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Comparing water quantity and quality in three inland valley watersheds with different levels of agricultural development in central Benin

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ABSTRACT

Achieving sustainable agricultural intensification in inland valleys while limiting the impacts on water quantity and water quality requires a better understanding of the valleys' hydrological behavior with respect to their contributing watersheds. This study aims at assessing the dynamics of hydrological processes and nitrate loads within inland valleys that are experiencing different land uses. To achieve this goal, an HRU-based interface (ArcSWAT2012) and a grid-based setup (SWATgrid) of the Soil Water Assessment Tool (SWAT) model were applied to three headwater inland valley watersheds located in the commune of Djougou in central Benin that are characterized by different proportions of cultivated area. Satisfactory model performance was obtained from the calibration and validation of daily discharges with the values of R^2 and NSE mostly higher than 0.5, but not for nitrate loads. The annual water balance reveals that more than 60% of precipitation water is lost to evapotranspiration at all sites, amounting to 868 mm in Kounga, 741 mm in Tossahou, and 645 mm in Kpandouga. Percolation (302 mm) is important in the Kpandouga watershed which is dominated by natural vegetation at 99.7%, whereas surface runoff (105 mm) and lateral flow (92 mm) are the highest in the Kounga watershed having the highest proportion of agricultural land use (14%). In all the studied watersheds, nitrate loads are very low (not exceeding 4000 KgN per year) due to the low fertilizer application rates, and the water quality is not threatened if a standard threshold of 10 mg/l NO_3-N is applied. The results achieved in this study show that SWAT can successfully be used in spatial planning for sustainable agricultural development with limited environmental impact on water resources in inland valley landscapes.

1. Introduction

During the past century, food production has increased in many parts of the world, due to the introduction of new agricultural technologies such as machinery, irrigation, improved seeds, chemical fertilizers and pesticides. Nevertheless, West Africa is still one of the most food-insecure regions in the world (Grebmer et al., 2008). Under the pressures imposed by rapid population growth and a very low gross domestic product, especially in the developing countries, few investments are made in agriculture and the social systems are highly vulnerable (Burton and Lim, 2005). Additionally, climate change also plays a crucial role in the future of agricultural production and food security (Edame et al., 2011; Sundström et al., 2014). Already in 1994, Achenbach (1994) noted the highest influence of rainfall variability on food security in the tropics and subtropics, although other factors, such as soil fertility, world market conditions, cash crops, and land degradation, as well as socio-economic, historical and religious aspects, are generally also involved (Achenbach, 1994). Thus, to sustain growing populations given the threat of climatic change, farmers usually expand the area cultivated with small plots of rainfed crops to compensate for static yields. However, this traditional smallholder production is still restricted by the physical conditions of the land, due to the insufficient coverage of the input facilities and the lack of capital that can be used to compensate for natural constraints (Danvi et al., 2016; Janssens et al., 2010).

In consideration of this demand for food, nutrition security, and escalating farmer distress, the focus has increasingly turned to the rainfed areas which were previously perceived as underperforming by policymakers (AFD, 2013). Actually, rainfed food

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crops are able to play a specific role in alleviating poverty by improving regional food security through supplying towns with local produce, and by increasing farmers' incomes through the creation of jobs in rural areas and improvement of the competitiveness of food crop supply chains (AFD, 2013). To meet this goal, inland valleys have become an important asset; studies and projects have examined their potential for agriculture, as well as their exclusive dependence on runoff water in the Sahelian zone and on both runoff water and drainage from the groundwater table in the Sudanian zone (IVC, 2005). Additionally, their high soil fertility and relatively secure water supplies mean that they are of potential interest for the application of intensive agricultural practices on the way to achieving food security (Rodenburg et al., 2014). Thus, national policies in the region are aiming to invest more in agricultural intensification in inland valleys in order to overcome food insufficiency by increasing per capita food production. For instance, the National Rice Development Strategy (NRDS) of Benin focuses on inland valleys and lowland intensification in terms of expanding agricultural land and increasing crop yields. As a matter of fact, many inland valleys are currently being developed, but certainly without the proper knowledge on how this will influence their hydrological functioning, given the lack of studies in this area.

In fact, inland valleys are a highly diverse and complex system of variable ecosystems from the upland areas through the hydromorphic fringe down to the swampy valley bottoms, and each valley has its own typical hydrology (Andriesse and Fresco, 1991). They are extensively distributed, regularly flooded during the rainy season and have noticeable impacts on watershed hydrology (Giertz et al., 2012). In the past, many studies conducted in West Africa have focused on their agro-ecological characterization (Andriesse et al., 1994; Andriesse and Fresco, 1991), the assessment of their agro-potential and the potential constraints on crop production (Djagba et al., 2013; Giertz et al., 2012; Ogban and Babalola, 2003; Totin et al., 2013), and the response of crop performance to agronomic management (Schmitter et al., 2015; ; Touré et al., 2009). However, few studies address the hydrology of these wetlands by describing the major processes involved within different physiographic units, assessing rainfall-runoff processes in their surrounding drainage areas and analyzing the frequency of floods in the valley bottoms (Kyei-Baffour et al., 2013; Masiyandima et al., 2003; etc.). Moreover, the lack of studies dealing with water quality is noticeable in inland valley streams. Knowing the adverse impacts of intensified agriculture, the discharge, water quality and water quantity of inland valleys may be affected, as most of the discharge is diverted to crop fields that continually receive fertilizers, pesticides, and herbicides. It is then returned to the river with the pollutants through surface and subsurface transport. Consequently, the water can become practically unsuitable for drinking in the future (Dahal et al., 2007).

Planning of agricultural development in inland valleys requires sophisticated and detailed spatial and quantitative information on suitable areas and the potential impacts on water quantity and water quality. This requires accurate and suitable tools that can capture soil variability, land topography and the complex hydrological processes that operate under current conditions, as well under different land use and climate change scenarios. Findings on the development of land suitability analysis tools to assess areas for potential rice production in inland valley landscapes have been presented in our previous study (Danvi et al., 2016). In this paper, a tool is evaluated for assessing the impact of land use on hydrology and water quality. The aim of this paper is, therefore, to evaluate the capacity of a spatially explicit hydrological model to capture water quantity and water quality processes in three diverse inland valleys and their contributing watersheds in Benin. Three first-order inland valleys were selected in central Benin and are characterized by different land cover and different agricultural intensification levels and have watersheds with a maximum area of 5 km^2. Two different methods of setting up the spatial model SWAT were used and tested; specifically the HRU-based interface ArcSWAT and the grid-based interface SWATgrid. The calibration and validation processes were performed using hydrological and water quality measurements collected during three hydrological years from 2013 to 2015. This paper is organized into five sections including this introduction. In the second section, the materials and methods are presented dealing with the research area and the modelling approach applied in this study. In the third section, the results achieved on the model performance, water balance and nitrate loads are shared, while the fourth section analyzes the uncertainties and addresses the differences between the discretization schemes. Finally, conclusions are drawn in the last section and recommendations are made.

2. Materials and methods

2.1. Research area

This study was carried out in the Upper Ouémé watershed, which covers approximately 14500 km^2 in central Benin (Duku et al., 2015). The three inland valleys are all located in the vicinity of the city of Djougou and are located in the sub-humid Sudan-Guinea climatological zone (Fig. 1). In general, the climate is sub-humid and alternates between rainy and dry seasons. It is arid from November to March and the subsequent period from April to October is humid. The wet season is characterized by a unimodal rainfall season of approximately 1250 mm per year that peaks in August (Fink et al., 2010; Duku et al., 2015). Rainfall-runoff variability is high in this watershed and results in annual runoff coefficients that range from 0.10 to 0.26, with the lowest values occurring in the savannahs and forest landscapes (Diekkrüger et al., 2010). The annual potential evapotranspiration is approximately estimated to be 1500 mm (Lohou et al., 2014); the average temperature is 25.4 °C, and the mean insolation received at the surface is 234 W/m^2 (IMPETUS, 2007).

