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Rice Intensification in a Changing Environment: Impact on Water Availability in Inland Valley Landscapes in Benin

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Abstract: This study assesses the impact of climate change on hydrological processes under rice intensification in three headwater inland valley watersheds characterized by different land conditions. The Soil and Water Assessment Tool was used to simulate the combined impacts of two land use scenarios defined as converting 25% and 75% of lowland savannah into rice cultivation, and two climate scenarios (A1B and B1) of the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios. The simulations were performed based on the traditional and the rainfed-bunded rice cultivation systems and analyzed up to the year 2049 with a special focus on the period of 2030–2049. Compared to land use, climate change impact on hydrological processes was overwhelming at all watersheds. The watersheds with a high portion of cultivated areas are more sensitive to changes in climate resulting in a decrease of water yield of up to 50% (145 mm). Bunded fields cause a rise in surface runoff projected to be up to 28% (18 mm) in their lowlands, while processes were insignificantly affected at the vegetation dominated-watershed. Analyzing three watersheds instead of one as is usually done provides further insight into the natural variability and therefore gives more evidence of possible future processes and management strategies.

Keywords: lowland rice; agricultural intensification; water resources; SWAT model

1. Introduction

Climate is a crucial factor in agricultural production and food security, especially in developing countries where investments are low and social system vulnerability is high [1]. As revealed by previous studies, the decline in food productivity is significant in the tropics in response to climate variability and low soil fertility [2–5]. Among the adaptive strategies to cope with this matter, an extensive development of inland valleys is being promoted in West Africa for their great potential as rice-based production systems due to the high and secure water availability and soil fertility [6,7]. Often known under the name *bas-fonds* in Benin, these landscapes usually comprise the valley bottom, hydromorphic fringes and uplands areas [8] and are actively developed to increase the local production [9,10]. Nevertheless, under the ongoing implementation of strategic technologies for rice intensification in inland valleys, no recent studies have investigated future changes on hydrological processes and the long-term impact on water resources through the evaluation of their possible vulnerability to climate change, apart from the ones carried out by Duku et al. [11,12]. However, knowing more about the interacting impacts of climate and land use changes on the hydrological processes in such wetlands is important for selecting of the best management strategies to ensure a sustainable agricultural development and water resources management.

Climate changes are generally referred to as long-term changes in weather patterns, including precipitation and temperature [13]. In the last century, significant changes in temperature and precipitation have already been observed, caused by anthropogenic activities. In addition to climate changes, land use changes associated with intensive agriculture and rapid urbanization may cause severe impacts on aquatic systems by influencing water quantity and quality [14]. Water resources have been significantly impaired due to increases or decreases in annual streamflow and seasonal shifts in flow frequency [15]. Hence, water availability for crop production could be affected, especially in areas where water resources are limited. The situation may even have large scale implications because of the increasing demand for food supplies and economic development [16]. Actually, numerous studies have assessed the impacts of land use and climate changes on water resources of agricultural watersheds in many countries around the world. To predict consequences of future land use changes on the water balance, most of the studies analyzed the past to understand the current situation [17]. Valuable spatially distributed information was generally provided from historic satellites images to accurately produce past land use classification [18,19]. However, for future projections, changes in agricultural land use were simulated using models capable of forecasting land use changes based on human activities and environmental processes [20,21]. The projected climate changes were commonly represented in most studies using climatic scenarios data developed for the target region [15,22–24]. Generally, land use and climate changes impacts were identified using hydrological models as supporting tools which provided valuable frameworks to investigating changes among various hydrologic pathways caused by climate and human activities in agricultural ecosystems [25–27]. As one of the various tools developed, the Soil and Water Assessment Tool (SWAT) model [28] was applied in many fields to assess water quantity and quality [2,29–34]. Likewise, the important and unrestricted application of the model for climate change and land use scenarios simulation was also confirmed by recent reviews of SWAT literature [35,36].

Although substantial advancements were made in assessing land use and climate change impacts on water resources in many countries [35], few studies have assessed in Benin how the long-term patterns in watershed's hydrological components could be influenced. Most of the existing research was conducted on evaluating the future impacts of climate or land use changes at larger spatial scales and specifically focused on rainfall–runoff processes [34], groundwater resources [37], erosion-related degradation processes based on sediment yields in the upper Ouémé watershed [2,5] and upland crop production [38–40]. Accordingly, with respect to the increasing development of inland valleys, no research has yet analyzed the impacts of climatic and agricultural change on their hydrological behavior and water resources. Thus, this study aims at analyzing the sensitivities of hydrological processes to projected climate changes under rice intensification and related influences on annual and seasonal water budget in three small headwater inland valley watersheds characterized by different land conditions. More specifically, this paper seeks to address: (1) the hydrological processes within the three investigated watersheds to the impact of land use and climate changes; and (2) which management options under rice intensification may help in compensating for potential negative effects of climate and land use changes on stream water availability. The projected results are expected to help in providing supporting data to decision-maker for sustainable rice cultivation planning and water resources management at such finer scale.

Assuming that spatially explicit and process-based models are best suited to predict the effects of changing environmental conditions [41], the SWAT model was applied to investigate the hydrological response of the inland valley watersheds to rice intensification under the A1B and B1 climate change scenarios of the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC SRES) for the projected period from 2030 to 2049. Calibrated model parameters from our previously conducted study in the same inland valleys [42] were used to simulate the climate scenarios in combination with two hypothetically projected land use scenarios defined as 25% and

75% of lowland converted into rice fields. Moreover, management scenarios were considered for the development of the lowland areas, namely, the traditional and the rainfed-bunded rice cultivation systems in association with fertilizer use. In this study, the use of three different watersheds compared to only one has the advantage that variations in land use and soil are considered, which may significantly influence model results.

2. Materials and Methods

2.1. Research Area

Kounga, Tossahou and Kpandouga are small inland valley watersheds with drainage areas not exceeding 5 km^2 and are located in the commune Djougou in central Benin (Figure 1). They all belong to the sub-humid Sudan-Guinea climatological zone, which is characterized by a yearly occurrence of one rainy season from April to October and one dry season from November to March. Statistical analysis of daily precipitation data recently issued by the African Monsoon and Multidisciplinary Analysis-Coupling the Tropical Atmosphere and the Hydrological Cycle (AMMA-CATCH) database revealed an average annual precipitation of 1312 mm and 1290 mm for Kounga and Tossahou from 2003 to 2015, respectively, and 1388 mm for Kpandouga from 2008 to 2015. From 2003 to 2015, records from the weather station installed in Djougou city indicate an average daily temperature of 27 °C and a daily mean insolation of 19 MJ m^{-2} received at the surface [43]. Four major soil types are encountered in the inland valleys, including Lixisol, Plinthosol, Sandy Gleysol, and Clayey Gleysol [42]. The natural vegetation is characterized by a high fraction of savannah woodland, which is particularly dominant within the Kpandouga watershed. The inland valleys were preferentially cultivated with rice, yam, corn, groundnut, cassava, sorghum and cotton. These crops are exclusively rainfed [2], and mineral fertilizers are only applied to cotton and corn fields in low amounts.

In all inland valleys, the intermittent streamflow and shallow groundwater table are highly dynamic and rainfall-dependent. From our previous study conducted at the contributing watersheds to assess water quantity and quality, it was revealed that more than 60% of precipitation water is lost through evapotranspiration in all watersheds. In the Kounga watershed, surface and subsurface runoff dominate due to the high level of agricultural intensification. In the Tossahou watershed, where the proportion of agricultural land use is lower than in Kounga (8% compared to 14%), subsurface flow and groundwater recharge are the major processes. However, runoff is low in the Kpandouga watershed, to the profit of groundwater recharge, which is high due to the predominant natural vegetation (about 99%) [42].

