitive parameters among the eleven. Second, these parameters were adjusted to obtain a good matching between the sediment data observed and those simulated by the SWAT model.

1) Sensitivity analysis

The optimization process which reflects the sensitivity of the 11 parameters was carried out by the global sensitivity analysis method. Five hundred (500) simulations were performed to obtain the most sensitive parameters. The principle of this method is to assign values (within the range of limit values) to the most sensitive parameters described in the table above and to perform many simulations (500). After each simulation, the values of the t-Stat and P-Value coefficients obtained are compared with the previous ones. The t-Stat and P-Value coefficients (in SWAT-CUP) identify the most sensitive and least sensitive parameter. Thus a parameter having a larger absolute value of t-Stat is more sensitive. The P-Value gives the importance of sensitivity. When P-Value is close to Zero then the sensitivity of the parameter is important.

2) Adjustment of the most sensitive parameters among the eleven selected

Once the sensitivity analysis was performed, the calibration of the SWAT model was performed against the sediment data. The SUFI-2 optimization algorithm [12] within SWAT-CUP 5.1.6 software was used. The principle consists in varying the value of the sensitive parameter by multiplying all of its values in each URH (R_Relative method) by the same coefficient until obtaining the best value of an objective function (the Nash-Sutcliffe coefficient (NS > 0.5) and the coefficient of determination $R^2 > 0.5$, R-factor and P-factor). P-factor values greater than 0.7 and R-factor values less than 1.5 are recommended to obtain good modeling [13]. It should be noted that the sediment calibration was carried out throughout the 2014-2015 period for which the sediment data were available.

The model was therefore not validated for sediment loadings because there was not a long series of sediment data in the basin studied to do it. The sensitivity analysis, calibration and validation procedure is shown schematized in **Figure 3** below.

3) Prospective simulation of sediment yield

The outputs of the six corrected climate models are edited in "txt" format and then integrated into the SWAT model to simulate the sediment fluxes for the 2040 (2035-2056), 2060 (2057-2078) and 2080 (2079-2100) horizons. Once the future flows are simulated, they are compared with the flows simulated over the reference period 1960-1981. The comparison between future simulations and simulations over the reference period is made possible because the reproduction of the processes over time spent (1960-1981) was validated beforehand, during the calibration/validation phase of the SWAT model [5]. The goal is to see what would be the evolution of sediment flows in the watershed of the Aghien lagoon. The calibration parameters, the soil map and land use were kept constant.

3. Results and Discussion

3.1. Sediment Calibration over the Period (2014-2015)

3.1.1. Sediment Sensitivity Analysis

The sensitivity analysis makes it possible to identify the main parameters of the
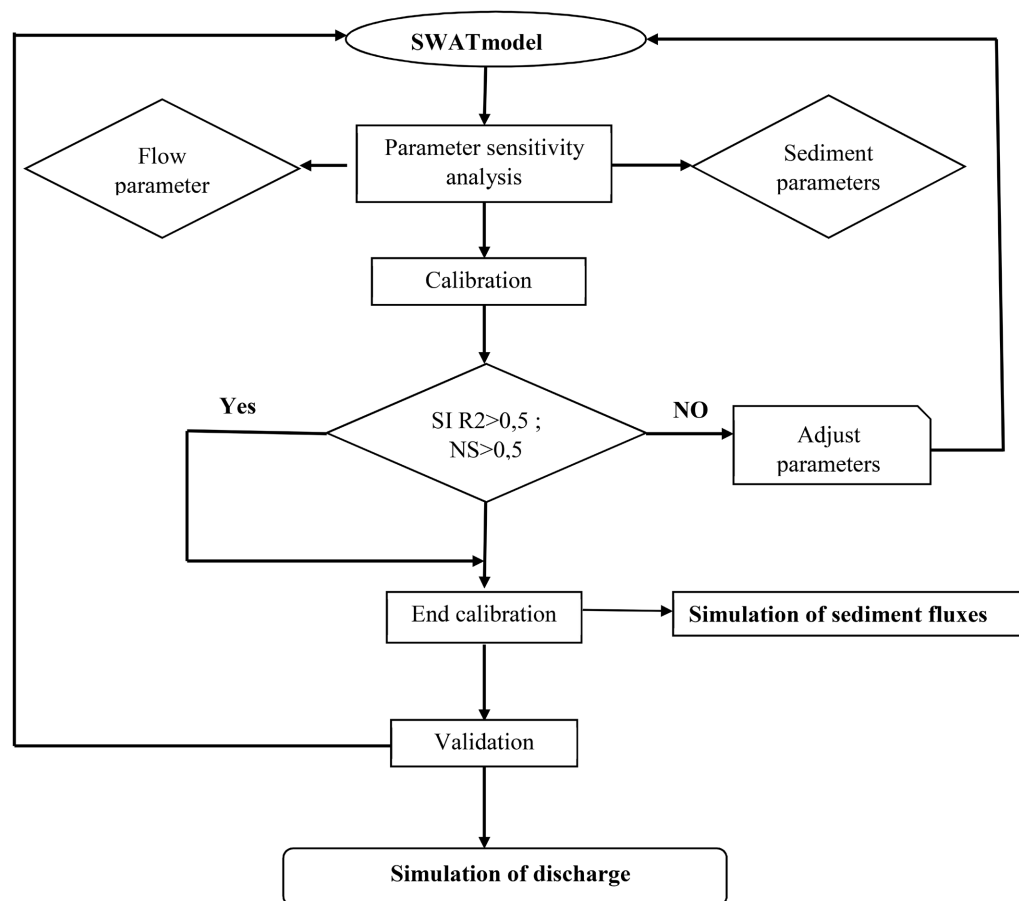