The selected sites are all inland stream valleys having small contributing watersheds with drainage areas of 4.06 km^2 for Kounga, 4.99 km^2 for Tossahou, and 3.85 km^2 for Kpandouga (Fig. 2). The uplands mostly dominate in all the inland valleys and make up 90% of the drainage area, while the remainder is allocated to the lowlands. In terms of their transverse profiles, Kounga and Tossahou are somewhat concave, while Kpandouga is convex. The local topography is very diverse at all three sites, with the occurrence of flat to gentle and steep slopes. Four major soil types were encountered at all the sites; they were classified as Lixisols, Plinthosols, Sandy Gleysols, and Clayey Gleysols, according to the WRB (2006). Lixisols and Plinthosols are predominant in the uplands. Sandy and Clayey Gleysols are predominant in the fringes and the valley bottoms. More specifically, Lixisols have the highest percentage of coverage (64% of the drainage area in Kounga, 57% in Tossahou and 59% in Kpandouga). Plinthosols cover 26% of the total area in Kounga and Kpandouga and 34% in Tossahou. Sandy and Clayey Gleysols cover only 0.08 and 0.03% in Kounga, 0.07 and 0.02% in Tossahou, and 0.11 and 0.05% in Kpandouga.

The land cover/land use is primarily characterized by gallery forest and woodland, tree savannah and plantations, shrub savannah, grass savannah, bare soil, settlements, and cultivated areas (Tables 1 and 2). The annual crops that are cultivated are yam (*Dioscorea* sp.) and cassava (*Manihot esculenta Crantz*). During the rainy season, corn (*Zea mays* L.), groundnut (*Arachis hypogea*), sorghum (*Sorghum bicolor*), cotton (*Gossypium* sp.), and rice (*Oryza sativa* L.) are grown. During the dry season, the inland valleys are not exploited heavily, except for Kounga, where the valley bottom is preferentially cropped with okra (*Abelmoschus esculentus*) in addition to other vegetables. In all the watersheds, mineral fertilizer is

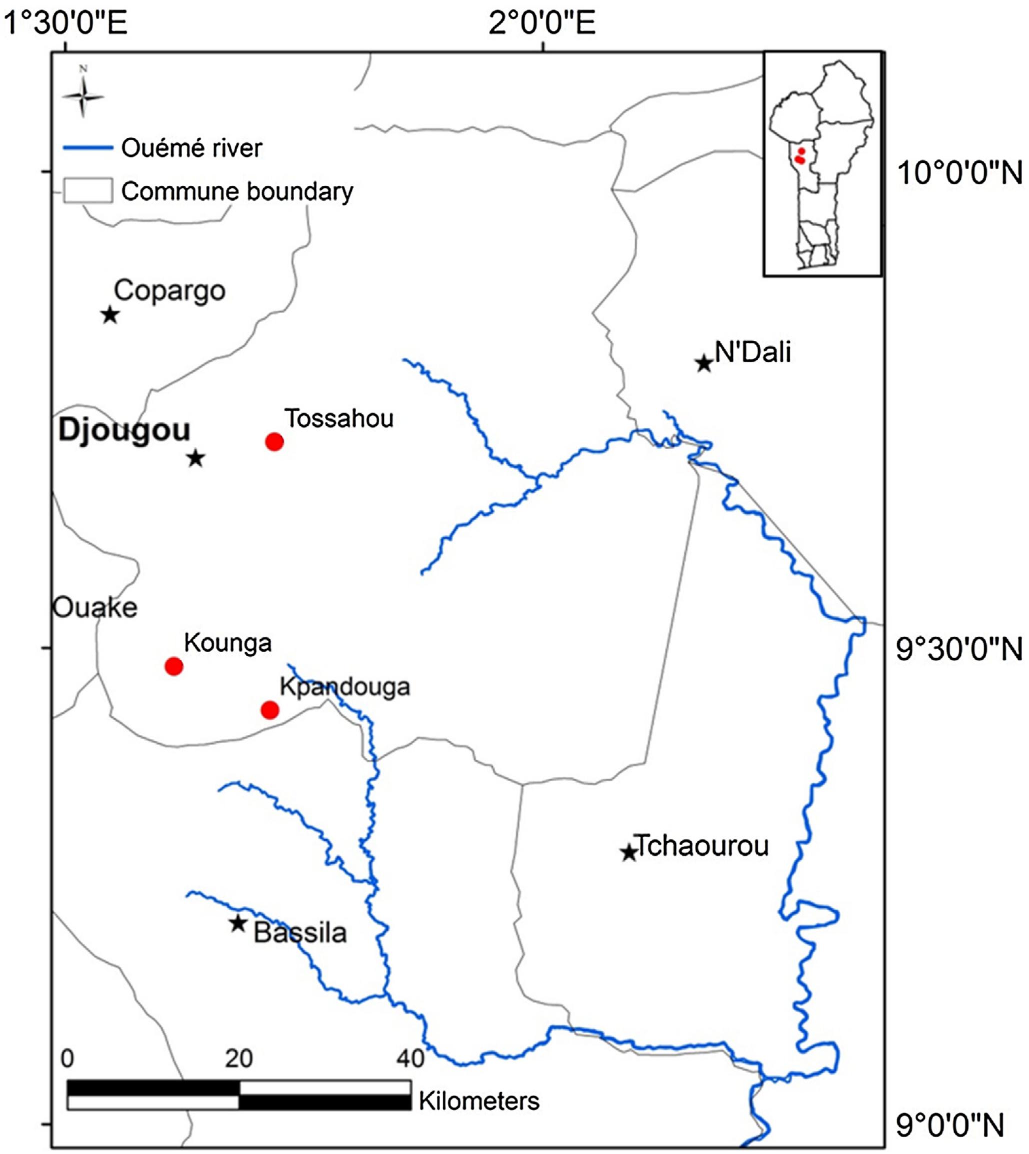

Fig. 1. The upper Ouémé watershed and the location of the inland valleys in Benin.

Table 1
Land use/land cover classes in the studied inland valley watersheds.

Land use/land cover class	Kounga		Tossahou		Kpandouga	
	ha	%	ha	%	ha	%
Gallery forest and woodlands	11	2.9	96	19	33	8.7
Tree savannah and plantations	110	27	35	7	228	59
Shrub savannah	136	33	170	34	52	14
Grass savannah	92	23	158	32	68	18
Bare soil	0	0	0.57	0.1	0.16	0.04
Settlements	0.4	0.1	0.12	0.02	0.48	0.06
Cultivated areas	56	14	40	8.0	3	0.7

ha, hectare.

Table 2
Cultivated crops in the studied inland valley watersheds.

Crops	Kounga		Tossahou		Kpandouga	
	ha	%	ha	%	ha	%
Cotton	25	45	5	13	––	––
Yam	9.5	17	6.4	16	1.3	44
Cassava	3	6	7	17	0.9	31
Corn	9.5	17	9	22	––	––
Sorghum	3	5	1.2	3	0.3	11
Peanut	1	2	8.4	21	––	––
Rice	5	9	3	7	0.4	14

only applied to cotton and corn fields at rates of 150 kg/ha of NPK (10-20-20) and 50 kg/ha of urea (45%N), and cattle grazing occurs during most of the year. In fact, based on the seasonal frequency of cropping and on the cultivated area, Kounga has a larger fractional area that is cultivated throughout the year (14%), while only 8% of Tossahou is cultivated and only during the rainy season. In Kpandouga, the fraction of cultivated area is very low (approximately 0.7%) and more than 90% of the drainage area is dominated by natural vegetation. This inland valley is cultivated only during the rainy season, and no cotton and corn were grown on the very few fields that were mapped.

2.2. *Modelling approach*

2.2.1. *Model description*

Within the framework of this study, we applied the interface ArcSWAT 2012 (Arnold et al., 2013) to calibrate and validate the