2.2. SWAT Model Overview and Performance during Calibration and Validation

The Soil and Water Assessment Tool (SWAT) is a continuous-time and semi-distributed hydrological and water quality model, which operates at a daily time step and has successfully been used across the world, including the research area, to assess the impact of land management and climate on water, nutrient and pesticide transport [2,44]. In this study, we directly used the calibrated and validated outputs of the GIS-based interface ArcSWAT2012 from our previous study on the inland valleys [42]. For preparing the model, climatic observations from the AMMA-CATCH database were used together with the following spatial data at a 30 m resolution: a digital elevation model (DEM), a soil map, and a land use map derived from a classified SPOT6-image. Parameter values for simulating plant growth were collected from the literature [45–49]. As no historical discharge data were available at the selected watersheds, daily observed streamflow data from 2013 to 2014 were measured and used for model calibration at Tossahou, and validation was conducted for the year 2015. At the watersheds Kounga and Kpandouga, calibration was performed for the year 2013 and validation for the year 2014 as resulting from repeat acts of vandalism at the gauging station. Due to precipitation data availability, simulations were performed for the periods 2003–2015 at Kounga and Tossahou, and 2008–2015 at Kpandouga. The model was run for a warm-up period of 5 years on each inland valley watersheds. The Soil Conservation Service Curve Number method was applied to simulate surface runoff, and the Penman-Monteith method was used to calculate potential evapotranspiration [28]. The initial setup was carried out in ArcSWAT for the delineation of watershed and sub-watershed areas using the DEM, subdivision of the sub-watershed areas into Hydrological Response Units (HRUs) which are homogeneous concerning soil, land use, climate, and management. After processing of the input data in ArcSWAT and before calibration using the SWAT Calibration and Uncertainty Programs (SWAT-CUP), a sensitivity analysis was carried out by applying the optimization algorithm SUFI-2 (Sequential Uncertainty Fitting) to identify the parameters to which the model was most sensitive [50]. Based on the sensitivity analysis, the parameters which were found sensitive were further used for model calibration and validation. For more details on the modelling approach applied and subsequent results, please refer to our previously published paper on the comparison of water quantity and quality in these selected inland valley watersheds [42].

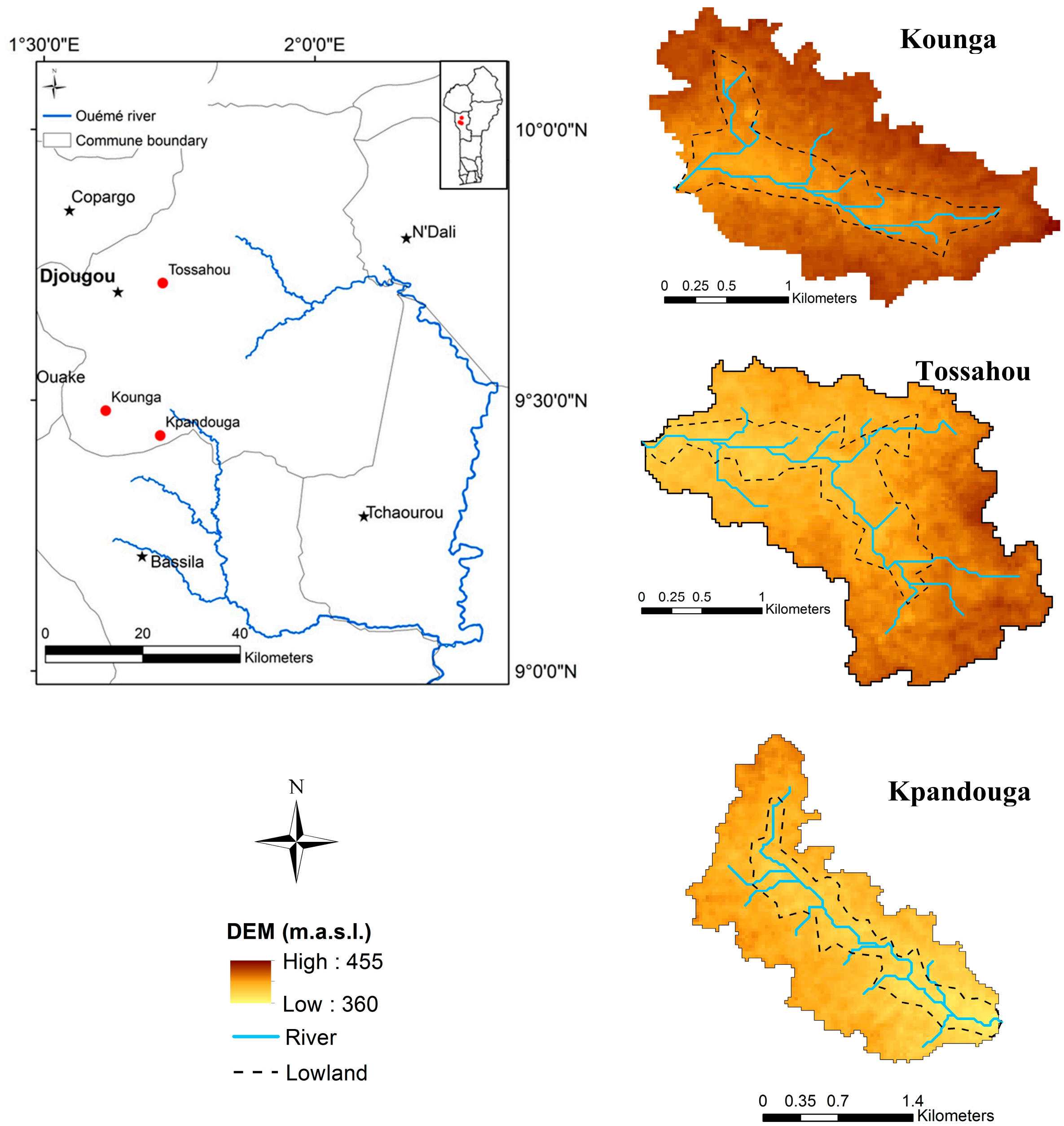

Figure 1. The upper Ouémé watershed and the location of the inland valleys in Benin [42].

For the calibration and validation, the model performance was rated satisfactory for streamflow (R^2 and NSE mostly higher than 0.5), with an overestimation of discharge that was suspected to relate to the low potential evapotranspiration simulated [51]. This problem was solved in the version used here by computing potential evapotranspiration outside SWAT. The new average potential evapotranspiration is about 1600 mm which is comparable to the 1500 mm previously recorded for the region by Lohou et al. [51]. To define the baseline conditions, the model was run over a past period from 1980 to 2003 (including a warm-up of 5 years) using historical climate data collected at a synoptic meteorological station installed at Parakou by the Agency for the Safety of Air Navigation in Africa and Madagascar (ASECNA). All calibrated model parameter values were maintained constant during the simulation of the different scenarios developed as follows.

2.3. Scenarios

2.3.1. Climate Change Scenarios

For quantifying climate change impacts, scenarios have to be used. Representative Concentration Pathway Scenarios have been developed for the IPCC fifth Assessment Report (AR5). Older SRES scenarios are comparable to the new RCP scenarios as SRES B1 is comparable with RCP 4.5 and SRES A1B with RCP 6.0. To assess the impact of climate change, we used scenario data converted from the results of the REgional climate MOdel (REMO), which is driven by the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC SRES) A1B and B1 for the African continent between the $-15°$ S and $45°$ N latitudes [52]. REMO has a resolution of $0.5° \times 0.5°$ and is nested in the European Centre Hamburg Model (ECHAM5). We decided to use the older SRES scenario because they are similar to the new RCP scenarios and because they have already been applied successfully in a number of studies in Benin [2,5].

