Modelling the hydrological impact of rice intensification in inland valleys in Benin (West Africa)

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Dedication

This dissertation is lovingly dedicated to our **LORD Almighty GOD** for His love, our Lord **Jesus Christ** for His grace, and our comforter **Holy Spirit** for His sweet communion. ***"****Not to us, O Lord, not to us but to Your name give glory, for Your mercy and loving-kindness and for the sake of Your truth and faithfulness!****"*** Psalms 115:1.

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Abstract

The aim of this study is to assess the impact of climate change and rice intensification on water availability, water quality, and rice production. A spatial explicit approach was developed to determine suitable areas for rice production in the investigated inland valleys. The *Soil Water Assessment Tool* (SWAT) model is applied to simulate the hydrological behavior of inland valleys and their contributing watersheds considering water quantity and water quality. Three small headwater inland valleys were selected in the commune of Djougou in central Benin namely Kounga, Tossahou and Kpandouga. Kounga is characterized by the highest proportion of agricultural land use, followed by Tossahou while Kpandouga is dominated by natural vegetation and has the smallest proportion of cultivated areas. The watersheds areas are small than 5 km² and do belong to the Upper Ouémé catchment in Benin.

For modelling purpose, soil and land use maps were generated for each inland valley watersheds. In addition to hydrological observations of shallow groundwater levels and streamflow, surface water quality was determined using weekly collected water samples at the outlets of the watersheds. In a first step, the HRU-based ArcSWAT2012 model was applied while in a second step, the grid-based SWATgrid model was used. Model results were analyzed concerning their capacity to capture water quantity and water quality processes within the selected watersheds. The satisfactory model performance obtained from calibration and validation of daily discharges was the base to simulate climate change, land use change, and management scenarios using the calibrated model parameters. The emission scenarios A1B and B1 of the *Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios* (IPCC SRES) were combined with two land use scenarios defined at 25 % and 75 % of lowland conversion into rice fields. The management scenarios were developed based on the current rice cultivation system in the inland valleys and the rainfed-bunded cultivation system with and without fertilizers inputs. The scenarios were quantified and analyzed up to the year 2049 with a special focus on the period of 2040 to 2049.

The suitability of the inland valley of Tossahou for rice production was investigated as a case study using a GIS-based approach that evaluates and combines biophysical factors such as climate, hydrology, soil and landscape, following the FAO parameter method and guidelines for land evaluation. Hence, soil and landscape suitability was assessed for three different rice cultivation systems: rainfed bunded, cultivation under natural flooding, and irrigated cultivation.

The results revealed that more than 60 % of precipitation water is lost by evapotranspiration at all inland valley watersheds. Percolation is important in the Kpandouga watershed (28 % of precipitation) having the largest portion of natural vegetation, whereas surface and subsurface runoff reach the highest values in the Kounga watershed (105 and 92 mm). At all sites, nitrate loads are very low which is in accordance with the low fertilizer application rates. The water quality is not threatened by the occurring agricultural practices if a standard threshold of 10 mg/l NO_3-N is applied. In future, the impacts of climate change will be more significant concerning streamflow than the impacts caused by land use change at all watersheds. Substantial reductions of streamflow by up to 35 %, 47 %, and 51 % are projected for Kpandouga, Tossahou and Kounga, respectively. However, an increasing development of the lowland into rice fields under the current cultivation system will compensate the climatic effect on streamflow by up to 15 % at Kpandouga but will slightly enhance the effect by up to 2 % at Kounga and up to 8 % at Tossahou. Changes to a rainfed-bunded cultivation system will have no significant impact on water availability downstream. The suitability assessment of the inland valley of Tossahou for rice production especially indicated that 52% of the inland valley is suitable for irrigated cultivation, 18% for cultivation under natural flood and 1.2% for rainfed bunded rice. Besides precipitation, an increase of temperature causes an increase in potential evapotranspiration which is a limiting factor for all cultivation systems. Flooding was the most limiting factor for cultivation under natural flood while irrigated and rainfed-bunded cultivation systems were mostly limited by steep slopes and soil texture respectively. However, the results revealed that the social and economic environment restrict the yields more than the biophysical properties of the inland valleys.

In all watersheds, the temporal pattern of precipitation strongly impacts the streamflow dynamic. However, the combined effect of topography, soil properties, land use, and shallow groundwater dynamics also determines the variation in runoff, which is highest in Kounga, followed by Tossahou, and lowest in Kpandouga. As the system is water limited and not energy limited, the prevalence of water scarcity within the inland valleys is projected in long term due to the expected reductions in rainfall under climate change. Moreover, the altering effect of changes in land use on hydrologic processes within the watersheds will have no substantial impact on streamflow downstream. Although the uncertainties and limitations encountered in modelling, the strong performance of the SWAT model in small watersheds has been confirmed. Thus, the results achieved in this study can be used in spatial planning for sustainable development of rice cultivation with limited environmental impact on water resources in inland valley landscapes. Additionally, the intensification of rice on areas of favorable conditions will foster an optimized production if the social and economic constraints as the access to credit, the subsidies acquisition, and the access to market are overcome.

Zusammenfassung

Diese Studie untersucht den Einfluss des Klimawandels und der Intensivierung des Reisanbaus auf Wasserverfügbarkeit, Wasserqualität, und Ertrag. Drei kleine Flachmuldentäler (Inland Valleys) und deren Einzugsgebiete wurden in der Commune Djougou in Zentralbenin zur Untersuchung ausgewählt: Kounga, Tossahou und Kpandouga. Der Anteil der landwirtschaftlichen Nutzfläche ist in Kounga am höchsten, gefolgt von Tossahou. In Kpandouga dominiert die natürliche Vegetation und die landwirtschaftliche Nutzfläche ist am geringsten. Die Einzugsgebiete sind jeweils kleiner als fünf Quadratkilometer und gehören zum oberen Ouémé Einzugsgebiet.

Ein räumlich verorteter Ansatz wurde entwickelt, um geeignete Reisanbauflächen in den untersuchten Inland Valleys zu identifizieren. Das Soil and Water Assessment Tool (SWAT) Modell wurde angewandt um das hydrologische Verhalten der Inland Valleys sowie der zugehörigen Einzugsgebiete in Bezug auf Wasserquantität und Wasserqualität zu simulieren.

Zur Modellierung wurden Boden- und Landnutzungskarten für die jeweiligen Einzugsgebiete erstellt. Messinstrumente wurden installiert, um den Abfluss und den oberflächennahen Grundwasserspiegel zu erfassen. Die Oberflächenwasserqualität wurde durch wöchentliche Wasserproben an den Gebietsauslässen bestimmt. In einem ersten Schritt wurde das HRU-basierte Modell ArcSWAT 2012 angewandt und nachfolgend das rasterbasierte Modell SWATgrid. Die Modelle wurden anhand der Abflüsse mit zufriedenstellendem Ergebnis kalibriert und validiert. Die kalibrierten Modelle wurden verwendet, um Klimawandel, Landnutzungswandel, und Managementszenarien zu berechnen. Die Emissionsszenarien A1B und B1 des Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC SRES) wurden mit zwei Landnutzungsszenarien kombiniert, für die eine Umwandlung von 25 bzw. 75 % der Inland Valleys in Reisfelder angenommen wurde. Die Bearbeitungsszenarien basieren auf dem heutigen Reisanbausystem in den Inland Valleys, bei dem Nassreis mit und ohne Düngung angebaut wird. Die Szenarien wurden bis zum Jahr 2049, mit besonderem Fokus auf die Periode 2040 bis 2049, quantifiziert und analysiert.

Die Eignung des Tossahou Inland Valleys zum Reisanbau wurde mithilfe eines GIS-basierten Ansatzes untersucht, bei dem die biophysischen Faktoren Klima, Hydrologie, Boden und Geomorphologie nach der FAO Parametermethode und den FAO Richtlinien zur Landevaluation analysiert wurden. Drei verschiedene

Reisanbausysteme wurden auf ihre Eignung untersucht: Nassreis mit Wasserrückhalt, Nassreis auf natürlich überfluteten Flächen, und bewässerter Reis.

Die Ergebnisse zeigen, dass in allen drei Einzugsgebieten 60 % des Niederschlags durch Evapotranspiration verloren gehen. Perkolation ist ein wichtiger Prozess in Kpandouga (28 % des Niederschlags), dem Einzugsgebiet mit dem größten Anteil natürlicher Vegetation. Oberflächenabfluss und unterirdischer Abfluss erreichen die höchsten Werte im Kounga Einzugsgebiet (105 bzw. 92 mm). Die Nitratgehalte sind in allen Gebieten bedingt durch den geringen Düngemitteleintrag sehr niedrig. Die Wasserqualität ist durch die momentane landwirtschaftliche Nutzung nicht gefährdet wenn ein Grenzwert von 10 mg/l NO3-N angenommen wird. In Zukunft werden Einflüsse des Klimawandels den Abfluss stärker beeinflussen als Änderungen der Landnutzung. Projektionen des Abflusses für die IPCC Szenarien A1B und B1 für Kpandouga, Tossahou und Kounga zeigen eine substanzielle Reduktion des Abflusses von 35 %, 47 % und 51 %. Allerdings wird die Zunahme an Reisanbauflüche in den Inland Valleys diesen Effekt in Kpandouga um bis zu 15 % kompensieren. In Kounga und Tossahou wird die Reduktion des Abflusses hingegen durch Landnutzungsänderungen um 2 bzw. 8 % verstärkt. Die Änderung des jetzt üblichen Reisanbaus in ein Nassreissystem mit Wasserrückhalt hat keine signifikante Auswirkung auf die Abflüsse. Die Analyse der Nutzungseignung des Tossahou Inland Valleys zeigt, dass 52 % der Fläche für den Anbau von bewässerten Reis geeignet sind, 18 % für Nassreis auf natürlich überfluteten Flächen, und 1,2 % für Nassreis mit Wasserrückhalt. Die Wasserverfügbarkeit, gesteuert durch Niederschlag und durch die von der Temperatur beeinflusste potentielle Evapotranspiration, ist der limitierende Faktor in allen Einzugsgebieten. Während die Ausdehnung der überfluteten Bereiche der am stärksten limitierende Faktor für den Reisanbau auf überfluteten Flächen ist, ist der Nassreisanbau mit Wasserrückhalt durch das Gefälle der Bodenoberfläche und durch die Bodentextur limitiert. Allerdings zeigen die Ergebnisse, dass die sozioökonomischen Faktoren die Erträge stärker limitieren als die biophysischen Gegebenheiten der Inland Valleys.

In allen Einzugsgebieten beeinflusst das zeitliche Niederschlagsmuster die Abflussdynamik stark. Allerdings bedingen die kombinierten Effekte von Topographie, Bodeneigenschaften, Landnutzung und die Dynamik des flachen Grundwasserspeichers Variationen im Abflussgang. Am höchsten sind diese in Kounga, gefolgt von Tossahou und Kpandouga. Da das untersuchte System wasser- und nicht energielimitiert ist, wird der Wassermangel in den Inland Valleys den Simulationen zufolge durch die Abnahme der Niederschläge aufgrund des Klimawandels verstärkt. Landnutzungsänderungen hingegen werden keine substanziellen Auswirkungen auf die Abflüsse haben. Trotz der beobachteten Unsicherheiten und Limitierungen des Modells hat sich SWAT als gut geeignet zur Modellierung in den kleinen Einzugsgebieten herausgestellt. Aufgrund dessen sind die Ergebnisse geeignet, in der räumlichen Planung zur nachhaltigen Intensivierung des Reisanbaus eingesetzt zu werden, um die Auswirkungen auf die Wasserressourcen zu minimieren. Durch die Intensivierung des Reisanbaus auf geeigneten Flächen können die Erträge erhöht werden, wenn die sozioökonomischen Limitierungen wie beispielsweise der Zugang zu Krediten, der Erwerb von Produktionszuschüssen und der Zugang zum Binnenmarkt bewältigt werden.

Résumé

Le but de cette étude est d'évaluer l'impact du changement climatique et de l'intensification du riz sur la disponibilité en eau, la qualité de l'eau, et la production du riz dans les bas-fonds. Pour ce faire, le modèle SWAT (*Soil Water Assessment Tool*) a été sélectionné pour décrire le comportement hydrologique des bas-fonds en relation avec leur bassin de drainage respectif en termes de quantité et de qualité de l'eau. Aussi, a été développée une approche explicite pour la détermination de zones adéquates et potentielles pour une production rizicole optimizée. Pour atteindre ces objectives, trois bas-fonds communément nommés Kounga, Tossahou, et Kpandouga ont été sélectionnés dans la commune de Djougou dans le Bénin central. Les bassins de drainage des bas-fonds couvrent une superficie de moins de 5 km² et appartiennent tous au bassin de la Haute Vallée de l'Ouémé. Le bas-fond de Kounga est caractérisé par une proportion plus élevée de terre cultivée suivi de celui de Tossahou. Kpandouga quant à lui est principalement dominé par la végétation naturelle et est très peu cultivé.

Des cartes de sol et d'occupation du sol ont été développées pour la modélisation à chacun des sites étudiés. Aussi, ont été effectués des suivis d'observations hydrologiques sur les variations de niveau de la nappe phréatique superficielle et de débit à l'exutoire des bassins ; et la qualité de l'eau y a été analysée à travers la collecte hebdomadaire d'échantillons d'eau. Dans un premier lieu, les interfaces ArcSWAT2012 et SWATgrid du modèle SWAT ont été utilisés pour comparer leur capacité à capturer les processus liés à la quantité et à la qualité de l'eau dans les différents bassins de drainage. La bonne performance du modèle obtenue pour la calibration et la validation des débits d'eau journaliers nous a permis de procéder par la suite à la simulation d'impacts en se basant sur des scenarios de changements climatiques, changements d'occupation de sol et de pratiques agricoles tout en faisant usage des paramètres calibrées obtenus à travers l'exécution de l'interface ArcSWAT. Les scénarios d'émissions A1B et B1 de ''l'*Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios* (IPCC SRES)'' ont été combinés à deux scénarios de changement d'occupation de sol définis en termes de conversion de la zone impliquant les franges et de la partie centrale des bas-fonds en champs de riz à 25 et 75 %. Le changement de pratiques agricoles a été simulé en se basant sur le système actuel de culture du riz dans les bas-fonds sélectionnés et sur le système de culture du riz pluvial avec réalisation de diguettes en incluant l'utilisation ou non d'engrais. Dans cette étude, tous les scenarios ont été analysés jusqu'en 2049 tout en se focalisant sur la période allant de 2040 à 2049.

En effet, le bas-fond de Tossahou a été prise comme étude de cas pour l'évaluation des zones potentielles à la culture du riz en faisant usage d'une approche basée sur le système d'information géographique qui évalue et combine des facteurs biophysiques tels que le climat, l'hydrologie, le sol, et la topographie, tout en suivant la méthode des paramètres et les recommandations de la FAO. Ainsi, la potentialité du bas-fond en termes de sol et topographie a été évaluée pour trois différents systèmes de culture du riz : le système de culture de riz pluviale sous diguettes, le système de culture sous riz inondée, et le système de culture de riz irriguée.

Les résultats ont révélé que plus de 60 % de l'eau provenant des pluies est perdue par évapotranspiration sur tous les bassins. La percolation d'eau est plus importante à Kpandouga (28 % de précipitation), pendant que les écoulements superficiels et hypodermiques d'eau atteignent des valeurs plus élevées à Kounga (105 et 92 mm). Dans tous les bassins, la perte en nitrate est vraiment basse pour raison de la faible quantité d'engrais appliquée, ce qui fait que les pratiques agricoles ne constituent pas une menace pour la qualité de l'eau au seuil standard de 10 mg/l NO_3-N. En outre, les impacts liés aux changements climatiques pourraient être plus important sur l'écoulement d'eau dans les trois bassins étudiés. Une diminution importante du débit d'eau allant jusqu'à 35 %, 47 %, et 51 % est respectivement projetée pour Kpandouga, Tossahou et Kounga. Toutefois, sous le système de culture actuel, une conversion élevée des bas-fonds en champ de riz compenserait l'effet climatique sur le débit d'eau de 15 % à Kpandouga, mais l'augmenterait légèrement jusqu'à 2 % à Kounga et 8 % à Tossahou. Un changement de système en culture de riz pluvial avec réalisation de diguettes n'aurait aucun effet significatif sur la disponibilité de l'eau à l'exutoire. L'évaluation des zones potentielles pour la culture de riz dans le bas-fond de Tossahou indique notamment que 52 % du bas-fond est convenable pour une culture irriguée de riz, 18 % pour une culture inondée et 1.2 % pour une culture de riz pluvial sous diguettes. En plus de la précipitation, l'augmentation de la température engendre une élévation de l'évapotranspiration potentielle qui est un facteur limitant pour tous les systèmes de culture de riz. Les événements d'inondation saisonniers et inattendus constituent un facteur limitant important pour la culture de riz inondée, pendant que les deux autres systèmes de culture sont beaucoup plus limités par l'occurrence de pentes abruptes et par la texture du sol.

Au niveau de tous les bassins de drainage, la distribution temporelle de la pluie influence fortement la dynamique du débit d'eau. Toutefois, l'effet combiné de la topographie, des propriétés du sol, de l'occupation des terres, et de la dynamique de la nappe phréatique détermine aussi la variation de l'écoulement qui est plus élevé à Kounga, suivi de Tossahou, et plus bas à Kpandouga. Du fait que le système est dépendant d'eau et non d'énergie, la prévalence d'une faible disponibilité en eau est projetée dans le futur en raison de la diminution des pluies sous l'effet des changements climatiques. Toutefois, les effets altérants de l'expansion des terres cultivées sur les processus hydrologiques dans les bassins seront sans impact substantiel sur le débit d'eau à l'exutoire. Malgré les incertitudes et limitations liés à la modélisation, la bonne performance du model SWAT dans les petits bassins a été confirmée. De ce fait, les résultats atteints dans cette étude peuvent être utilisés dans la planification spatiale pour un développement durable de la culture du riz avec un impact environnemental limité sur les ressources en eau dans les bas-fonds. De plus, l'intensification du riz dans les zones de conditions favorables pourra assurer une production optimisée si les contraintes d'ordre social et économique telles que l'accès au crédit, l'obtention de subvention, et l'accès au marché pour écouler les produits de récolte sont abordées avec succès.

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Abbreviations

AFD	French agency for development (Agence Francaise de Développement)
AMMA-CATCH	African Monsoon and Multidisciplinary Analysis-Coupling the Tropical Atmosphere and the Hydrological Cycle
ArcSWAT	Hydrological Response Unit-based Soil Water Assessment Tool interface
ASECNA	Agency for Aerial Navigation Safety in Africa and Madagascar (L'Agence pour la Sécurité de la Navigation aérienne en Afrique et à Madagascar)
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AWC	Available Water Content of soil at saturation [mm/mm]
BD	Soil Bulk Density [g/cm^3]
BS	Base Saturation [%]
Cal	Soil calcium carbonate content [%]
CCR	Rice farmers consultation committee of Benin (Comité de Concertation des Riziculteurs du Bénin)
CEC	Cation Exchange Capacity [cmolcM.kg]
CECapp	Apparent cation exchange capacity [cmolcM.kg]
CMN	Rate factor for humus mineralization of active organic nitrogen [-]
CN2	Curve Number for moisture condition II [-]
DAS	Day After Sowing
De	Depth of flood [cm]
DEM	Digital Elevation Model
DD	Drainage density factor affecting the flow separation ratio [-]
DGE	General Department of Water (Direction Générale de l'Eau)
Du	Duration of flood [month]
ECHAM	European Centre Hamburg Model
EPA	Environmental Protection Agency
EPCO	Plant uptake compensation factor [-]
ESCO	Soil evaporation compensation factor [-]
ET	Actual evapotranspiration [mm]

FAO	Food and Agriculture Organisation
GDEM	Global Digital Elevation Model
GIS	Geographic Information System
GPS	Global Positioning System
GW_DELAY	Groundwater delay [-]
GWQ	Groundwater flow [mm]
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur [-]
GW_REVAP	Groundwater re-evaporation coefficient [-]
HRU	Hydrological Response Units
HRU_SLP	Hydrological response unit average slope steepness [-]
IMPETUS	Integrative management project for an efficient and sustainable use of freshwater resources in West Africa
IPCC SRES	Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios
ITRA	Togolese Institute of agronomic research (Institut Togolais de Recherche Agronomique)
IV	Inland Valley
IVC	Inland Valley Consortium
IWMI	International Water Management Institute
K	Saturated hydraulic conductivity [mm/hr]
L1	Land use change scenario of lowland conversion at 25 %
L2	Land use change scenario of lowland conversion at 75 %
LAI	Plant Leaf Area Index [m^2/m^2]
LATQ	Lateral flow [mm]
MAAF	Ministry of Agriculture, Fisheries and Forestry
MAEP	Ministry of Agriculture, Livestock, and Fisheries (Ministère de l'Agriculture, de l'Elevage, et de la Pêche)
MOS	Model Output Statistics
NASA	National Aeronautics and Space Administration
NCA	National Climate Assessment

NERICA	New Rice for Africa
NF	Cultivation under natural flooding
NPERCO	Nitrogen percolation coefficient [-]
NRDS	National Rice Development Strategy
NSE	Nash-Sutcliffe Efficiency
PAPPI	Development Project of Small Irrigated Perimeters
PASR	Agricultural Services Restructuring Project
PBIAS	Percent bias
PET	Potential Evapotranspiration [mm]
p-factor	percentage of observations falling within the 95 % prediction uncertainty range
PHU	Total heat units required for plant maturity
PREC	Precipitation [mm]
PUASA	Emergency Program to Support Food Security
PVC	Polyvinyl chloride
R^2	Coefficient of determination
RA	Rainfed-bunded system
REMO	Regional climate Model
r-factor	Relative width of the 95 % probability band
RG1	Tipping-bucket Rain Gauge
$RH_{harvest}$	Relative Humidity at harvest stage [%]
RI	Irrigated rice cultivation
S	Slope [%]
SBC	Sum of Basic Cations [cmolcM.kg]
SCS	Soil Conservation Services
SLSUBBSN	Average slope length [-]
SMART-IV	Sawah, Market Access and Rice Technologies for Inland Valleys
SOC	Soil Organic carbon Content [%]
SOL_AWC	Available water capacity of the soil layer [-]
SPOT	Earth observation satellites (Satellites d'Observation de la Terre)
SUFI	Sequential Uncertainty Fitting
SURQ	Surface runoff [mm]

SWAT	Soil Water Assessment Tool
SWAT-CUP	Soil Water Assessment Tool - Calibration and Uncertainty Programs
SWATgrid	Grid-based Soil Water Assessment Tool interface
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurements
TEMP	Temperature [°C]
T_{max}	Mean maximal temperature [°C]
T_{mean}	Mean temperature [°C]
T_{min}	Mean minimal temperature [°C]
TN	Total nitrogen
TOPAZ	Topographic Parametrization
TPI	Topographic Position Index
USDA	United States Department of Agriculture
WASCAL	West African Science Service Center on Climate and Adapted Land Use
WEGE	Weather Generator
WMO	World Meteorological Organization
WRB	Word Reference Base
WYD	Total water yield [mm]
95PPU	95 % Prediction Uncertainty

Chapter 1

General introduction

1.1. Background and significance of the study

Likewise in Asia, rice has become one of the most important cereal crops in West Africa (Bada and Ndiaye, 2010). In the attempt to reduce the increasing imports by improving the production in many countries such as Benin, inland valleys have recognized to be of high potential for the development of rice-based smallholder farming systems (Speth et al., 2012; Giertz et al., 2008). This potential is mainly due to soil fertility and to specific hydrological conditions in the valley bottoms where groundwater is at or near the surface during most of the year or seasonally, depending on the climatological zone. Additionally, lateral inflow of groundwater from the higher parts of the landscape effectively prolongs the growing period for crops in the transition between these valleys bottoms and the adjacent uplands (Windmeijer and Andriesse, 1993).

Benin has an estimated wetland area of 322,000 ha which are only developed at a small proportion for food production (Worou et al., 2012). Thus, extensive research has been performed focusing on their agro-potential and geomorphologic aspects (e.g. Giertz et al., 2012). The aim of most of the studies was to improve sustainable water resources management strategies as well as agricultural practices to be adopted at field scale in order to optimize the crop production. For instance, recent studies have been dealing with determining constraints on the use of inland valleys ecosystems (Giertz et al., 2012), investigating the inland valleys soil fertility potential for rice production (Abe et al., 2010), assessing constraints and opportunities linked to the contribution of such valleys intensification to sustainable rice cropping development (Adetonah et al., 2010; Rodenburg et al., 2014) as well as assessing the soil water dynamics of inland valleys and rice crop growth as affected by the use of water-saving and nutrient management technologies such as bunding and fertilizers application for increasing rice production (Worou et al., 2012).

Nonetheless, it is important to point out that the current way through which tremendous increases in food production were achieved over the past 50 years has involved the intensification of agriculture by use of high-yielding crop varieties, fertilization, and irrigation (Matson et al., 1997). Irrigation and fertilizers have played and will play in future an important role in increasing crop production, especially cereal yields, required to feed the expanding world population (Balu et al., 1996). However, a development of rice cultivation in the inland valleys towards the goal of increasing food security will also impact water resources. Changes in water quantity may occur from altered hydrological processes at the watershed scale, and the expansion of irrigated areas may result in groundwater overuse and streamflow depletion (Vörösmarty and Sahagian, 2000). While supplementary irrigation reduces some of the uncertainties related to the seasonal rainfall variabilities and promotes increased production, land transformation involved due to clearing, plowing, leveling, canals and bunds construction for water distribution, etc. and the quantity of water applied might disturb the local or regional water balance. Besides the effect on water quantity, water quality could be also affected, as losses of nitrogen occurring from rice fields mainly through ammonia volatilization, denitrification, leaching, and runoff not only cause losses of nitrogenous fertilizers, but have environmental consequences (Bandyopadhyay et al., 2004) such as severe stream water eutrophication.

Much research have been carried out in other region of the world to study the water discharge and nutrient loads from paddy rice culture and their impacts on downstream water bodies (App et al., 1984; Ishikawa et al., 1992; Kaneki, 1989; Kyaw et al., 2005; Li and Yu, 1999; Maruyama and Tanji, 1997; Misawa, 1987; Nagasaka et al., 1998; Pathak et al., 2004; Tabuchi, 1986; Tabuchi and Takamura, 1985). A general finding is that temporal variabilities in nutrient export and concentration in stream flow are subject to basic controls such as climate, nutrient availability, and agricultural activities (Arheimer and Liden, 2000; Kemps and Dodds, 2001; Pionke et al., 1999). As far as Africa is concerned, studies on assessing the impacts of agricultural intensification on water resources are scarce and only few studies have been carried out in Benin. Bossa et al. (2012) investigated the effects of crop patterns and management scenarios on nitrogen (N) and phosphorus (P) loads to surface water and groundwater in the Donga-Pont catchment a tributary of the Ouémé catchment. From this work, it was found that decreases in sediment and nutrient loads were due to reductions in rainfall and that the effects of decline in rainfall were counterbalanced by the effects of land use changes. As a conclusion, the results showed a relationship between agriculture and water quality controlled by the management practices such as fertilizer inputs (Bossa et al., 2012).