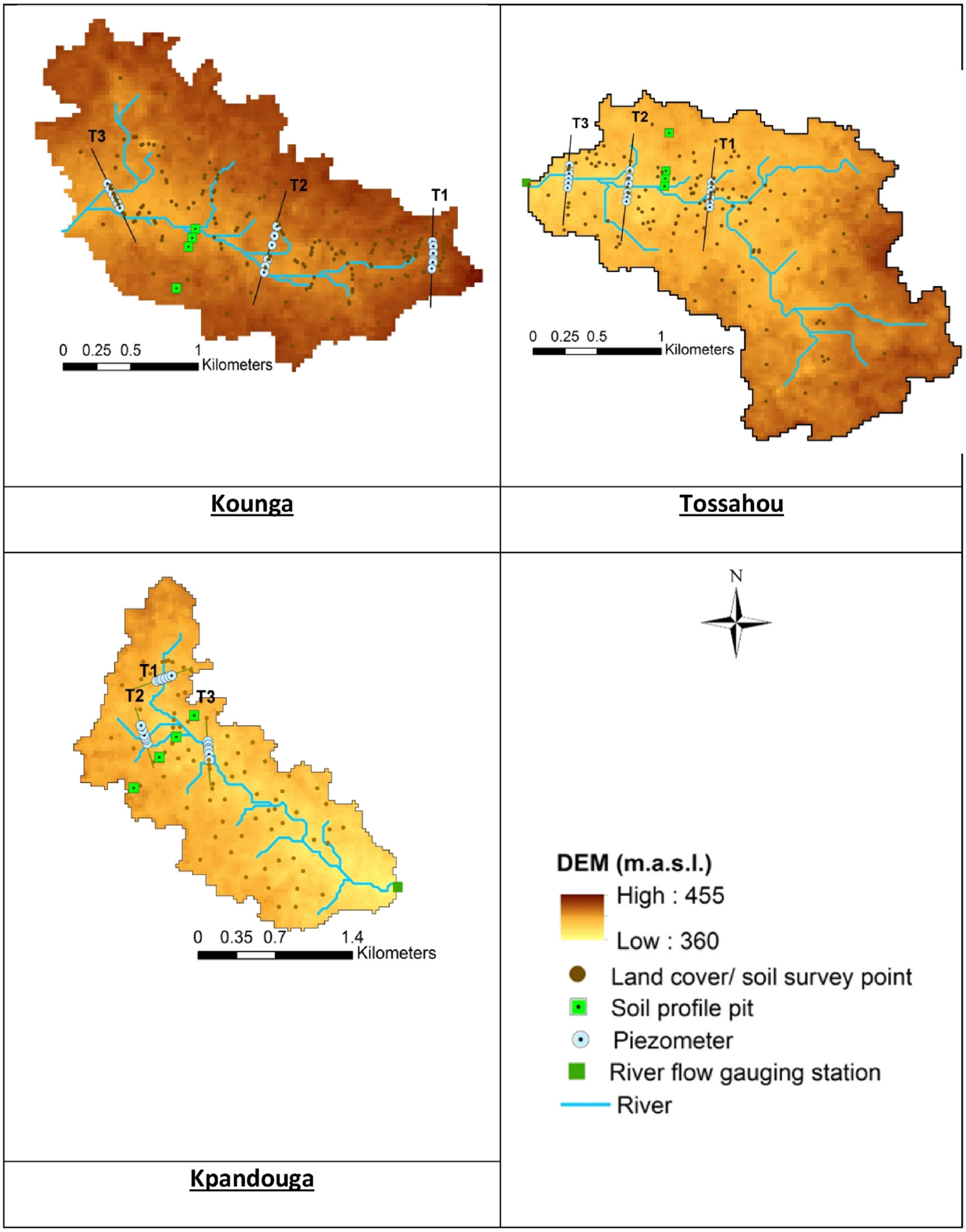

Fig. 2. Watersheds contributing to the inland valleys: elevations, drainage patterns and the locations of instruments.

SWAT (Soil and Water Assessment Tool) model for three inland valley watersheds in order to assess their hydrological characteristics and to predict nitrate loads. In addition, the interface SWATgrid (Rathjens et al., 2014) is used for evaluating the ability of both hydrological models to capture water quantity and water quality processes in terms of their differing spatial discretization schemes.

SWAT is a semi-distributed, physically based, and continuous hydrologic model that was developed to predict the impact of land management practices on water, sediment, agricultural chemicals, and crop yields in complex watersheds with varying soils, land use, and management conditions over long periods of time. It discretizes watersheds into a number of subwatersheds which consist of hydrologic response units (HRUs) having unique soil, land use, and topographic properties (Arnold et al., 2013). The model runs on a daily time step, and the hydrological cycle is divided into land and routing phases. The land phase controls the amount of water, sediment, and nutrients and the pesticide loads entering the main channel in each subwatershed. Land phase processes include weather, hydrology (canopy storage, infiltration, evapotranspiration, surface runoff, lateral subsurface flow, and return flow), plant growth, erosion, and nutrient transport and management operations. The routing phase includes processes such as sediment and nutrient routing, in addition to surface runoff, lateral flow and return flow from the land phase, which are then routed through

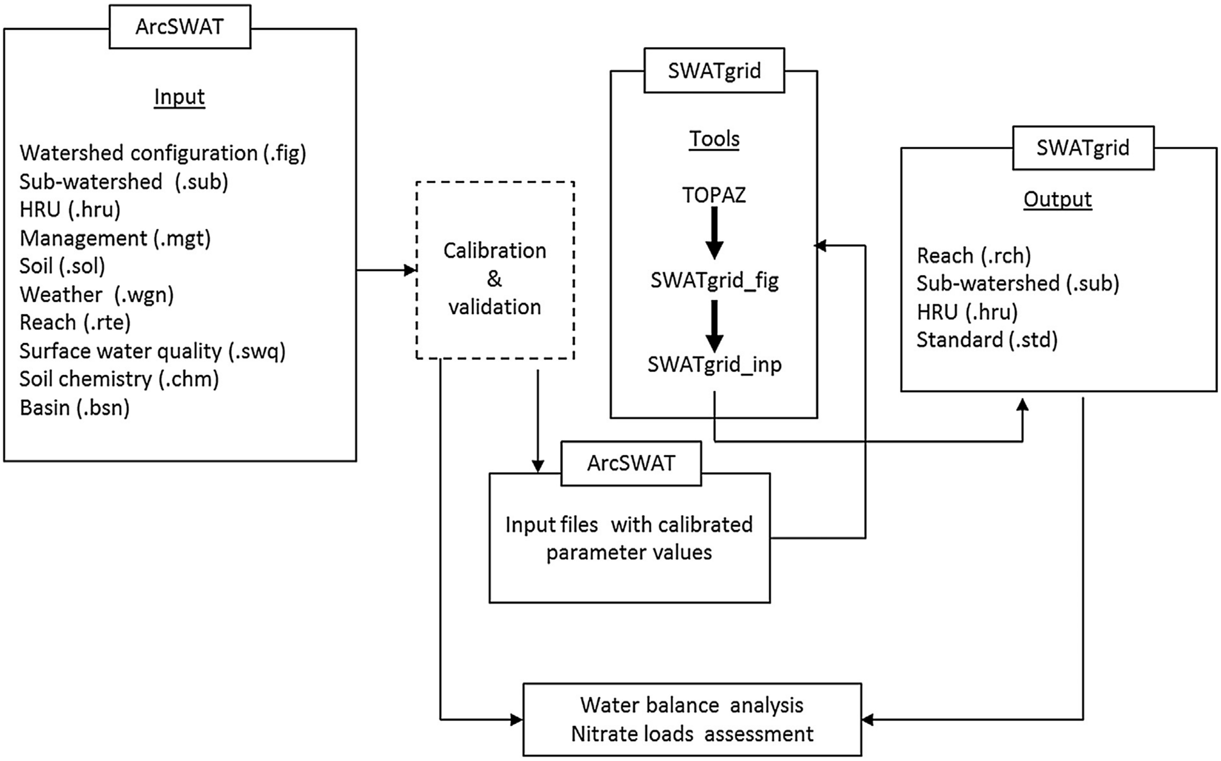

Fig. 3. Modelling approach applied in this study and schematic illustration of the general organization of SWATgrid.

the channel network of the watershed to the outlet (Neitsch et al., 2009).

Currently, the grid-based version SWATgrid is driven by results from ArcSWAT and the TOpographic PArametriZation tool (TOPAZ) (Garbrecht and Martz, 2000) which is used to derive flow paths from an input DEM (Digital Elevation Model) (Fig. 3). Thus, files with calibrated and validated parameter values from ArcSWAT were used in this case to run SWATgrid. The watershed is delineated into spatially interacting grid cells, and surface runoff, as well as lateral and shallow groundwater flows, are computed for each grid cell individually before being routed to one of the eight adjacent cells. The spatial distribution of flow separation is controlled by the drainage density factor (Rathjens et al., 2014).

2.2.2. Model input data

A wide range of input data was required and used to prepare ArcSWAT and SWATgrid for each of the defined watersheds. These data included topography, land use, soils, weather, hydrometry, and water quality (Table 3). To account for topography, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) with a resolution of 30 m was used (Fig. 2). Because no spatial information on the distribution of soil physical and chemical properties or on land use and land cover units was available at the scale of the inland valleys, it was essential in this study to develop supporting maps to account for the different patterns and changes in soil and the vegetation attributes of land and their utilization.