The A1B scenario describes a globalized world of rapid economic growth and comparatively low population growth [2,53]. Similarly, the B1 scenario characterizes a future globalized world with a low population growth but with a rapid change of the economic structures toward a service and information economy with reduced material intensity and the introduction of clean and sustainable technologies [2]. The climate scenarios data were already downscaled and bias corrected by Speth et al. [54] for the climate station in Djougou, thus readily available to be used in this study which focused on hydrological process-understanding. As reported by Bossa et al. [2], because of a systematic underestimation of the rainfall amount and variability in the initial REMO runs over West Africa, the Model Output Statistics (MOS) were applied to adjust the rainfall data based on parameters such as temperature, sea level pressure and wind components. In the next step, the MOS-corrected regional-mean precipitation was transformed from REMO to a local pattern of rain events using a weather generator (WEGE) developed in the Integrative management project for an efficient and sustainable use of freshwater resources in West Africa (IMPETUS). Thus, the generated virtual station data were statistically adjusted to match the observed daily precipitation at the rainfall stations in the Upper Ouémé watershed in Benin [54]. For more information about the climatic scenarios A1B and B1, reference is made to Paeth et al. [52] and Speth et al. [54]. The downscaled REMO data (period 2010–2049) were used for all watersheds to make the simulations comparable. At all inland valley watersheds, the period from 2030 to 2049 was analyzed.

2.3.2. Land Use Change Scenarios

In this study, changes of savannah into agricultural land use for future projections are simulated based on human activities with respect to land suitability. Farmers assume the lowlands areas to be more suitable to rice cultivation in terms of soil fertility and water availability. From a biophysical point of view, the natural vegetation within the lowlands are more likely converted under agricultural intensification. Thus, the lowland conversion scenarios were mainly designed based on the conversion of savannah and gallery forest covered into rice fields. The original land use map was reclassified to dissociate the natural vegetation units in the upland areas from those in the lowland for which the expansion of rice cultivated areas were simulated. The boundary between upland and lowland areas was drawn following the pattern of the major soil types encountered along the toposequence within the inland valleys which were classified as Lixisol in the middle of the hillslope, Plinthosol near the drainage divide, and, at the bottom of the hillslope, Sandy Gleysol mostly on the fringes, and Clayey Gleysol in the valley bottom [42]. Accordingly, Lixisol and Plinthosol predominantly occur at the uplands while the Sandy and Clayey Gleysols are encountered in the lowlands. Thus, the boundary between the Plinthosol and the Sandy Gleysol (from the upland to the valley bottom) was used for boundary between upland and lowlands areas. Two hypothetical scenarios were simulated by using the land use refinement tools of ArcSWAT: (1) L1, 25% of the area covered with natural vegetation in the lowland is converted to rice fields; and (2) L2, 75% of the area covered with natural vegetation in the lowlands is converted to rice fields. Under these scenarios, the location of the cultivated rice fields was already predetermined by the location of the area classified as 100% covered by savannah and gallery forest in the lowlands. Thus, the refinement tools helped to simply redefine every savannah and gallery forest HRUs as partly made of 25% or 75% of rice depending on the scenarios. For each inland valley, the resulting area and percentage of land use types that were simulated in each land use scenario are illustrated in Figure 2.

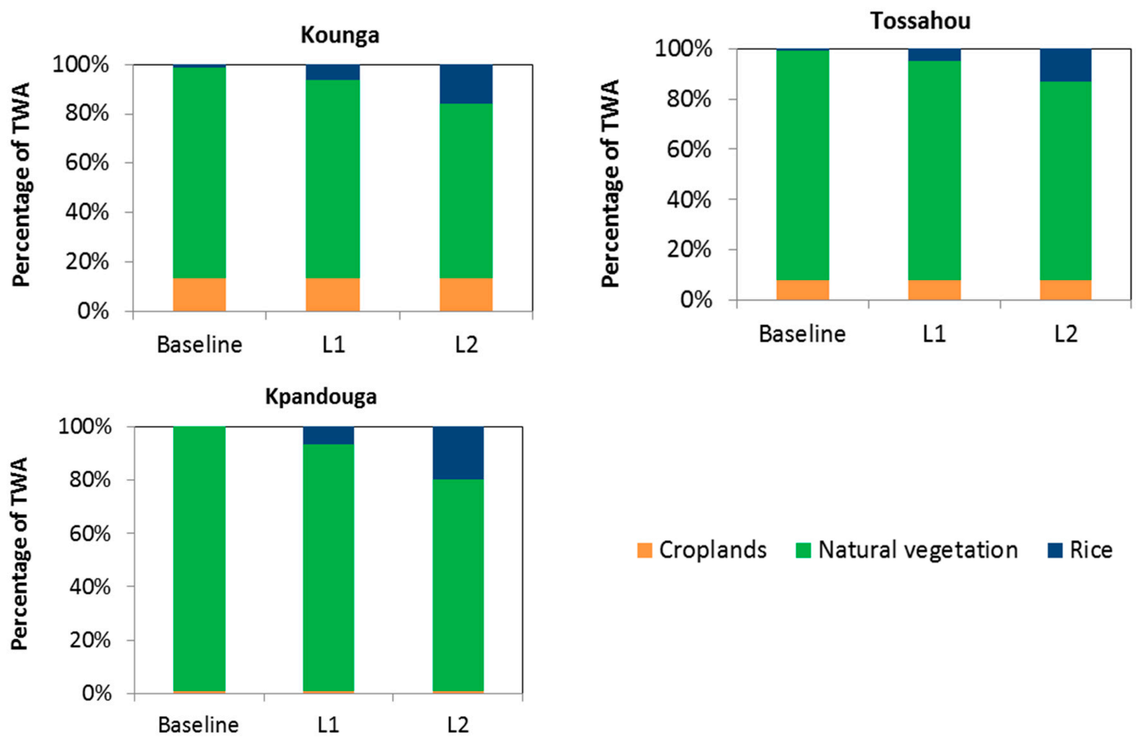

Figure 2. Percentage of land use types for the different land use scenarios in inland valley watersheds of Kounga, Tossahou and Kpandouga. TWA refers to total watershed area. L1 and L2 are land use change scenarios of 25% and 75% lowland conversion, respectively. Baseline refers to the baseline conditions of no vegetation land conversion into rice fields within the lowlands.

2.3.3. Management Scenarios

The lowland rice intensification was designed based on two management scenarios, including the traditional system of rice cultivation and the rainfed-bunded cultivation system. The traditional rice cultivation system refers to unbunded rainfed rice fields grown by direct seeding with no particular water control structures. The rainfed-bunded cultivation system refers to bunded rice fields with direct seeding and partial water management at which the ponding of water is initiated two weeks after sowing to account for the seedlings, and water is released before fertilizer application and two weeks before harvest. To simulate the bunded rice fields in ArcSWAT, we apply the pothole approach, which consists of setting all rice Hydrological Response Units (HRUs) to potholes with 100% of the area draining into them [28,55]. This method was used to account for the periods of ponding and release of water that occur in the rice fields during the growth period. In the pothole module, all rainfall water is first allowed to flow into the potholes. Consequently, the ponded water is subjected to infiltration into the soil, to evaporation from the water surface, to overflowing into the stream or to remaining in the pothole under an impounded condition [28,55]. In this study, the maximum level of water allowed to stand in the bunded fields was set at 10 cm. The growth period of rice for all scenarios is chosen to be 120 days.

Each management scenario is divided into two treatments, classified as with or without the use of fertilizers. The fertilizers are applied at the same rate, and the treatment is designed via split application, resulting in a total application of 105 kg N ha^{-1}, 84 kg P ha^{-1} and 42 kg K ha^{-1} [54]. The first fertilizer is applied 15 Days After Sowing (DAS) and accounts for 40% of N, 100% of P and 100% of K of the total amount in the form of NPK. Each of the last two fertilizer applications contain 30% N of the total amount of fertilizer in the form of urea and are applied at maximum tillering (55 DAS) and flowering (90 DAS) [56].

2.3.4. Combined Scenarios Analysis

Two clusters of scenarios combinations were simulated in this study. The first cluster investigates the combined impacts of climate and land use change, which were simulated under the traditional cultivation system with no fertilizer inputs. The second cluster combines climate change, land use change and management scenarios, as illustrated in Table 1. Herein, the simulations were performed under both cultivation systems with fertilizer inputs and under the rainfed-bunded cultivation system without fertilizer application.

Table 1. Scenario combinations of climate, land use and management.