Therefore, only aiming at intensifying rice cultivation to improve production in inland valleys, just because resources are available and remain widely unexploited, is not sufficient. Beyond this and to promote sustainable management, it is important to determine the magnitude of the environmental impact. The AfricaRice Center (Benin) in cooperation with the University of Bonn (Germany) supervised this study within the SMART-IV project. The acronym SMART-IV stands for "*Sawah, Market Access and Rice Technologies for Inland Valleys*". The project aimed at sustainable improvement of rice production in inland valleys by introducing the 'Sawah' technology to African rice farmers. Sawah technology refers to the typical terraced and bunded fields that provide the conditions to submerge the fields. This was typically found in Asian conditions and has shown to increase rice yields significantly. The target countries of the SMART-IV project are currently Togo and Benin. Financed by the *Japanese Ministry of Agriculture, Fisheries and Forestry* (MAFF), the project is multi-disciplinary and include economists, water managers, soils fertility scientists as well as GIS and developments experts from the *Africa Rice Center*, the *Cellule Bas-Fonds* in Benin, the *'Institut Togolais de Recherche Agronomique'* (ITRA) in Togo and the *International Water Management Institute* (IWMI) in Ghana.

At the end of this study, it should be possible to describe how and to define at which extent rice intensification may impact the hydrological behavior of inland valleys by investigating the major hydrological processes, by assessing how their spatial and temporal variability affects the generation of streamflow, and by analyzing the resulting changes of nitrogen concentration in water discharge from the contributing watersheds.

1.2. Objectives of the study

The general objective of this study is to acquire a better understanding of the impacts of the agricultural practices caused by rice intensification on water quantity in inland valleys in Benin. In addition, this study aims to contribute in improving strategies for attaining food security through the promotion of an ecological and sustainable management of rice-growing ecosystems and water resources of wetlands in Benin. However, assuring a sustainable management of water resources under rice intensification in the inland valleys requires a thoroughly detailed knowledge on their hydrological behaviors with respect to their contributing watersheds, on the degree to which they may be affected by the agricultural practices involved, and the impact of possible changes which may occur on the major hydrological processes. Thus, specifically in this work:

(1) we evaluate the capacity of a spatially explicit hydrological model to capture water quantity and water quality processes in three headwater inland valley watersheds with different levels of agricultural development in Benin;
(2) we assess the future changes caused by rice intensification in the water balance under climate change at the inland valley watersheds. Moreover, for Benin to be self-sufficient in rice in the near future while limiting the environmental impacts induced under intensification, it is important to implement an efficient development strategy which must potentially improve rice production in the inland valleys, and which must be technically and economically affordable to the small-scale

farmers as they currently produce 90 % of the country rice outputs (United States Department of Agriculture, 2013).

(3) we develop therefore, a spatially explicit approach to determine suitable areas within the inland valleys for an optimal rice production because traditional smallholder still depend on the physical condition of the land.

Subsequently, the research questions arising are:

(1) How accurately can a physically based and spatially distributed model describe the hydrological behavior of an inland valley as affected by its contributing watershed properties;
(2) what are the spatial and temporal changes on water availability in inland valleys under rice intensification;
(3) how to determine fields suitable for rice growing for aiding small-scale farmers in improving their production and sustaining their life.

1.3. Outline of the dissertation

To address the specific objectives described before, this dissertation is organized in eight chapters starting with an introduction of the study background and significance, the objectives and an overview of rice production in Benin. Chapter 2 describes the research area as well as the agricultural management practices involved at the selected watersheds. Chapter 3 contains a review of the Soil Water Assessment Tool (SWAT) model applied in this study. In chapter 4, the model input data used, the experimental field setup and the data monitored over the period of investigation from 2013 to 2015 are presented. Chapter 5 compares the water quantity and water quality in the three inland valley watersheds selected with different levels of agricultural development in central Benin. Chapter 6 assesses the impacts of climate change and lowland rice intensification on water availability in these inland valleys. Chapter 7 develops a spatially explicit approach to identify the suitable areas for rice cultivation in an inland valley. Finally, chapter 8 summarizes the findings made out of this research and makes some recommendations for future studies.

Chapter 2

Research area

2.1. Location

Benin is a West African country drained by a dense river network with the Ouémé as the main river which is 510 km and represents the largest watershed of the country (Sintondji et al., 2014), covering an area of 49256 km² (Bossa, 2012). This study is carried out at the Upper Ouéme´ watershed where three headwater inland valleys are selected in the vicinity of the city of Djougou which belongs to the sub-humid Sudan-Guinea climatological zone (Figure 2.1).

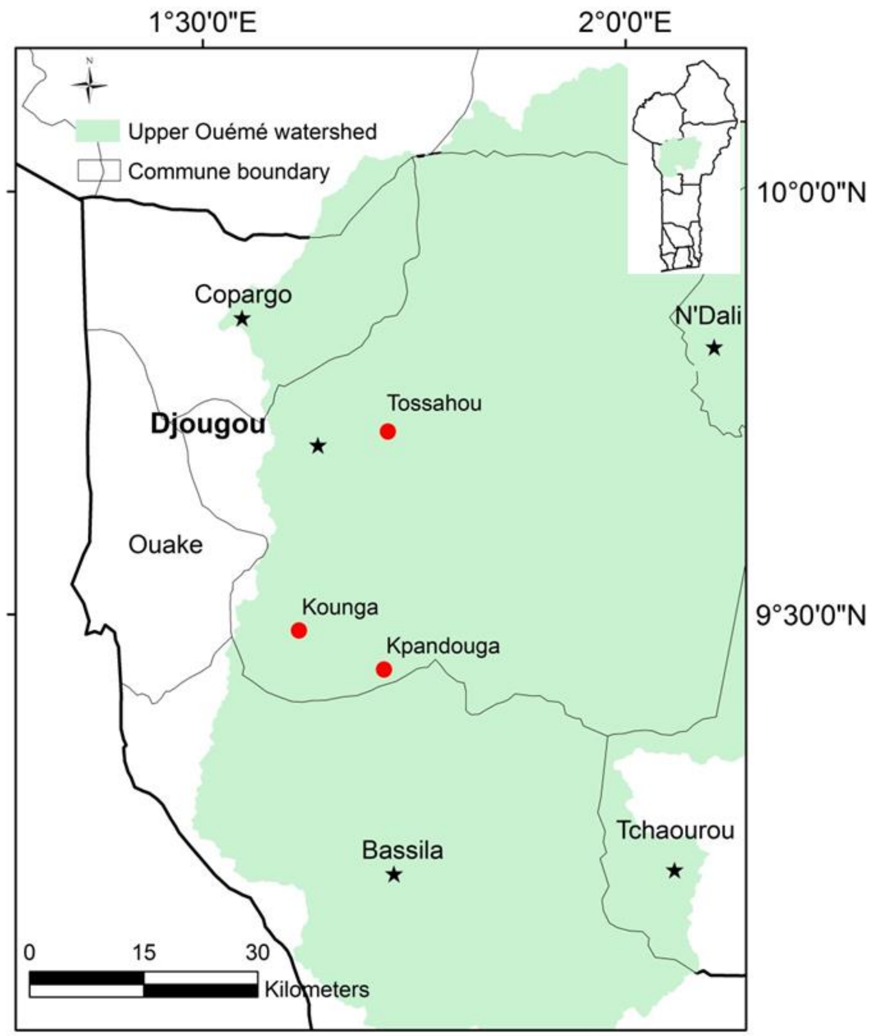
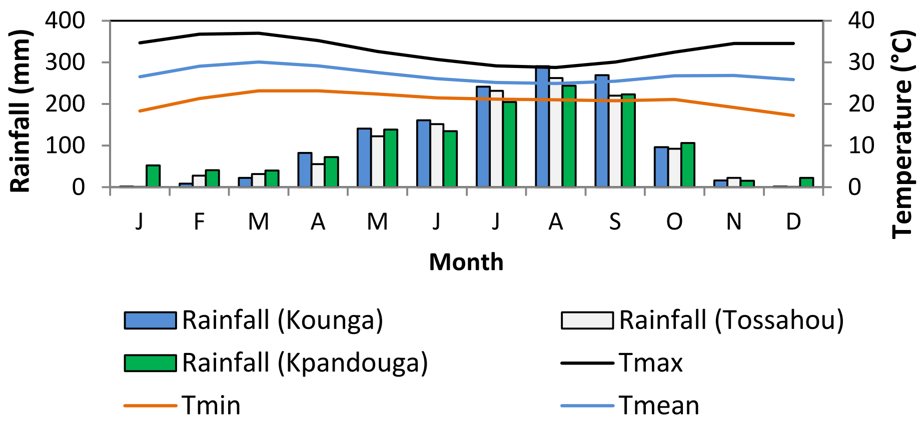


Figure 2.1. The Upper Ouémé watershed, its communes Bassila, Djougou, N´Dali, and Tchaourou (marked as star) as well as the location of the inland valleys Kounga, Kpandouga, Tossahou (ret dots) in Benin.

The investigated watersheds are characterized by different land cover and different agricultural intensification levels and have drainage areas of 4.06 km² for Kounga, 4.99 km² for Tossahou, and 3.85 km² for Kpandouga. Kounga is located in the southern part of commune Djougou in the village Pelebina, around 20 km from the city of Djougou. Kpandouga is also located at the southern part of the commune but belongs to a village with the same name Kpandouga, around 35 km from the city of Djougou. The inland valley of Tossahou is located in the eastern part of the commune around 9 km from the city of Djougou and belongs to the village Tossahou. A detailed characterization of watersheds is given in chapter 4.

2.2. Climate

The climate is sub-humid with a distinct dry and rainy season. It is dry from November to March while the rainy season is from April to October (See Figure 2.2). Mean annual rainfall is 1250 mm per year that peaks in August (Fink et al., 2010; Duku et al., 2015). The annual potential evapotranspiration is 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/m² (IMPETUS, 2007). High temporal variability in insolation is caused by a high cloud cover in the rainy season, and during the dry season by dust particles transported by the northeasterly dry and dusty harmattan winds from the Sahara towards the Guinea coast (Knippertz and Fink, 2006; IMPETUS, 2007). 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 220 W/m^2 received at the surface (AMMA-CATCH, 2015).



Tmax, maximum temperature; Tmin, minimum temperature; Tmean, mean temperature.

Figure 2.2. Average monthly rainfall measured in Kounga (from 2003 to 2015), Tossahou (from 2003 to 2015), Kpandouga (from 2008 to 2015), and monthly temperature measured in Djougou (from 2003 to 2015). Data source: African Monsoon and Multidisciplinary Analysis-Coupling the Tropical Atmosphere and the Hydrological Cycle (AMMA-CATCH) database.

2.3. Hydrology

Benin contributes to the river systems of the Niger, the Volta, the Mono, the Couffo, and the Ouémé. In the Ouémé catchment, rainfall-runoff variability is high, leading to an annual runoff coefficients varying from 0.10 to 0.26 with the lowest values occurring in the savannahs and forest landscapes (Diekkrüger et al., 2010; Bossa et al., 2012b). In the Upper Ouémé catchment, most of the precipitation comes from squall lines which results in a short period of high intensive rainfall followed by a longer tail with low intensities. The severe rainfall generally occurs at night because they origin from the Jos plateau in Nigeria where clouds were generated in the later afternoon (Giertz, 2004). The watersheds are mainly characterized by a periodic discharge from June to December, and the rivers dry out from December to May. In the small rivers, the time between the peak of rainfall and the peak of discharge is extremely short and overbank flow is common (Giertz et al., 2006).

As is often seen in West Africa, two aquifers could be identified: 1) fractured rock aquifer at the depth of about 20 m below the surface and 2) a shallow saprolite aquifer with a fluctuating groundwater table depending of the rainfall pattern. The shallow aquifer is often used for water supply and is replenished during the rainy season (Giertz et al., 2006). However, the irrigation sector is relatively poorly developed in the watershed (Duku et al., 2015).

Likewise the entire Ouémé basin, the upper Ouémé watershed features a widespread occurrence of swampy depressions named as inland valleys or *bas fonds* in French that are regularly flooded during the rainy season (Diekkrüger et al., 2010). These inland valleys are important for food production (Giertz et al., 2012). Moreover, they are expected for having high impacts on the hydrological processes occurring in the watershed (Bossa, 2012).

2.4. Geomorphology, geology and soils

In the research area, the relief is defined as an undulating pediplan with altitudes from 255 to 333 m above sea level overlying a Precambrian crystalline basement (Giertz et al., 2006). The Precambrian consists predominantly of complex migmatites, granulites and gneisses, including less abundant mica shists, quartzites and amphibolites. Synandpost-tectonic intrusions of mainly granites, diorites, gabbros and volcanic rocks are present (Wright and Burgess 1992; Reichert et al., 2010). The major soil types are fersialitic and ferralitic soils with gravelly or plinthic horizons, and hydromorphic soils occurring near the river (Hiepe, 2008). According to the World Reference Base classification, the main soil types are classified as Lixisols and Acrisols (ISSS Working Group RB, 1998). Junge (2004) revealed they mainly occur on the middle part of the hillslopes. They are characterized by loamy sand in the ochric horizon, by clay accumulation in an argic horizon and by plinthitic gravel as evidence of the accumulation of iron compounds. The shallow Plinthosol occurs near the drainage divide and at the bottom of the hillslope. Gleysols are predominant in inland valleys and could be characterized by a sandy or a clayey texture. The sandy Gleysols are often encountered at the borders of the inland valleys, while in the center the clayey Gleysols are prevalent (Giertz, 2006; Junge, 2004).

2.5. Vegetation

The natural vegetation in central Benin is dominated by a mosaic of wet savannah woodland and small forest islands types which are severely degraded in the north-western part of the region (Duku et al., 2015; Giertz et al., 2006). Only very few small forest areas remain undisturbed, mainly holy forests (forêts sacrées). The highest proportion is located inside protected zones, the so called forêts classées. The wood savannahs and gallery forest are mainly characterized by species such as Anogeissus leiocarpus, Daniellia oliveri, and Lophira lanceolate. Hydromorphics soils are characterized by species such as Anogeissus leiocarpus, Pterocarpus santalinoides, Terminalia macroptera, Acacia caffra, and plantation species such as Mangifera indica, Carica papaya, Psidium quayaya, Tectona grandis (teck), Dolonix regia, and Anacardium occidentale (Bossa, 2012). The agricultural land use in central Benin is unequally distributed in space, and of higher proportion in areas of higher population densities. This is also the case in the commune Djougou which has been reported in 2000 to feature the highest population density with 46.1 inhabitants per km², and to have the highest proportion of agricultural land use with nearly 22 % of the total surface in use, while more than 50 % of the area is occupied by savanna (Judex et al., 2010).

2.6. Overview of rice production in Benin

Food production is gradually receiving more scientific and financial investments due to increasing population growth with increasing global food demand and changing food preferences. With a relatively high demographic growth rate and 10 008 749 inhabitants (in 2013) on an area of 114 763 km², Benin is one of the world developing countries whose economy is largely dependent on agriculture (Kuhn et al., 2010). Despite its huge potential in terms of water availability and agricultural lands which can be used for a diversified and intensive agriculture, rice supply cannot keep up with demand (Worou et al., 2012). Rice production has really been initiated after the year 1960 as reported by the *Comité de Concertation des Riziculteurs du Bénin* (CCR). During the period from 1961 to 1978, production has experienced a rapid increase under the development of irrigated systems. In the beginning of the 80s, theses large irrigated areas were abandoned and production of rice substantially decreased consequently from 20 000 tons/a to less than 10 000 tons/a. The sector has been restored at the beginning of the years 90s and has been boosted since then (CCR, 2004). In Benin, agriculture contributes with 31.6 % to the country's gross domestic product (FAO Stat, 2011), and rice is usually grown in the lowland part of inland valleys where also gravity irrigation is practiced, and at the upland part where farmers can perform either rainfed upland rice or irrigated rice using pumped water (Totin et al., 2013). Production is usually sold and not used in subsistence farming due to its high value (Igué, 2000). However, the rice self- sufficiency rate of the country is about 53%, resulting in the need for annual imports (e.g. 522,772 metric tons were imported in 2010) to meet the growing rice demand (MAEP, 2010; Totin et al., 2013). In fact, the productivity of rice systems in inland valleys is very low in Benin due to biophysical and socio-economic constraints (Djagba et al., 2013), including sub-optimal functioning markets for acquiring fertilizers and for the commercialization of rice products, a lack of financial services to make the necessary investments for intensification, poor management and maintenance of irrigation infrastructures; and inadequate national policies (Saito et al., 2015; Schmitter et al., 2015). Aiming at being self-sufficient in rice in the near future, the government has been actively promoting agricultural development of rice since 2008 (NRDS, 2011). Consequently, this strategy has permitted the local rice production to increase from 73,853 metric tons in 2008 to 167,000 tons in 2011 for the improved input facilities (seeds, fertilizers, etc.) made available to farmers through a range of several programmes and projects. These include for instance, the Emergency Program to Support Food Security (PUASA), the NERICA Project, the Development Project of Small Irrigated Perimeters (PAPPI) and the Agricultural Services Restructuring Project (PASR) (Totin et al., 2013). Currently, 90% of the rice outputs are produced by small-scale farmers using only 7 to 10% of the total arable land available (United States Department of Agriculture, 2013), with the average rice farm size for the users and non-users of credit being approximately 0.82 and 0.63 ha, respectively (Kinkingninhoun-Medagbe et al., 2015).

Chapter 3

Modelling approach

3.1. Model description

Numerous studies evaluate and compare hydrological models (Cornelissen et al., 2013; Refsgaard and Knudsen, 1996; Staudinger et al., 2011). One of the findings is that no single model can be identified as ideal over the range of possible hydrological situations. In the framework of this study, we have selected the distributed watershed model SWAT (Soil and Water Assessment Tool) (Arnold et al., 1998) to be appropriate to assess the watersheds hydrological characteristics and facilitate informed decisions for safeguarding water quantity and quality (Shrestha et al., 2015). In fact, SWAT has been successfully applied worldwide for hydrological processes assessment, water quality studies, and recently for crop yield assessment (Bossa, 2012; Srinivasan et al., 2010). Moreover, it was also successfully applied for several catchments in Benin and even the whole West African sub-continent (4 million km²) for modelling water availability (Duku et al., 2015; Bossa, 2012; Sintondji, 2005; Busche et al., 2005; Hiepe, 2008; Schuol et al., 2007).

The SWAT model is a physically-based continuous-event model developed to predict the impact of land management practices on water, sediment, crop growth, and the fate of agricultural chemicals in large, complex watersheds with varying soils, land use, and management conditions over long periods of time. It offers the ability to discretize the watershed into a number of subwatersheds or homogenous subbasins (hydrologic response units, HRUs) having unique soil and land use properties, representative hillslopes, and grid cells (Arnold et al., 2013). The simulation is performed at a daily time step and the hydrological cycle is divided into land and routing phases (Figure 3.1). The land phase controls the amount of water, sediment, nutrient and pesticide loadings to 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, nutrients and management operations. The routing phase includes processes such as sediment and nutrient routing, in addition to the surface runoff, lateral flow and return flow from the land phase which are then routed through the channel network of the watershed to the outlet (Neitsch et al., 2009).

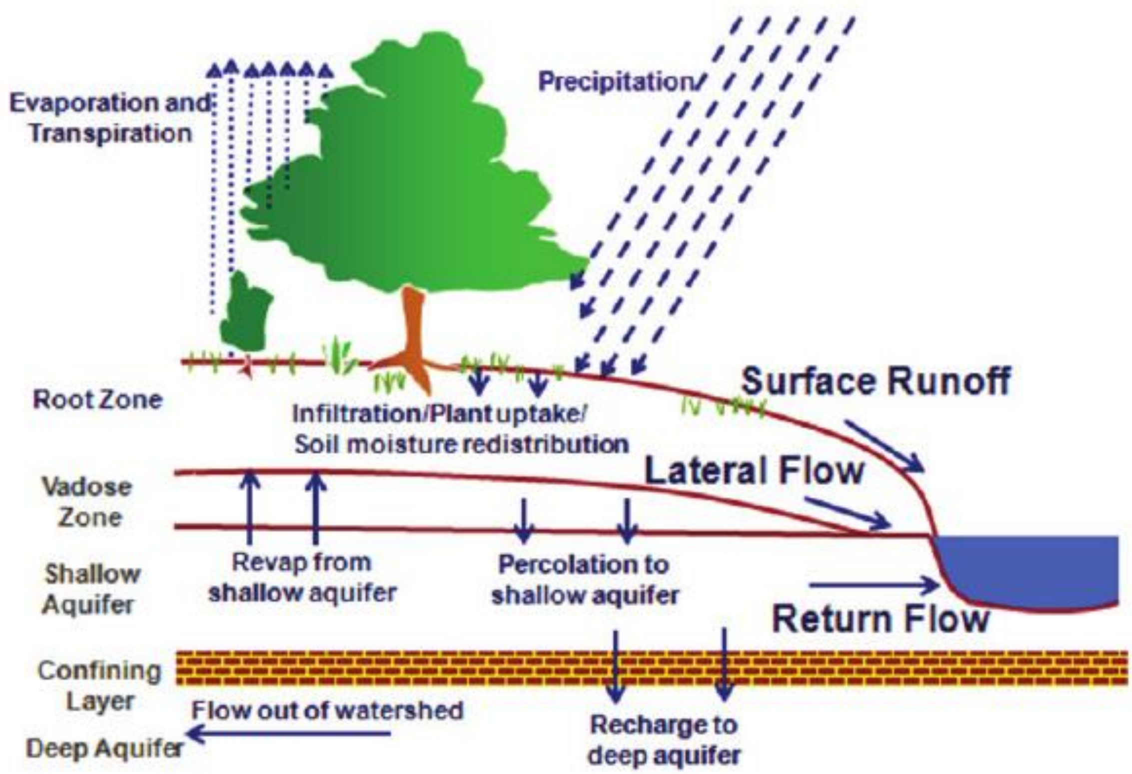


Figure 3.1. SWAT schematic representation of hydrological cycle. (Neitsch et al., 2009).

In SWAT, the land phase is simulated based on the water balance equation as following:

$$SW_t = SW_0 + \sum_{i=0}^{t} (R_i - Q_i - ET_{a,i} - W_{seep,i} - Q_{gw,i})$$

(Eq. 3.1)

Where SWt is the final soil water content [mm], SW_0 is the initial soil water content on on day i [mm], t is the time [days], Ri is the amount of precipitation on day i [mm], Q_i is the amount of surface runoff on day i [mm], $Et_{a,i}$ is the amount of evapotranspiration on day i [mm], and $W_{seep,i}$ is the amount of water entering the vadose zone from the soil profile on day i [mm], and Q_{gw},i is the amount of return flow on day i [mm] (Neitsch et al., 2009).

The surface runoff can either be simulated using the SCS (Soil Conservation Services) curve number method (SCS, 1972, 1986) or the Green and Ampt infiltration equation. In this study the simulation is based on the SCS-approach as following:

$$Q = \frac{(R - 0.2S)^2}{(R + 0.8S)} \qquad \text{for } R > 0.2S$$

(Eq. 3.2)

$$Q = 0 \qquad \text{for } R \leq 0.2S$$

(Eq. 3.3)

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

(Eq. 3.4)

Where Q is the daily surface runoff [mm], R is the daily rainfall [mm], and S is a retention parameter (Neitsch et al., 2009).

Numerous methods have been developed to estimate the potential evapotranspiration (PET). Depending on data availability, PET can be calculated using three different approaches incorporated in SWAT such as the Penman-Monteith method (Monteith, 1965; Allen et al., 1989), the Priestley-Taylor method (Priestley and Taylor, 1972) and the Hargreaves method (Hargreaves et al., 1985). In this study, the Penman-Monteith method was used, which requires solar radiation, air temperature, relative humidity and wind speed, and some additional components that account for energy needed to sustain evaporation, the strength of the mechanism required to remove the vapor and aerodynamic and surface resistance terms :

$$\lambda E = \frac{\Delta * (H_{net} - G) + \rho_{air} * c_p * [e_z^0 - e_z]/r_a}{\Delta + \gamma * (1 + \frac{r_c}{r_a})}$$

(Eq. 3.4)

Where **λ**E is the latent heat flux density [MJ m^{-2} d^{-1}], E is the depth rate evaporation [mm d^{-1}], Δ is the slope of the saturation vapor pressure-temperature curve [kPa °C^{-1}], H_{net} is the net radiation [MJ m^{-2} d^{-1}], G is the heat flux density to the ground [MJ m^{-2} d^{-1}], ρ_{air} is the air density [kg m^{-3}], c_p is the specific heat at constant pressure [MJ kg^{-1} °C^{-1}], $e°_z$ is the saturation vapor pressure of air at height z [kPa], e_z is the actual water vapor pressure of air at height z [kPa], γ is the psychrometric constant [kPa °C-1], r_c is the plant canopy resistance [s m^{-1}], and r_a is the diffusion resistance of the air layer (aerodynamic resistance) [s m^{-1}] (Neitsch et al., 2009).

Percolation is calculated for each soil layer in the profile and shallow aquifer recharge from the bottom of the soil profile. Water is allowed to percolate if the water content exceeds the field capacity water content for that layer and the layer below is not saturated. The amount of water that moves from one layer to the underlying layer is calculated using the storage routing methodology and based on the fiollowing equation:

$$SW_{perc,ly} = SW_{ly,excess} * \left(1 - e^{\frac{-\Delta t}{TT_{perc}}}\right)$$

(Eq. 3.5)

Where $SW_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day [mm], SW_{ly},excess is the drainable volume os water in the soil layer on a given day [mm], Δt is the length of the time step [hrs], and TT_{perc} is the travel time for percolation [hrs] (Neitsch et al., 2009).

Swat incorporates a kinematic storage model for subsurface flow developed by sloan et al. (1983) and summarized by Sloan and Moore (1984). The model simulates the subsurface flow in a two-dimensional cross-section along a flow path down a steep hillslope. The kinematic wave approximation of saturated subsurface or lateral flow assumes that the lines of flow in the saturated zone are parallel to the impermeable boundary and the hydraulic gradient equals the slope of the bed. The following equation is applied in the model :

$$Q_{lat} = 0.024 * \left(\frac{2 * SW_{ly,excess} * K_{sat} * slp}{\emptyset_d * L_{hill}} \right)$$

(Eq. 3.6)

Where $SW_{ly,excess}$ is the drainage volume of water stored in the saturated zone of the hillslope per unit area [mm], K_{sat} is the saturated hydraulic conductivity [$mm.h^{-1}$], slp is the slope as the increase in elevation per unit distance, $\emptyset_d$ is the drainable porosity of the soil layer [mm/mm], L_{hill} is the hillslope length [m], and 0.024 is a factor needed to convert meters to millimeters and hours to days (Neitsch et al., 2009).