The land use map was derived from supervised classification of a SPOT-6 satellite image with a resolution of 1.5 m that was specially acquired for the research area. The different landscape elements were identified and subsequently validated based on reference points. The reference data were randomly collected during field checking using Global Positioning System (GPS) units and compared to the classified maps for accuracy assessment. 169, 134, and 76 observations points were checked to provide ground truth data in Kounga, Tossahou, and Kpandouga respectively (Fig. 2). A subsequent accuracy check based on the number of correct plots shows approximate total accuracy values of 79% in Kounga, 82% in Tossahou, and 89% in Kpandouga. To obtain more information on the cultivated areas, the different fields were mapped with GPS within each watershed. The resulting layer was finally overlaid with the classified map to obtain the final maps.

A soil mapping procedure was implemented to assess the spatial distribution of the predominant soil types and related properties in each inland valley. The approach, developed by Jenness et al. (2013) for classifying landscapes into major landform units based on the Topographic Position Index (TPI) and slope was used for the spatial delineation of soil units. The TPI is simply the difference between a cell's elevation value and the average elevation of the neighborhood around that cell (De Reu et al., 2013). Within each watershed, the TPI data sets were generated by using the Land Facet Corridor Designer extension for ArcGIS 10.2. The spatial distribution of the soil units was defined by analyzing the relationship between the terrain attributes and the dominant soil components based on the high frequency of occurrence of a soil type within a typical landform unit. For this purpose, field data from visual and spatial surveys on the occurrence of the major soil groups at the same land use survey points were used (Fig. 2). For acquiring more information on the soil, a profile was opened in each soil type along the toposequence and recorded over a depth ranging from 57 to 200 cm, depending on the occurrence of an ironstone pan, in accordance with the Word Reference Base (WRB, 2006). Additionally, core and disturbed samples were collected from each layer in the profiles for laboratory analysis in order to determine the hydraulic, physical and chemical properties of the soils, such as their saturated hydraulic conductivity, bulk density, water content at saturation, texture, organic carbon content, and pH. The physical and chemical properties were analyzed in the soil laboratory of the University of Bonn, whereas the hydraulic properties were measured in the soil laboratory of the West African Science Service Center on Climate and Adapted

Table 3
Spatial data used in the SWAT model.

Type of Data	Description	Source	Resolution or scale
Topography	ASTER global digital elevation model (GDEM)	NASA	30 m
Land use/land cover	Classified SPOT-6 satellite image acquired on the 19th February 2014	Own representation	30 m
Soils	Derived from landform classification and field surveys	Own representation	1:22 500
Weather	Rainfall, temperature, relative humidity, solar radiation, and wind speed	AMMA-CATCH	1 gauge per IV
Hydrometry	Water level and river discharge at the outlet	Field measurements	1 gauge per IV
Water quality	Nitrate concentration in the river at the outlet	Water sampling and analysis	1 gauge per IV
Plant characteristics	Biomass, PHU, LAI, etc.	Diverse sources from the literature	–––

NASA, National Aeronautics and Space Administration; AMMA-CATCH, African Monsoon and Multidisciplinary Analysis–Coupling the Tropical Atmosphere and the Hydrological Cycle; IV, Inland Valley; PHU, total heat units required for plant maturity; LAI, plant Leaf Area Index.

Land Use (WASCAL) project in Tanguiéta. However, the saturated hydraulic conductivity was calculated by using the pedotransfer function of Rawls and Brakensiek (1985) because it had already successfully used in Central Benin (Bormann and Diekkrüger, 2003).

To assess the seasonal variability of hydrological processes in all the inland valleys, climate data, including precipitation, temperature, relative humidity, solar radiation and wind speed (measured every 5 min) were obtained from the African Monsoon and Multidisciplinary Analysis-Coupling the Tropical Atmosphere and the Hydrological Cycle (AMMA-CATCH) database (AMMA-CATCH, 2015). Within each watershed, a total of 300 days of grazing occurred and cattle manure (1%N-0.4%P-3%ORGN-0.7%ORGP-95%NH3N) was applied daily at of 38 kg/ ha, as adopted in a previous study conducted by Bossa et al. (2012) within the same area. For modelling plant growth, parameter values were taken from the literature (Bossa, 2012; Cournac et al., 2002; De Wasseige et al., 2003; Mulindabigwi, 2005; Orthmann, 2005; Worou et al., 2012).

2.2.3. Monitoring data

Hydrological and water quality measurements for calibration and validation of the model were carried out during three consecutive hydrological years between January 2013 and December 2015. To calculate the daily discharge from the catchments, we installed a pressure sensor at the outlet of each inland valley, and the water level was recorded every 5 min assuming the time of concentration of the inland valley contributing watersheds (with respect to their small size) not being less than 10 min. Daily discharges were calculated using the velocity-area method, following the recommendations of the World Meteorological Organization (WMO, 2008). Measurements of groundwater levels were taken along three watershed cross-sections that divided each inland valley into upstream, midstream, and downstream sections (Fig. 2). However, due the difficulty of access, the transects in Kpandouga are located in the cultivated area of the valley, which corresponds to the upstream section. The quality of the surface water in terms of nitrate loads was assessed by analyzing water samples collected every seven days at the outlets of the watersheds. Quantities of 500 ml of water were collected weekly from the midst of the main river channel cross-section. This sampling rate was actually applied following the failure of the multiprobe parameter at the beginning of the wet season 2013 during field monitoring, which was acquired for frequently and automatically recording water quality parameters values. Moreover, apart from transportation issues, the monitored sites are not closely located (being 15 km to 35 km distant from our base in Djougou center), and as numerous additional data were to be manually collected in the framework of this study, all the inland valleys could not be monitored at the same time and daily. The nitrate concentrations in the samples were measured in the laboratory of the General Department of Water (DGE), and the average daily loads were calculated based on daily discharge data estimated at the gauging station. For each wet season, the sampling was performed from August to October, when the runoff was well established.

2.2.4. Model setup and evaluation

2.2.4.1. Model configuration. In accordance with the availability of precipitation data, simulations were performed for the periods 2003–2015 at Kounga and Tossahou and 2008–2015 at Kpandouga. To ensure the establishment of both basic flow conditions and that the hydrologic processes were in equilibrium, and to minimize the effect of initial conditions, the models were run for a warm-up period of 5 years on each site (Yang et al., 2007; Zhang et al., 2007; Rocha et al., 2015). Surface runoff was simulated by using the Soil Conservation Service curve number method, and the Penman-Monteith method was used to calculate potential evapotranspiration (Neitsch et al., 2009). The initial setup carried out in ArcSWAT included the delineation of watershed and sub-watershed areas using the DEM, subdivision of the sub-watershed areas into HRUs, and generation of the daily climate input files. For other different inland valleys watersheds Kounga, Tossahou and Kpandouga, a total of 19, 18, and 15 sub-watersheds were defined, respectively. With a threshold value of 0.1% for land use and 10% for soil and slope classes, a total of approximately 605 HRUS were defined for Kounga, 662 for Tossahou and 457 for Kpandouga. Comparatively, the SWATgrid was run with a grid resolution of 30 m as the DEM and the watersheds were discretized into 5062 grid cells for Kounga, 6405 for Tossahou, and 4818 for Kpandouga after preprocessing of the calibrated input parameter set. Thus, the discretization scheme is only ten times better in terms of the reduction of the spatial loss of information in data such as land-use or soil maps. However, more accuracy in water balance simulations is expected at the watershed scale, given that the model accounts for lateral fluxes between grid cells.

After processing of the input data in ArcSWAT and before calibration using the SWAT Calibration and Uncertainty Programs (SWAT-CUP), a relative sensitivity analysis was carried out by applying the optimization algorithm SUFI-2 (Sequential Uncertainty Fitting) in order to identify the parameters to which the model was most sensitive (Abbaspour, 2014). SWAT-CUP is a computer program which links the SUFI-2 procedure to SWAT and enables the model sensitivity analysis, calibration, validation, and uncertainty analysis. SUFI-2 is an algorithm which analyzes the strength of the calibration by quantifying the degree to which all uncertainties impact the model results. The parameter uncertainty refers to all sources of uncertainties such as uncertainty in driving variables, conceptual model, parameters, and measured data (Abbaspour, 2014). Based on the relative sensitivity analysis, Table 4 presents the parameters which were found sensitive and used for calibration in Kounga, Tossahou and Kpandouga.

Table 4
Parameters used for the calibration procedures.