Single Scenarios	
Scenarios	Description
A1B and B1	Climate scenarios from the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC)
L1 and L2	Land use change scenarios of 25% (L1) and 75% (L2) lowland conversion
a and b	Traditional cultivation system with (a) and without (b) fertilizer application
RA1 and RA2	Rainfed-bunded system with (RA1) and without (RA2) fertilizer application
First Cluster of Scenarios Combination	
Scenarios	Description
A1B/B1+L1+b and A1B/B1+L2+b	Combined climate and Land use change scenarios under traditional rice cultivation system without fertilizer application
Second Cluster of Scenarios Combination	
Scenarios	Description
A1B/B1+L1+a and A1B/B1+L2+a	Combined climate and Land use change scenarios under traditional rice cultivation system with fertilizer application
A1B/B1+L1+RA1 and A1B/B1+L2+RA1	
	Combined climate and Land use change scenarios under rainfed-bunded rice cultivation system with fertilizer application
A1B/B1+L1+RA2 and A1B/B1+L2+RA2	
	Combined climate and Land use change scenarios under rainfed-bunded rice cultivation system without fertilizer application

3. Results and Discussion

3.1. Water Balance during Baseline Periods

The simulated results of the annual water balance for the baseline period of 1985–2003 are presented in Table 2.

Table 2. Seasonal and annual water budget simulated for the baseline period (1985–2003).

Components (mm)	Kounga			Tossahou			Kpandouga		
	Annual	**Dry**	**Wet**	**Annual**	**Dry**	**Wet**	**Annual**	**Dry**	**Wet**
PREC	1258	5	176	1258	5	176	1258	5	176
SURQ	125	0	18	95	0	14	78	0	11
LATQ	160	1	22	88	0	12	52	1	7
GWQ	78	2	10	207	0	29	322	2	45
PERC	137	3	18	267	3	36	360	0	51
ETa	832	38	92	807	33	92	768	30	89
ETp	1672	165	121	1672	165	121	1672	165	121
WYD	370	3	51	404	2	56	470	4	64

Note: Annual, annual values of the hydrological components; Dry, average monthly values simulated during the dry season from (November to March); Wet, average monthly values simulated during the wet season (from April to October); SURQ, surface runoff; LATQ, lateral flow; GWQ, groundwater flow; PERC, percolation; ETa, actual evapotranspiration; ETp, potential evapotranspiration; WYD, total water yield.

The highest values of actual evapotranspiration (832 mm), surface runoff (125 mm), and subsurface flow (160 mm) are simulated at the Kounga watershed where the portion of cultivated areas is the highest. Groundwater flow and percolation are high in the other two watersheds with the highest values of 322 and 360 mm, respectively, simulated at Kpandouga, where natural vegetation is predominant. Subsequently, the average annual total water yield is estimated as 370 mm in Kounga, 404 mm in Tossahou, and 470 mm in Kpandouga. The seasonal water balance analysis revealed that evapotranspiration is the major process occurring in the dry season at all sites. In general, its value is smaller compared to the wet season due to very low precipitation. Mean monthly actual evapotranspiration is 38 mm in Kounga, followed by Tossahou (33 mm) and Kpandouga (30 mm). In Kounga, the water table was observed to remain close to the ground surface (<0.8 m) in the lowland areas throughout the year which explains the higher ETa rate. Contrary, ground water is only accessible during the wet season in Tossahou and Kpandouga with average depths of 0.62 m and 1.04 m, respectively [42]. Thus, the differences in evapotranspiration among the three watersheds are therefore likely related to the occurrence of a shallow groundwater table.

3.2. Impact of Climate Changes

3.2.1. Projected Changes in Temperature and Precipitation

In comparison to the baseline conditions, the mean annual temperature is projected to increase by 2.3 °C under the A1B and 1.7 °C under the B1 climatic conditions for the period 2030–2049. However, precipitation will decline more on average under A1B (by 133 mm) than under B1 (by 87 mm). Within the year, temperature will decrease in the dry season by 0.1 and 0.9 °C under A1B and B1 in a month, but increase in the wet season by 3.9 °C (A1B) and 3.6 °C (B1). In contrast, precipitation is projected to decline in the wet season (by 23 mm and 16 mm under A1B and B1) with a marginal increase around 5 mm under both A1B and B1 in the dry season. The projected changes in precipitation and temperature under the climate scenarios A1B and B1 within the year are presented in Figure 3.

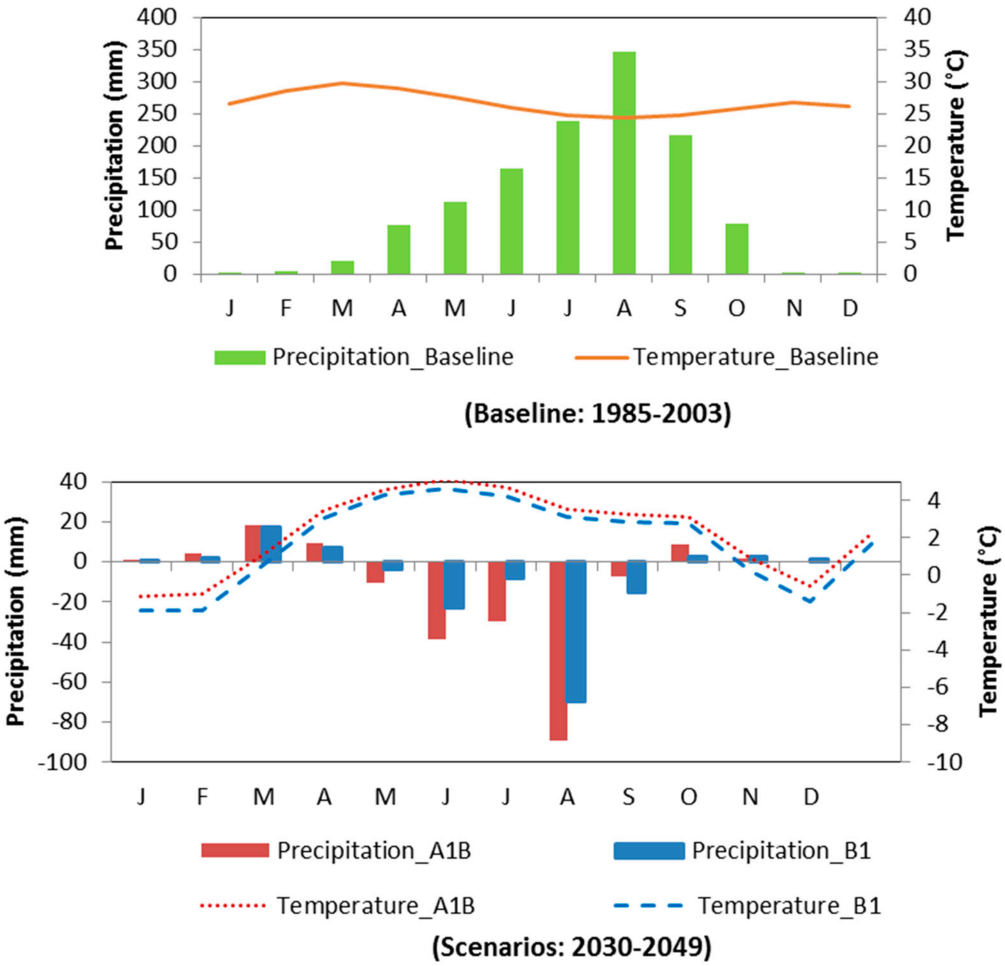

Figure 3. Monthly average precipitation and temperature during baseline period from 1985 to 2003, and changes in precipitation and temperature under climate change scenarios A1B and B1 during the period from 2030 to 2049.

3.2.2. Projected Changes in the Seasonal Water Balance

As depicted by Figure 4, the hydrological processes occurring within all the selected watersheds will be seasonally affected to different extent by the changes induced in temperature and precipitation.