As far as the groundwater flow is concerned, an unconfined and a deeper confined acquifers are simulated. The water balance for the shallow acquifer is expressed by the following equation:

$$aq_{sh,i} = aq_{sh,i-1} + W_{rchrg} - Q_{gw} - W_{revap} - W_{deep} - W_{pump,sh}$$

(Eq. 3.7)

Where, $aq_{sh,i}$ is the shallow aquifer storage on the day i [mm], $aq_{sh,i-1}$ the shallow aquifer storage the day before [mm], W_{rchrg} the recharge entering the aquifer [mm], Q_{gw} the groundwater flow or baseflow into the main channel [mm], W_{revap} the amount of water moving into the soil zone as response to water deficiencies [mm], W_{deep} the amount of water percolating from the shallow aquifer into the deep aquifer [mm], $W_{pump,sh}$ the amount of water remove from the shallow aquifer by pumping on day i [mm] (Neitsch et al., 2009).

The water balance for the deep aquifer is:

$$aq_{dp,i} = aq_{dp,i-1} + W_{deep} - W_{pump,dp}$$

(Eq. 3.8)

Where $aq_{dp,i}$ is the amount of water stored in the deep aquifer on day i [mm], $aq_{dp,i-1}$ is the amount of water stored in the deep aquifer on the day i-1 [mm], W_{deep} is the amount of water percolating from the shallow aquifer into the deep aquifer on day i [mm] (Neitsch et al., 2009).

The amount of nitrate moved with the water is calculated by multiplying the concentration of nitrate in the mobile water fraction by the volume of water moving in each pathway to obtain the mass of nitrate lost from the soil layer. The nitrate concentration is calculated:

$$conc_{NO3,mobile} = NO3_{ly} * \left(\frac{1 - e^{\frac{-W_{mobile}}{(1-\theta_e) * SAT_{ly}}}}{W_{mobile}} \right)$$

(Eq. 3.9)

Where $conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water for a given layer [kg N/mm], $NO3_{ly}$ is the amount of nitrate in the layer [kg N/ha], W_{mobile} is the amount of mobile water in the layer [mm], θ_e is the fraction of porosity from which anions are excluded, and SAT_{ly} is the saturated water content of the soil layer [mm] (Neitsch et al., 2009).

The amount of mobile water in the layer is the amount of water lost by surface runoff, lateral flow or percolation:

$$W_{mobile} = Q_{surf} + Q_{lat,ly} + Q_{perc,ly} \qquad \text{for top 10 mm}$$

(Eq. 3.10)

$$W_{mobile} = Q_{lat,ly} + Q_{perc,ly} \qquad \text{for lower soil layers}$$

(Eq. 3.11)

Where W_{mobile} is the amount of mobile water in the layer [mm], Q_{surf} is the surface runoff generated on a given day [mm]), $Q_{lat,ly}$ is the water discharged from the layer by lateral flow [mm]), and $W_{perc,ly}$ is the amount of water percolating to underlying soil layer on a given day [mm] (Neitsch et al., 2009).

In this study, the interface ArcSWAT 2012 (Arnold et al., 2013) was applied to calibrate and validate the model for the three inland valley watersheds in order to assess their hydrological characteristics and predict nitrate loads, and to evaluate the impact of rice intensification on water availability within them. In addition, the grid-based interface SWATgrid (Rathjens et al., 2014) of the model SWAT was 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. SWATgrid is driven by results from the interface 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) (Figure 3.2). Thus, files with calibrated and validated parameter values from ArcSWAT were used to run SWATgrid (See Tables A2-4 in Appendix A). 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).

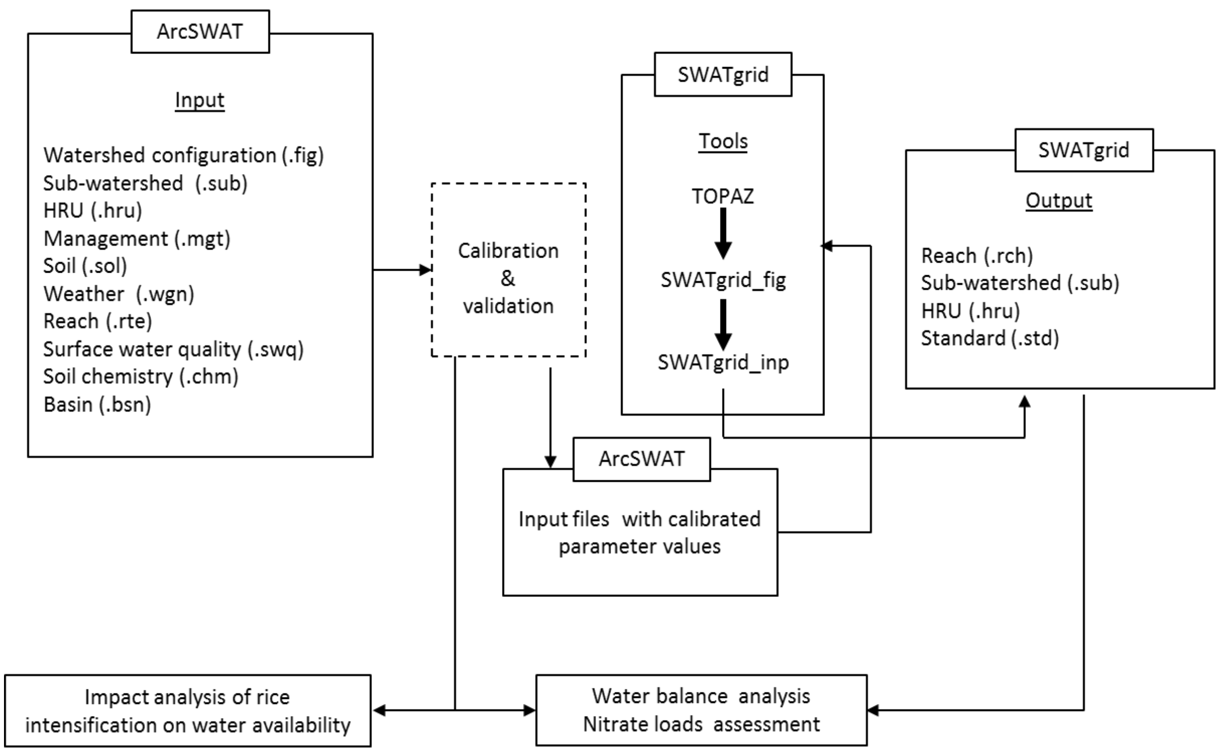


Figure 3.2. Modelling approach applied in this study and schematic illustration of the general organization of SWATgrid (own representation).

3.2. SWAT model setup and evaluation

3.2.1. 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 that the hydrologic processes were in equilibrium, and to minimize the effect of initial conditions (Yang et al., 2007; Zhang et al., 2007; Rocha et al., 2015), the models were run for a warm-up period of 5 years on each site. 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 the 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 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. Thus, the SWATgrid discretization scheme is 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 important than the spatial resolution of the model units is that SWATgrid 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 is most sensitive (Abbaspour, 2014). 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.

3.2.2. 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 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.

Chapter 4

Experimental setup and data collection in the selected inland valleys

4.1. Introduction

Generally known as bas-fonds in Benin, inland valleys are complex landscapes of great interest for intensive agricultural practices on the way to achieve food security in the country (Giertz et al., 2012; Totin et al., 2013). However, this requires a good assessment of such wetlands properties, which likely vary in time and from one physiographic unit to another. Throughout this research, the selected inland valleys were studied for their hydrology, water quality and associated functions using the SWAT model which requires spatial and temporal data as for instance on climate, land use, soil, topography, etc. Hence, field instrumentation and data collection were undertaken during the monitoring extending from 2013 to 2015 for most of the required information was not available at such a small scale. In the following sections are presented the experimental setup and a summary of the data acquired for conducting this study.

4.2. Materials and methods

4.2.1. Model input data

In fact, 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 4.1). 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 to generate the stream networks and watershed configurations, and to estimate topographic parameters. 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. Moreover, within each watershed, a total of 300 days of grazing occurred and cattle manure (1 % N - 0.4 % P - 3 % org-N - 0.7 % org-P - 95 % NH_3-N) was simulated daily at of 38 kg/ha, as adopted in a previous study conducted by Bossa et al. (2012b) within the same area. For modelling plant growth, parameter values were taken from literature (Bossa, 2012b; Cournac et al., 2002; de Wasseige et al., 2003; Mulindabigwi, 2005; Orthmann, 2005; Worou et al., 2012).

Table 4.1. 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	30 m
Weather	Temperature, relative humidity, solar radiation, and wind speed	AMMA-CATCH	1 weather station in Djougou
Weather	Rainfall	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 sampling location per IV
Plant characteristics	e.g. Biomass, PHU, LAI…	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.

4.2.2. Climate data and climate scenarios

To assess the seasonal variability of hydrological processes in all inland valleys as presented in chapter 5, 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) (see Figure 2.2).

To assess the impact of climate change as presented in chapter 6, we define the baseline conditions from 1980 to 2003 based on the historical climate data collected at a synoptic meteorological station installed at Parakou by the Agency for Aerial Navigation Safety in Africa and Madagascar (L'Agence pour la Sécurité de la Navigation aérienne en Afrique et à Madagascar, ASECNA). Scenario data downscaled 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 (Paeth et al., 2009) were used (see Figure 4.1) as possible futures. REMO has a resolution of 0.5° x 0.5° and is nested in the European Centre Hamburg Model (ECHAM5). The A1B scenario describes a globalized world of rapid economic growth and comparatively low population growth (Bossa et al., 2012; IPCC, 2007). 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 (Bossa et al., 2012). The climate scenarios were already downscaled and bias corrected by Speth et al. (2010) for the climate station in Djougou, which was used in this study. As reported by Bossa et al. (2012), because of a systematic underestimation of the rainfall amount and variability in the original 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 IMPETUS-project (Speth et al., 2010). Thus, the generated virtual station data match the observed daily precipitation at the rainfall stations in the Upper Ouémé watershed in Benin (Speth et al., 2010).

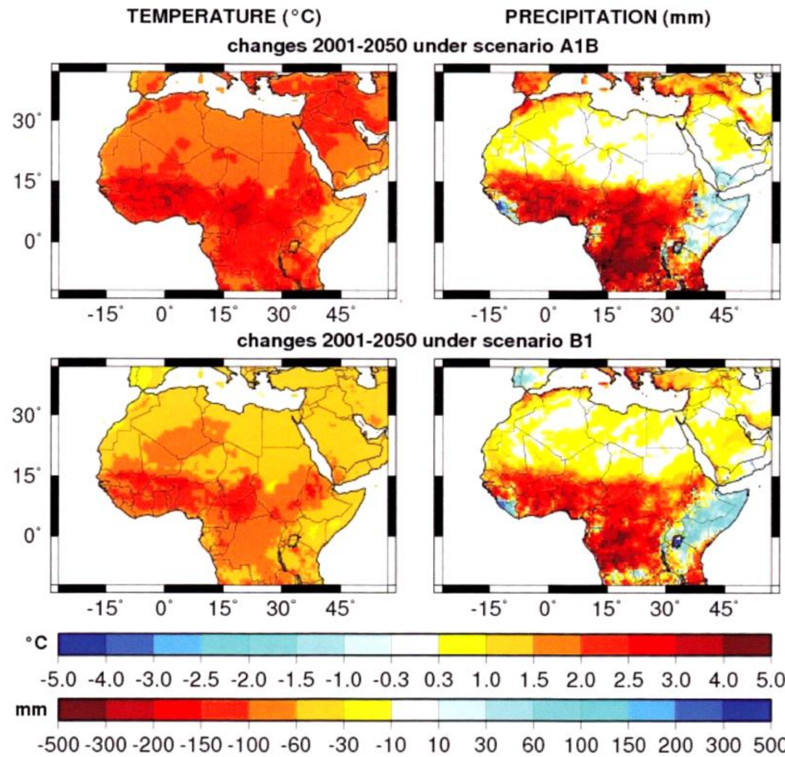


Figure 4.1. Projected changes in annual precipitation and near-surface temperatures until 2050 over tropical and northern Africa due to increasing greenhouse gas concentrations and man-made land cover changes, REMO outputs (Paeth, 2004).

To assess the climatic suitability of the inland valley of Tossahou for rice production as presented in chapter 7, precipitation was automatically measured every 5 min using a tipping-bucket rain gauge (RG1 by Delta-T) with a sensitivity of 0.2 mm per tip and coupled to data logger (Delta-T, 1996) (Figure 4.2). Temperature and relative humidity were recorded hourly by a Gemini Tiny Tag sensor. The sensor was shielded with a purpose-build radiation shield and installed at a height of 2 m above ground (Figure 4.3). Radiation and wind speed data were measured every 5 min at a climate station (of the SMART-IV project) located 30 km from Pelebina village. All measurements were undertaken over the 2013 wet season from April to October.

Figure 4.2. Tipping bucket rain gauge installed at Tossahou.

Figure 4.3. Gemini Tiny Tag sensor installed at Tossahou.

4.2.3. Hydrological data collection

Hydrological and water quality measurements were carried out during three consecutive hydrological years between January 2013 and December 2015 for the calibration and validation of the SWAT model. The locations of the different instruments installed to carry out the measurements are depicted by Figure 4.4.

Discharge data

The surface water stage of the river was collected every 5 min at stream gauges equipped with a DLN70 water pressure sensor from EcoTech installed at two distinct cross-sections located in the downstream part of each inland valley, close to the outlet of the contributing watershed. After the end of first wet season, the cross-section presenting the best rating curve was selected at each inland valley watershed and retained for the rest of the monitoring period. Daily discharges were calculated using the velocity-area method, and following the recommendations of the World Meteorological Organization (WMO, 2008). The velocity-area method involves the calculation of discharge from velocity measurements and depth observation at defined verticals which are marked along the cross-section in a way to reflect the variation of the stream bed as well as the horizontal variation of velocity as closely as possible. Intervals between the verticals should not be greater than 1/20th of the total width and the generalized form of the working equation used for gauging is expressed as follow:

$$\sum_{i=1}^{m} b_i d_i \overline{V}_i$$

(Eq. 4.1)

Where Q is the total discharge; b_i, d_i, $\overline{V_i}$ and are the width, depth and mean velocity of the water in the ith of the *m* verticals or segments into which the cross-section is divided. (WMO, 2008).

The velocity of water was frequently measured at the different gauging stations with the OTT Hydromet Nautilus C2000 coupled to a Sensa Z300 handheld. The measuring process at a typical cross-section is depicted by Figure 4.5.

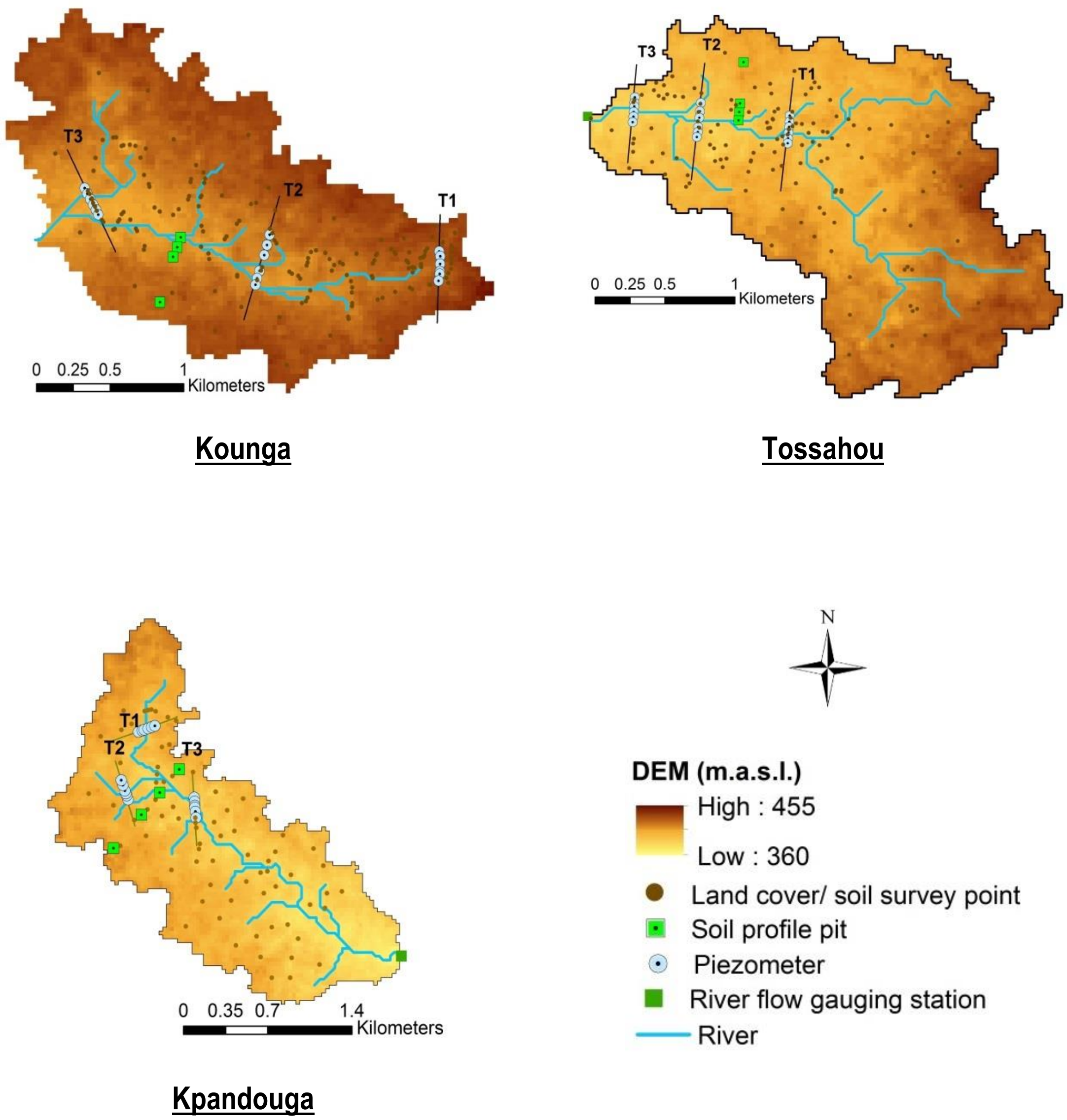


Figure 4.4. Watersheds contributing to the inland valleys: elevations, drainage patterns and the locations of instruments.

Figure 4.5. (A) Gauging station for recording water level every 5 min at Kounga; and (B) Velocity measurement in Kpandouga at a typical cross-section with the blue rope marking the cross-section (positions of verticals are quite invisible but marked on the rope).

Surface water quality data

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. The nitrate concentration of 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.

Shallow groundwater data

Measurements of the shallow groundwater level were taken along three watershed cross-sections that divided each inland valley into upstream, midstream, and downstream sections in order to assess its spatial and temporal variability (Figure 2.2). However, due to difficulty of access, transects in Kpandouga are located in the cultivated area of the valley, which corresponds to the upstream section. In each transect six piezometers were installed as depicted in Figure 4.6.

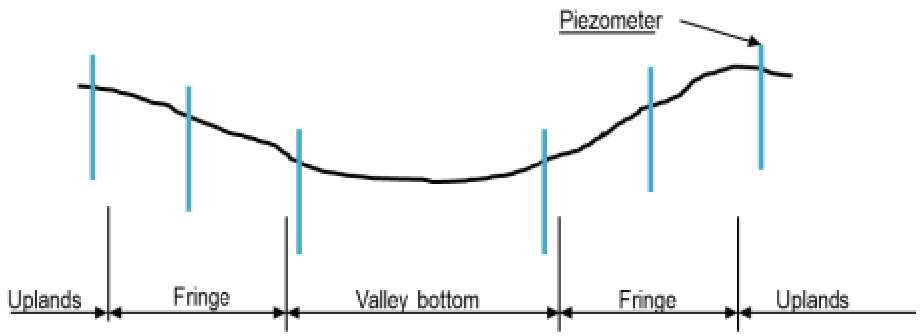


Figure 4.6. Arrangement of the piezometers installed in a transect for monitoring groundwater level

The measurement system was custom build with PVC-tubes gauging approximately 2 meters depth and screened over 30 cm from the bottom. The insertion of the tubes was done by hand augering. The annular space inside the hole was filled with the extracted material and properly sealed at the surface with concrete after the settling of the soil. All the pipes were closed at the top with cups which were pierced to avoid build-up of pressure in the piezometer during phases of groundwater rise. The water level in the pipes was read every three days with an electric contact meter (Type KLL Mini) by SEBA HYDROMETRIE equipped with an optical and acoustic signal and an accuracy of < 1 cm (SEBA HYDROMETRIE, 2014) (Figure 4.7).

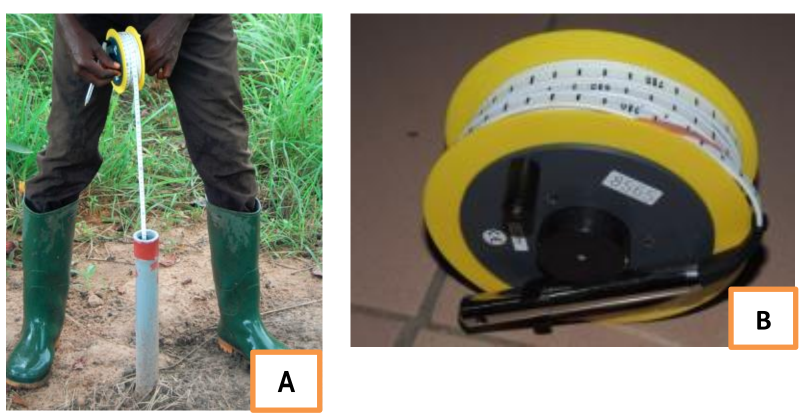


Figure 4.7. (A) Measurement of the shallow groundwater level; (B) electric contact meter used for reading the depth of water in the pipes.

4.2.4. Spatial assessment

Land use mapping

The land use maps were derived from a supervised classification of SPOT-6 satellite images with a resolution of 1.5 m especially acquired for the three inland valley watersheds using ArcGIS 10.2. The different landscape elements were identified and subsequently validated based on reference points. Reference data were randomly collected during field checking using Global Positioning System (GPS) units. 169, 134, and 76 observations points were analyzed to provide ground truth data in Kounga, Tossahou, and Kpandouga respectively (Figure 2.2). 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.

The results from the identification of the cultivated fields and cultures were used in chapter 7 to evaluate the actual extent to which the agro-potentiality of the inland valley of Tossahou is used as a whole. The outputs from the overlay of layers were used to link the observed yields to the management practices involved at the fields while determining the limiting factors.

Digital soil mapping

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 Jennes 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):

$$\mathrm{TPI} = \mathrm{Zo} - \bar{\mathrm{Z}}$$

$$\bar{\mathrm{Z}} = \frac{1}{\mathrm{n_R}} \sum_{\mathrm{i \epsilon R}} \mathrm{Z_i}$$

(Eq. 4.2)

Zo, elevation of the central point; $\bar{\mathrm{Z}}$, average elevation around the central point within a predetermined radius (R) ; $\mathrm{Z_i}$, elevation of the cell i; $\mathrm{n_R}$, number of cell within the predetermined radius.

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 (Figure 2.2). 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 - 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 (see Figure 4.8). 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 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 been used in central Benin (Bormann and Diekkrüger, 2003).

Figure 4.8. (A) Opened soil profile pit; (B) collection of soil core sample at the topsoil; (C) disturbed soil sample collected during soil description.

4.2.5. Agricultural management practices

Survey of farmers

In order to investigate the different management practices involved at the inland valley watersheds, a group and several individual interviews were conducted with the farmers to collect quantitative and qualitative information on land preparation, cultivated crops, sowing date, frequency and date of weeding and fertiliser application, and harvest date (Figure 4.9). Moreover, for the validation of the generated suitability maps presented in chapter 7, additional qualitative information were surveyed with 12 rice farmers on soil and land properties such as soil quality, soil moisture and flood depth. The farmers were also questioned about possible suitable and not suitable areas for rice production and the factors likely to restrict cultivation from their experience in the inland valley.

Figure 4.9. Interactive group interviews of farmers in the village of Tossahou.

Rice yields observation

The rice yields were especially measured at Tossahou between October 27th and November 30th during the wet season 2013 and used in the validation of the generated suitability maps in chapter 7. From the 27 fields that were mapped, only 15 could be harvested by cutting with a sickle in accordance with the farmers' decision. Depending on the field size, two to six sub-plots of 1 m^2 were marked at locations chosen to represent the variability within each field (Roel et al., 2007). For fields where rice was grown in association with other crops such as yams or maize, 2×2 m^2 sub-plot size was adopted to account for heterogeneity as much as possible. Grain yield and total above-ground biomass were determined in each sub-plot. Grain moisture upon harvest was measured using a Riceter m401 grain moisture tester (Figure 4.10), and the yields were converted to 14% moisture content, as recommended (Schmitter et al., 2015).

Figure 4.10. (A) Determining harvested rice plants from sub-plots in the Tossahou lowland; (B) Manual separation of grain and biomass for each sub-plot; (C) Grain moisture measurement using the Riceter m401 grain moisture tester.

4.3. Results and discussion

4.3.1. Climate data

The results of the statistical analysis of the data collected from the AMMA-CATCH database have been presented in chapter 2 (See Figure 2.3). The historical rainfall data collected at a synoptic meteorological station were plotted together with the rainfall scenarios A1B and B1 in order to evaluate the projected relative changes in the future. As for the reference period from 1985 to 2003, the average annual rainfall amount of 1198 mm was recorded. As for the relative changes depicted by Figure 4.11, the results show that the rainfall amount will increasingly decline in the research area with the maximum drops of 13 % under A1B and 5 % under B1 occurring between the years 2040 and 2049.

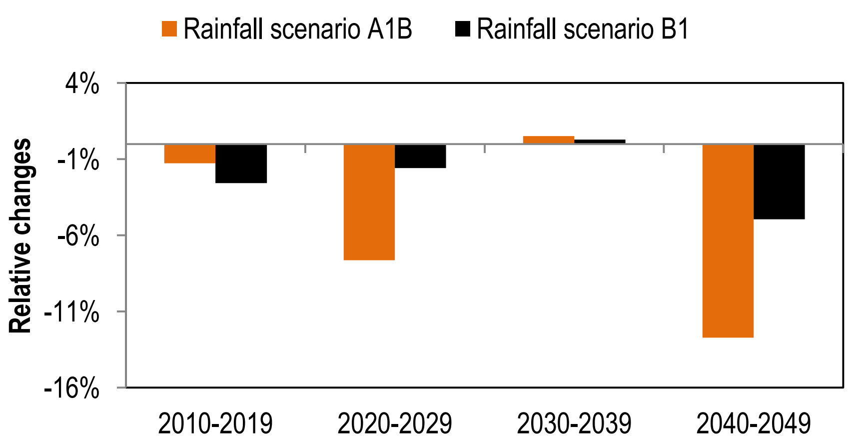


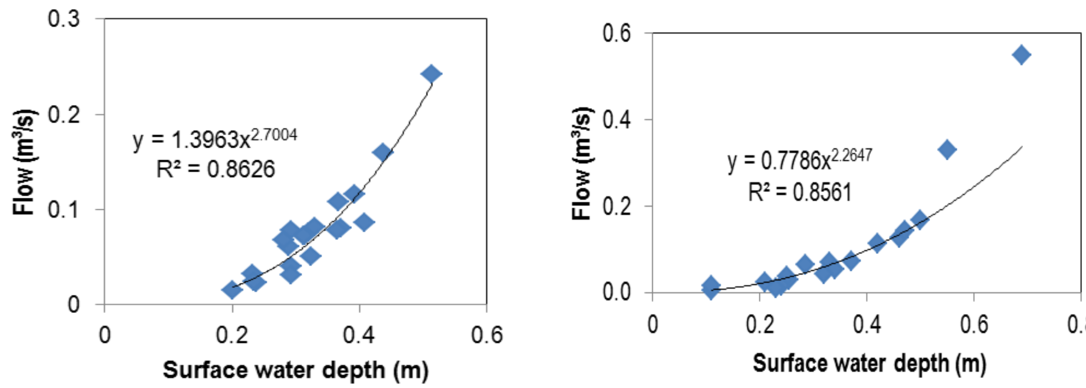
Figure 4.11. Relative changes projected in future rainfall (reference period: 1985-2003) for the research area.