Figure 3. Diagram of the sensitivity analysis, calibration and validation procedure of the SWAT model.

watershed and their precision required for calibration. A total of 11 model parameters were evaluated to determine their relative sensitivity to sediment in watershed of the Aghien lagoon. The results show that five of the parameters are the most sensitive with values of P-values less than 0.6 and absolute values t -stat between 13 and 0.45. These parameters are: the soil occupation and conservation factor C (USLE_C), the anti-erosion practices factor P (USLE_P), SPEXP the exponent for the transport of sediments in the channel, the channel erodibility factor CH_EROD and CH_COV the vegetative cover factor of the channel. These are shown in Table 3, ranked from most sensitive to least sensitive.

3.1.2. Adjustment of Sediment Sensitive Parameters

He statistical summary of the evaluation of the model's performance in the BVLA shows the values of the coefficient of determination (R^2) and the P-factor of 0.86 and 0.58 respectively but also a relatively low value of NS of 0.51. These values strongly suggest a good agreement between the observed sediment and simulated values. The R-factor (thickness of the uncertainty band) is 2.28. This R-factor value, much greater than 1.5 (guide value), highlights a certain level of uncertainty in the model with respect to the sediments. Nevertheless, the dynamics of sediment concentrations are fairly well represented as shown in Figure 4 even though the model underestimates the sediment concentrations in July

Table 3. Parameters sensitive to sediment transport simulation (SWAT model).

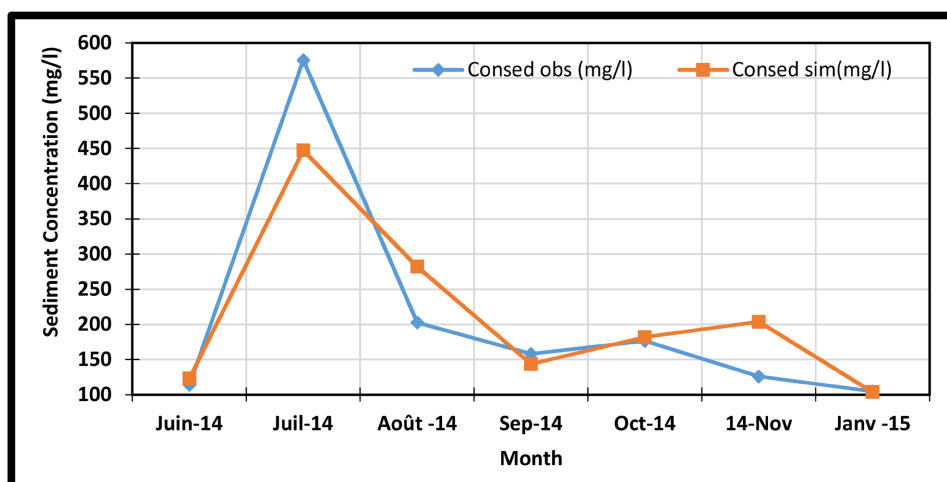| Paramètres	t-Stat	P-Value	Sensitivity rank
USLE_P	−13.321	0.00012	1
USLE_C	7.262	0.0015	2
SPEXP	2.076	0.0027	3
CH_EROD	−0.741	0.651	4
CH_COV	0.411	0.57	5