Parameter Name	Description
CN2[a,b,c]	Curve number for moisture condition II
GW_REVAP[a,b,c]	Groundwater re-evaporation coefficient
ALPHA_BF[b]	Base flow alpha factor
GWQMN[b,c]	Threshold depth of water in the shallow aquifer required for return flow to occur
GW_DELAY[b,c]	Groundwater delay
EPCO[b]	Plant uptake compensation factor
ESCO[a,b]	Soil evaporation compensation factor
SOL_AWC[a,b,c]	Available water capacity of the soil layer
SLSUBBSN[b,c]	Average slope length
NPERCO[a,b,c]	Nitrogen percolation coefficient
CMN[a,b]	Rate factor for humus mineralization of active organic nitrogen
HRU_SLP[b,c]	Average slope steepness
DD[a,b,c]	Drainage density factor affecting the flow separation ratio

[a] Parameters selected for Kounga.
[b] Parameters selected for Tossahou.
[c] Parameters selected for Kpandouga.

As nitrate fluxes strongly depend on water fluxes, the model was calibrated and validated using the daily observed streamflow first, and afterwards using the nitrate loads in the stream water collected at the outlet of each watershed (Pohlert et al., 2005). No further calibration was carried out in SWATgrid; the calibrated parameter sets were kept unchanged, except for the drainage density parameter, which was adjusted manually (Duku et al., 2015). Calibration of the streamflow was performed from the year 2013 to 2014 and the validation was performed for the year 2015 in Tossahou. In Kpandouga and Kounga, calibration was performed for 2013 and validation was performed for 2014. Concerning the nitrate load in all inland valleys, calibration was performed from 2013 to 2014 and validation was performed for 2015. However, not enough discharge measurements were available during the simulation period in Kounga and Kpandouga, as a result of repeated acts of vandalism at the gauging station.

2.2.4.2. Model performance evaluation. There is no conventional standard procedure for model evaluation available, as model evaluation depends on the aim of the study (Rathjens and Oppelt, 2012). In this study, three quality measures were used to evaluate model performance, specifically the coefficient of determination (R^2), the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) and the percent bias (PBIAS) (Gupta et al., 1999). The coefficient of determination was used to determine what proportion of in situ variance can be explained by the model (Rathjens and Oppelt, 2012). The NSE coefficient is a normalized measure that helps determine the relative magnitude of the residual variance compared to the variance of the measured data (Nash and Sutcliffe, 1970). The PBIAS was calculated to measure the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999). In this study, and in accordance with the recommendations by Moriasi et al. (2007), the model performance was considered to be satisfactory if $\text{NSE} > 0.50$ and $R^2 > 0.50$, and PBIAS was within the range −25 to 25% for streamflow and −70 to 70% for nutrients.

3. Results

3.1. Model calibration and validation

Tables 5 and 6 show the model quality measures obtained for calibration and validation at daily time steps for streamflow and nitrate loads for all gauging sites. The simulated and observed discharge and nitrate loads are compared in Figs. 4 and 5.

Table 5
ArcSWAT model quality indicators of calibration and validation for streamflow and nitrate loads.

Gauging sites	Calibration					Validation		
	p-factor	r-factor	NSE	PBIAS	R^2	NSE	PBIAS	R^2
Streamflow								
Kounga	0.54	0.74	0.73	−15.7	0.74	0.50	−7.57	0.50
Tossahou	0.03	0.04	0.48	−43.3	0.50	0.53	42.3	0.54
Kpandouga	0.08	0.34	0.56	−37.7	0.58	0.30	8.66	0.39
Nitrate loads								
Kounga	0.19	1.46	−0.33	−45.0	0.24	−1.6	−100	0.09
Tossahou	0.13	0.09	0.37	−70.3	0.47	−5.15	−337	0.60
Kpandouga	0.00	0.09	−0.06	26.5	0.00	0.26	−24.9	0.00

p-factor, percentage of observations falling within the 95% prediction uncertainty range; r-factor, relative width of the 95% probability band; NSE, Nash-Sutcliffe efficiency coefficient; PBIAS, percent bias; R^2, coefficient of determination.

Table 6
SWATgrid performance (NSE, PBIAS, and R^2) for streamflow simulation during the calibration and validation periods.

Gauging sites	Calibration			Validation		
	NSE	PBIAS	R^2	NSE	PBIAS	R^2
Kounga	0.79	−35.52	0.77	0.47	−13.51	0.45
Tossahou	0.55	−58.28	0.51	0.42	−26.49	0.45
Kpandouga	0.50	−64.15	0.51	0.31	−37.75	0.31

NSE, Nash-Sutcliffe efficiency coefficient; PBIAS, percent bias; R^2, coefficient of determination.

The predictive performance of ArcSWAT is considered to be satisfactory for streamflow calibration and validation for all the watersheds that contribute to the monitored inland valleys. At most of the gauging stations, the NSE and R^2 values were greater than 0.5. Despite the fact that some values at the monitoring station in Kpandouga were slightly lower during the validation period, the model produces acceptable simulation results. The negative values obtained for the PBIAS indicator at most of the stations indicates that the model overestimated the discharge, which may result from the low predicted potential evapotranspiration values, which range from 1154 to 1200 mm. These low potential evapotranspiration values may be related to the accuracy of measured solar radiation data used in the modelling. In the application of the SUFI-2 algorithm for calibration, the p-factor and r-factor are measures used to analyze the parametric uncertainty. Thus, the analysis of the results reveals a high variation between the observed and calibrated discharge curves, and the calibrated curves are dominated by overestimation segments. The p-factor values show that only 54% of the measured data were bracketed by the 95% prediction uncertainty (95PPU) at Kounga, compared to 3% and 8% at Tossahou and Kpandouga, respectively. In all the inland valleys, acceptable values (ranging from 0.04 to 0.74) are reached for the r-factor, which stands for the average thickness of the 95PPU band (the distance between the 2.5th and 97.5th percentiles of the cumulative distribution of the simulated variable) divided by the standard deviation of the measured data. In general, the evaluated goodness of fit for nitrate loads during both calibration and validation reflects unsatisfactory model performance, expressed by the low values of the quantitative statistics. However, the model performance is acceptable for the calibration at Kounga and Tossahou. The analysis using the p-factor and r-factor reveals that the observed and calibrated values differ significantly.

As shown in Table 6, the quality measures indicate that SWATgrid yielded satisfactory performance in the simulation of discharge, especially during the calibration period, in all the inland valley watersheds.