4.3.2. Streamflow dynamic and water quality

Streamflow dynamic

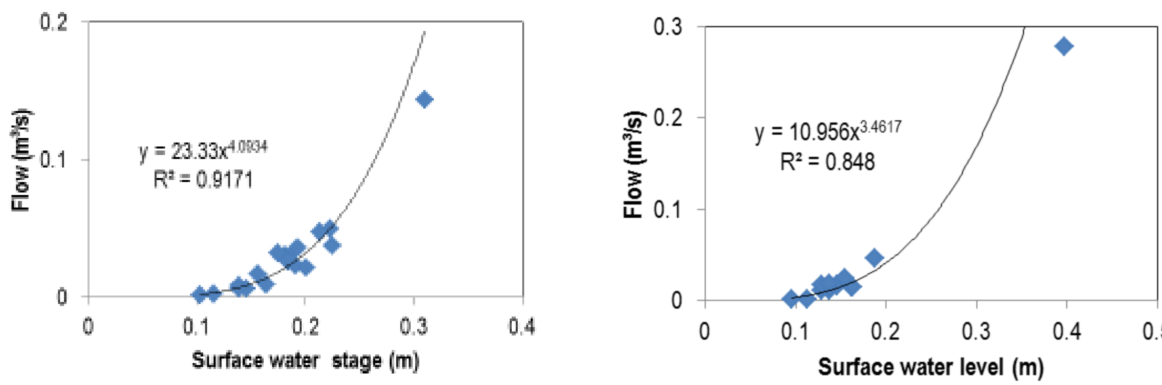
Figures 4.12, 4.13, and 4.14 depict the stage-discharge rating curves of the gauging stations derived by applying a power-law equation. They were yearly taken in order to account for varying channel conditions such as vegetation growth and sediment deposit. Although satisfactory correlation coefficient values were presented by all gauging stations, it should be mentioned that the velocity of water in high flow during storm events could not be gauged as they mostly occur in the night. Moreover, due to regular overbank flow as results of high rainfall, the exact quantity of peak flow is uncertain.

Actually, the resulting hydrographs from observations at the outlets (gauge stations) in each watershed reveal a dominance of peaks and a highly rainfall-driven streamflow dynamic (Figure 4.15). Due to frequent acts of vandalism perpetrated on the gauging stations and sensors failure to work at Kounga and Kpandouga especially during the wet seasons 2014 and 2015, the collected data were not consistent enough to be used for a direct comparative analysis. In 2013 in Kounga, the streamflow was initiated soon in the month of July with a maximum average daily discharge of 0.51 m^3/s recorded on September 23th. In the same year in Tossahou, the streamflow was triggered later on by the end of August. The highest peak of 0.35 m^3/s was also recorded in the month of September on the 29th. Likewise, the streamflow was approximately initiated around the same time in Kpandouga but with the highest peak of 0.64 m^3/s recorded earlier on August 17th. At the end of the wet season 2013, the recession of water was more attenuated in Kounga than in the others inland valleys. Approximately, the streamflow decreased over 69 days before stopping, while in Tossahou and Kpandouga it lasted just around 21 and 20 days respectively.



(2013) **(2014)**

Figure 4.12. Rating curves established at the gauging station in the inland valley of Kounga for the calibration year 2013 and validation year 2014



(2013) **(2014)**

Figure 4.13. Rating curves established at the gauging station in the inland valley of Kpandouga for the calibration year 2013 and validation year 2014.

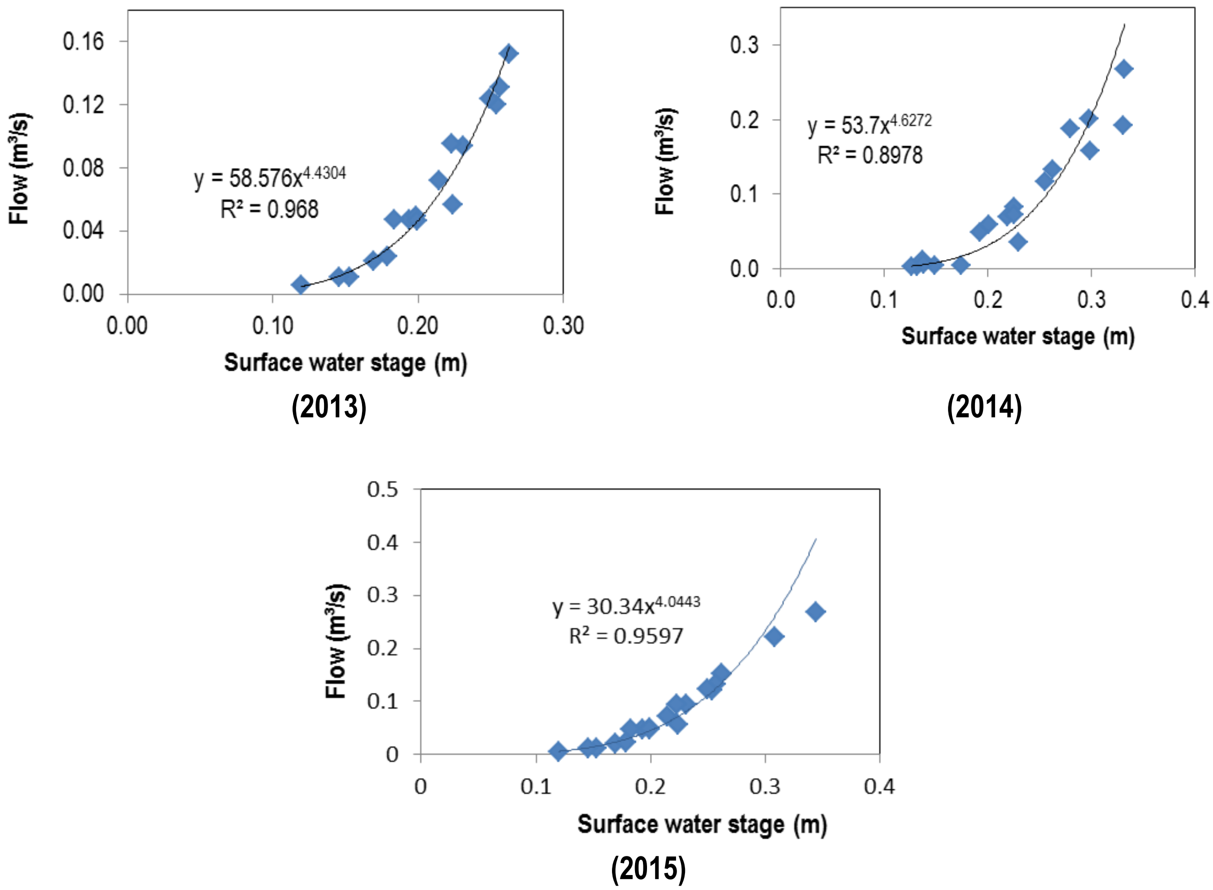


Figure 4.14. Rating curves established at the gauging station in the inland valley of Tossahou for the calibration period 2013-2014 and validation year 2015.

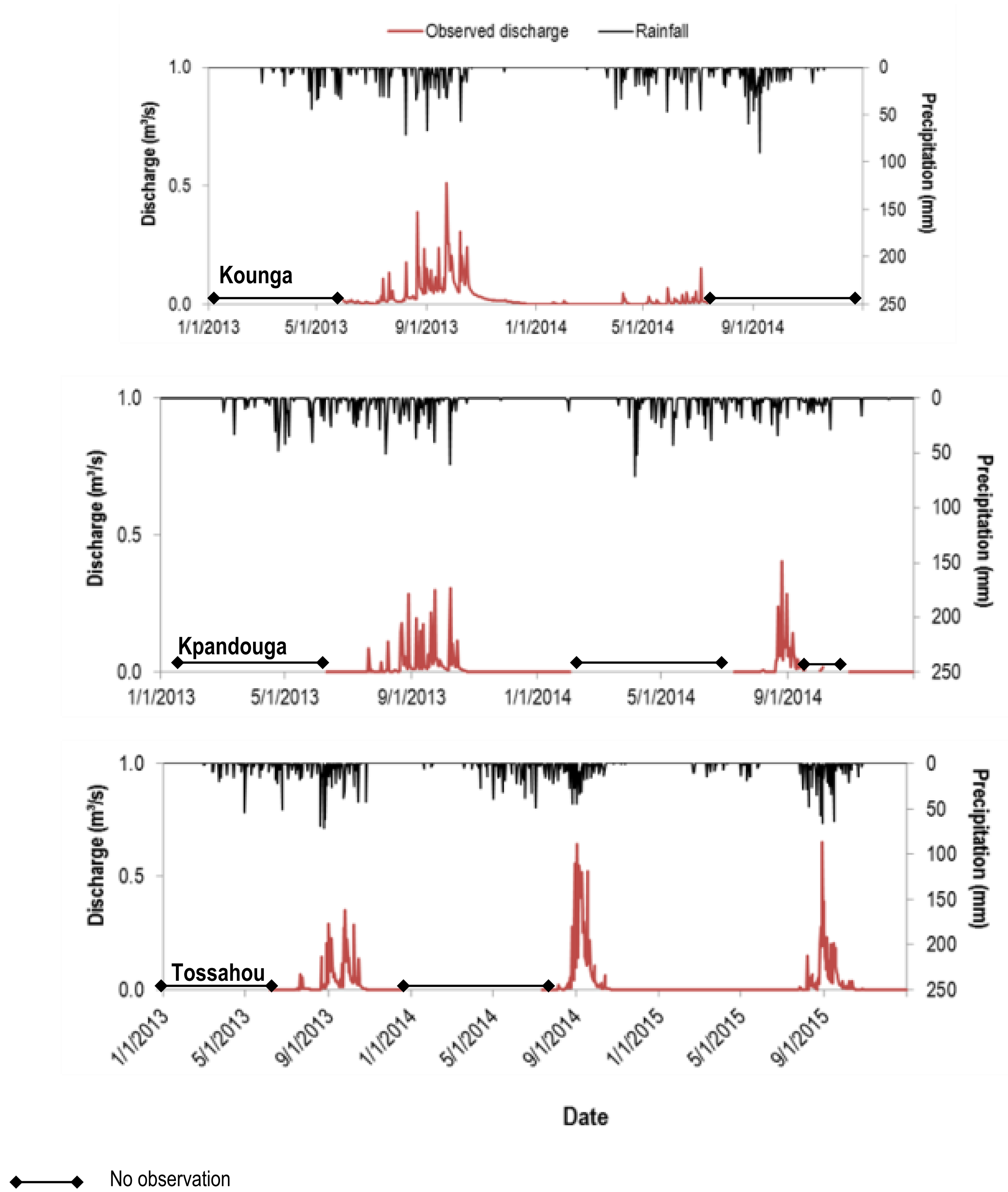


Figure 4.15. Daily discharge recorded at the outlets of the inland valley watersheds.

Stream water quality

The results of the water quality observations showed more recognizable differences among the inland valleys in terms of nitrate. In general, the concentration of nitrate ($N0_3$-N) was very low in all inland valleys with values less than 10 mg/L. Over the period 2013-2015, the average nitrate concentration in Kpandouga was relatively low with 5.3 mg/L, while it reached 5.5 mg/L in Kounga and 6.5 mg/L in Tossahou.

4.3.3. Shallow Groundwater storage

Valley bottom

The fluctuations of the shallow groundwater were very high and rainfall-dependent at all sites. The water table was higher in Kounga, and accessible all over the year (Figure 4.16). In the wet seasons (from 2013 to 2014), the daily average water level was ranging from 14 cm to 45 cm below the ground surface in the valley bottom. In the middle of the season when the rainfall is at its peak (from August to September), the level of the static water in the piezometer was 2 cm above the surface level. During the dry season, the water table is lower with a depth ranging between 54 cm to 92 cm.

In Tossahou, the groundwater was accessible during the rainy season and only at the upper part of the valley bottom during the dry season. In the rainy season, the water table depth was ranging from 23 cm to 52 cm on average. In the middle of the rainy season, the water table level rose in the piezometers to more than 10 cm above the ground surface. During the dry season, the water table remained accessible at a depth of 65 cm at the upstream part, but depleted beyond the maximum of 2 meters depth that was monitored by the piezometers in midstream and at downstream.

At the end of the wet season, the depletion of the shallow groundwater table was more rapid in Kpandouga. The water table dropped below 2 meters depth in the soil during the dry season in all piezometers. During the rainy season, the average water table level ranged between 52 cm to 98 cm. In the middle of the rainy season, the water table remained below 40 cm mostly, except during the wet season 2013 where it was measured 8 cm above the ground surface at upstream on average.

Uplands

Towards the uplands in all inland valleys, a perched groundwater table occurred over a short period of time and depleted rapidly after the rainfall ceased. Due to insufficient rainfall amount in the dry season, no water table level could be measured in the piezometers. Over the wet seasons, the daily average depth observed in the lower hillslope, ranged between 55 cm to 82 cm in Kounga, 36 to 94 cm in Tossahou, and 137 to 156 cm in Kpandouga.

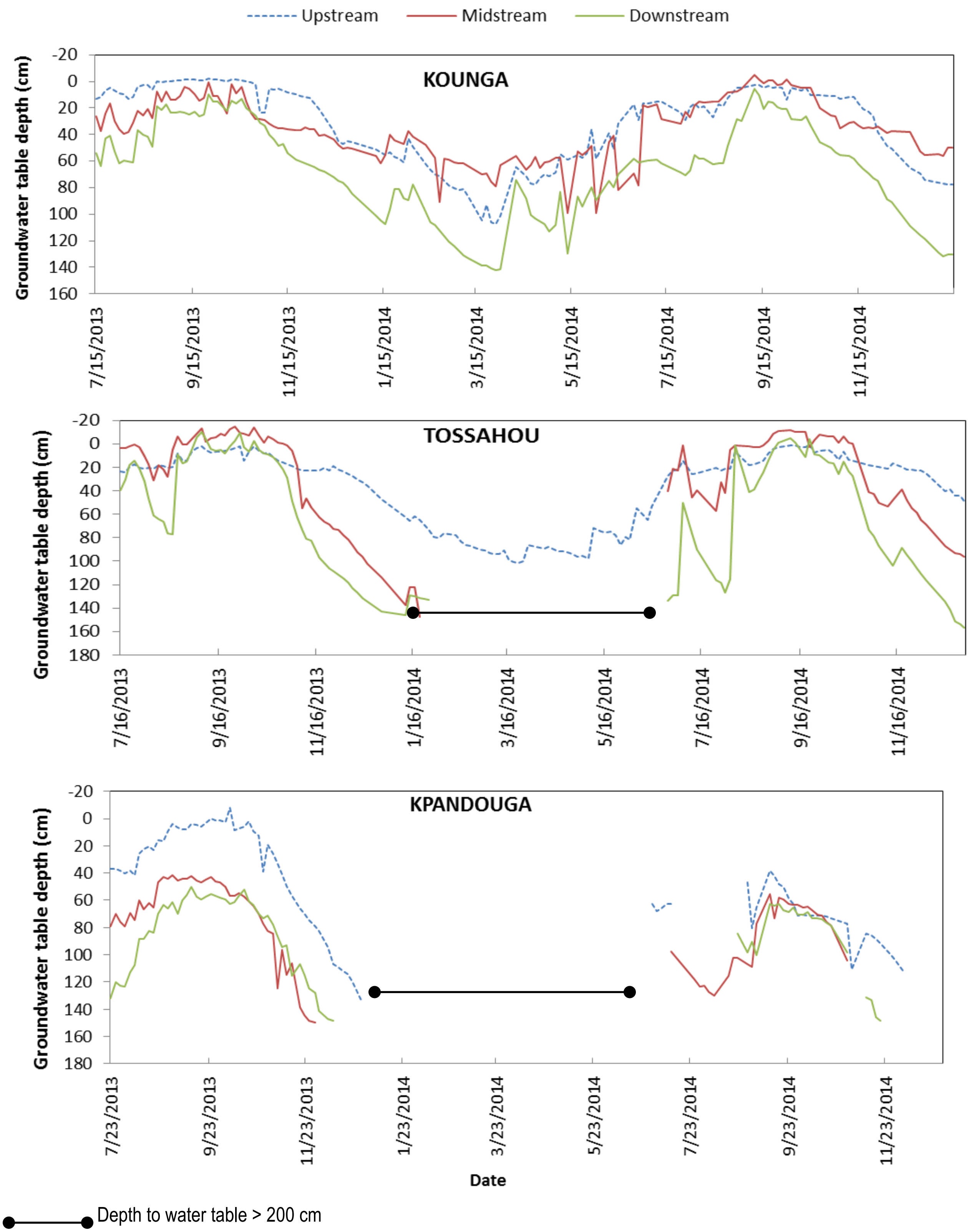


Figure 4.16. Average daily groundwater table depth observed within the valley bottom over the period from 2013 to 2014.

4.3.4. Land use classification

An accuracy check of the land use classification based on the number of correctly classified plots shows total accuracy values of 79 % in Kounga, 82 % in Tossahou, and 89 % in Kpandouga. The land use is primarily characterized by gallery forest and woodland, tree savannah and plantations, shrub savannah, grass savannah, bare soil, settlements, and cultivated areas (Table 4.2).

Table 4.2. Land use/land cover classes in the studied inland valley watersheds

	Kounga		Tossahou		Kpandouga	
Land use /land cover class	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.

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 (Table 4.3). Figure 4.17 depicts the different land use units classified within each inland valley watersheds.

Table 4.3. Cultivated crops in the studied inland valley watersheds

	Kounga		Tossahou		Kpandouga	
Crops	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

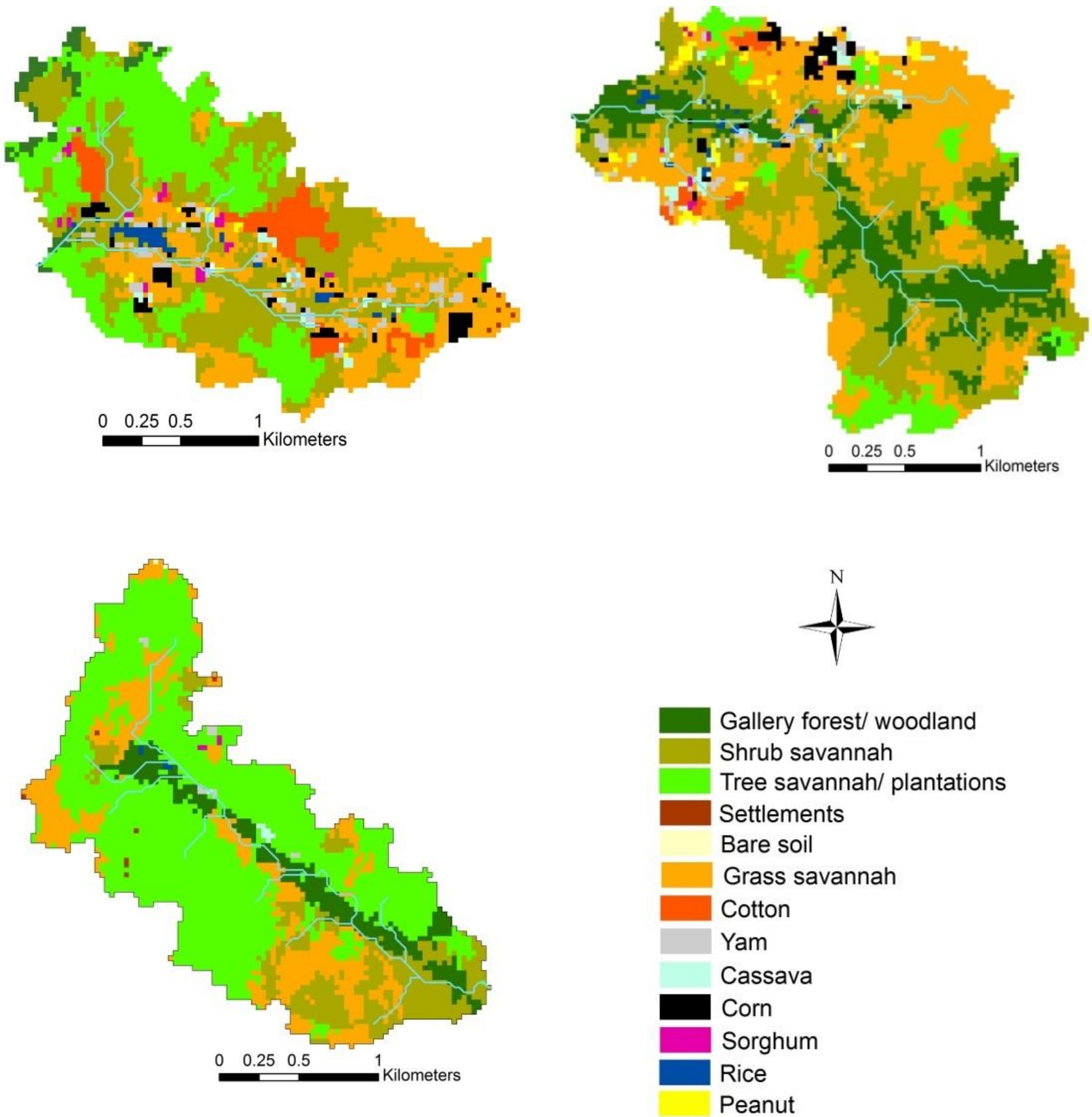


Figure 4.17. Land use units. Classified from 1.5 m resolution SPOT6 multi-spectral image (acquired on 19-02-2014 from SPOT IMAGE SA).

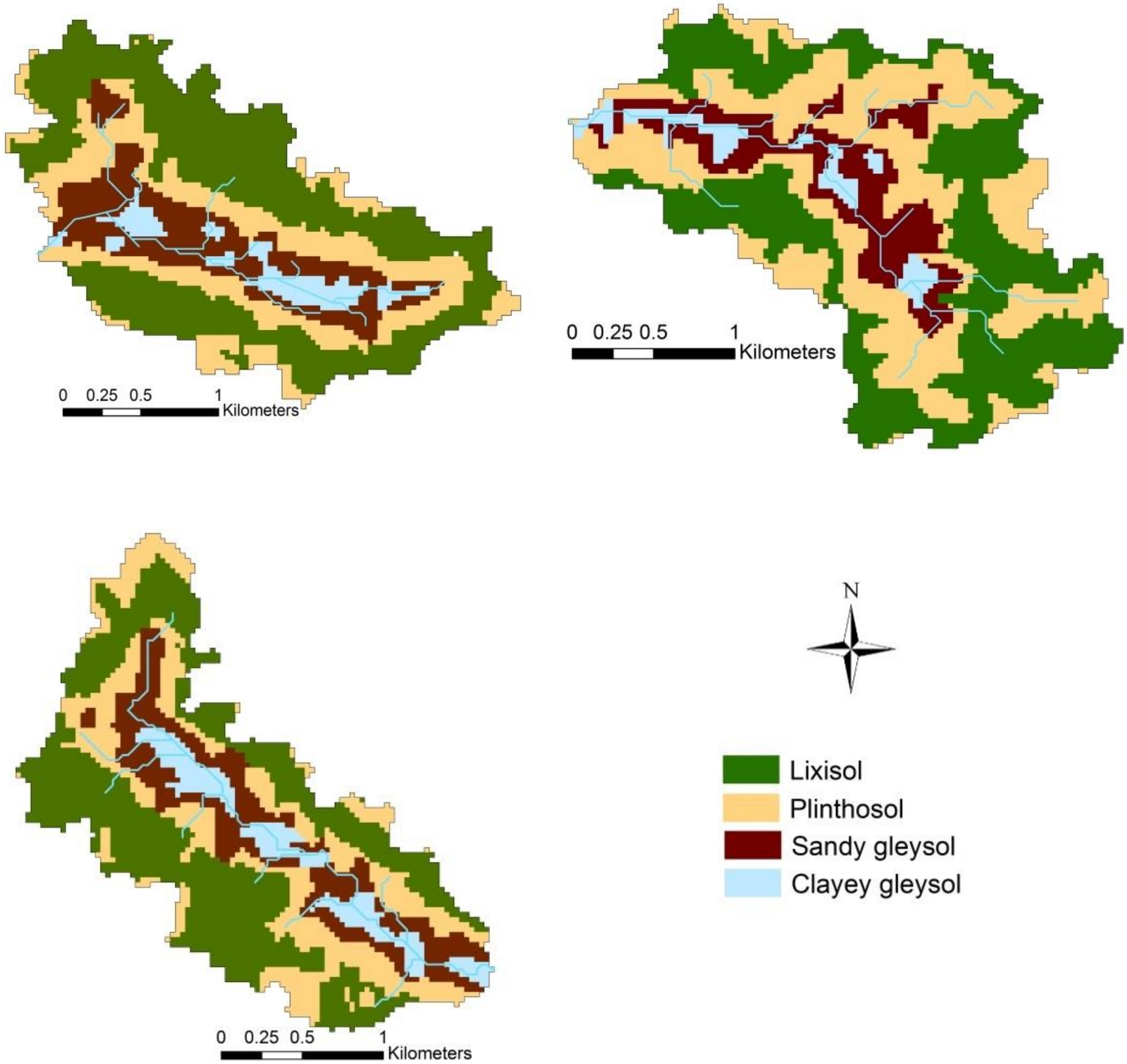


Figure 4.18. Major soil types in the inland valleys.

4.3.5. Soil spatial distribution

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) (Figure 4.18). 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) within all inland valley watersheds. As illustrated in Table 4.3., their subsoil layers are particularly enriched of clay by up to 55 %. Plinthosols are shallow and of less dominance in the uplands covering 26 % of the total area in Kounga and Kpandouga, and 34 % in Tossahou. Sandy and Clayey Gleysols are strongly influenced by water and 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 valley bottom is characterized by a clayey texture. Details on the soil layers properties which were used as input data in the SWAT model as presented in Table 4.4.

Table 4.4. Soil layers description and properties.