In the wet season, the decrease in surface runoff projected at Kounga (65% (12 mm) and 54% (10 mm) under A1B and B1), Tossahou (71% (10 mm) and 63% (9 mm) under A1B and B1), and Kpandouga (63% (7 mm) and 60% (7 mm) under A1B and B1) is due to the decline of precipitation. In fact, the marginal increase in actual evapotranspiration does not exceed 5% (5 mm) in Kounga and Tossahou, while in Kpandouga a slight decrease of 3% (2 mm) was expected under A1B and B1. Moreover, a similarity in patterns was observed between the simulated changes at Kounga and Tossahou and the ones projected in temperature, while the projections at Kpandouga follow the pattern of changes in precipitation. Thus, actual evapotranspiration is inferred more sensitive in the wet season to changes in temperature at Kounga and Tossahou of higher portion of cultivated areas, and to changes in precipitation at Kpandouga predominated by natural vegetation. The increase in actual evapotranspiration computed for Kounga and Tossahou can be explained by a higher amount of energy initiated at warmer temperature [24]. In Kpandouga, the projected reduction in actual evapotranspiration can be due to limited soil water availability resulting from the decline of precipitation and favored by a low groundwater contribution which water table depth is the deepest among the inland valleys [57]. Consequently, the total water yield is projected to decline in Kounga

(50% (25 mm) and 40% (20 mm) under A1B and B1) and Tossahou (39% (22 mm) and 29% (17 mm) under A1B and B1) more than in Kpandouga (27% (17 mm) and 16% (10 mm) under A1B and B1).

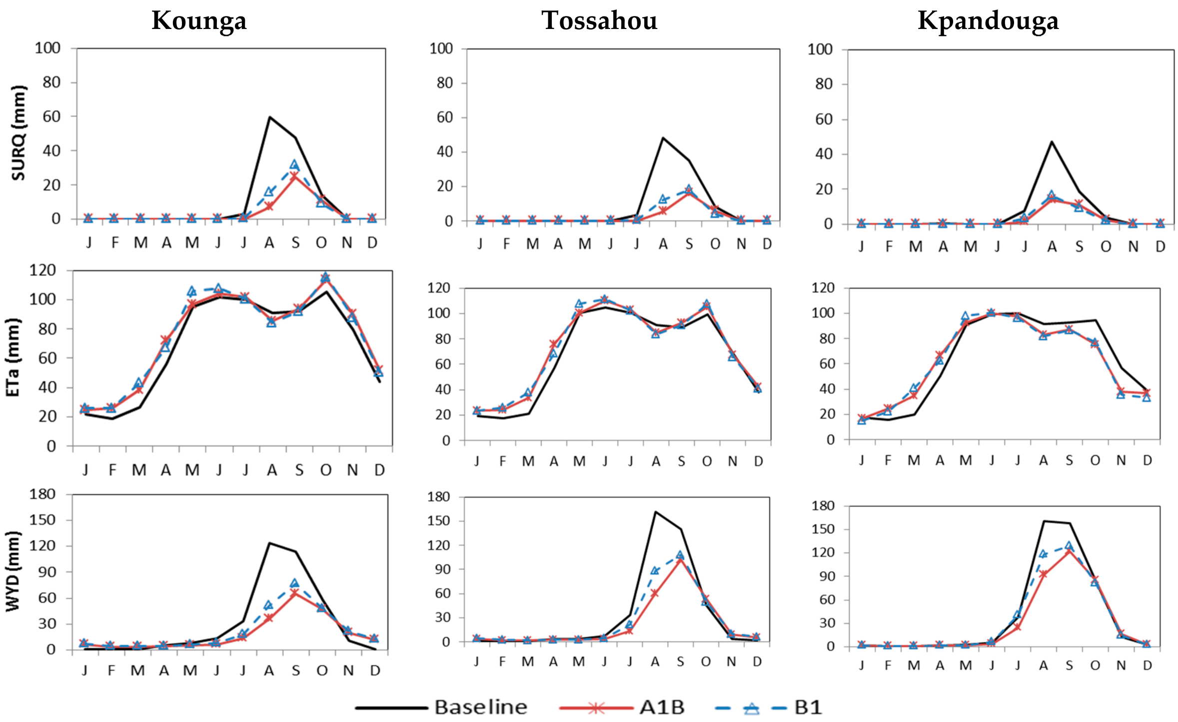

Figure 4. Comparison of monthly simulated water balance components between baseline period (1985–2003) and the projected period (2030–2049) under climate changes. A1B and B1 are climate change scenarios; ETa is actual evapotranspiration; SURQ is surface runoff; and WYD is total water yield.

In the dry season, the increase of precipitation will marginally affect. More explicitly, the increase in evapotranspiration is high in Kounga compared to Tossahou and Kpandouga. The differences mainly occur in the months of November and December in which lesser changes are projected on average in Tossahou (4% (1 mm) and 1% (1 mm) under A1B and B1) in comparison to Kounga (16% (9 mm) and 13% (8 mm) under A1B and B1), while evapotranspiration will eventually decrease in Kpandouga (19% (10 mm) and 26% (13 mm) under A1B and B1). This implies that the differences in the groundwater table depletion featured among the inland valleys, also determine the quantity of soil water available to evaporation in the dry season [58].

3.2.3. Projected Changes in the Annual Water Balance

As depicted in Figure 5, the changes in the annual water balance components reveal the restrictive effect of climate change on water availability within all the inland valley watersheds from 2030 to 2049. Surface runoff will decrease at all sites. However, evapotranspiration will increase in response to warmer temperatures under A1B and B1 in Kounga and Tossahou (not exceeding 10% (76 mm)), while in Kpandouga the projections indicate a minimal reduction under both climatic scenarios by 2% (14 mm (A1B) and 17 mm (B1)) probably due to the decline in precipitation. Actually, potential evapotranspiration is projected to increase by 9% (142 mm) under A1B and 1% (21 mm) under B1. Thus, the system in Kpandouga is water limited and not energy limited, which means that an increase in potential evapotranspiration caused by higher temperatures is not influencing actual evapotranspiration. Consequently, the total water yield will decline to a higher extent in Kounga and Tossahou due to the combined effect of increased evapotranspiration and reduced amount of water from precipitation. This is similar to the findings made by Ligaray et al. [59] at the assessment of the hydrological response of the Chao Phraya River basin to climate change in Thailand, who came to the conclusion that streamflow variations were yielded according to the change of rainfall amount, while scenarios with increased air temperatures predicted future water shortages.

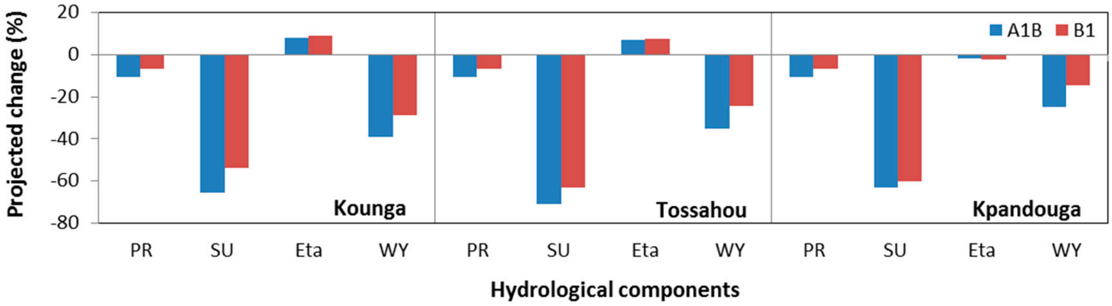

Figure 5. Changes in the annual water balance components under climate change scenarios during the projected period of 2030–2049. A1B and B1 are climate change scenarios; ETa is actual evapotranspiration; PR is precipitation; SU is surface runoff; and WY is total water yield.