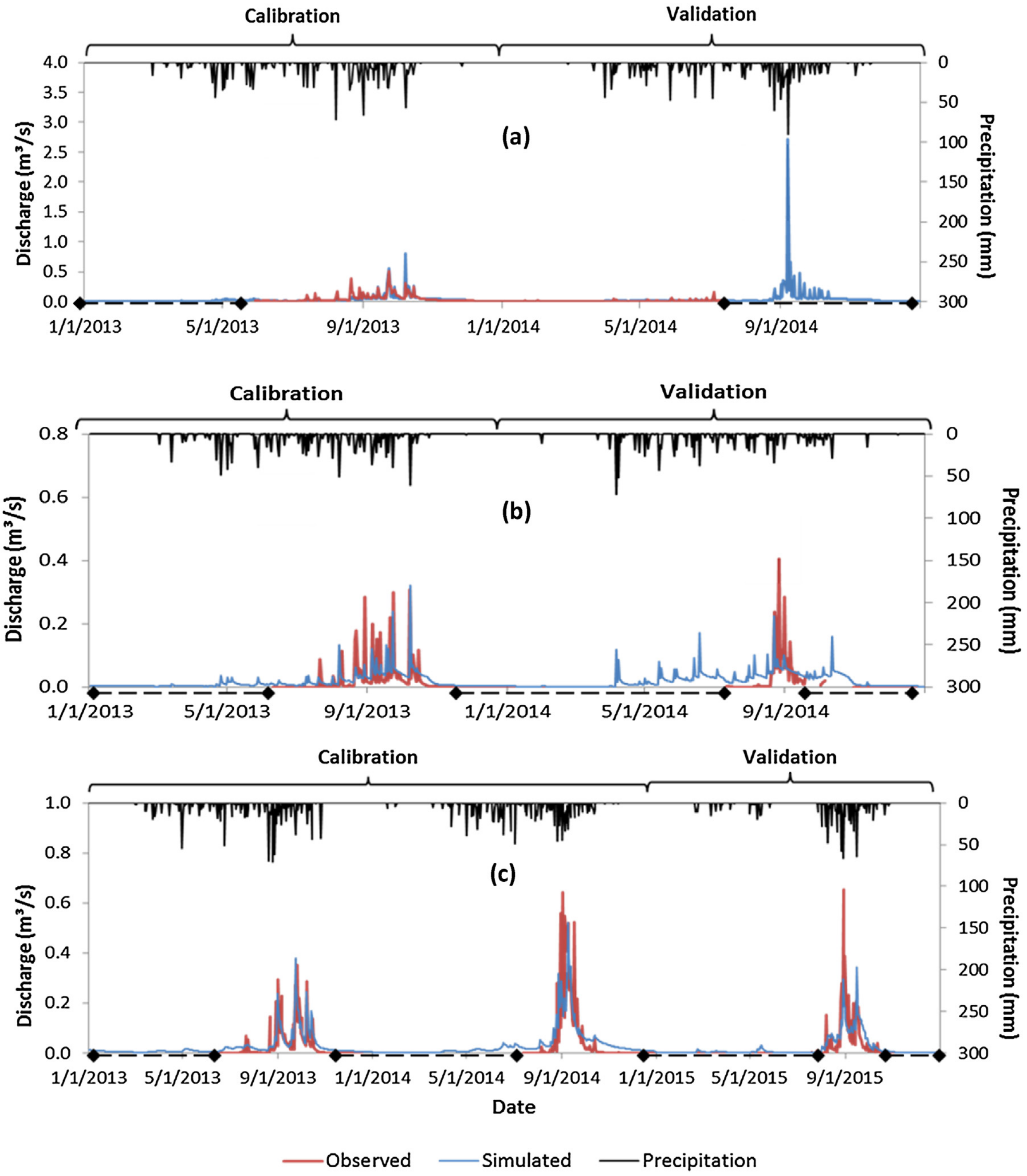

Fig. 4. Measured and simulated daily discharges at the outlets of the contributing watersheds of (a) Kounga (calibration year: 2013; validation year: 2014), (b) Kpandouga (calibration year: 2013; validation year: 2014), (c) Tossahou (calibration period: 2013–2014; validation year: 2015) using ArcSWAT.

3.2. Annual water budgets and nitrate loads within the inland valleys

In SWAT, the water balance is the driving force behind all the hydrological processes occurring within a watershed (Arnold et al., 2013). Its most influential components include precipitation, surface runoff, lateral flow, base flow and evapotranspiration. Table 7 summarizes the average annual basin values of water balance and nitrate loads in each inland valley during the simulated period.

The results of ArcSWAT show that water from precipitation is predominantly lost to evapotranspiration in all the inland valleys at ratios of 73%, 60%, and 73% for Kounga, Tossahou and Kpandouga, respectively. The highest ratio of water yield is exhibited by Kounga (21% of precipitation), while the lowest one is associated with Kpandouga (14% of precipitation). In Kounga, runoff is more important than groundwater flow. More explicitly, 17% of the precipitation is converted to runoff (9% becomes surface runoff and 8% becomes lateral flow), while only 4% becomes groundwater flow. Water loss through percolation within the inland valleys is estimated to be 11%. Surface runoff and lateral flow make the same contribution to streamflow and represent approximately 40% of total discharge. In Tossahou, percolation and runoff are dominant and represent 16% and 11% of precipitation. However, lateral and groundwater flows contribute more to streamflow, and they make up 50% and 40% of the total discharge. In this inland valley, approximately 2% of precipitation is estimated to be removed via surface runoff, while 9% and 7% are lost through lateral and groundwater flows. In Kpandouga, percolation is more important, and it accounts for 28% of

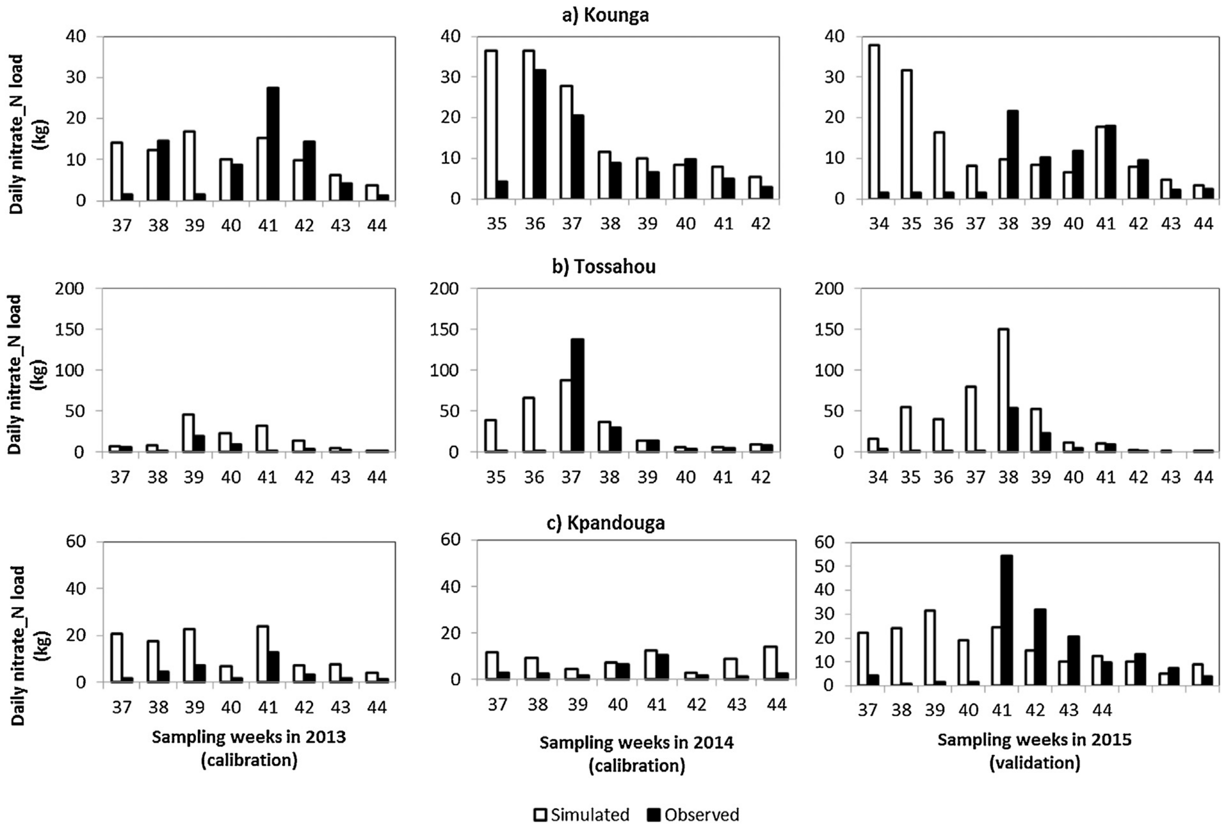

Fig. 5. Simulated and observed nitrate loads during calibration and validation at Kounga, Tossahou, and Kpandouga using ArcSWAT.

Table 7
Average annual water balance components and nitrate loads simulated by ArcSWAT and SWATgrid.

Water balance component	Kounga[a]			Tossahou[a]			Kpandouga[a]		
	ArcSWAT	SWATgrid	Diff[b]	ArcSWAT	SWATgrid	Diff	ArcSWAT	SWATgrid	Diff
Precipitation (mm)	1195	1195	0	1009	1009	0	1070	1070	0
Surface runoff (mm)	105	62	43	21	21	0	26	13	13
Lateral flow (mm)	92	104	−12	88	63	25	49	46	3
Groundwater flow (mm)	47	63	−16	70	83	−13	60	59	1
Percolation (mm)	130	126	4	161	156	5	302	260	42
Water yield (mm)	252	236	16	188	156	32	153	128	25
Actual evapotranspiration (mm)	868	849	19	741	765	−24	645	687	−42
Potential evapotranspiration (mm)	1154	1154	0	1203	1203	0	1160	1160	0
Nitrate load (kg N)	2612	1542	1070	3594	1190	2404	3178	418	2760

[a] Kounga (2013–2014); Tossahou (2013–2015); Kpandouga (2013–2014).
[b] Diff, difference between ArcSWAT and SWATgrid simulations.

precipitation, while surface runoff represents 2%, lateral flow represents 5% and groundwater flow represents 6%. Surface runoff contributes less to streamflow at around 20%, but groundwater and lateral flow contribute 40% and 30% of total discharge. Although the model did not perform very well in the simulation of nitrate loads at the outlets of the watersheds, the results are low, and the highest annual average value of 3594 kg is simulated in Tossahou. Subsequently, the simulated annual average concentration also reflects low values, 2.6 mg/l for Kounga, 3.8 mg/l for Tossahou and 5.3 mg/l for Kpandouga. As a result of the discretization, lower runoff is simulated by SWATgrid for all the inland valleys. The differences between the average annual water yield values were 16, 32 and 25 mm for Kounga, Tossahou, and Kpandouga, respectively. In the same order, the quantity of water simulated through percolation is significantly reduced by 42 mm at Kpandouga, but it is only slightly different at Kounga (4 mm) and Tossahou (5 mm). Unlike Kounga, more evapotranspiration is simulated at Tossahou and Kpandouga, and the predicted nitrate loads are lower in all the inland valleys.