Inland valleys	Soil types	Layers	Z (mm)	BD (g/cm^3)	AWC (mm/mm)	K[a] (mm/hr)	Clay (%)	Silt (%)	Sand (%)	Coarse[a] (%)	Cal[a] (%)	SOC[a] (%)	pH	
KPANDOUGA	Lixisol	1	100	1.6	0.22	23.7	14.9	21.7	63.5	48.2	0.06	0.9	7.1	
		2	550	1.7	0.25	0.98	26.8	25.0	48.1	76.9	0.08	0.9	6.15	
		3	1210	1.5	0.30	0.13	48.1	19.2	32.7	62.3	0.05	0.3	6.05	
		4	1610	1.5	0.35	1.16	27.8	40.2	32.0	56.8	0.03	0.18	6.15	
	Plinthosol	1	260	1.5	0.27	13.10	25.2	21.0	53.8	31.1	0.13	0.68	6.25	
		2	650	1.6	0.24	4.61	27.1	18.8	53.9	39.4	0.07	0.45	5.8	
	Sandy Gleysol	1	330	1.5	0.19	132.46	1.0	14.1	84.9	21.2	0.08	0.47	5.75	
		2	870	1.6	0.19	149.43	1.0	9.5	89.5	24.1	0.11	0.06	5.95	
		3	1110	1.8	0.24	27.3	7.2	15.7	77.1	70.7	0.08	0.07	6.6	
		4	1376	1.9	0.32	1.94	1.9	45.3	52.8	55.5	0.07	0.05	6.9	
	Clayey Gleysol	1	249	1.6	0.22	0.0081	63.2	30.0	15.2	22.1	0.19	2.1	6.93	
		2	690	1.4	0.27	0.0072	55.7	32.7	16.3	24.3	0.22	2.32	6.14	
		3	1700	1.6	0.2	0.0021	32.4	32.2	21.0	18.7	0.34	1.97	6.22	
TOSSAHOU	Lixisol	1	120	1.3	0.41	180.53	8.6	20.7	70.6	53.1	0.07	0.74	6.15	
		2	640	1.4	0.26	13.57	30.1	19.8	50.1	54.2	0.09	0.29	5.65	
		3	1330	1.5	0.24	0.034	52.2	23.7	24.0	68.9	0.08	0.16	5.65	
	Plinthosol	1	310	1.6	0.3	41.52	7.0	24.2	68.8	37.5	0	0.66	6.15	
		2	990	1.7	0.26	0.00026	60.2	20.1	19.7	79.6	0.08	0.16	6.3	
	Sandy Gleysol	1	690	1.5	0.33	96.33	4.8	17.7	77.6	33.7	0.1	0.30	6	
		2	970	1.6	0.2	5.578	23.1	24.6	52.3	75.4	0.12	0.37	6.35	
		3	1500	1.6	0.31	5.51	6.6	50.7	42.6	54.5	0.05	0.10	7.5	

	Clayey Gleysol	1	380	1.6	0.17	0.00751	50.14	30.3	19.5	20.0	0.22	1.87	5.93
		2	700	1.6	0.23	0.00481	50.543	37.9	11.6	15.1	0.32	2.92	6.08
		3	1600	1.7	0.21	0.00111	50.707	31.8	17.4	15.0	0.24	1.93	6.28
KOUNGA	Lixisol	1	120	1.5	0.25	49.32	15.6	19.5	64.9	45.0	0.04	1.67	6.7
		2	355	1.6	0.27	0.74	34.1	19.3	46.6	65.6	0.13	1.18	5.85
		3	1085	1.5	0.20	0.02	54.8	19.9	25.2	65.7	0.15	0.39	5.9
		4	1770	1.6	0.28	0.006	53.08	20.8	25.9	66.4	0.05	0.14	5.85
	Plinthosol	1	280	1.6	0.23	55.21	8.5	19.7	71.8	28.6	0.09	0.77	6.25
		2	570	1.6	0.21	0.48	35.8	18.7	45.4	37.0	0.04	0.47	6
	Sandy Gleysol	1	170	1.6	0.25	72.09	4.3	16.6	79.0	27.5	0.04	0.56	5.55
		2	380	1.5	0.27	94.37	7.1	19.0	73.9	27.5	0.04	0.19	5.65
		3	690	1.6	0.25	47.59	17.8	11.2	71.0	30.7	0	0.14	5.8
		4	2000	1.7	0.30	0.031	44.1	13.4	42.1	56.6	0	0.13	6.9
	Clayey Gleysol	1	250	1.5	0.25	0.006	60.1	28.2	20.2	25	0.12	1.7	5.86
		2	765	1.5	0.21	0.006	45.5	37.1	13.8	18.1	0.24	1.92	6
		3	1500	1.6	0.21	0.001	30.6	29.5	19.3	16.2	0.21	2.01	6.32

Z, depth of the soil layer in the soil profile; BD, soil bulk density; AWC, available water content of soil at saturation; K, saturated hydraulic conductivity; Coarse, sol particles of diameter > 2 mm; Cal, soil calcium carbonate content; SOC, soil organic carbon content.

4.3.6. Management practices and rice yield observation

Management practices within the inland valleys

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 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. The operation schedules are more or less similar among the inland valleys and determined by the occurrence of the first rainfall events. Thereby in the rainy season, there is a preferential growing period for each crop that the farmers follow (Table 4.5). However, sometimes a delay occurred for the sowing or the harvest when the farmer has another coinciding and faster paying activity to deal with. From the interviews with farmers, this took a matter of one or two weeks but did not exceed a month. In all inland valleys, the major means to maintain soil fertility is through bush-fallowing. In addition, mineral fertilizers were exclusively applied on cotton and maize fields while animal manure was mostly used in gardening.

Table 4.5. Major cropping seasons from baseline survey of the inland valleys during field investigation. Own representation.

	Cropping season											
Crops	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Yam												
Cassava												
Corn												
Rice												
Cotton												
Sorghum												

Results of rice yield observation in Tossahou

All of the harvested rice fields were cultivated under natural flood with a grain yield ranged from 0.3 ± 0.1 to 3 ± 1.6 t/ha. The biomass yields were ranged between 0.5 ± 0.2 and 4.6 ± 3.0 t/ha (Figure 4.19). The plant density within the harvested plots varies between 3 and 20 plants/m². Pearson bivariate correlation analysis revealed a highly significant positive correlation between grain and straw yield ($r = 0.891$, $P < 0.000$), and no significant correlation between grain yield and plant density ($r = 0.379$, $P = 0.172$).

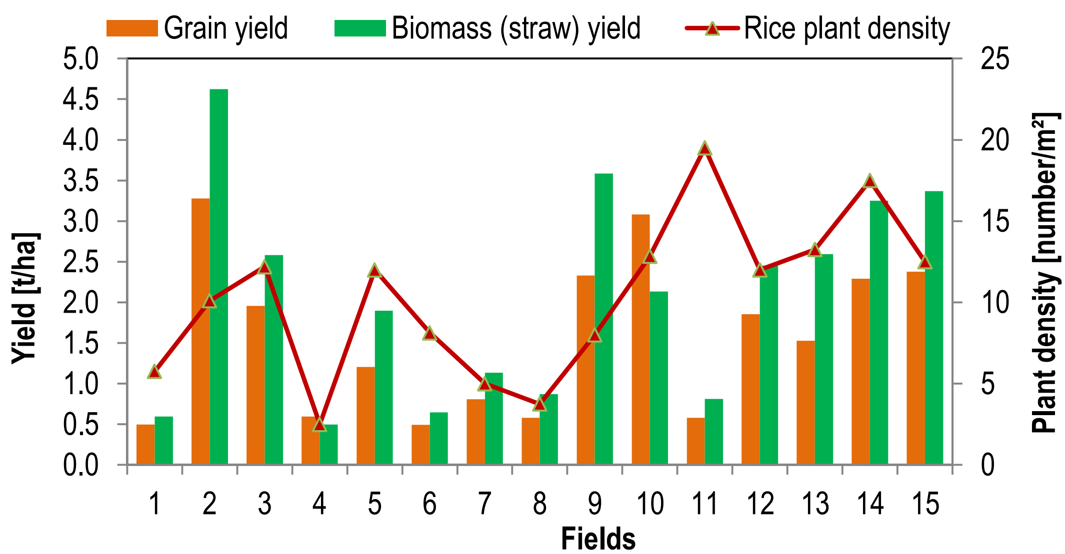


Figure 4.19. Observed Rice grain and straw yields within the inland valley of Tossahou.

4.4. Conclusions

The experimental setup and data collection performed in this chapter have enabled to acquire relevant information for characterizing the three inland valley watersheds and to produce a database which was not accessible at the beginning of this study. Although the underlying limitations encountered in this study are evident, the quality of the established dataset was sufficient enough to account for the different key characteristics of the selected watersheds and to allow a successful run of the SWAT model for achieving the target goals. Moreover, the created database is helpful in solving the issues of low data availability in the region and can be used as reference for other studies in the future.

Chapter 5

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

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5.1. 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 NO3-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.

Keywords: Africa, agricultural intensification, environmental impact, water resources, inland valleys, SWAT.

5.2. 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 under-performing by policymakers (AFD, 2013). Actually, rainfed food 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.

5.3. Materials and methods

The location of the selected inland valleys is described in chapter 2. The modelling approach (model configuration, model evaluation and input data) that we applied for this study has previously been developed in chapter 3.

5.4. Results

5.4.1. Model calibration and validation

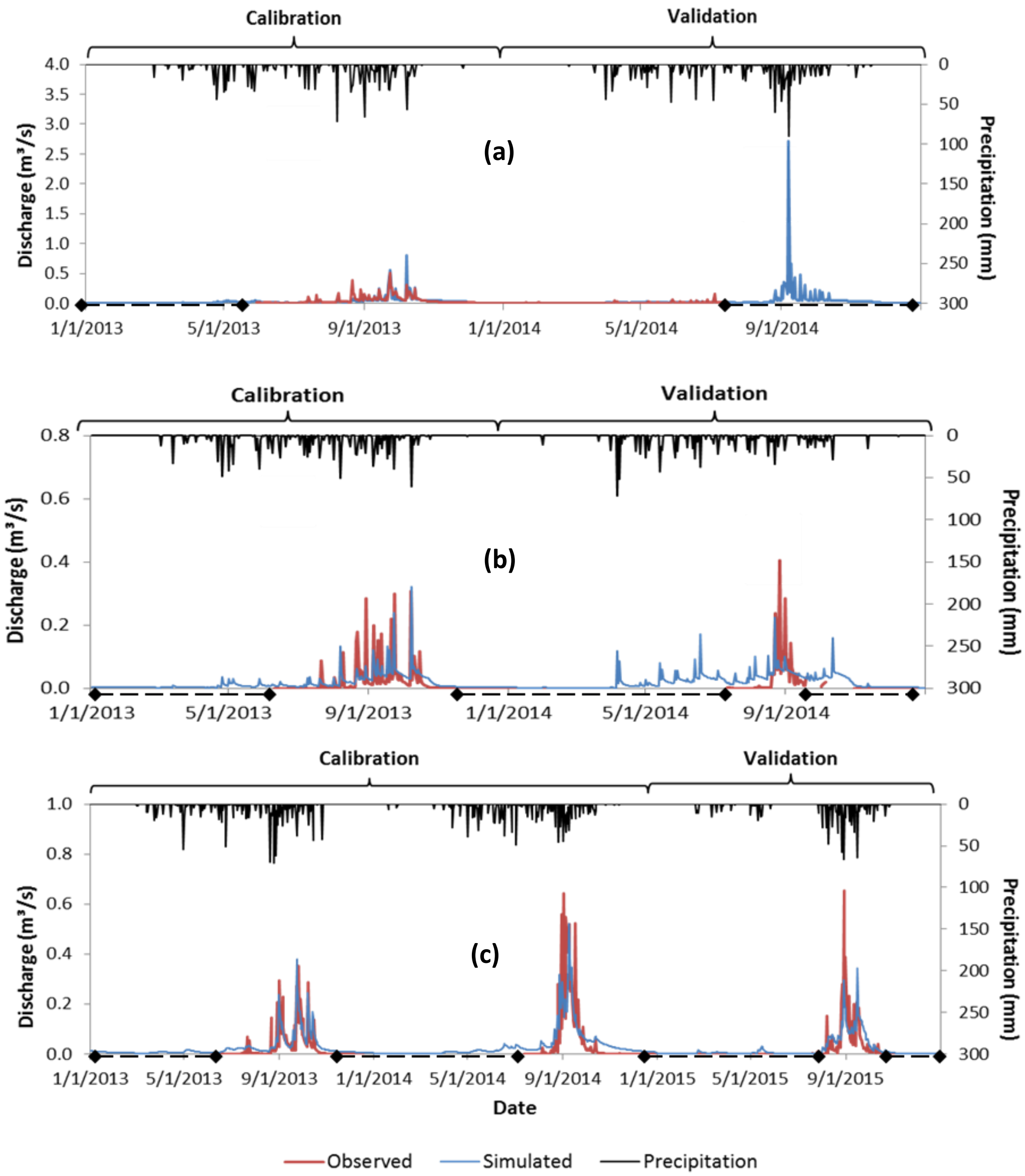
The predictive performance of ArcSWAT is considered to be satisfactory for streamflow calibration and validation for all the watersheds that contribute to the monitored inland valleys (Table 5.1). The simulated and observed discharge and nitrate loads are compared in Figures 5.1 and 5.2. At most of the 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 1,154 to 1,200 mm. These low potential evapotranspiration values may be related to the accuracy of measured solar radiation data used in the modelling.

Table 5.1. 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.

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.



◆– – – –◆No measurements.

Figure 5.1. 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.

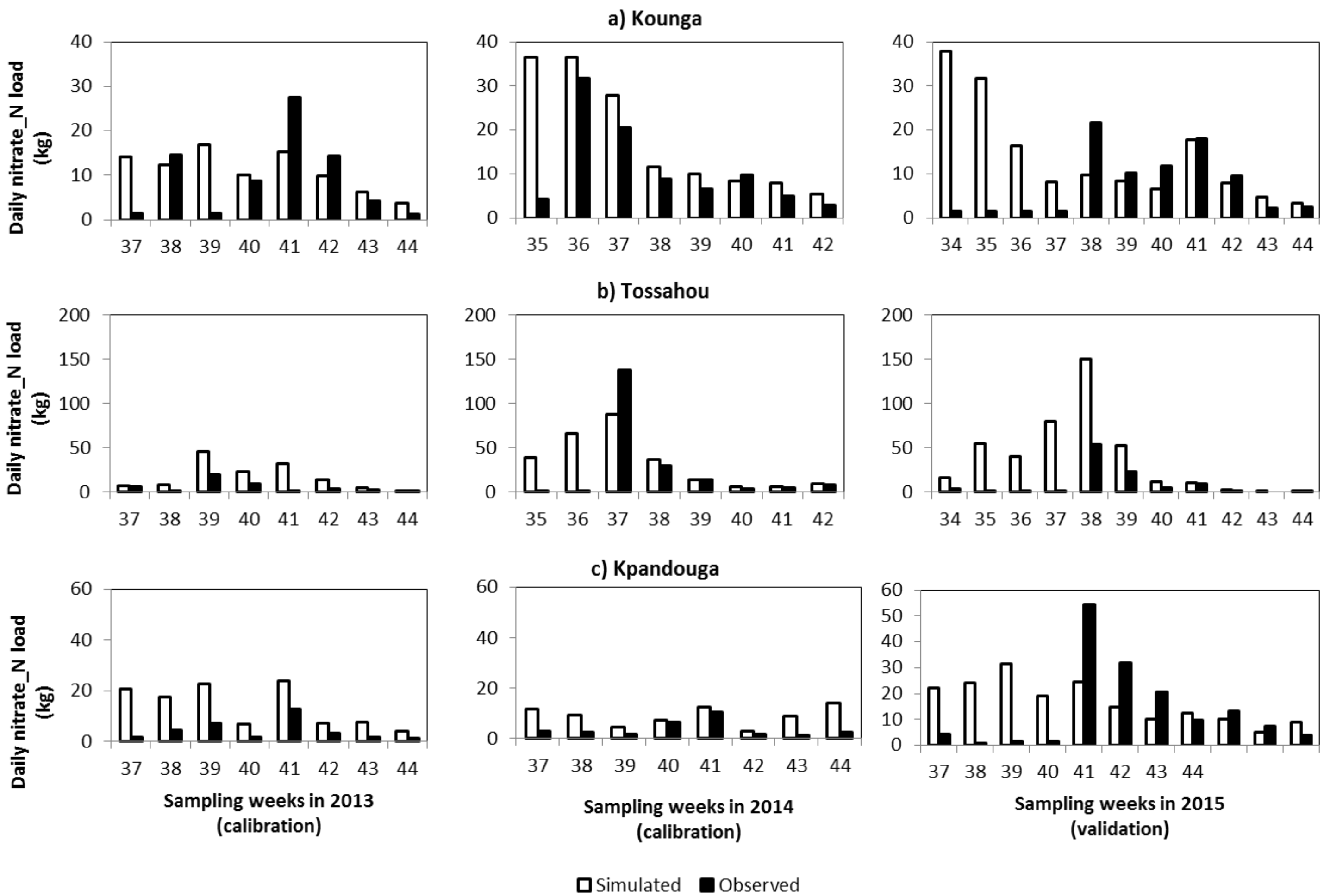


Figure 5.2. Simulated and observed nitrate loads during calibration and validation at Kounga, Tossahou, and Kpandouga using ArcSWAT.

As shown in Table 5.2, 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. Tables 5.3-5.5 respectively display the parameters that were found sensitive for calibration for Kounga, Tossahou, and Kpandouga.

Table 5.2. 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.

Table 5.3. Calibrated parameter values for Kounga.

Parameters	Initial range	Fitted values
CN2[b]	r[a] (-1…0.2)	-0.268693
ESCO[b]	v[a] (0…1)	0.263804
GW_REVAP[b]	v (0.02…0.2)	0.135042
SOL_AWC[b]	r (-1…1)	0.284807
NPERCO[b]	0.200	0.000503
CMN[b]	0.00030	0.000987
DD[b]	5	7

[a] v, the parameter value is replaced by the fitted value; r, the parameter value is multiplied by (1+the fitted value).

[b] CN2, curve number for moisture condition II; ESCO, soil evaporation compensation factor; GW_REVAP, groundwater re-evaporation coefficient; SOL_AWC, available water capacity of the soil layer; NPERCO, nitrogen percolation coefficient; CMN, rate factor for humus mineralization of active organic nitrogen; DD, drainage density factor affecting the flow separation ratio.

Table 5.4. Calibrated parameter values for Tossahou.

Parameters	Initial range	Fitted values
SLSUBBSN[b]	r[a] (-0.5…0.5)	0.177402
ESCO[b]	v[a] (0…0.3)	0.009174
SOL_AWC[b]	r (0.05…0.5)	0.612440
HRU_SLP[b]	r (-0.3…0.3)	0.505360
GW_REVAP[b]	v (0.02…0.2)	0.101032
EPCO[b]	v (0.2…1)	0.965901
ALPHA_BF[b]	v (0.6…1)	0.864657
CN2[b]	r (-0.5…0.1)	-0.591065
GW_DELAY[b]	v (0…31)	9.229615
GWQMN[b]	v (500…1000)	826.235168
NPERCO[b]	0.200	0.002559
CMN[b]	0.00030	0.000826
DD[b]	5	8

[a]v, the parameter value is replaced by the fitted value; r, the parameter value is multiplied by (1+the fitted value).

[b]CN2, curve number for moisture condition II; ESCO, soil evaporation compensation factor; GW_REVAP, groundwater re-evaporation coefficient; SOL_AWC, available water capacity of the soil layer; NPERCO, nitrogen percolation coefficient; CMN, rate factor for humus mineralization of active organic nitrogen; DD, drainage density factor affecting the flow separation ratio; SLSUBBSN, average slope length; HRU_SLP, average slope steepness; EPCO, plant uptake compensation factor; GW_DELAY, groundwater delay; GWQMN, threshold depth of water in the shallow aquifer required for return flow to occur.

Table 5.5. Calibrated parameter values for Kpandouga.

Parameters	Initial range	Fitted values
HRU_SLP[b]	r[a] (0…0.5)	0.037297
SLSUBBSN[b]	r (-0.5…0.1)	0.146397
SOL_AWC[b]	r (0…0.5)	-0.440814
GW_REVAP[b]	v[a] (0.15…0.2)	0.136588
GW_DELAY[b]	v (0…30)	1.434834
GWQMN[b]	v (3000…6000)	3620.248779
NPERCO[b]	0.200	0.995000
DD[b]	5	7

[a] v, the parameter value is replaced by the fitted value; r, the parameter value is multiplied by (1+the fitted value).

[b] GW_REVAP, groundwater re-evaporation coefficient; SOL_AWC, available water capacity of the soil layer; NPERCO, nitrogen percolation coefficient; DD, drainage density factor affecting the flow separation ratio; SLSUBBSN, average slope length; HRU_SLP, average slope steepness; GW_DELAY, groundwater delay; GWQMN, threshold depth of water in the shallow aquifer required for return flow to occur.

5.4.2. 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., 2012). Its most influential components include precipitation, surface runoff, lateral flow, base flow and evapotranspiration.

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) (See Table 5.6). 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 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 kgN 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.

Table 5.6. Average annual water balance components, and nitrate loads simulated by ArcSWAT and SWATgrid.

	Water balance component								
	PREC[b] (mm)	SURQ[b] (mm)	LATQ[b] (mm)	GWQ[b] (mm)	PERC[b] (mm)	WYD[b] (mm)	ET[b] (mm)	ETP[b] (mm)	NITR[b] (kg N)
Kounga[a]									
ArcSWAT	1195	105	92	47	130	252	868	1154	2612
SWATgrid	1195	62	104	63	126	236	849	1154	1542
Diff[b]	0	43	-12	-16	4	16	19	0	1070
Tossahou[a]									
ArcSWAT	1009	21	88	70	161	188	741	1203	3594
SWATgrid	1009	21	63	83	156	156	765	1203	1190
Diff[b]	0	0	25	-13	5	32	-24	0	2404
Kpandouga[a]									
ArcSWAT	1070	26	49	60	302	153	645	1160	3178
SWATgrid	1070	13	46	59	260	128	687	1160	418
Diff[b]	0	13	3	1	42	25	-42	0	2760

[a] Kounga (2013-2014); Tossahou (2013-2015); Kpandouga (2013-2014).

[b] Diff, difference between ArcSWAT and SWATgrid simulations; PREC, precipitation; SURQ, surface runoff; LATQ, lateral flow; GWQ, groundwater flow; WYD, total water yield; ET, actual evapotranspiration; ETP, potential evapotranspiration; NITR, nitrate loads.

5.5. Discussion

5.5.1. Uncertainty analysis and differences between the discretization schemes

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 Figure 5.2, the high discrepancies occurring between observed and simulated values of nitrate loads in the period from the 34^{th} to 40^{th} 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.

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 (Figure 5.3).

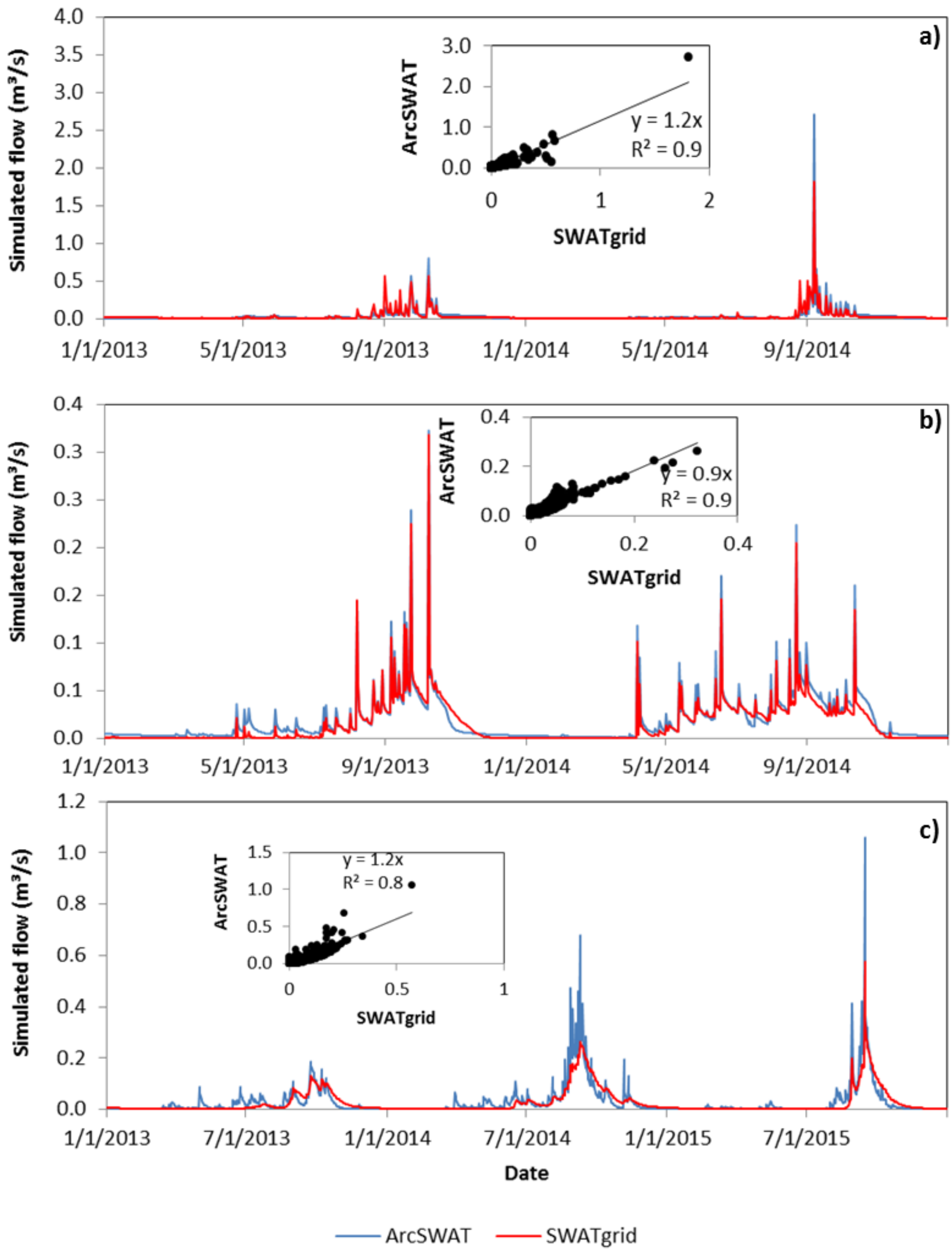


Figure 5.3. Comparison of flow (m³/s) simulated by ArcSWAT and SWATgrid, and corresponding scattergrams at the outlets of (a) Kounga (from 2013 to 2014), (b) Kpandouga (from 2013 to 2014), and (c) Tossahou (from 2013 to 2015).

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 5.6). 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).

5.5.2. 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 precipitation 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.

5.6. 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 SWATgrid is an effective tool that would require a spatial calibration in order to perform an effective quantitative evaluation of processes.

Chapter 6

Rice intensification in a changing environment: impact on water availability in inland valley landscapes in Benin

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6.1. Abstract

This study aims to assess the impact of rice intensification on the water balance under conditions of climate and land use change in three headwater inland valley watersheds (Kounga, Tossahou and Kpandouga) characterized by different initial land conditions. The Soil and Water Assessment Tool (SWAT) was used to simulate the combined impacts of two land use scenarios (defined at 25 % and 75 % of lowland conversion) and two climate scenarios (A1B and B1) of the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC SRES). The simulations were executed based on two management scenarios, (1) the current rice cultivation system and (2) the rainfed-bunded rice cultivation system, and analyzed up to the year 2049 with a special focus on the period of 2040 to 2049.