As for water availability, the decrease in precipitation may initiate at long term the prevalence of water scarcity within all of the inland valley watersheds and consequently lead to limited water availability downstream [60,61]. This specific interrelationship between precipitation and streamflow was also observed at a larger scale in a previous study conducted by Bossa et al. [2] in the same region, who modeled the effects of crop patterns and management scenarios on nitrogen and phosphorus loads to surface water and groundwater in the Donga-Pont river watershed, revealing a decrease in water yield resulting from reductions in rainfall under both A1B and B1 scenarios.

3.3. Impact of Land Use Changes

Distinguishing the effects of land use changes from concurrent climate variability is very challenging for impact assessment on watershed hydrology [15]. Under the traditional cultivation system with no fertilizer input, the simulation of the lowland conversion scenarios revealed different effects on the annual water balance among the inland valley watersheds. As depicted by Figure 6, the conversion of natural vegetation into rice fields in the lowland initiates a slight change in evapotranspiration in all watersheds with no substantial difference between the land use scenarios. The projections during the period of 2030–2049 reveal a reduction in evapotranspiration at Kounga and Kpandouga while in Tossahou it will rise by up to 4% (29 mm) under A1B and B1 due to the increase in biomass at the rice fields and the retention of surface water within the semi permeable levee in the valley bottom. Hence, this can explain the reduction of surface runoff, which is also expected at the same watershed. Similar findings were obtained by Quyen et al. [18], who related the decrease in surface flow to an increased growth of land cover while assessing the effect of land use change on water discharge in a watershed in Vietnam. Consequently, the total water yield will increase in Kounga (up to 7% (25 mm)) and Kpandouga (up to 17% (79 mm)), but decrease up to 8% (33 mm) in Tossahou. In fact, the decline initiated in evapotranspiration at Kounga and Kpandouga, is probably due to the induced reduction of areas densely covered by vegetation.

This pattern is consistent with the observations made by Tao et al. [62], who modeled the impact of different land use scenarios on hydrological processes in a watershed in East China. One of their findings was that the increased evaporation from leaves was actually caused by the increase in forested area. As a result, the streamflow will increase in both Kounga and Kpandouga inland valley watersheds through higher surface runoff due to reduced cover on fast runoff generation, and to the substantial capacity of vegetation to intercept or retain water losses caused by the extensive agricultural development. This altering effect of land use changes on the hydrologic system was also revealed in other studies [17,19,20] and may potentially impact the water resources within the watershed. Thus, the removal of natural vegetation will affect the hydrological processes more in

Kounga and Kpandouga with slight changes expected in Tossahou. Unlike Kounga, the Tossahou and Kpandouga inland valleys present the same patterns in hydrological processes under both conversion levels. Specifically, these differences underline the complexity of inland valleys hydrology which makes it difficult to compare them. Thus, Kounga depicts more sensitivity in behavior to an expansion of rice cultivation although the hydrological processes are affected within all of the watersheds.

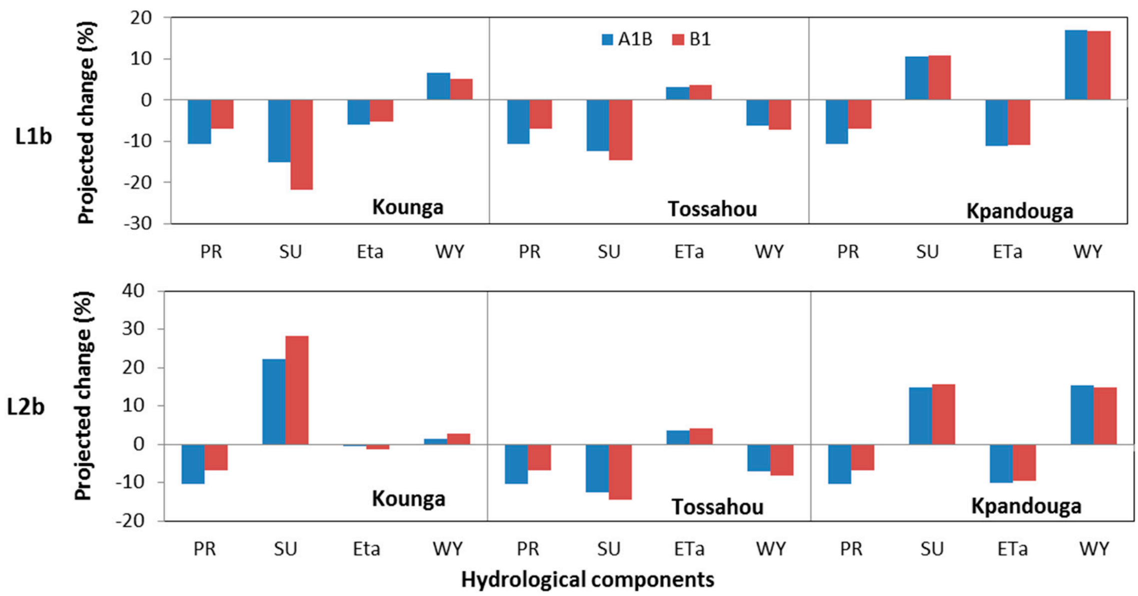

Figure 6. Changes in the annual water balance components under climate and land use change during the projected period of 2030–2049 compared to climate change scenarios alone. L1b and L2b are land use change scenarios of 25% and 75% lowland conversion with no fertilizer application, respectively. A1B and B1 are climate change scenarios; ETa is actual evapotranspiration; PR is precipitation; SU is surface runoff; and WY is total water yield.

3.4. Impact of Climate and Land Use Changes under the Traditional Cultivation System

The projected changes of the water balance were simulated for the traditional rice cultivation system with no fertilizer application. The simulated trends during the projected period 2030–2049 are depicted in Figure 7 in comparison to the baseline conditions.

Under combined land use and climate change scenarios, the projected decline induced by climate change in streamflow is dominant despite the counteracting effects of land conversion on some hydrological processes within the watersheds. This was similarly observed by Bossa et al. [2] in the simulation of land use and climate change effects in the Donga River at Donga-Pont. However, the reducing effect of climate change on stream water availability within the Kpandouga watershed is offset substantially (up to 58% under A1B) by the projected increase under land use change. At all watersheds, the patterns of changes induced in the hydrological processes look more similar under both land use scenarios. At 75% lowland conversion, the reduction of streamflow in the Kounga watershed is associated to a rise in evapotranspiration (8% (65 mm), and decrease in surface runoff (43% (54 mm) and 26% (32 mm)) under A1B and B1. The same pattern occurs in Tossahou where evapotranspiration is projected to increase by 4% (29 mm and 33 mm under A1B and B1), while surface runoff will reduce by 13% (12 mm under A1B) and 15% (14 mm under B1). Although the reduction of evapotranspiration enabled by the decline of densely-covered savannah woodland areas may enhance the processes in the soil at Kpandouga [60], the decline in surface runoff contribute more in decreasing the total water yielded. In fact, the higher increase in evapotranspiration at Tossahou in comparison to Kounga is probably due to the combined effect of biomass production at the rice fields and warmer temperature under climate change [19]. Conversely, the changes induced at Kounga are mostly related to the variation of temperature with respect to the reducing effect of land use change projected at the conversion of the natural vegetation in comparison to the baseline conditions.