Figure 4. Hydrogram of monthly observed (blue) and simulated (red) sediment concentrations (NS = 0.51; R-factor = 2.28; P-factor = 0.58).
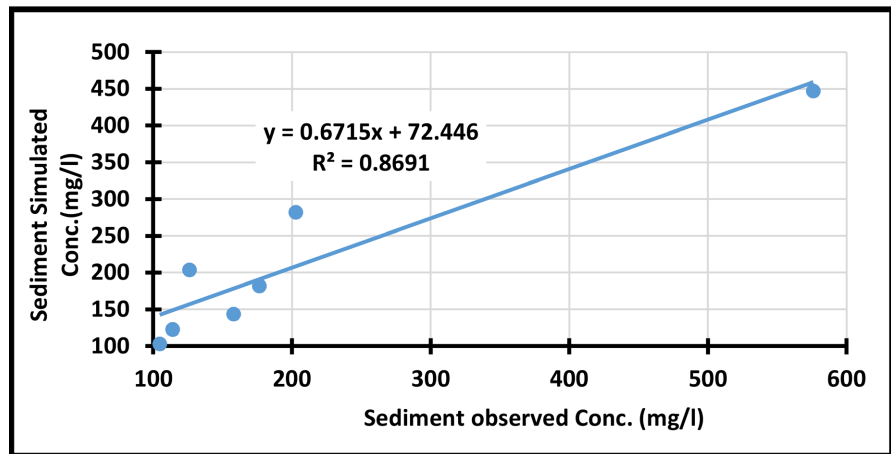
Figure 5. Correlation of monthly concentrations (mg/l; equivalent to kg/m^3) observed and simulated for the calibration period June 2014-January 2015 (R^2 = 0.869).

2014 and overestimates them in November 2014. The dispersion of the concentrations of simulated and observed sediment are close to each other as shown in Figure 5, which shows that the simulation of sediment concentrations by the SWAT model is satisfactory.

4. Evolution of Sediment Yield in the Watershed of the Aghien Lagoon

The SWAT model was used to determine the impact of climate change on sediment Yield, by 2040, 2060 and 2080 horizons for the RCP 4.5 and RCP 8.5 climate scenarios. The annual sediments transported in the Aghien Lagoon watershed for the reference period (1960-1981) are 13.731 kg/ha/year. Under the RCP 4.5, scenario they are 15.558 kg/ha/year, 15.605 kg/ha/year, 15.974 kg/ha/year respectively for the horizons 2040 (2035-2056), 2060 (2057-2078) and 2080 (2079-2100). Under the RCP 8.5 scenario, the annual flows of sediments transported in the catchment area of the Aghien lagoon, by 2040, 2060 and 2080 horizons are respectively 16.057 kg/ha/year, 16.244 kg/ha/year, 16.288 kg/ha/year. Thus, the annual sediment flows would increase on average by 14.42% under RCP 4.5 and by 17.95% under RCP 8.5. Seasonally, sediment flows could decrease during the short dry season (August, September): Under the RCP 4.5 scenario, they would decrease by 55.60% and under RCP 8.5 by 77.57%. The flows should increase during the great rainy season (May-June-July) by 36.83% under RCP 4.5 and by 59.02% under RCP 8.5. They could also be up during the great dry season (December to April) by 35.58% under RCP 4.5 and 40.08% under RCP 8.5. Finally, an increase in sediment flows of 37.43% and 51.05% is also expected during the short rainy season respectively under the RCP 4.5 and RCP 8.5 scenarios. The average rates of change of sediments flows modeled under RCP 4.5 for the base period for horizons 2040, 2060 and 2080 are respectively 11.12%, 14%, 29.12%. Under the RCP 8.5 scenario, the average sediment variation rates forecast for the 2040, 2060 and 2080 horizons are 22.37%, 19.32% and

30.89% respectively. Table 4 shows the variations in annual and seasonal sediment fluxes at the horizons (2040 (2035-2056), 2060 (2057-2078) and 2080 (2079-2100)) under RCP 8.5 and RCP 4.5.

5. Discussion

The results of modeling the impacts of climate change on the quantitative availability of the Aghien lagoon obtained showed that the average of the 6 (six) CORDEX AFRIQUE climate models gives a decrease in precipitation, the flow of the lagoon and an increase in evapotranspiration in the future, which will accentuate the reduction in flows in the catchment area of the Aghien lagoon [4]. In fact, the flow of the Aghien lagoon would decrease by 8%, 10% and nearly 10% for the RCP 4.5 scenario respectively by 2040 (2035-2056), 2060 (2057-2078) and 2080 (2078-2100) and would decrease by 16% by 2040 and by more than 18% by 2060 and 2080 for the RCP 8.5 scenario. Our study found that the annual sediment fluxes should increase by 14% under RCP 4.5 and nearly 18% under RCP 8.5. The trends in sediment yield and discharge do not occur in the same direction. Indeed, our results clearly demonstrate that the sediment yield

Table 4. Variations of sediment yield, annual and seasonal for the reference period (1960-1981) and future periods (2035-2056; 2057-2078; 2079-2100) under the RCP 4.5 and RCP 8.5 scenarios.