The results suggest that from a long-term perspective, the effect of climate change would overwhelm the changes induced by land use in streamflow for all watersheds. In detail, substantial reductions of streamflow by up to 35 %, 47 %, and 51 %, respectively, are projected for Kpandouga, Tossahou and Kounga. A pronounced development of the lowland into rice fields under the current cultivation system will compensate the climatic effect on streamflow by up to 15 % at Kpandouga but will slightly enhance the effect by up to 2 % at Kounga and up to 8 % at Tossahou. Changes to a rainfed-bunded cultivation system will have no significant impact on water availability downstream. Moreover, under both management scenarios, the water balance will not be affected by the increase in biomass in the rice fields from the use of fertilizers.

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

6.2. Introduction

Climate is a crucial factor in agricultural production and food security, especially in the developing countries where investments are low and social system vulnerability is high (Paeth et al., 2008). As revealed by previous studies, the decline in food productivity is significant in the tropics in response to climate variability and low soil fertility (Bossa et al., 2012; Lal, 1990; Steiner, 1996; Hiepe, 2008). As for attaining a regional self-sufficiency in rice production in Sub-Saharan Africa, the use of systematic analysis approaches for the selection and development of high-potential and low-risk unexploited areas, as well as the improvement of already used areas, has currently become essential for small-scale farming systems (Rodenburg et al., 2014). Most often, the implementation is performed in inland valleys, which are well known in West Africa for their great potential as rice-based production systems due to the high and secure water availability and soil fertility (Danvi et al., 2016; Rodenburg et al., 2014). Often known under the name bas-fonds in Benin, these landscapes usually comprise the valley bottom, hydromorphic fringes and uplands areas (Windmeijer and Andriesse, 1993) and are actively developed through improved input facilities, such as high yielding rice varieties and fertilizers used to increase the local production (Totin et al., 2013). Giertz et al. (2012) analyzed the current use and constraints on the use of inland valleys in central Benin in relation to their agro-potential. 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. Therefore, the acquisition of improved knowledge on the interacting impacts of climate and land use changes on hydrological processes in such wetlands will be an important asset for sustainable agricultural development and water resource management.

Climate change is generally referred to as a long-term change in weather patterns, including precipitation and temperature (Sun et al., 2015). In the last century, significant changes in temperature and precipitation have already been observed, caused by anthropogenic activities. In addition to climate change, land use changes associated with intensive agriculture and rapid urbanization may cause severe impacts on aquatic systems by influencing water quantity and quality (Chien et al., 2013). Water resources have been significantly impaired due to increases or decreases in annual streamflow and seasonal shifts in flow frequency as well as flood and drought events (Liew et al., 2012). Hence, water availability for crop production could be affected, especially in areas where water resources are limited. The situation may become more dramatic because of the increasing demand for food supplies and economic development (Liu et al., 2016).

Actually, most of the studies conducted in Benin on evaluating the future impacts of climate or land use change were conducted at larger spatial scales and specifically focused on rainfall-runoff processes (e.g., Sintondji, 2005), groundwater resources (e.g., Barthel et al., 2009), erosion-related degradation processes based on sediment yields in the upper Ouémé watershed (e.g., Bossa et al., 2012; Hiepe, 2008) and upland crop production (e.g., Regh et al., 2014; Worou et al., 2013; Worou et al., 2012). Accordingly, in this paper, we analyzed the impacts of climatic and agricultural changes on the water resources of small-scale watersheds. Thus, this study aims to investigate the hydrological response of three headwater 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 2040 to 2049. Assuming that spatially explicit and process-based models are best suited to predict the effects of changing environmental conditions (Beven and Binley, 1992), we applied the Soil and Water Assessment Tool (SWAT) model (Neitsch et al., 2009). Calibrated model parameters from the previously conducted study in the same inland valleys and presented in chapter 4 were used to simulate the climate scenarios in combination with two land use scenarios defined at 25 % and 75 % of lowland converted into rice fields. Moreover, management scenarios were considered for the development of the lowland areas, namely, the current rice cultivation system and the rainfed-bunded rice cultivation system in association with fertilizer use. 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. Accordingly, the paper seeks to address the following research questions: (1) how important is climate change compared to land use change, and (2) which management options may help in compensating for the potential negative effects of climate and land use change? The projected results are expected to help in planning suitable strategies for climate change mitigation and adaptation and in sustainable management of water resources in such wetlands.

6.3. Material and methods

6.3.1. Baseline periods

To define the baseline conditions, the model was run over a past period from 1980 to 2003 (including a warm-up period 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). The downscaled REMO-data for this station (period 2010-2049) were used for all catchments to make the simulations comparable. At all inland valley watersheds, the time period from 2040 to 2049 was applied to analyze the projected and induced changes. All calibrated parameter values were maintained constant during the simulation of the climatic scenarios (A1B and B1) and the others developed as follows.

6.3.2. Land use scenarios

In this study, the lowland conversion scenarios were mainly designed based on the conversion of natural vegetation (savannah and gallery forest) into rice fields. The original land use map was reclassified to dissociate the vegetation cover units in the upland areas from the lowland areas for which the expansion of rice cultivated areas were simulated. Two hypothetical scenarios were simulated by using the land use refinement tools of ArcSWAT: (1) L1, 25 % of the areas covered with natural vegetation in the lowland is converted to rice fields, and (2) L2, 75 % of the areas covered with natural vegetation in the lowlands is converted to rice fields. For each inland valley, the resulting area and percentage of land use types that were simulated in each land use scenario are illustrated in Tables 6.1, 6.2, and 6.3.

Table 6.1. Area and percentage of land use/land cover types for the different land use scenarios in Kounga.

Land use/land cover types	Baseline		Scenario L1		Scenario L2	
	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)
Gallery forest/woodland	1164.0	2.9	1123.8	2.8	1043.5	2.6
Shrub savannah	13631.3	33.4	12571.1	30.8	10450.7	25.6
Tree savannah	11009.5	27.0	10832.0	26.5	10477.0	25.7
Grass savannah	9116.4	22.3	8404.0	20.6	6979.2	17.1
Rice	501.8	1.2	2492.1	6.1	6472.5	15.9
Cotton	2536.9	6.2	2536.9	6.2	2536.9	6.2
Yam	975.1	2.4	975.1	2.4	975.1	2.4
Cassava	359.9	0.9	359.9	0.9	359.9	0.9
Corn	1022.4	2.5	1022.4	2.5	1022.4	2.5
Sorghum	321.9	0.8	321.9	0.8	321.9	0.8
Pnut	113.4	0.3	113.4	0.3	113.4	0.3
Settlements	47.3	0.1	47.3	0.1	47.3	0.1

L1, land use change scenario of lowland conversion at 25 %; L2, land use change scenario of lowland conversion at 75 %.

Table 6.2. Area and percentage of land use/land cover types for the different land use scenarios in Tossahou.

Land use/land cover types	Baseline		Scenario L1		Scenario L2	
	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)
Gallery forest/woodland	9557.5	19.1	8645.3	17.3	6820.8	13.6
Shrub savannah	16912.5	33.8	16057.0	32.1	14346.0	28.7
Tree savannah	3545	7.1	3545.0	7.1	3545.0	7.1
Grass savannah	15674.5	31.3	15331.8	30.7	14646.3	29.3
Rice	312	0.6	2422.5	4.8	6643.5	13.3
Cotton	558	1.1	558.0	1.1	558.0	1.1
Yam	690	1.4	690.0	1.4	690.0	1.4
Cassava	747	1.5	747.0	1.5	747.0	1.5
Corn	888.5	1.8	888.5	1.8	888.5	1.8
Sorghum	123	0.2	123.0	0.2	123.0	0.2
Pnut	917	1.8	917.0	1.8	917.0	1.8
Settlements	19	0.04	19.0	0.04	19.0	0.04
Bare soil	56.5	0.1	56.5	0.1	56.5	0.1

L1, land use change scenario of lowland conversion at 25 %; L2, land use change scenario of lowland conversion at 75 %.

Table 6.3. Area and percentage of land use/land cover types for the different land use scenarios in Kpandouga.

Land use/land cover types	Baseline		Scenario L1		Scenario L2	
	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)
Gallery forest/woodland	3332.6	8.7	2603.3	6.8	1144.7	3.0
Shrub savannah	5154.8	13.4	4753.5	12.3	3951.0	10.3
Tree savannah	22572.9	58.6	21572.2	56.0	19570.8	50.8
Grass savannah	7052.4	18.3	6655.9	17.3	5862.8	15.2
Rice	47.4	0.1	2575.2	6.7	7630.8	19.8
Yam	132.1	0.3	132.1	0.3	132.1	0.3
Cassava	85.1	0.2	85.1	0.2	85.1	0.2
Sorghum	37.7	0.1	37.7	0.1	37.7	0.1
Settlements	66.2	0.2	66.2	0.2	66.2	0.2
Bare soil	18.9	0.05	18.9	0.05	18.9	0.05

L1, land use change scenario of lowland conversion at 25 %; L2, land use change scenario of lowland conversion at 75 %.

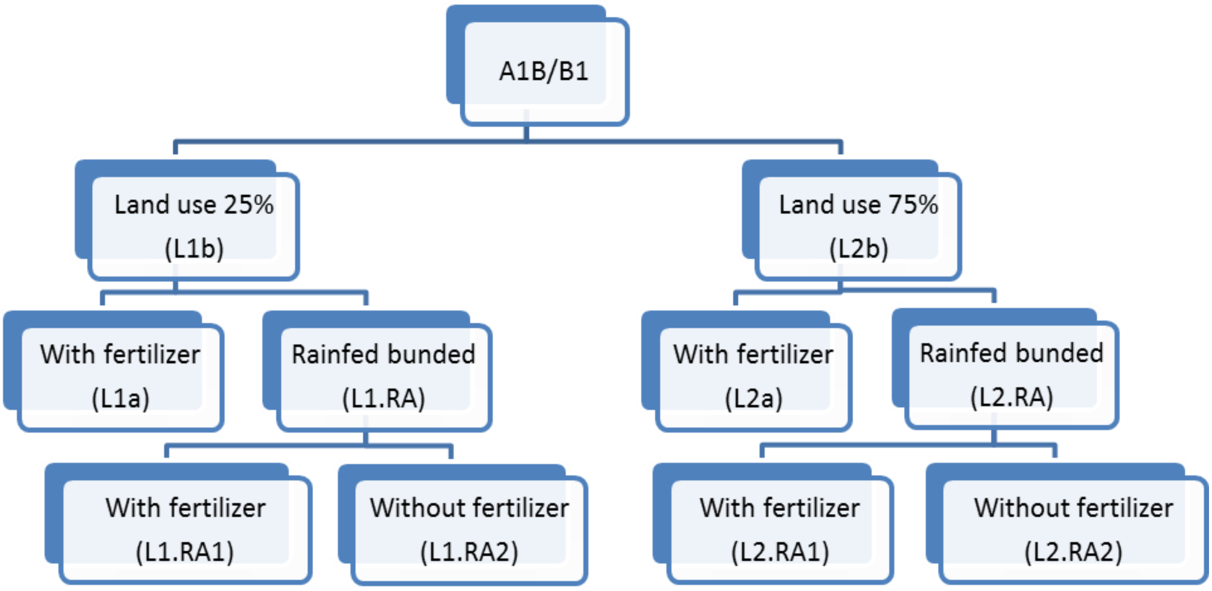
6.3.3. Management scenarios

The lowland rice intensification was designed based on two management scenarios, including the current system of rice cultivation and the rainfed-bunded cultivation system. The current rice cultivation system refers to rainfed rice fields grown by direct seeding with neither bund implementation nor other water control structures. The rainfed-bunded cultivation system refers to bunded rice fields with direct seeding and partial water management. 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 (Neitsch et al. 2009; Sakaguchi et al., 2014). 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 in 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 (Neitsch et al. 2009; Sakaguchi et al., 2014). 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. 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.

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} (Schmitter et al., 2015). The first fertilizer is applied 15 DAS (Days After Sowing) 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) (Schmitter et al., 2015).

6.3.4. Combined scenario analysis

Two combinations of scenarios were simulated in this study. The first scenario combination investigates the impacts of climate and land use change, which were simulated under the current cultivation system with no fertilizer inputs. The second combination includes the climate, land use and management scenarios, as depicted by Figure 6.1. Herein, the simulations were performed under both cultivation systems with fertilizer inputs and under the rainfed-bunded cultivation system without fertilizer application.



A1B and B1, climate change scenarios; L1 and L2, land use change scenarios of 25 % and 75 % lowland conversion, respectively; a, current rice cultivation system with fertilizer application; b, current rice cultivation system without fertilizer application; RA, rainfed-bunded system; RA1, rainfed-bunded rice cultivation system with fertilizer application; RA2, rainfed-bunded rice cultivation system without fertilizer application.

Figure 6.1. Illustration of the combination of climate (A1B/B1), land use and management scenarios.

6.4. Results

6.4.1. Water balance during baseline periods

The simulated results of the annual water balance for the baseline period of 1985 to 2003 are presented in Table 6.4. The highest values of actual evapotranspiration (837 mm), surface runoff (125 mm), and subsurface flow (159 mm) are simulated at the Kounga watershed where the portion of cultivated areas is the highest. Groundwater flow is high in the other watersheds, with the highest value of 357 mm simulated at Kpandouga, where natural vegetation is predominant. Subsequently, the average annual total water yield is estimated as 361 mm in Kounga, 387 mm in Tossahou, and 448 mm in Kpandouga.

Table 6.4. Changes in the annual water balance under climate change compared to baseline conditions during the period from 2040 to 2049.

Scenarios	PREC (mm)	TEMP (°C)	ET (mm)	SURQ (mm)	LATQ (mm)	GWQ (mm)	WYD (mm)
KOUNGA							
Baseline (1985-2003)	1259	26.6	837	125	159	77	361
A1B	-213 (-17 %)	2.4 (9 %)	36.9 (4 %)	-105 (-83 %)	-90 (-56 %)	6 (8 %)	-183 (-51 %)
B1	-119 (-9 %)	2.4 (9 %)	70.4 (8 %)	-85 (-68 %)	-81 (-51 %)	31 (40 %)	-130 (-36 %)
TOSSAHOU							
Baseline (1985-2003)	1259	26.6	811.2	95	87	205	387
A1B	-213 (-17 %)	2.4 (9 %)	32 (4 %)	-81 (-85 %)	-25 (-28 %)	-84 (-41 %)	-182 (-47 %)
B1	-119 (-9 %)	2.4 (9 %)	59 (7 %)	-69 (-72 %)	-16 (-19 %)	-42 (-20 %)	-118 (-30 %)
KPANDOUGA							
Baseline (1985-2003)	1259	26.6	771.7	78	52	318	448
A1B	-213 (-17 %)	2.4 (9 %)	-32 (-4 %)	-57 (-74 %)	-15 (-29 %)	-96 (-30 %)	-155 (-35 %)
B1	-119 (-9 %)	2.4 (9 %)	-15 (-2 %)	-51 (-66 %)	-10 (-19 %)	-39 (-12 %)	-84 (-19 %)

A1B and B1, climate change scenarios; PREC, precipitation; TEMP, temperature; ET, actual evapotranspiration; SURQ, surface runoff; LATQ, lateral flow; GWQ, groundwater flow; WYD, total water yield.

6.4.2. Impact of climate change

Table 6.4 summarizes the projected changes in temperature, precipitation, and water balance under A1B and B1 in the inland valley watersheds. In comparison to the baseline conditions, the mean annual temperature is projected to increase by 2.4 °C until 2049 under both the A1B and B1 climatic conditions. However, precipitation will decline more on average under A1B (by 213 mm) than under B1 (by 119 mm). As a consequence, evapotranspiration will slightly increase at Kounga and Tossahou (up to 4 % under A1B and 8 % under B1) and marginally decrease at Kpandouga by 4 % and 2 % under A1B and B1. With respect to the decline in the rainfall amount, surface runoff and subsurface flow will be significantly reduced in all watersheds. This will consequently result in substantial decreases in the total water yield by 51 and 36 % under A1B and B1, respectively, at the Kounga watershed, by 47 and 30 % at Tossahou, and by 35 and 19 % at Kpandouga.

6.4.3. Effect of land use change

An increased lowland conversion initiates a slight change in evapotranspiration in all watersheds, which is more noticeable at Kpandouga through a decline reaching up to 11 % under B1 (see Table 6.5). Actually, the changes induced in the water balance components are remarkably different among the watersheds but do not influence the total water yield significantly. At the watersheds of Kounga and Kpandouga, the total water yield will increase by up to 2 % and 15 %, respectively, whereas a decline of up to 8 % (under climate scenario B1) is projected at Tossahou.

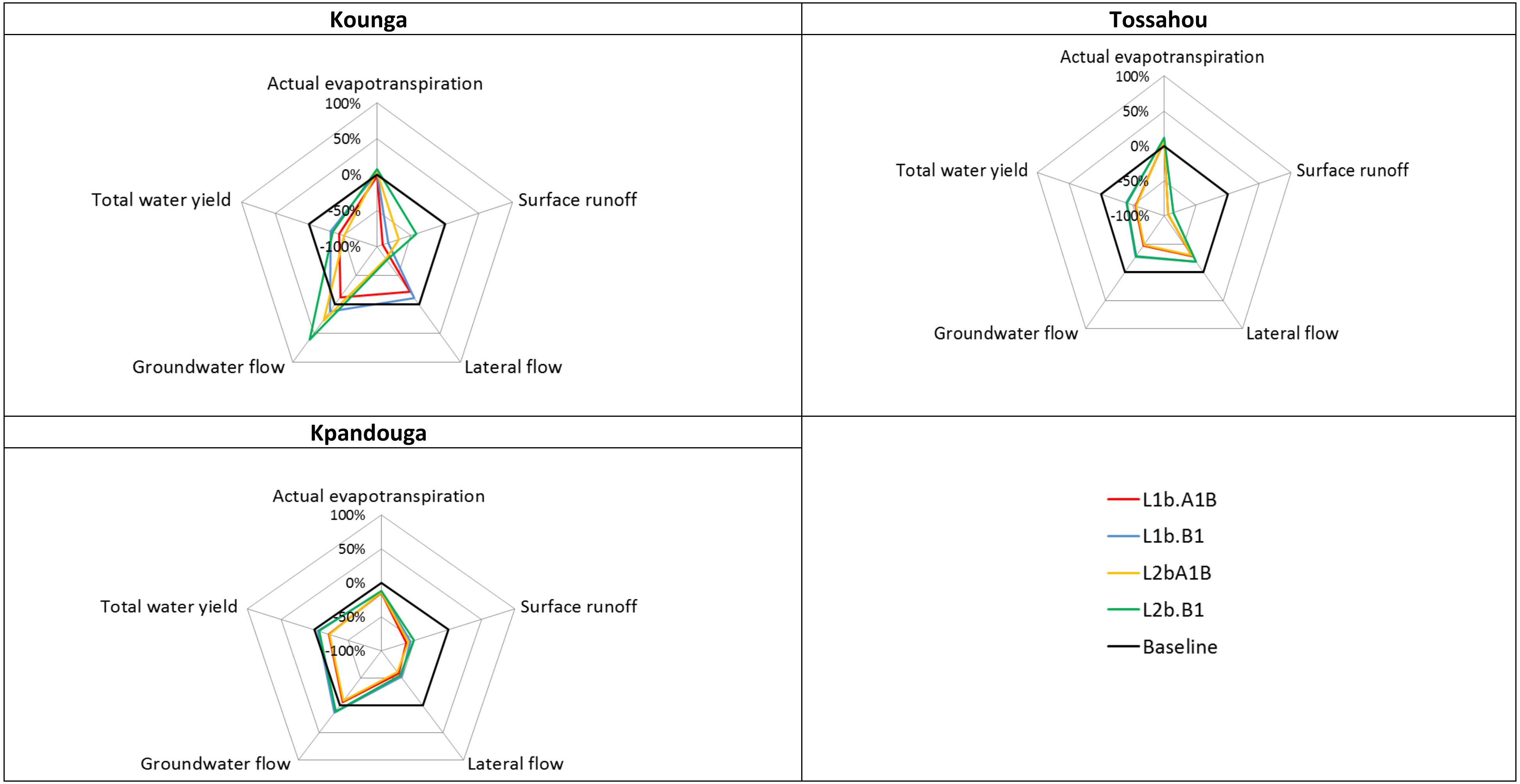
Table 6.5. Changes in water balance under land use change scenarios compared to baseline conditions from 2040 to 2049 without the use of fertilizers.

Scenarios	ET (%)	SURQ (%)	LATQ (%)	GWQ (%)	WYD (%)
KOUNGA					
L1 (A1B)	-6	-8	35	-20	8
L1 (B1)	-5	-16	40	-27	6
L2 (A1B)	0	15	-22	20	0
L2 (B1)	-1	25	-25	21	2
TOSSAHOU					
L1 (A1B)	3	-9	0	-6	-5
L1 (B1)	3	-14	0	-7	-7
L2 (A1B)	3	-9	-1	-8	-7
L2 (B1)	4	-14	-1	-9	-8
KPANDOUGA					
L1 (A1B)	-11	11	-29	24	16
L1 (B1)	-11	10	-33	26	17
L2 (A1B)	-9	14	-31	22	15
L2 (B1)	-10	14	-36	23	15

L1 and L2, land use change scenarios of 25% and 75 % lowland conversion, respectively; A1B and B1, climate change scenarios; ET, actual evapotranspiration; SURQ, surface runoff; LATQ, lateral flow; GWQ, groundwater flow; WYD, total water yield.

6.4.4. Changes due to climate and land use with the current cultivation system

In this section, the projected changes of the water balance were simulated for the current rice cultivation system with no fertilizer application. The simulated trends during the projection period are depicted in Figure 6.2 in comparison to the baseline conditions. Although the hydrological processes within the inland valleys are affected by land use change, the climatic effect on streamflow is dominant in all of the watersheds. In the Kounga watershed, the combined effects of climate and land use change increase groundwater flow up to 28 % (A1B) and 61 % (B1) for 75 % lowland conversion but reduce surface and subsurface runoff. In the Tossahou watershed, the changes in the water balance components reveal a decline in the total water yield through a reduction of surface runoff, subsurface flow and groundwater flow for all land conversion and climate scenarios. Evapotranspiration and subsurface flow are further reduced by up to 14 % and 60 % at Kpandouga, whereas the decline in surface runoff and groundwater flow are lower compared to the climate change projections. Supplementary information on the water balance component is presented in Tables 6.6 -6.8.



Baseline period from 1985 to 2003; L1 and L2, land use change scenarios of 25 % and 75 % lowland conversion, respectively; b, current rice cultivation system with no fertilizer application; A1B and B1, climate change scenarios.

Figure 6.2. Predicted changes in the water balance without the use of fertilizers under land use and climate change during the period of 2040-2049.

Table 6.6. Annual water balance in Kounga for current rice cultivation system under land use and climate change.

Scenarios	ET (mm)	SURQ (mm)	LATQ (mm)	GWQ (mm)	WYD (mm)
Baseline (1985-2003)	837	125	159	77	361
L1a.A1B (2040-2049)	824	11	125	66	199
L1a.B1 (2040-2049)	863	19	142	85	244
L1b.A1B (2040-2049)	823	11	125	67	200
L1b.B1 (2040-2049)	861	20	142	87	246
L2a.A1B (2040-2049)	883.8	35	35	93	160
L2a.B1 (2040-2049)	914	62	39	116	217
L2b.A1B (2040-2049)	872	40	34	98	170
L2b.B1 (2040-2049)	899	72	38	123	233

L1 and L2, land use change scenarios at 25 % and 75 % lowland conversion; a, current rice cultivation system with fertilizer application; b, current rice cultivation without fertilizers application; A1B and B1, climate change scenarios; ET, actual evapotranspiration; SURQ, surface runoff; LATQ, lateral flow; GWQ, groundwater flow; WYD, total water yield.

Table 6.7. Annual water balance components in Tossahou for current rice cultivation system under land use and climate change.

Scenarios	ET (mm)	SURQ (mm)	LATQ (mm)	GWQ (mm)	WYD (mm)
Baseline (1985-2003)	811	95	87	205	387
L1a.A1B (2040-2049)	868	5.8	62.2	107	168
L1a.B1 (2040-2049)	900	13.3	70.9	146.9	226
L1b.A1B (2040-2049)	866	6	62	109	170
L1b.B1 (2040-2049)	898	13	71	149	228
L2a.A1B (2040-2049)	876	6	62	100	160
L2a.B1 (2040-2049)	909	13	70	139	216
L2b.A1B (2040-2049)	871	6	62	105	165
L2b.B1 (2040-2049)	902	13	71	145	224

L1 and L2, land use change scenarios at 25 % and 75 % lowland conversion; a, current rice cultivation system with fertilizer application; b, current rice cultivation without fertilizers application; A1B and B1, climate change scenarios; ET, actual evapotranspiration; SURQ, surface runoff; LATQ, lateral flow; GWQ, groundwater flow; WYD, total water yield.

Table 6.8. Annual water balance in Kpandouga for current rice cultivation system under land use and climate change.

Scenarios	ET (mm)	SURQ (mm)	LATQ (mm)	GWQ (mm)	WYD (mm)
Baseline (1985-2003)	772	78	52	318	448
L1a.A1B (2040-2049)	662	29	22	297	347
L1a.B1 (2040-2049)	675	34	25	360	422
L1b.A1B (2040-2049)	659	29	22	300	350
L1b.B1 (2040-2049)	672	34	25	363	425
L2a.A1B (2040-2049)	677	30	20	284	333
L2a.B1 (2040-2049)	692	37	23	345	407
L2b.A1B (2040-2049)	666	31	21	292	343
L2b.B1 (2040-2049)	682	38	24	353	416

L1 and L2, land use change scenarios at 25 % and 75 % lowland conversion; a, current rice cultivation system with fertilizer application; b, current rice cultivation without fertilizers application; A1B and B1, climate change scenarios; ET, actual evapotranspiration; SURQ, surface runoff; LATQ, lateral flow; GWQ, groundwater flow; WYD, total water yield.

6.4.5. Changes in management due to climate and land use change

In this section, the results are compared to those presented in section 6.4.4 (under the current cultivation system) to assess the relative effect induced by the use of fertilizers and the development of the rainfed-bunded rice cultivation system. Under fertilizer application, the changes induced in the water balance are similar in each inland valley watershed (Table 6.9). Moreover, the implementation of rainfed-bunded rice cultivation shows no significant effect on the availability of surface water downstream (see Tables 6.10 and 6.11). Supplementary information on the water balance component is presented in Tables 6.12-14.

Table 6.9. Relative changes induced by the application of fertilizers to the current cultivation system under land use and climate change scenarios from 2040 to 2049.

Scenarios	ET (%)	SURQ (%)	LATQ (%)	GWQ (%)	WYD (%)
KOUNGA					
L1a.A1B	0	0	0	-1	0
L1a. B1	0	-1	0	-2	-1
L2a.A1B	1	-4	0	-7	-4
L2a.B1	2	-8	1	-9	-5
TOSSAHOU					
L1a.A1B	0	0	0	-1	-1
L1a. B1	0	0	0	-1	-1
L2a.A1B	1	0	0	-2	-2
L2a.B1	1	0	0	-3	-3
KPANDOUGA					
L1a.A1B	0	0	0	-1	-1
L1a. B1	0	0	0	-1	-1
L2a.A1B	1	-1	-1	-2	-3
L2a.B1	1	-1	-1	-2	-3

L1 and L2, land use change scenarios of 25% and 75 % lowland conversion, respectively; a, current cultivation system with fertilizer application; A1B and B1, climate change scenarios; ET, actual evapotranspiration; SURQ, surface runoff; LATQ, lateral flow; GWQ, groundwater flow; WYD, total water yield.