4. Discussion

4.1. Uncertainty analysis and differences between the discretization schemes

4.1.1. Model uncertainties

Constraining uncertainty in predictions is one of the major issues in the calibration of watershed models. Although the calibration results are considered satisfactory for streamflow at all sites, the p-factor and r-factor indicate that the measured data were not bracketed very well using the SUFI-2 algorithms. Moreover, the level of performance of the model likely reflects a large range of uncertainty in the predictions, which might be attributed to the conceptual model itself, the inherent non-uniqueness of parameter combinations, possible errors in the input data, and the quality of the discharge data used for validation (Abbaspour, 2014; Bormann, 2005). Within the framework of this study, the quality of the rainfall data used constitutes the primary source of errors and has a major impact on discharge modelling. Rainfall data are crucial inputs for runoff predictions and are very uncertain, due to their high spatial and temporal variability and the errors that occur during the measurement process (Dulal et al., 2007). As the rainfall data were obtained from the rain gauge that is closest to each inland valley, they are likely subject to systematic errors, including losses due to wind, wetting, evaporation, and splashing, as well as the limited near-point sampling and insufficient spatial coverage of the gauges. Although in modelling rainfall-runoff processes, the discharge data are usually considered to be accurate, it is subject to uncertainty, due to error in the measurements and uncertainty in the rating curve (Dulal et al., 2007). In our case, the quality of the discharge data could be related to errors induced by the occurrence of missing records during the measurement of stream water levels due to sensor malfunctions or acts of vandalism at the hydrometric stations, and errors that occur due to the limitations of the stage-discharge equations for capturing the peak flows of storm events (Rocha et al., 2015).

With respect to the small sizes of the contributing watersheds, the resolution of the DEM (30 m) was not fine enough to accurately account for the topography. Additionally, to increase the model's computational efficiency and operational feasibility, the land use and soil maps were resampled to the same resolution as the DEM, which likely resulted in some loss of information (Duku et al., 2015). In fact, the limitations of the applied methods in terms of accurately classifying land use and soil units may also lead to possible errors in the spatial representation of patterns. Moreover, potential uncertainties could be induced by the highly dynamic human activities that occur within the inland valleys, which might not be accounted for in the model or acceptably parameterized within the SWAT model (e.g., the dynamic conversion of land during shifts in cultivation, weeding on crop fields, wells used for agriculture, and domestic water use).

The main limitation faced during the calibration of nitrate loads comes from the common difficulties in modelling complex nitrogen processes within the inland valleys. Modelling nutrient transport is challenging due to the knowledge gaps that exist in the mathematical representation and description of landscape and in-stream biogeochemical processes (Rode et al., 2010). In other words, effective assessment of nutrient availability requires a thorough understanding of the rates at which nutrient elements enter, move within, and leave the soil and are mineralized from organic materials (Havlin et al., 2013). Another source of uncertainty is related to the discontinuous nature of the observations and the insufficient amount of water samples available on a weekly basis, which is a very large time step with respect to the short length of the period during which continuous flow occurs (from mid-August to mid-October). Conditions were only favorable for collecting the water samples during the permanent flow regime, and the collection was done early in the morning. In accordance with management practices, most of the fertilizer had already been applied a few weeks before, corresponding to a period of substantial runoff occurrence. Although the degree of fertilizer application is low, the exact amount of fertilizer used in the watersheds is unknown. Thus, due to its high solubility, a major part of the nitrate could have already been flushed into the stream by the earlier storm events which occurred mainly during the night time and were not sampled. As depicted by Fig. 4, the high discrepancies occurring between observed and simulated values of nitrate loads in the period from the 34th to 40th week during calibration and validation are probably related to the quality of measurements caused by errors in water sampling and water analysis in the laboratory. Additionally, it should be mentioned that disturbances from grazing activities occurred frequently in the vicinity of the gauging station at the time of sampling.

4.1.2. Differences between the discretization schemes

For both model setups (ArcSWAT and SWATgrid), the resulting mean annual water balance is realistic and consistent. This is confirmed by the good match between the daily discharges derived from the SWATgrid and the ArcSWAT setup at the different outlets (with R^2 values that range from 0.8 to 0.9), which reveals that the simulated discharge is not significantly affected by the change in discretization schemes (Fig. 6). However, some relative differences could be observed between the simulated water balance components. In particular, the discretization used in the grid-based setup results in reduced surface runoff, percolation and water yield at all sites. However, the reduction is to some extent compensated by the higher evapotranspiration (42 mm) simulated at Kpandouga, the higher lateral flow (12 mm) and groundwater flow (16 mm) simulated at Kounga, and the higher evapotranspiration (24 mm) and groundwater flow (13 mm) at Tossahou (Table 7). These changes can be explained by the observation made by Rathjens and Oppelt (2012), who pointed out that the modifications that affect the distribution and composition of land use types, soil types and slopes also have an impact on the modelled streamflow components. Moreover, these authors indicated that the drainage density (defined as the length of all channels in the watershed divided by the total drainage area) increases as the number of grid cells increases. Consequently, transmission and deep aquifer losses have increased and reduced discharge has occurred in the watershed they investigated, which is named Bünzau. This watershed is located in the Northern German lowlands and is characterized by flat topography and shallow groundwater levels (Rathjens and Oppelt, 2012). In addition, the differences can also originate from the different concepts applied by which the lateral fluxes between grid cells are accounted for in SWATgrid, unlike ArcSWAT, in which no interaction between HRUs is considered. In fact, a constant flow separation ratio is applied in ArcSWAT to partition the amount of flow into landscape and channel flows (Arnold et al., 2010). On the other hand, in SWATgrid, the spatially distributed proportions are taken into account by using the modified topographic index. This index is mainly adjusted by the drainage density and applied to identify areas of high probability of runoff occurrence within the watershed (Rathjens et al., 2014).

4.2. Hydrological processes and nitrate loads under different degrees of agricultural intensification

In all inland valley watersheds, changes in streamflow are strongly controlled by the temporal pattern of precipitation. Actually, more than 60% of the available water from precipitation leaves the watersheds via evapotranspiration. This is similar to the results obtained by Giertz et al. (2010), who showed that 67% of precipitation was lost to evapotranspiration with values ranging between 720 and 894 mm in different sub-watersheds of the Upper Ouémé (Donga pont, Donga Affon, Beterou, and Agimo) that were investigated while assessing hydrological processes. Regardless of rainfall and other factors, the variation in runoff, which is highest in Kounga, followed by Tossahou, but lowest in Kpandouga, may result from the combined effects of topography, soil properties, land use, and shallow groundwater dynamics. Kpandouga is substantially covered (68%) by dense vegetation (gallery forest and tree savanna), whereas Kounga (30%) and Tossahou (26%) have relatively less vegetation cover, which may contribute to the restriction of overland flow and enable more water to infiltrate and recharge the shallow aquifer. This is confirmed by the annual water balance of Kpandouga, which indicates that percolation is the dominant process, after evapotranspiration, while the loss through surface runoff only represents approximately 2% of precipitation. In Kounga, cropland is dominant and steeper slopes prevail in both the fringes and the uplands, where the soil texture is mostly sandy loam. The precipita-