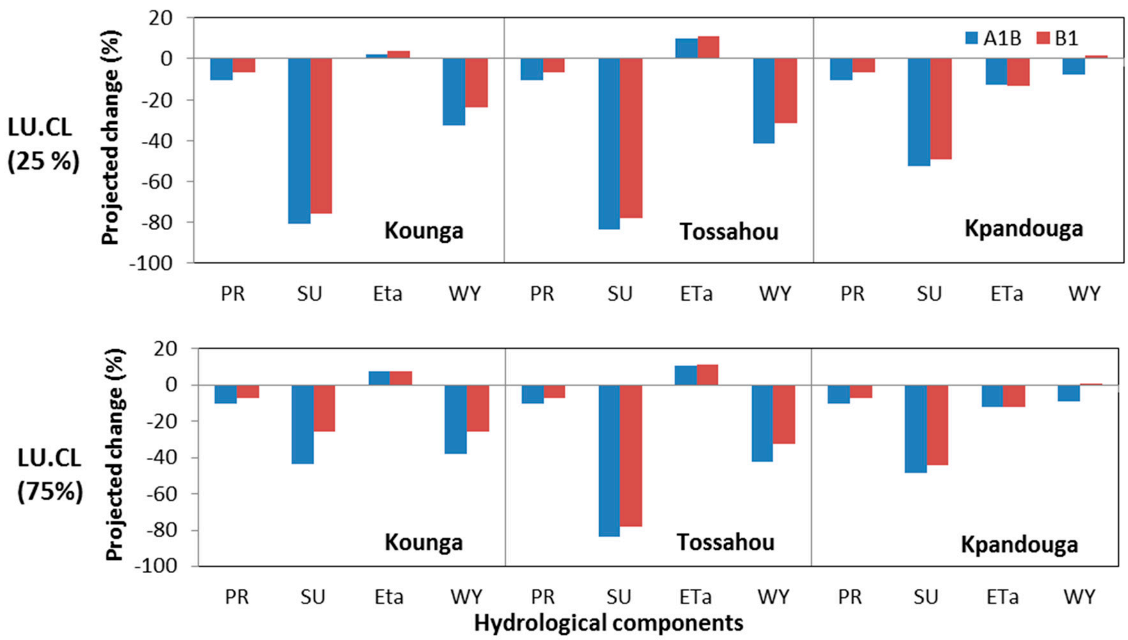

Figure 7. Changes in the annual water balance components induced by land use and climate change (LU.CL) scenarios during the projected period of 2030–2049 under traditional rice cultivation system with no fertilizers application compared to baseline condition from 1980 to 2003. A1B and B1 are climate change scenarios; ETa is actual evapotranspiration; PR is precipitation; SU is surface runoff; and WY is total water yield.

3.5. Effect of Management Practices under Climate and Land Use Changes

3.5.1. Traditional Cultivation System with Fertilizers Application

In this section, the simulated results are compared to those presented in Section 3.4 under the traditional cultivation system to assess the relative effect induced by using fertilizers, which may affect the biophysical conditions of the watersheds through the improvement of biomass production at the rice fields.

The changes induced in the annual water balance do not exceed 15% (20 mm) (under A1B and B1) and are similar in pattern under both land use scenarios, as depicted by Figure 8. However, an enhanced biomass production will affect more the hydrological processes at increased lowland conversion. Total water yield will decrease through increased evapotranspiration associated with a substantial decline in surface runoff at all sites.

The systematic increase in evapotranspiration (even at higher lowland conversion) may reveal a supplementary use of soil water through the higher performance of rice plants as both crop yield and water use efficiency can improve at fertilizers application [63,64]. Comparatively, the Kounga watershed exhibits more sensitivity with pronounced changes, followed by Tossahou and Kpandouga. Thus, the degree to which fertilizers use influences the hydrological processes is not only dependent on the level of land conversion, but can also be offset by the predominance of natural vegetation within the inland valley watersheds.

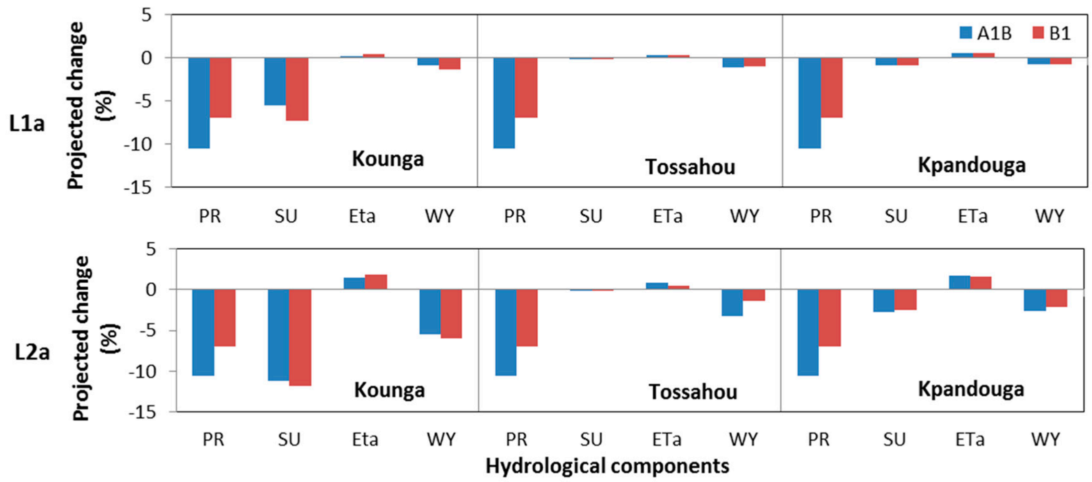

Figure 8. Relative changes induced by the application of fertilizers at the current cultivation system under land use and climate change scenarios from 2030 to 2049. L1a and L2a are land use change scenarios of 25% and 75% lowland conversion under traditional rice cultivation system with fertilizer application, respectively. A1B and B1 are climate change scenarios; ETa is actual evapotranspiration; PR is precipitation; SU is surface runoff; and WY is total water yield.

3.5.2. Rainfed-Bunded Rice Cultivation System with No Fertilizers Application

In this section, the simulated results are compared to those presented in Section 3.4 under the traditional cultivation system to assess the effect of the water saving conditions on the hydrological processes within the inland valley watersheds under an extensive development of the rainfed-bunded cultivation system throughout the lowland areas.

The projections are marginal at Kpandouga, thus conferring to the watershed a low sensitivity in response to bunds construction at the rice fields (See Figure 9). Nonetheless, an increase of changes in hydrological processes is noticeable at higher lowland conversion. Although no substantial change will occur in evapotranspiration and total water yield, surface runoff is projected to decrease by up to 5% (2 mm) under A1B and B1. This can be explained by the fact that the ponding water retained within the rice fields is more subjected to infiltrate and recharge the shallow aquifer. Consequently, part of the infiltration water is rooted to the stream under the topographic gradient. In fact, the implementation of bunds functions as runoff trapping within the lowland before it gathers enough energy to run downstream under heavy rainfall events or too intense to be absorbed by the soil [65]. Conversely, at the Tossahou and Kounga watersheds, surface runoff is expected to increase up to 28% (4 mm) and 21% (18 mm). This may result from the combined effects of: (1) their lowlands morphology which is slightly concave with a flat valley bottom; (2) the low height of bunds (10 cm) used in the pothole module to simulate the maximum level of water recommended for rice plants to stand in the bunded fields, for which the water retention impact may be significant at field but not at the inland valley watershed scale; and (3) the short period of high intensive rainfall (August–September) which occurs in the middle of the growing season when the ponding condition in most of the rice fields may be settled already.

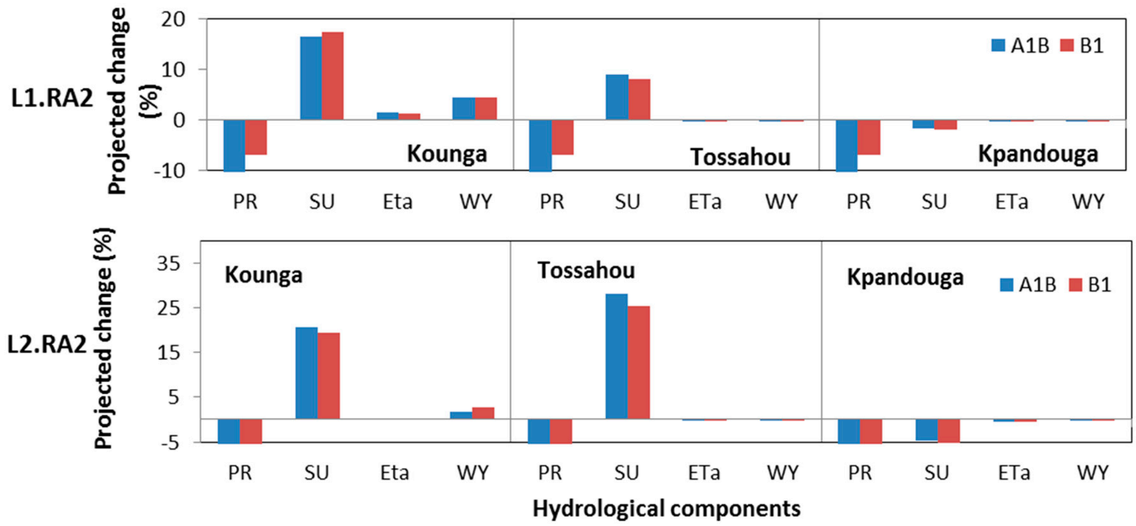

Figure 9. Relative changes induced by the development of the rainfed-bunded cultivation system compared to the current cultivation system with no use of fertilizers under land use and climate change scenarios from 2030 to 2049. L1 and L2 are land use change scenarios of 25% and 75% lowland conversion, respectively. RA2 is rainfed-bunded rice cultivation system with no fertilizer application. A1B and B1 are climate change scenarios; ETa is actual evapotranspiration; PR is precipitation; SU is surface runoff; and WY is total water yield.