Table 6.10. 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 2040 to 2049.

Scenarios	ET (%)	SURQ (%)	LATQ (%)	GWQ (%)	WYD (%)
KOUNGA					
L1.RA1.A1B	2	2	0	11	3
L1.RA1.B1	1	3	0	13	3
L2.RA1.A1B	0	2	0	1	0
L2.RA1.B1	0	3	0	-1	-1
TOSSAHOU					
L1.RA1.A1B	0	0	0	0	0
L1.RA1.B1	0	1	0	0	0
L2.RA1.A1B	0	1	0	0	0
L2.RA1.B1	0	3	0	0	0
KPANDOUGA					
L1.RA1.A1B	0	0	1	1	0
L1.RA1.B1	0	-1	1	1	0
L2.RA1.A1B	-1	-1	2	2	0
L2.RA1.B1	-1	-2	2	2	0

L1 and L2, land use change scenarios of 25% and 75 % lowland conversion, respectively; RA1, rainfed-bunded rice cultivation system with fertilizer application; A1B and B1, climate change scenarios; ET, actual evapotranspiration; SURQ, surface runoff; LATQ, lateral flow; GWQ, groundwater flow; WYD, total water yield.

Table 6.11. 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 2040 to 2049.

Scenarios	ET (%)	SURQ (%)	LATQ (%)	GWQ (%)	WYD (%)
KOUNGA					
L1.RA2.A1B	2	2	0	10	2
L1.RA2.B1	1	3	0	13	3
L2.RA2.A1B	0	9	2	4	-1
L2.RA2.B1	0	13	4	2	-2
TOSSAHOU					
L1.RA2.A1B	0	1	0	0	0
L1.RA2.B1	0	2	0	0	0
L2.RA2.A1B	0	3	0	0	0
L2.RA2.B1	0	5	0	0	0
KPANDOUGA					
L1.RA2.A1B	0	-1	1	1	0
L1.RA2.B1	0	-1	1	1	0
L2.RA2.A1B	-1	-2	2	2	0
L2.RA2.B1	-1	-2	3	2	0

L1 and L2, land use change scenarios of 25% and 75 % lowland conversion, respectively; RA2, rainfed-bunded rice cultivation system with fertilizer application; A1B and B1, climate change scenarios; ET, actual evapotranspiration; SURQ, surface runoff; LATQ, lateral flow; GWQ, groundwater flow; WYD, total water yield.

Table 6.12. Annual water balance in Kounga for rainfed rice cultivation under land use and climate change.

Scenarios	ET (mm)	SURQ (mm)	LATQ (mm)	GWQ (mm)	WYD (mm)
Baseline (1985-2003)	837	125	159	77	361
L1.RA1.A1B (2040-2049)	836	13	125	75	208
L1.RA1.B1 (2040-2049)	874	23	142	96	257
L1.RA2.A1B (2040-2049)	836	13	125	75	209
L1.RA2.B1 (2040-2049)	873	24	142	97	258
L2.RA1.A1B (2040-2049)	884	37	35	93	159
L2.RA1.B1 (2040-2049)	915	66	39	116	213
L2.RA2.A1B (2040-2049)	873	51	37	101	169
L2.RA2.B1 (2040-2049)	900	88	44	125	227

L1 and L2, land use change scenarios at 25 % and 75 % lowland conversion; RA1, rainfed-bunded rice cultivation system with fertilizer application; RA2, rainfed-bunded rice cultivation without fertilizers application; A1B and B1, climate change scenarios; ET, actual evapotranspiration; SURQ, surface runoff; LATQ, lateral flow; GWQ, groundwater flow; WYD, total water yield.

Table 6.13. Annual water balance in Tossahou for rainfed rice cultivation under land use and climate change.

Scenarios	ET (mm)	SURQ (mm)	LATQ (mm)	GWQ (mm)	WYD (mm)
Baseline (1985-2003)	811	95	87	205	387
L1.RA1.A1B (2040-2049)	868	6	62	107	168
L1.RA1.B1 (2040-2049)	900	14	71	147	226
L1.RA2.A1B (2040-2049)	866	7	62	109	170
L1.RA2.B1 (2040-2049)	897	15	71	149	228
L2.RA1.A1B (2040-2049)	875	7	62	100	160
L2.RA1.B1 (2040-2049)	908	16	71	138	216
L2.RA2.A1B (2040-2049)	870	8	62	105	166
L2.RA2.B1 (2040-2049)	901	18	71	145	224

L1 and L2, land use change scenarios at 25 % and 75 % lowland conversion; RA1, rainfed-bunded rice cultivation system with fertilizer application; RA2, rainfed-bunded rice without cultivation fertilizers application; A1B and B1, climate change scenarios; ET, actual evapotranspiration; SURQ, surface runoff; LATQ, lateral flow; GWQ, groundwater flow; WYD, total water yield.

Table 6.14. Annual water balance in Kpandouga for rainfed rice cultivation under land use and climate change.

Scenarios	ET (mm)	SURQ (mm)	LATQ (mm)	GWQ (mm)	WYD (mm)
Baseline (1985-2003)	772	78	52	318	448
L1.RA1.A1B (2040-2049)	661	28	22	299	347
L1.RA1.B1 (2040-2049)	674	34	26	362	421
L1.RA2.A1B (2040-2049)	657	28	23	302	350
L1.RA2.B1 (2040-2049)	671	34	26	365	425
L2.RA1.A1B (2040-2049)	673	29	21	289	333
L2.RA1.B1 (2040-2049)	688	36	24	351	406
L2.RA2.A1B (2040-2049)	662	30	22	298	344
L2.RA2.B1 (2040-2049)	677	36	25	360	416

L1 and L2, land use change scenarios at 25 % and 75 % lowland conversion; RA1, rainfed-bunded rice cultivation system with fertilizer application; RA2, rainfed-bunded rice cultivation fertilizers application; A1B and B1, climate change scenarios; ET, actual evapotranspiration; SURQ, surface runoff; LATQ, lateral flow; GWQ, groundwater flow; WYD, total water yield.

6.5. Discussion

6.5.1. Projected impacts on water availability

According to the scenarios used in this study, the impact of climate change on evapotranspiration is marginal in all of the watersheds with respect to the decreased rainfall and increased temperature from 2040 to 2049. This can be explained by the fact that the system is water limited and not energy limited, which means that an increase in potential evapotranspiration caused by higher temperatures is not influencing actual evapotranspiration. As for water availability, the decrease in precipitation may initiate the prevalence of water scarcity within the inland valleys and consequently lead to limited water availability downstream (McDonald et al., 2011; NCA, 2014) (Figure 6.3). Actually, this specific interrelationship between precipitation and streamflow was also observed at a larger scale in a study previously conducted by Bossa et al. (2012) in the same region, which 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.

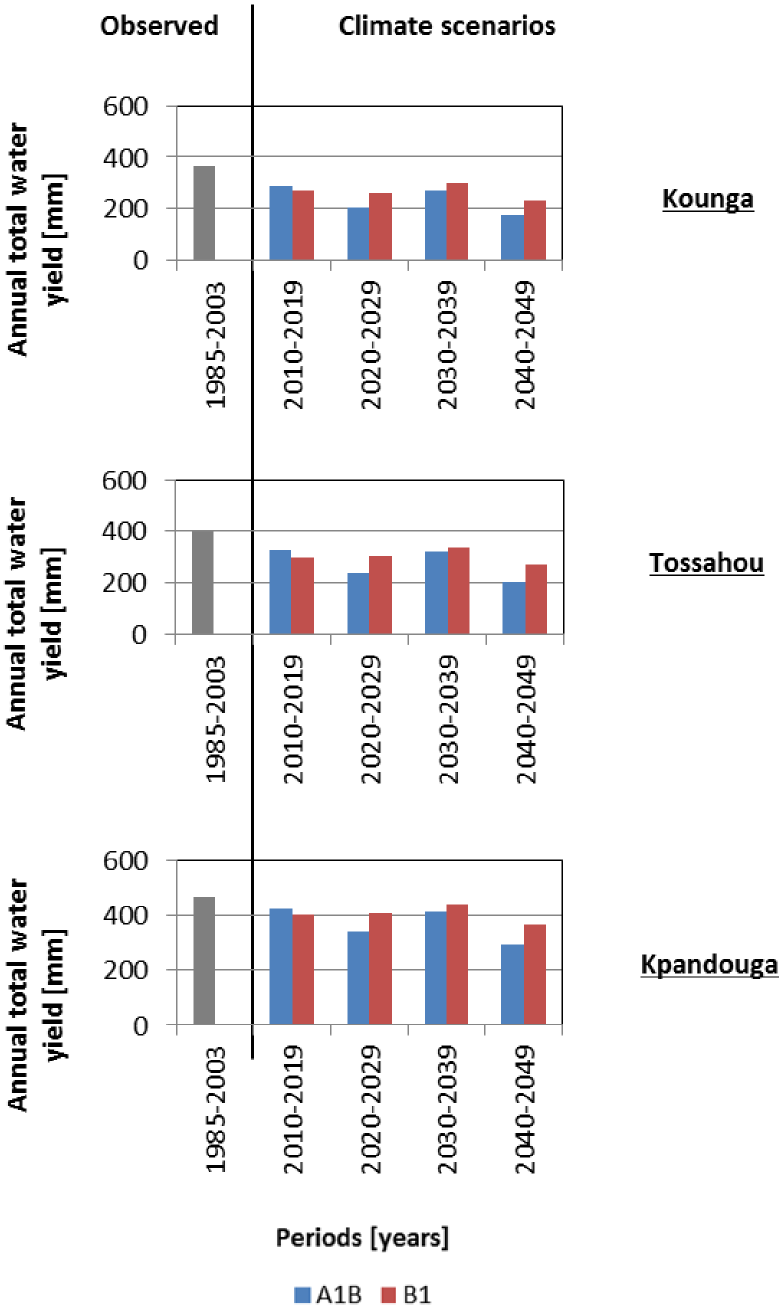


Figure 6.3. Simulated mean annual total water yield under the climate scenarios A1B and B1.

Distinguishing the effects of land use changes from concurrent climate variability is very challenging for impact assessment on watershed hydrology (Liew et al., 2012). Under the current cultivation system with no fertilizer input, the simulation of the lowland conversion scenarios revealed different effects on the water balance among the inland valley watersheds. Although the hydrological processes within the watersheds are affected (substantially in Kounga and Kpandouga), the resulting effect on the streamflow downstream is marginal. At the watershed of Tossahou, the projected decline in the total water yield can be due to the slight rise in evapotranspiration, probably induced by the increase in biomass at the rice fields. Hence, this can explain the preferential reduction of surface runoff, which is also expected at the watershed. Similar findings were reached by Quyen et al. (2014), 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. In contrast, in the Kpandouga watershed, the lowland conversion initiates a decline in evapotranspiration probably due to the induced reduction of the areas densely covered by vegetation. This pattern is consistent with the observations made by Tao et al. (2015), 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 would increase in Kpandouga through more generation of surface runoff and groundwater flow due to the substantial capacity of vegetation to intercept or retain water being lost because of the extensive agricultural development. This altering effect of land use changes on the hydrologic system was also revealed in other studies (e.g., Pervez and Henebry, 2015; Schilling et al., 2008; Wagner et al., 2013) and may potentially impact the water resources within the watershed.

Under combined land use and climate change scenarios, the climatic decline projected in streamflow is dominant despite the counteracting effects induced by land conversion on some hydrological processes within the watersheds. This was similarly observed by Bossa et al. (2012) in the simulation of land use and climate change effects in the Donga-Pont river watershed and may be favored in the inland valleys due to their high dependency on rainfall as headwater wetlands for water supply. Thus, climate is expected to become the most important source of issues related to water availability. In fact, the insignificant changes induced in the water balance under fertilizer application were expected, as no special modification in water management was involved in the rice fields. Moreover, the change in practices to the development of the rainfed-bunded cultivation system will have a marginal effect in terms of water available for agriculture downstream.

6.5.2. Limitations and uncertainties

The strong performance of the SWAT model in small watersheds, as reported by Qiao et al. (2015), is an essential asset in this study, which was also confirmed by Danvi et al., (2017). However, an improvement of the pothole module in SWAT would allow an effective application of the impounding approach during hydrological simulation of watersheds containing rice fields (Sakaguchi et al., 2014). Apart from the model structure, the uncertainties related to model parametrizations as developed in our previous study (Danvi et al., 2017) are also among the major challenges for assessing the future impact of lowland rice intensification in the inland valley watersheds. Moreover, the model was calibrated and validated in all watersheds using only the streamflow, and the projected estimates of the other water balance components may also carry additional uncertainties (Dulal et al., 2007; Pervez and Henebry, 2015; Rocha et al., 2015). In this study, unknown uncertainties may additionally relate to the downscaled precipitation and temperature data used to analyze the impacts of climate change. Hence, we recommend a comparative analysis of the projected results to those simulated by other selected hydrological models to reduce the uncertainties and provide a better long-term impact assessment.

6.6. Conclusions

This study revealed the dominant impacts of climate change on streamflow in three inland valley catchments irrespective of their different levels of agricultural intensification. In accordance with the projections from 2040 to 2049, the streamflow is projected to experience a significant decline, which might lead to a severe water shortage downstream for agricultural land and affect the inland valley ecosystems in response to the decreased precipitation. Increased lowland development will affect the hydrological processes within the watersheds but will also result in a marginal increase of streamflow in Kounga and Kpandouga, with a slight decline projected in Tossahou. Compared to the current cultivation system, insignificant changes on streamflow are projected with the implementation of the rainfed-bunded system in the lowlands. Hence, under the constraining climatic conditions, its large-scale adoption with adequate use of fertilizers would be profitable in terms of maintaining or even increasing rice production in the headwater inland valleys where possibilities for irrigation are very restricted. Nonetheless, 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.

In conclusion, the use of the SWAT model is revealed to be an important asset for predicting the future impact of rice intensification on inland valley water availability. However, the application of other future climate change models for comparison would be more consistent and useful for the recommendation of sound adaptation strategies and policies in watershed planning and management.

Chapter 7

A spatially explicit approach to assess the suitability for rice cultivation in an inland valley in central Benin

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7.1. Abstract

The selection of optimal areas for specific cultivation systems is an important step in achieving increased, sustainable rice production in Benin. This study aims to determine suitable areas for rice production in the inland valley of Tossahou using a GIS-based approach that evaluates and combines biophysical factors such as climate, hydrology, soil and landscape, following the FAO parameter method and guidelines for land evaluation. Soil and landscape suitability was assessed for three different rice cultivation systems: rainfed bunded (RA), cultivation under natural flooding (NF), and irrigated cultivation (RI). The results show that in the inland valley (mostly including the hydromorphic zones and the valley bottom) 52% is suitable for irrigated cultivation, 18% for cultivation under natural flood and 1.2% for rainfed bunded rice. Precipitation and temperature were limiting factors for all cultivation systems. Flooding was the most limiting factor for NF while RI and RA were mostly limited by steep slopes and soil texture respectively. As a first attempt in Benin, this study can play an important role in achieving optimised rice production in inland valleys, and additional studies including socio-economic aspects, carried out in the same area, or in areas under similar conditions, are relevant to close the yield gap and improve the selection approach.

Keywords: Benin; inland valley suitability assessment; GIS; rice production; wetlands.

7.2. Introduction

An inland valley is defined as a landscape that comprises a complete toposequence from the interfluves to the valley bottom with its seasonally waterlogged depression (Windmeijer and Andriesse, 1993). Often known under various regional names, such as *bas-fonds*, *fadamas* or inland swamps in West Africa, *mbuga* in East Africa and *vleis*, *dambos*, *mapani*, *matoro*, *inuta* or *amaxhaphozi* in Southern Africa (Acres et al., 1985), in practice, the term refers only to the waterlogged area and its hydromorphic fringes (Giertz et al., 2012; IVC, 2005; Thenkabail and Nolte, 1996). In West Africa, inland valleys have important potential for rice-based production systems due to their being largely unexploited, higher water availability, lower soil fragility and higher fertility (Giertz et al., 2012; Rodenburg et al., 2014; Schmitter et al., 2015). However, in Benin, the productivity of rice systems in such wetlands is low due to biophysical and socio-economic constraints (Djagba et al., 2013), including sub-optimal functioning markets for acquiring fertilisers and for the commercialisation of rice products; a lack of financial services to make the necessary investments for intensification; poor management and maintenance of irrigation infrastructures; and inadequate national policies (Saito et al., 2015; Schmitter et al., 2015). In Benin, agriculture contributes to 31.6 % of the country's gross domestic product (FAO Stat, 2011). Rice is usually grown to be sold and is not used in subsistence farming due to its high value (Igué, 2000). As the country aims to be self-sufficient in rice in the near future, the government has been actively promoting agricultural development of rice since 2008 (NRDS, 2011). Indeed, local rice production has increased (from 73,853 metric tons in 2008 to 167,000 tons in 2011) because of improved input facilities (e.g. seed, fertiliser) made available to farmers through a range of programmes and projects that were set up after the food crisis of 2008. These include the Emergency Program to Support Food Security (PUASA), the NERICA Project, the Development Project of Small Irrigated Perimeters (PAPPI) and the Agricultural Services Restructuring Project (PASR) (Totin et al., 2013). Currently, 90% of the rice outputs are produced by small-scale farmers using only 7 to 10% of the total arable land available (USDA, 2013), with the average rice farm size for the users and non-users of credit being approximately 0.82 and 0.63 ha, respectively (Kinkingninhoun-Medagbe et al, 2015). Despite this recent increase in rice production, following the implementation of technologies and techniques developed and offered by the government and agricultural development projects, traditional smallholder production is still dependent on the physical conditions of the land. This is due to the insufficient coverage of the input facilities, and also to the lack of capital to compensate for natural constraints in terms of rainfall variability, low chemical fertility and unfavourable physical characteristics of soils (Janssens et al., 2010). Moreover, due to the increasing population pressure, farmers move to more marginal areas and expose themselves to environmental risks. Consequently, they often produce low yields as they are not willing to make more investments. Thus, our method should be of interest to development agencies and NGOs that are interested in assessing suitable areas for development and investment.

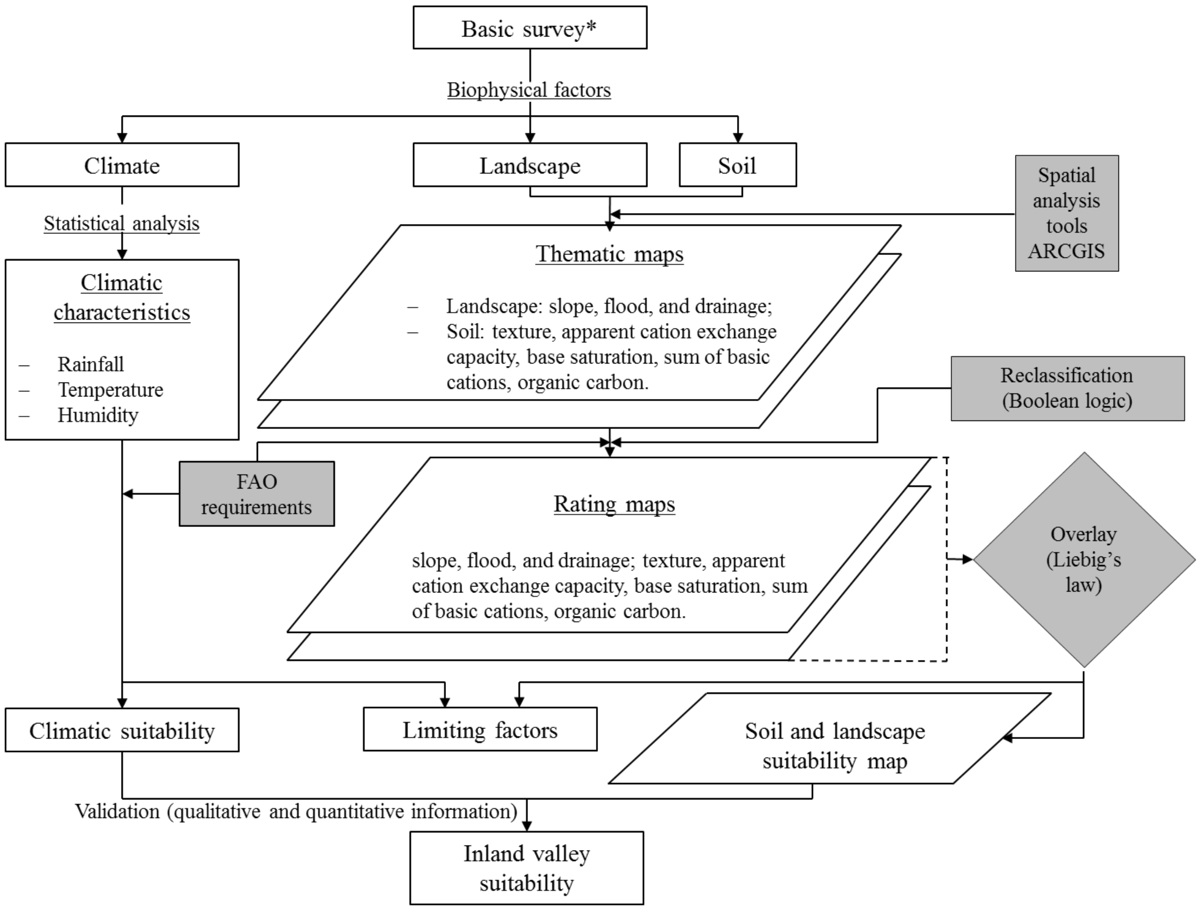
Knowing that not all inland valleys are necessarily suitable for crop production (Kotze, 2011; Sakané et al., 2011), several bio-physical and socio-economic factors should be investigated during the land evaluation process. Recent studies have developed different quantitative and qualitative methods and approaches to planning land suitability, either for agriculture in general (Krishna and Regil, 2014; Liu et al., 2006; Mokarram and Aminzadeh, 2010) or for specific crop production, such as paddy rice, wheat, maize, mustard, mango and sugarcane (Halder, 2013; Martin and Saha, 2009; Singh, 2012), within a given watershed. Generally, these methods integrate remote sensing or a multi-criteria evaluation, coupled with GIS, and combine, depending on the research, layers of factors such as climate, drainage density, geology, hydrology, landform, land use, soil, topography and vegetation, via a weighted overlay approach (Krishna and Regil, 2014) or a pairwise comparison matrix (Kihoro et al., 2013). Some studies rate the factors based on the proposed method of Sys et al. (1993) and define the suitability ranked classes using the qualitative approach described by the FAO (FAO, 1976; (Halder, 2013; Martin and Saha, 2009; Mustafa et al., 2011), and others rely on expert opinion, local agronomists and researchers' knowledge (Kihoro et al., 2013). Among other older studies in West Africa, a GIS-based model developed by Fujii et al. in 2010 was recently applied to select suitable rice cultivation areas in inland valleys in the Mankran and Jolo-Kwaha watersheds from different agro-ecological zones in Ghana that have high potential for rice production (Fujii et al., 2010). However, very few studies address land use planning for rice-based systems in inland valleys.

This study was undertaken in Benin with the goal of assessing the suitability of inland valleys, as a function of the biophysical environment, for three rice cultivation systems: rainfed bunded (RA), cultivation under natural flood (NF) and irrigated cultivation (RI). To evaluate suitability spatially, we used the proposed method of Sys et al. (1991, 1993) and the FAO Guidelines for Land Evaluation (FAO, 1976). The parameters analysed were soil, climate, hydrology and topography. Maps of these parameters were required for the generation of the final suitability maps. Rating maps were overlaid for each cultivation system using Liebig's law of the minimum, which states that plant growth is controlled by the scarcest (limiting) resource and that an increase in this resource increases yields the most (Casanova et al., 2002; Gorban et al., 2010; Spektrum, 1999). For the validation of the suitability maps, in association with the identification of limiting factors for rice production, we proceeded to the identification and classification of the predominant types of agricultural land use, to the assessment of the spatial distribution of rice yields, and to stakeholder interviews in the inland valley. This approach was chosen because of data availability and in accordance with the requirements for the different rice cultivation systems. It was essentially led by the following research questions: (i) How can areas suitable for rice production be identified to aid farmers in selecting favourable fields for a potential rice growth achievement? (ii) How can a resulting suitability map be validated? (iii) What are the physical factors limiting the inland valley suitability for rice production? This study contributes to improving development strategies and land use planning to promote a sustainable management of rice-growing wetland ecosystems in Benin.

7.3. Methodology

7.3.1. Suitability analysis

In this study we first applied the FAO guidelines approach for land evaluation (FAO, 1976) which defines and describes the suitability classes based on the rice growth requirements. Thereafter we assessed the environmental physical conditions (including climate, landscape and soil) required for the different cultivation systems which were developed by Sys et al. (1991, 1993). Using the FAO guidelines and crop requirements, the added-value of the research is the GIS-based implementation approach to produce suitability rating maps for each of the parameters involved, and to combine them to generate the final suitability maps based on the limiting factor analysis. Figure 7.1 is a flowchart describing the GIS-based approach used in this study.



*Basic survey includes climatic and hydrological data measurement, soil sampling for soil map, and land use survey for using GPS for landscape.

Figure 7.1. Methodological approach for the inland valley suitability evaluation.

FAO land evaluation approach

The framework of the FAO land evaluation approach is a collection of concepts, principles and procedures with which an evaluation system can be developed. The concepts are scale-independent and can be employed at different levels of intensity and for all types of land use if the requirements can be defined (FAO, 1976; Verheye et al., 2009). The evaluation approach is plant specific and first requires the identification of crop growth requirements, which are subsequently matched with the attributes of the land of interest in terms of slope, flooding and drainage conditions, as well as soil properties. The methodology then follows either a two-stage or a parallel approach. The parallel approach was employed in this study and the emphasis was on quantitative land classification.

Two land suitability orders and five land suitability classes are distinguished. The land suitability orders are suitable (S) and not suitable (N). The suitable order describes land that is expected to yield benefits under sustained use, which justifies the inputs without the risk of damage to land resources. The not suitable order is used to describe land where sustained use of the land under consideration is not possible due to deficits in land quality. The order suitable is composed of the highly suitable (S1), moderately suitable (S2) and marginally suitable (S3) classes, while the order not suitable is composed of the currently not suitable (N1) and not suitable (N2) classes. The currently not suitable class consists of land that is assumed to exhibit limitations which may be overcome in time but cannot be used currently due to technical limitations or unacceptable costs.