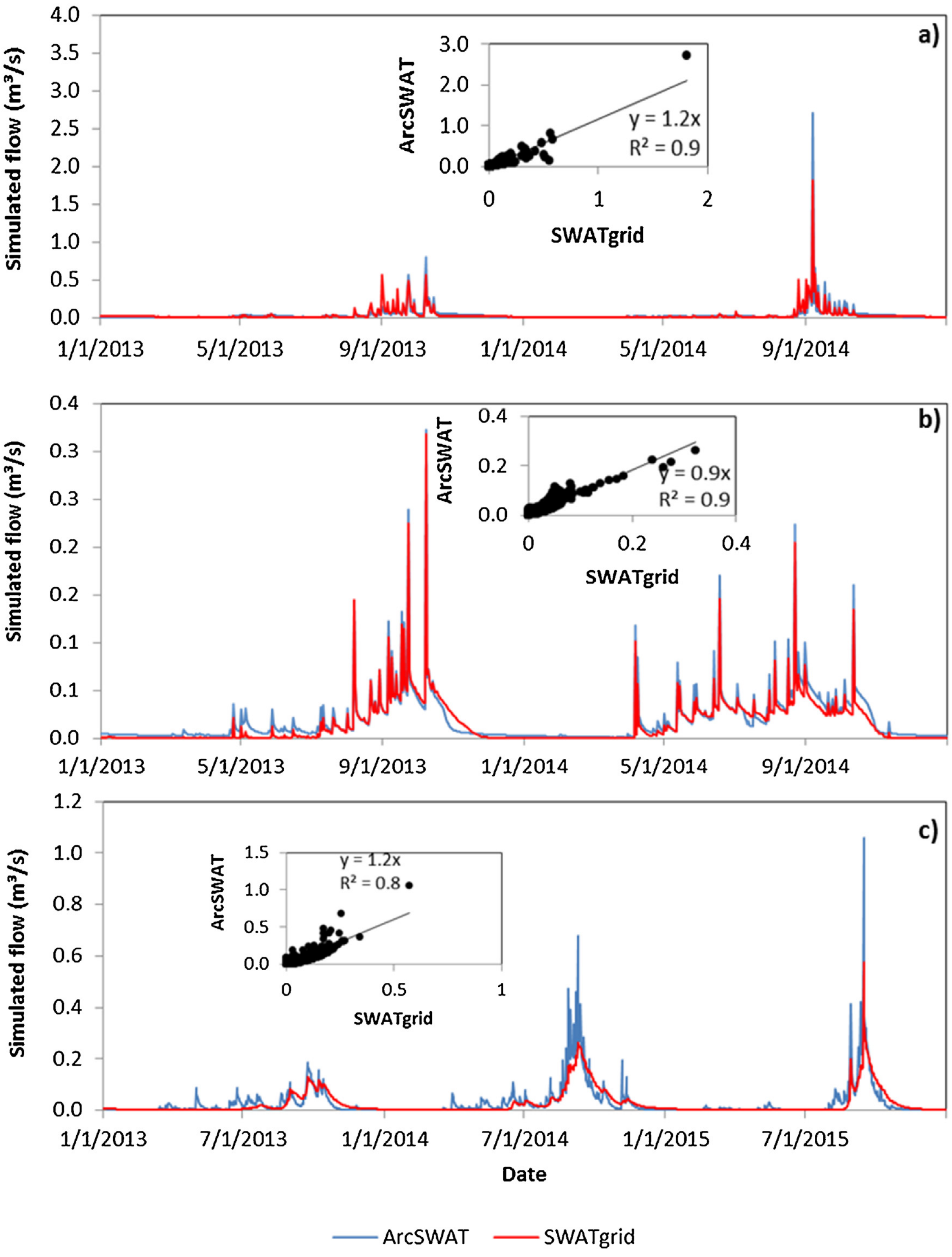

Fig. 6. Comparison of flow (m^3/s) simulated by ArcSWAT and SWATgrid, and corresponding scattergrams at the outlets of (a) Kounga (from 2013 to 2014), (b) Kpandouga (from 2013 to 2014), and (c) Tossahou (from 2013 to 2015).

tion amount was the highest of any of the three watersheds, and the water table remained close to the ground surface (<0.8 m) throughout the year in the lowland areas. On the other hand, in Tossahou and Kpandouga, the water table is only accessible during the wet season (with average depths of 0.62 m and 1.04 m, respectively). As a result, the inland valley of Kounga generates the largest amount of surface runoff and lateral flow during the simulated period. Thus, the risk of seasonal occurrence of flooding may be high in its lowland areas. In accordance with field observations, Kounga flooded earliest, followed by Tossahou later in the wet season, which lasted from the middle of August to October. However, some qualitative information gained from a collective interview with farmers indicates that seasonal flooding seldom occurs in Kpandouga. Hence, these seasonal differences in flood duration (and possibly depth) may depend on the morphology of the valleys, their longitudinal gradients, the lithology of the substrata (permeability), and on precipitation (Windmeijer and Andriesse, 1993). In Tossahou, the relatively low contribution from surface runoff might result from the combined effects of the predominantly sandy loam soil texture (Danvi et al., 2016), the wide and flat valley bottom, and the presence of some semipermeable levees constructed using traditional means (using ironstone fragments gathered together) across the valley bottom to reduce the velocity of the overland flow and enable rice cultivation. Thus, the retained water is more likely to infiltrate and contribute to the shallow aquifer, as reflected by the valley's high percolation ratio. Subsequently, the streamflow is sustained to a great degree via subsurface and groundwater flows with respect to the steeper areas characterizing the fringes and uplands.

The low nitrate loads simulated in all of the watersheds are probably related to the low rate of fertilizer application and to the dilution of the concentrations within the soil water system before the water reaches the stream channel. In fact, nitrate is very susceptible to leaching because of its minimal retention by soils (Neitsch et al., 2009). A study conducted by Lam et al. (2010) to determine the contribution of point and diffuse sources to nitrate loads in the Kielstau lowland watershed in Northern Germany using the SWAT model has indicated that diffuse sources are the main contributor to nitrate loads in the entire watershed. The authors point out that the contributions from diffuse sources of nitrate are higher for agricultural land, due to the high application of fertilizers, and lower for other land use types, especially for areas of forest cover in the watershed (Lam et al., 2010). Thus, the low level of nitrate loads predicted in the inland valleys may be accurate and is attributed to substantial contributions from vegetation cover and from cattle manure during grazing.

In summary, surface and subsurface flows are the dominant hydrological processes in the inland valley of Kounga where the land use is predominantly agriculture. They represent an essential portion of the streamflow and may play an important part in agricultural water management, especially in lowland rice production (Masiyandima et al., 2003). However, as a result of agricultural intensification, runoff generation and flooding risks may increase in Kounga due to its currently high level of cultivation and shallow groundwater table in the lowland areas. In Tossahou, where the level of cultivation is lower than that in Kounga, subsurface flow and groundwater recharge are more important. The prevalence of natural vegetation within Kpandouga tends to promote the recharge of groundwater, which may be altered in the future if more areas are cultivated to a great degree. However, the anthropogenic activities that are ongoing in all the inland valleys studied currently have no impact on water quality in terms of the nitrate content in the river, given that the concentration values do not exceed the standard limit of 10 mg/l NO_3-N that is recommended by the Environmental Protection Agency (EPA) as representing a threat to human health. Although the weaknesses of the SWAT model in representing subsurface flow in flat areas at a regional scale have been reported by some authors (Eckhardt et al., 2002; Hiepe, 2008; Sintondji, 2005), the importance of this hydrological process has been revealed at a local scale by previous studies conducted by Giertz et al. (2010) and Giertz (2004). In the same way, this study emphasizes the ability of the model to accurately capture the pattern of lateral flow in small inland valleys.

5. Conclusions

In this study, the SWAT model was applied to assess the dynamics of hydrological processes, as well as nitrate loads, in the inland valleys of Kounga, Tossahou, and Kpandouga, which are located in Djougou, central Benin. The results revealed that most of the water loss occurred via evapotranspiration in all three watersheds. The water balance indicates that surface and subsurface runoff contribute more to streamflow within the Kounga watershed. Within the watersheds of Tossahou and Kpandouga, the major contributions to streamflow come from subsurface runoff and groundwater flow. However, the conversion ratio of precipitation to runoff is the lowest in the Kpandouga watershed, which is attributable to the dominance of natural vegetation and the small proportion of cultivated areas. Regardless of the model's poor performance in simulating nitrate loads, the predicted annual values are very low in all watersheds, and this nitrogen originates to a great degree from the vegetation cover and cattle manure. Moreover, the low nitrate concentrations observed in stream water reveal no significant impact of the agricultural practices, which reflect different cultivation levels, on the water quality. Within the framework of this study, the SWAT model produced satisfactory results regardless of the uncertainties in the data, and it has proved to be a flexible and reliable tool for simulating the impact of agricultural management on the hydrological behavior of inland valleys. Furthermore, the calibrated model can be used by researchers or water management decision makers for future works to investigate the environmental impacts of changes of climate, land use, and management practices at long-term on water resources in the inland valleys. Thus, this will help in the study and development of effective adaptation strategies and policies in agricultural watershed management. Still, additional observations of discharge and nitrate loads are necessarily to be collected over a longer period in order to improve the dataset and properly validate the model for conducting an accurate water quality assessment in the inland valleys. Given the need for detailed spatial analysis, the grid-based version SWAT-grid is an effective tool that would require a spatial calibration in order to perform an effective quantitative evaluation of processes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agwat.2017.07.017.

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