3.5.3. Rainfed-Bunded Rice Cultivation System with Fertilizers Application

In this section, the simulated results are compared to those presented in Section 3.4 under the traditional cultivation system to assess the combined effect of fertilizers use and bunds construction on the annual water balance components at the different watersheds. As expected, the lowest changes on streamflow will occur at Kpandouga followed by Tossahou, whereat surface runoff is somewhat expected to increase up to 17% (2.6 mm) under the climatic scenarios (Figure 10).

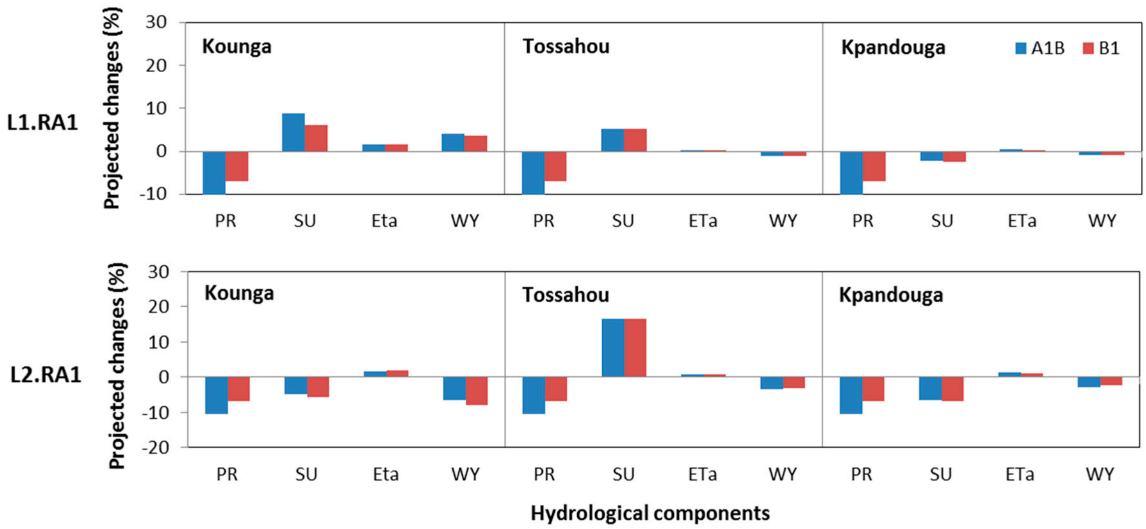

Figure 10. Relative changes induced by the development of the rainfed-bunded cultivation system compared to the current cultivation system with the use of fertilizers under land use and climate change scenarios from 2030 to 2049. L1 and L2 are land use change scenarios of 25% and 75% lowland conversion, respectively. RA1 is rainfed-bunded rice cultivation system with fertilizer application. A1B and B1 are climate change scenarios; ETa is actual evapotranspiration; SU is surface runoff; PR is precipitation; and WY is total water yield.

However, this rise of surface runoff is slightly lower than the one projected at 28% (4 mm) with no fertilizers application under the same bunded conditions. Similarly, at Kounga, this counteracting influence is even pronounced leading surface runoff to decrease eventually. Thus, the generation of overland flow at the flash-flood areas in the lowland may be limited in this case by the increased biomass production and higher performance of the rice plants within Kounga and Tossahou. This goes along with the fact that the reductive effects of rice cultivation at fertilizers application on surface runoff (via an increased evapotranspiration) is less hindered at these two watersheds, whereat the portion of cultivated areas was formerly higher (14% for Kounga and 8% for Tossahou) in comparison to Kpandouga (0.7%) at the baseline conditions [40]. Consequently, knowing that bunded conditions enhance the applied nitrogen efficiency of rainfed lowland rice [39,66–68], the changes initiated in the biophysical conditions will subsequently induce a marginal reduction on water availability downstream, as depicted in Figure 10, to the profit of an improved rice production at all of the inland valley watersheds.

4. Conclusions

This study assessed the effects of climate change and rice intensification on hydrological processes in three inland valley watersheds of different proportions of cultivated area (namely, Kounga, Tossahou and Kpandouga). Comparing three watersheds offers the value of considering the influence of land use and soil patterns on model results and investigating the extent to which they determine the hydrological response to the changes of climate and agricultural practices. In accordance with the projections from 2030 to 2049, the streamflow will significantly decline in response to the increased temperature and reduced precipitation, commonly through the reduction of surface runoff at all of the watersheds (both annually and in the wet season). The inland valley watersheds with a high fraction of cultivated area (Kounga and Tossahou) are projected to be more affected by this reduced stream water availability through a rise in evapotranspiration. Under the higher drought stress characterizing the dry season, only evapotranspiration responded to the marginal increase in precipitation at all sites. Consequently, the increase initiated is highest at Kounga because of its shallow depth of groundwater table throughout the year which depletes more rapidly in the other inland valleys. An increased lowland development will affect the hydrological processes within all watersheds but result in a marginal increase of streamflow through surface runoff in Kounga and Kpandouga due to the removal of natural vegetation, and a slight decline in Tossahou due to the increased biomass production at rice cultivation and the surface water retention between the semipermeable levees implemented in the valley bottom. Compared to the traditional cultivation system, minor changes on streamflow were projected either at fertilizers application or at the implementation of the rainfed-bunded system in the lowlands. The application of fertilizer increases evapotranspiration in response to the increase in biomass. With the implementation of the rainfed-bunded system in Kpandouga, surface runoff will slightly decrease, indicating an infiltration of a major part of the ponding water retained within the bunded fields. In contrast, an increase of surface runoff is expected in Kounga and Tossahou, revealing probably a short-term submergence of rice plants during the growing season within the lowlands. However, this rise in surface runoff will be partly offset by the increased biomass at the use of fertilizers. In fact, the results achieved in this study revealed climate change as the major driver for the changes initiated in the inland valleys' hydrology. Consequently, the small-scale farmers who are direct beneficiary of the agricultural land development might be confronted to limited water availability in the future within the watersheds. This implies that land use planners or decision makers shall preferentially account for improving the water use efficient at intensified rice farming to cope with such constraining rainfed conditions. Hence, in addition to a large-scale development of rainfed-bunded lowland rice with adequate use of fertilizers for saving water and increasing production, the adoption of conservation methods as mulching for instance could be more profitable in terms of maximizing the recharge of the soil profile during the rainfall events in these headwater inland valleys where possibilities for irrigation are very restricted.

In the light of all findings, this research provides new insights in the importance of climate change on the water balance in inland valleys in West Africa. However, future studies are recommended to focus on assessing the long-term effect on rice yields and water quality to limit the environmental impacts on water resources.

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Author Contributions: Alexandre Danvi wrote the paper and applied the SWAT model. Simone Giertz, Sander J. Zwart and Bernd Diekkrüger directed this research, collaborated on model application and reviewed the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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