Scenarios	1960-1981	2040 (2035-2056)		2060 (2057-2078)		2080 (2079-2100)	
	Baseline period	sediment (kg/ha)	variation (%)	sediment (kg/ha)	variation (%)	sediment (kg/ha)	variation (%)
Annual (average)	13,731	0	0	0	0	0	0
Great rainy season	58,628	0	0	0	0	0	0
Great dry season	59,097	0	0	0	0	0	0
Short rainy season	26,687	0	0	0	0	0	0
Short dry season	20,370	0	0	0	0	0	0
RCP 4.5							
Annual (average)		15,558	13.30	15,605	12	15,974	16.33
Great rainy season		61,328	4.60	67455	15.05	68,700	17.18
Great dry season		70,148	18.69	63740	7.85	64,445	9.04
Short rainy season		29,402	10.17	30157	13	30,493	14.26
Short dry season		15,819	−22.34	15907	−21.90	18,055	−11.36
RCP 8.5							
Annual (average)		16,057	16.93	16244	18.29	16,288	18.61
Great rainy season		69,419	18.40	69419	18.40	71,661	22.22
Great dry season		67,357	13.97	65552	10.92	68,075	15.19
Short rainy season		30,443	14.07	30443	14.07	31,354	22.91
Short dry season		15,466	−24.07	15466	−24.07	14,374	−29.43

will increase even if the discharge decreases. Despite a decrease in precipitation, sediment loads keep going to increase, which could be due to an increase in temperature. Decreased precipitation and increased temperature can lead to water stress, which reduces plant growth and therefore worsens the rate of erosion. The study by [14] and [15] indicated that increased temperature can worsen the rate of soil erosion through its influence on vegetation and alteration, which can increase sediment flow in rivers. The study conducted by [15] in the Lower Pearl River Basin in China reported that a temperature increase of 3°C causes the rise of the sediment load by nearly 14%. Under the two scenarios, in August and September, although the flow increases, the sediments fluxes decrease (55.6% under RCP 4.5 and 77.5% under RCP 8.5). The decrease in sediment fluxes during these months may be due to the significant influence of increased evapotranspiration and crop growth processes under warmer climate, as mentioned by [16]. Increased sediment loads can intensify many problems associated with the accelerated loss of lagoon storage through sedimentation and siltation of water distribution systems. This loss is associated with a reduction in the carrying capacity and increased water turbidity of the lagoon [17]. The increase in water turbidity can also have negative consequences on animal and vegetable biodiversity of the Aghien lagoon. Thus, in view of the evolution of sediment flows, a probable degradation of the water quality of the Aghien lagoon mainly caused by the increase in sediment could occur in the future.

6. Conclusion

The SWAT model was used to reproduce the sediment yield of the Aghien lagoon watershed located in the southeast of Côte d'Ivoire in the north of the district of Abidjan. There were limited sediment data available. The data available on sediment flows were limited to the period from June 2014 to January 2015. The model was therefore calibrated over this entire period and therefore was not tested over a validation period. Thus, the calibration of the SWAT model for sediments using SWAT-Cup version 5.1.6 was satisfactory with a Nash-Sutcliffe (NS) and determination (R^2) coefficient of 0.51 and 0.86, respectively. Using a longer period of sediment data could improve calibration results and allow model validation for sediment. Nevertheless, given the good calibration results, simulations were carried out. The future trends (horizons 2040 (2035-2056), 2060 (2057-2078) and 2080 (2078-2100)) have shown that sediment yield could be up 14.42% under the RCP 4.5 scenario and 17.95% under the RCP 8.5 scenario. The quality of the lagoon's water could therefore be degraded in the future by an increase in sediment flows.

7. Recommendation

Solutions based on "biological engineering" could be implemented. For example, consideration should now be given to reducing sediment flow by using grass strips to limit runoff and prevent soil erosion. Shading in the immediate envi-

ronment of the Aghien lagoon could also be ensured by afforestation of the banks in order to limit the increase in temperature which could lead to water stress, which will reduce plant growth and therefore worsen the rate of erosion of the ground. The decision-makers and managers of the Aghien lagoon basin should take into account the trends described by our results in the implementation of adaptation measures to climate change to ensure the sustainability of the said lagoon. Moreover, these results seem to be transposable to other watersheds with comparable geographical characteristics, particularly in the West African zone.

Acknowledgments

Data Availability Statement

Some or all data, models, or codes used during the study were provided by a third party. Direct requests for these materials may be made to the provider as indicated in the Acknowledgments.

Conflicts of Interest

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

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