Outline of data requirements

The FAO crop requirements approach by Sys et al. (1991, 1993) can be divided into two parts, the climatic requirements and the landscape and soil requirements, which are dependent on the intensification level in the study area. As we saw no evidence of an irrigation scheme or agricultural machinery being used and the rice fields were manually prepared using the hoe, a low level of management was chosen to best describe the inland valley. The climatic requirements for rice cultivation, according to Sys et al. (1993), assume a growing cycle between 90 and 120 days and are divided into four groups: precipitation, temperature, humidity and radiation characteristics. An overview of all climatic requirements used for the three cultivation systems is given in Table 7.1.

Table 7.1. Climatic requirements for different rice cropping systems as applied.

	Suitability class[a]			
	S1	S2	S3	N2
P 1 month (mm)				
RA/NF	175<P<500	125< P<175 or 500<P<650	100<P<125 or 650<P<750	P<100 or P>750
P 2 and 3 month (mm)				
RA/NF	175<P<500	125<P<175 or 500<P<650	100<P<125 or 650P<750	P<100 or P>750
P 4 month (mm)				
RA/NF	50<P<300	30<P<50 or 300<P<500	P<30 or 500<P<600	P<600
T_{mean} growth cycle (°C)				
RA/NF	24<T<36	18<T<24 or T>36	10<T<18	T<10(RU),T<18(RB/RF)
T_{max} mean (°C)				
RA/NF/RI	30<T<40	26<T<30 or 40<T<45	21<T<26 o r45<T<50	T<21 or T>50
T_{mean} 2 month (°C)				
RA/NF/RI	24<T<36	18<T<24 or 36<T<42	10<T<18 or 42<T<45	T<10 or T>45
T_{min} 4 month (°C)				
RA/NF/RI	14<T<15	10<T<14 or 25<T<28	7<T<10 or 28<T<30	T<7 or T>30
RH 1 and 2 month (%)				
RA/NF/RI	50<RH<90	40<RH<50 or 90<RH<100	30<RH<40	RH<30
$RH_{harvest}$ (%)				
RA/NF/RI	33<RH<80	30<RH<33 or rH>80	RH<30	-

Adapted from Sys et al. (1991, 1993).

P, total precipitation (mm); T, temperature; $T_{mean,}$ growth cycle, mean temperature during growing cycle; T_{max} mean, mean maximal temperature of warmest month; T_{min}, mean minimal temperature ripening stage (4th month); $RH_{harvest}$, relative humidity at harvest stage (4th month).

RA, rainfed bunded; NF, rice cultivated under natural flood; RI, irrigated rice.

[a]S1, Highly suitable; S2, Moderately suitable; S3, Marginally suitable; N2, Not suitable.

Likewise, the soil and landscape requirements are also divided into four groups: topography, wetness, physical soil characteristics and soil fertility characteristics. The topography group includes the relief of the research area. The wetness group is defined by flooding and drainage. The duration and depth of floods are considered to define the flood classes presented in Table 7.2. Drainage is appraised as good, moderate, imperfect, poor or very poor and requires a differentiation of the suitability of fine loamy and clayey and coarse loamy and sandy families. The only factor evaluated in the physical soil characteristics group was the soil texture due to insufficient data on other characteristics. In the soil fertility characteristics group, the suitability of the apparent cation exchange capacity (in cmol(+)/kg clay), base saturation (%), sum of basic cations (in cmol(+)/kg soil), quantity of organic carbon (%) and pH value (measured in water) are evaluated (see Table 7.3).

Table 7.2. FAO flood classes.

Flood depth subclasses	Duration of floods subclasses			
	1 (Du< 2 months)	2 (2<Du<3 months)	3 (3<Du<4 months)	4 (Du> 4 months)
1(0<De<10 cm)	11	21[a]	31	41
2(10<De<20 cm)	12	22	32	42
3(20<De<40 cm)	13	23	33	43
4(40<De<80 cm)	14	24	34	44
5 (De>80 cm)	15	25	35	45

Adapted from Sys et al. (1991, 1993).

Du, duration of flood; De, depth classes.

[a] 21, flood class with duration of flood between 2 and 3 month (duration of floods subclass 2) and flood depth between 10 and 20 cm (flood depth subclass 1).

Table 7.3. Soil and landscape requirements for different rice cropping systems as applied.

Suitability class	S1[b]	S2[b]	S3[b]	N1[b]	N2[b]
Slope (%)					
RA[c]	0<S<4	4<S<8	8<S<25	-	S>25
NF[c]	S=0	0<S<2	2<S<4	4<S<6	S>6
RI[c]	0<S<1	1<S<2	2<S<4	-	S>4
Flood (classes)					
RA	0,11,12,21,22	13,23,41,42	14,23,24,34,43	15,25,44	35,45
NF	32,32	33,41and 43	21and 24,34,44	-	11-15,25,35,45
RI	0,11,12,21,31,32	13,23,33,41and 43	14,24,34,44	-	15,25,35,45
Drainage[a]					
RA	imp	poor,mod	good	-	very poor
NF	poor	v. poor,impt	mod	-	good
RI	imp-mod	poor,good	v. poor	-	-
Texture					
RB	SiC-SiCL	CL	SiL	-	L-LS

NF/RI	SiC-CL	SiL-SCL	SL-LS	-	-
CEC$_{app}$ (cmolcM.kg^{-1}) [a]					
RB/NF/RI	CEC>24 and <16	CEC<16 (-)[c]	CEC<16 (+)[c]	-	-
BS (%)[a]					
NF	BS>50 and <35	35<BS<20	BS<20	-	-
RA/RI	BS>80 and <50	50<BS<35	35<BS<20	BS<20	-
SBC (cmolcM.kg^{-1}) [a]					
NF	SBC>4 and <2.8	2.8<SBC<1.6	SBC<1.6	-	-
RA/RI	SBC>6.5and <4	2.8<SBC<4	2.8>SBC>1.6	SBC<20	-
pH				Only RU	RB/NF/RI
RA/NF/RI	6.5>pH>5.5	5.5->pH>5.0	5.0>pH>4.5	pH<4.5	pH<4.5
SOC (%)[a]					
RA/NF/RI	SOC>2 and <1.5	1.5<SOC<0.8	SOC<0.8	-	-

Adapted from Sys et al. (1991, 1993).

[a] Drainage: v. poor – very poor, mod – moderate, imp – imperfect.

CECapp, apparent cation exchange capacity; BS, base saturation; SBC, sum of basic cations; SOC, soil organic carbon; S, slope; 0, no flooding; 11 to 45, flood classes values from Table 3.

[b] S1, Highly suitable; S2, Moderately suitable; S3, Marginally suitable; N1, Currently not suitable; N2, Not suitable

[c] RA, rainfed bunded; NF, rice cultivated under natural flood; RI, irrigated rice; (-), slightly; (+), considerably.

Spatial implementation in GIS environment

To evaluate the soil and landscape criteria, thematic maps were developed for each of the following factors: texture, apparent cation exchange capacity, base saturation, sum of basic cations, organic carbon, pH, slope, flooding and drainage. To create the suitability maps for the three analysed rice cultivation systems, the created raster maps of the landscape and soil requirements were reclassified along with the suitability by using Boolean logic. According to Boolean logic, boundaries that determine whether an element is included in a set are clearly defined, meaning that the element is either included or excluded in a set. However, the approach does not allow partial memberships of an element in a set as values are restricted to two points, 0 if excluded and 1 if included (Banai, 1993; Collins et al., 2001; Nisar Ahamed et al., 2000; Sicat et al., 2005). In total, 22 distinct rating maps were created for the different factors and cultivation systems. To generate the composite suitability maps, the rating maps were overlaid in accordance with the cultivation system. For the overlay process based on Liebig's law of the minimum, the rating of the worst factor in a region overrides the rating of all other factors, effectively determining land suitability by the limiting factor (Kiefer, 1965).

Validation of the suitability maps

The accuracy of the suitability maps was validated in two ways. First, the locations of the mapped rice fields (areas from 0.04 to 0.51 ha) and yields (as presented in Figure 4.17 in chapter 4) were correlated to the predicted suitability classes for the respective cultivation system. Second, the results were compared to the farmers' opinions of the areas that are best suited for the cultivation of rice based on their own knowledge and experience. Over the total number of 18 farmers who cultivated rice in the inland valley, 12 were randomly chosen and individually interviewed following a questionnaire form in a face-to-face interchange. For rainfed bunded and irrigated cultivation, no validation could be made because no fields of the respective cultivation systems were observed with the exception of a single bunded field. Thus, the suitability results obtained for such cultivation systems may reveal more uncertainties from the fringes toward the highest areas.

7.3.2. Meteorological and hydrological data collection

To assess the climatic suitability of the target region for rice production, precipitation was automatically measured every 5 min using a tipping-bucket rain gauge with a resolution of 0.2 mm, and temperature and relative humidity were recorded hourly by a Gemini Tiny Tag sensor. Radiation and wind speed data were measured every 5 min at a climate station (of the SMART-IV project) located 30 km from Pelebina village. All measurements were undertaken over the 2013 wet season from April to October.

7.3.3. Soil properties analysis and mapping

To determine the soil site suitability for each cultivation system, 100 topsoil samples of the A horizon, organically enriched notably by detritus resulting from plant senescence, were collected from different positions in the inland valley at a depth of 15–20 cm using a 1.5 m auger drill. Subsequently, the soil texture, soil organic carbon (SOC) to total nitrogen (TN) ratio, cation exchange capacity (CEC), pH and phosphorus (P) were determined in the soil scientific laboratory of the University Bonn. To estimate soil properties at unsampled locations, the choice of the optimal interpolation technique is an important issue in site-specific analysis. In this study, this was performed by applying the inverse distance weighted method of interpolation using Arc GIS 10.2.

7.3.4. Landscape data

The landscape suitability was mainly analysed based on characteristics such as slope, flood and drainage. Slope is an important factor in determining the suitability for rice cultivation (Dengiz, 2013; Gumma et al., 2009; Kuria et al., 2011). A common procedure is to derive slope maps from a digital elevation model (Gumma et al., 2009; Masoud et al., 2013). The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) was used for the research area. However, the performance of the derived slope model was inadequate due to the coarseness of the DEM, and no significant correlation could be determined between the derived values and the field measurements with a clinometer (field data includes slope information of the three transects and data from visited rice fields). Therefore, an alternative slope map was generated by first comparing evaluation values from the DEM to the observed slope values, as it was observed that the slopes became gentler with descending altitude, which is typical for inland valleys (Windmeijer and Andriesse, 1993). Based on this information, the DEM was reclassified according to altitude and local clinometric observations. The reclassified slope values were then correlated with the observed values from 38 observations in total, and a correlation of $r = 0.660$ ($p \leq 0.01$) was observed.

Flooding is undeniably one of the most important factors in assessing land suitability for rice cultivation. To map the extent and depth of flooding, several datasets were used to delineate flooded areas: the DEM, the numbers of days the piezometers were flooded and a GIS shapefile of flooded areas created during the IMPETUS inventory campaign in 2006 by Giertz et al. (2012). Qualitative information from stakeholder interviews on the location of areas likely to be flooded and the respective length of flood periods and frequency was also included in the evaluation process. This information is of vital importance in augmenting sparsely available hydrological information (Lightfoot et al., 2009; Sicat et al., 2005). The drainage characteristics of the inundated areas were derived from the previously created flood map and the classification was done according to the flood duration as defined in the FAO soil drainage classes by Sys et al. (1991).

7.3.5. Spatial assessment

At this study scale, no land use map was available for the extraction of the location of the different rice cultivation systems implemented in the inland valley. Thus, cultivated fields and cultures were identified, recorded and mapped using GPS to record present agricultural land use. This step was mostly important to check the fitness of the different rice fields to the predicted suitable areas and to evaluate the actual extent to which the agro-potentiality of the inland valley is used as a whole. Related outputs from the overlay of layers were also used to link the observed yields to the management practices involved at the fields while determining the limiting factors. The mapping of the cultivated fields was conducted from July to November during the rainy season. Post processing and calculation of surface areas were conducted using Arc GIS 10.2.

7.3.6. Survey of farmers

Relevant information from the qualitative interviews with farmers was used to validate the generated suitability maps. The 12 rice farmer interviewees were questioned about possible suitable and not suitable areas for rice production and the factors likely to restrict cultivation from their experience in the inland valley. They were additionally asked to give quantitative and qualitative information on management practices, such as land preparation, sowing date, frequency of weeding and fertiliser application, and on soil and landscape properties, such as soil quality, soil moisture and flood depth. The cultivation under natural flood rice cultivation system was the current system most commonly adopted by the farmers in the inland valley.

7.4. Results

7.4.1. Landscape characteristics

The resulting map of the reclassified slope shows the highest values to be between 8 and 16% in the far eastern part of the inland valley, while slopes of values from 6 up to 8% were found in the east, northeast and southeast. In the central part, they were moderate (2–6%) and gentle in the valley bottoms (1–2%). The topography is decidedly flatter in the western part, with inclinations between 1 and 2%, and flattening to 0 to 1% near the outlet of the valley in the northwest.

Based on the delineation of the flooded areas and reclassification of the flood map, 9% of the inland valley area is flooded for less than two months and up to 20 cm deep during an average rainy season and is accordingly classified as moderately to imperfectly drained; 14.7% is flooded for 3 to 4 months up to 20 cm deep and is poorly drained; and 2.3% of the area is inundated for 3 to 4 months to 20 to 80 cm deep and is very poorly drained.

7.4.2. Soil properties

The soil sample analysis shows a high variability of soil texture throughout the inland valley. The predominant soil texture in the study area and especially on the fringes is sandy loam according to the USDA classification (USDA, 2014). In the valley bottom, this texture is featured along with the silty clay loam texture (Table 7.4). The soils in the inland valley were moderately acid with pH values between 5.11 and 6.5. Values between 0.31 and 4.25 g/kg were found for SOC, and the apparent CEC values ranged from 13.31 cmolc/kg clay up to 831.16 cmolc/kg clay.

The Pearson bivariate correlation shows that most of the soil properties are significantly correlated with the morphology of the inland valley (Table 7.5). For instance, significant differences in the soil properties, such as clay, silt sand, SOC and apparent CEC are seen between the fringes and the valley bottom. A significant decrease of 51% for clay ($p < 0.001$), 36 % for silt ($p < 0.001$) and 40% for SOC ($p = 0.001$) are revealed from the valley bottom to the fringes. The sand content ($p < 0.001$) and the apparent CEC ($p = 0.007$) increases significantly towards the fringes at 48% and 81%, respectively.

Table 7.4. Descriptive statistics of topsoil properties in the fringes (*n* = 65) and the valley bottom (*n* = 35) from 100 soil samples.

	Minimum		Maximum		Mean		SD	
	Valley bottom	Fringes	Valley bottom	Fringes	Valley bottom	Fringes	Valley bottom	Fringes
Sand (%)	5.3	4.7	88.6	90.6	46.5	69.0	0.9	0.7
Silt (%)	9.4	7.6	64.9	47	32.4	20.6	13.9	9.5
Clay (%)	1.9	1.7	50.7	50.5	21.1	10.4	14.1	9.4
pH (H_2O)	5.1	5.1	6.3	6.5	5.7	5.7	0.3	0.2
SOC (%)	0.5	0.3	4.3	3.4	1.5	0.9	0.9	0.7
CEC_{app} (cmolcM.kg)	13.1	22.8	519.1	831.2	101.2	183.2	113.5	181.2
BS (%)	1.2	2.4	100	100	62.8	34.4	35.6	33.7
SBC (cmolcM.kg)	0.3	0.3	25.1	29.5	8.8	3.9	7.5	5.3

SD, standard deviation ; SOC, soil organic carbon; CEC_{app}, apparent cation exchange capacity; BS, base saturation; SBC, sum of basic cations.

Table 7.5. Correlation values of soil properties with the inland valley morphological characteristics using laboratory results of the analysis of the same 100 soil samples used in Table 12.

	Soil properties							
Mor[a]	Clay	Silt	Sand	pH	SOC	CEC_{app}	BS	SBC
p	< 0.0001	< 0.0001	< 0.0001	n.s.	< 0.0001	0.02	<0.0001	< 0.0001
r	-0.42	-0.45	0.47	0.003	-0.36	0.24	-0.37	-0.35

SOC, soil organic carbon; CECapp, apparent cation exchange capacity; BS, base saturation; SBC, sum of basic cations.

[a]Mor, variable accounting for morphology taking values of 1 for the valley bottom and 2 for the fringes.

7.4.3. Suitability mapping

The climatic suitability of the inland valley for the different rice cultivation systems ranges from high to moderate with respect to precipitation, temperature and relative humidity. For all cultivation systems, the limiting factors were the precipitation in the fourth month and the average temperature in the second month during the monitoring period. As the rainy season 2013 was considerably drier than the long-term average, the suitability would have been likewise lower. It was therefore decided to use averaged daily precipitation data from nearby Djougou for the years 1996 to 2005. The precipitation in the first month was not suitable for the cultivation of rainfed bunded and the cultivation under natural flood. Based on the ten-year average, this changed to highly suitable. Likewise, the precipitation in the fourth month was marginally suitable for rainfed bunded and cultivation under natural flood. When using the rainfall average, the suitability turned out to be moderate (see Table 7.6).

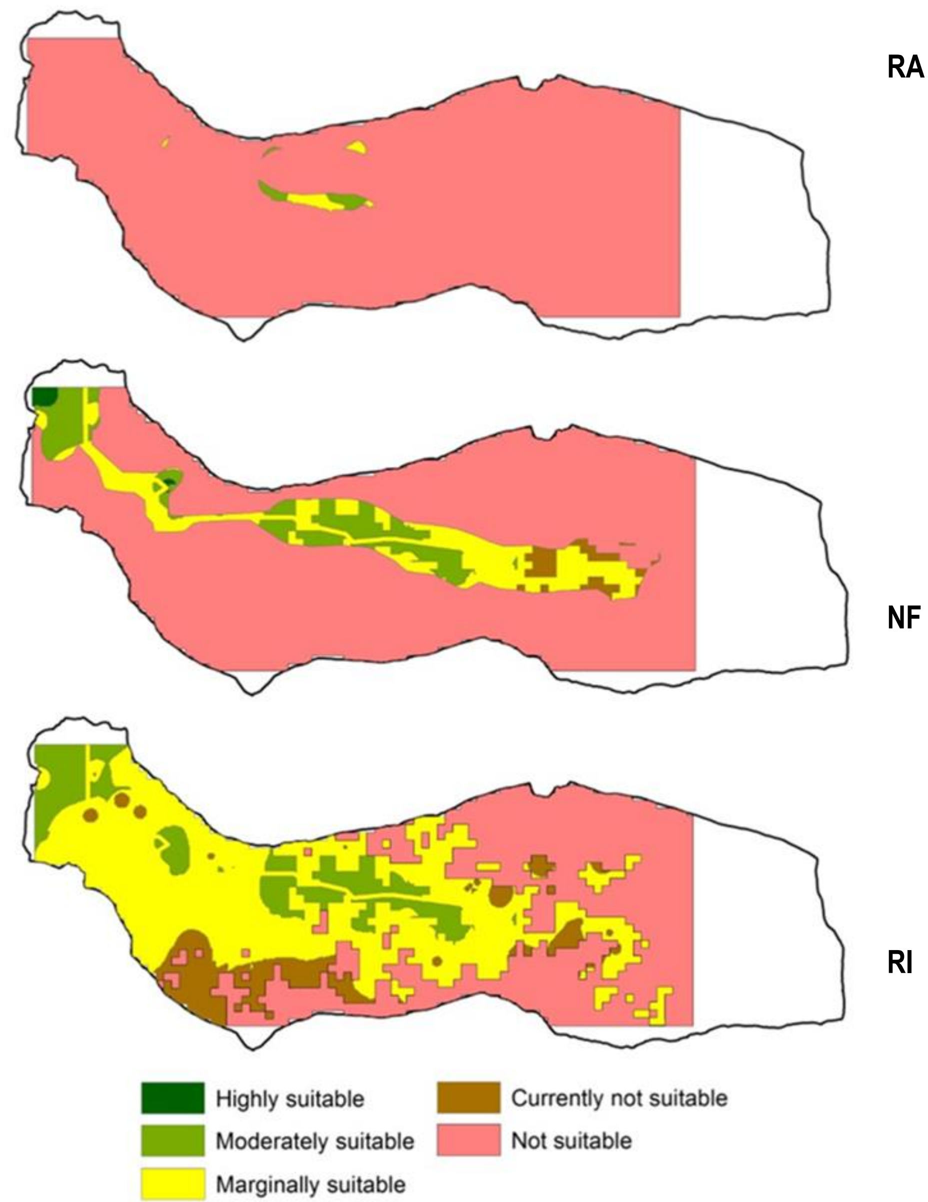
Table 7.6. Climatic suitability.

Climatic characteristics	2013(1996–2005)	RA	NF	RI
Prec. 1st month (mm)	91 (288)	N 2 (S 1)	N 2 (S 1)	-
Prec. 2nd month (mm)	236	S 1	S 1	-
Prec. 3rd month (mm)	203	S 1	S 1	-
Prec. 4th month (mm)	9 (30)	S 3 (S 2)	S 3 (S 2)	-
T_{mean} growth cycle (°C)	24.9	S 1	S 1	S 1
T_{max} mean (°C)	34.7	S 1	S 1	S 1
T_{mean} 2nd month (°C)	23.6	S 2	S 2	S 2
T_{min} 4th month (°C)	19.1	S 1	S 1	S 1
RH 1st and 2nd month (%)	88.7	S 1	S 1	S 1
$RH_{harvest}$ (%)	75.9	S 1	S 1	S 1

T_{mean} growth cycle, mean temperature during growing cycle; $RH_{harvest}$, relative humidity at harvest stage (4th month); S1, Highly suitable; S2, Moderately suitable; S3, Marginally suitable; N2, Not suitable.

RA, rainfed bunded; NF, rice cultivated under natural flood; RI, irrigated rice.

Regarding landscape and soil, the suitability values were 52.1 % for irrigated cultivation, 17.8 % for cultivation under natural flood and only 1.2 % for rainfed bunded (Figure 7.2). More precisely, most of the inland valley is moderately suitable for irrigated cultivation at 9.7 %, with 42.2 % being marginally suitable. The highly suitable class is not represented for irrigated cultivation. As far as cultivation under natural flood is concerned, 0.4 % is highly, 6.5 % moderately and 10.8 % marginally suitable. For rainfed bunded, only 0.6 % is moderately and 0.7 % is marginally suitable. The most-limiting factor determined for cultivation under natural flood was flooding, with 17.4 % and 80 % of the area being not suitable and currently not suitable, respectively. The suitability map for irrigated cultivation shows that the western and southern parts of the valley are not or currently not suitable, mainly due to steep slopes. Concerning the cultivation of rainfed bunded, soil texture is the most-limiting factor, with 94 % of the area being not suitable as the sandy loam texture predominant in the inland valley is classified not suitable (Sys et al., 1991, 1993). However, this parameter was not the most limiting for the other rice cultivation system. For the suitability analysis, a set of parameters from the FAO recommendation was selected to be used for every cultivation system. Prior to the assessment, the extent to which these parameters might be limiting could not be appraised effectively.



RA, rainfed bunded; NF, rice cultivated under natural flood; RI, irrigated rice.

Figure 7.2. Results of soil and landscape suitability evaluation.

7.4.4. Validation

Out of the 27 rice fields mapped within the inland valley, 26 were cultivated under natural floods, and only one under bunded conditions. All 26 fields lie within the area identified as being suitable for rice cultivation under natural floods. However, the field cultivated for rainfed bunded was located in an area determined by the classification approach to be unsuitable due to the sandy texture of the soil. Thus, the creation of bunds was for the farmer a means to harvest water and make the soils suitable.

The average yield observed in the natural floods was 1.4 ± 1 t/ha. In areas highly suitable for cultivation under natural floods the average yield was 2.4 ± 0.9 t/ha. The yield observed in areas classified as moderately, marginally and currently not suitable was respectively 2.1 ± 0.3 t/ha, 1.0 ± 0.6 t/ha, 1.1 ± 1.1 t/ha. No field was mapped in the areas classified as not suitable.

Most interviewees indicated either areas close to the valley outlet or in the midstream valley bottom, which are flooded during the rainy season, to be suitable for rice cultivation. The descriptions coincided with the suitability map for cultivation under natural flood, in which these areas were considered to be either moderately or highly suitable. Some other farmers stated that the lower slopes of the valley, which stay moist during the rainy season, are best suited for rice cultivation. No farmer mentioned the cultivation of bunded rice, and this might indicate some unknown factor restricting adoption of the system.

7.5. Discussion

7.5.1. Suitability of the inland valley and limiting biophysical factors for rice cultivation

No significant correlation could be determined between rice yield and suitability class. The spatial extent of the areas suitable for rice cultivation under natural flood was expected. According to their own experience, the farmers refer to the valley bottom as a landscape unit endowed with limited risks of water scarcity and high level of fertility on which they could produce rice before flooding occurs. Therefore, other parts of the inland valley predicted to be suitable for rice cultivation were preferentially used to grow yams, a major staple crop and more profitable for many households, in association with other crops such as sorghum or maize.

The low percentage of suitable areas for the production of rainfed bunded rice can be explained by the constraints of the soil texture, as sandy soils dominate in the inland valley. Coarse-textured soils are generally less productive, with low inherent fertility and low water-holding capacity in relation to high percolation rates (Haefele et al., 2014), by which nutrients are easily leached beyond the root zone. This reflects the importance of increasing rainwater utilisation efficiency by percolation limitation on well-drained soils, which was indicated by Garrity et al. (1992) to improve rice yield in the lowland.

Though steep slopes restrict the suitability for irrigated cultivation to half of the inland valley total area, this percentage was higher than expected as infrastructural constraints prohibit irrigation at the moment. No irrigation scheme was implemented in the research area, the exception being small household vegetable gardens that were irrigated with well water using either watering pots or calabashes. Additionally, there is no municipal water supply, and the local population relies on open wells and a few foot-pumps to access drinking water. However, similar studies conducted in the Tana delta area in Kenya (Kuria et al., 2011) and in the Central Anatolian region of Turkey (Dengiz, 2013) found that adverse soil physical and chemical properties were limiting the suitability for irrigated rice cropping to 67% and 55.5% of highly to moderately suitable land (Kihoro et al., 2013). Specifically, these studies revealed within their related sites of investigation, an important and unused potential areas for growing rice to achieving optimum utilisation of available land resources. Basically, the suitability analysis was conducted following the FAO guidelines by matching both land characteristics and rice requirements to produce a final suitability map for each study area. In the Tana delta area, the GIS-based approach used by Kuria et al (2011) involved the combination of selected theme layers of landforms, agricultural lands, soil properties (texture, sodicity and salinity), which revealed that 9% of the study area was currently unsuitable due to limitation factors such as partly sandy clay texture, saline, low water retention and high hydraulic conductivity (Kihoro et al., 2013; Kuria et al., 2011). In the Central Anatolian region, the overlay of topography (landform and slope) and soil (nutrients availability, drainage, texture, hydraulic conductivity, salinity, pH) theme layers showed that 34% of the study area was unsuitable due to both soil and topographic conditions (Dengiz, 2013). As in other previous studies, the selected approach to assess the suitability for rice cultivation in this investigation demonstrates the capability of GIS to integrate spatial and attribute data to extract additional and reliable meaning with high accuracy (Halder, 2013; Kihoro et al., 2013; Krishna and Regil, 2014; Kuria et al., 2011; Liu et al., 2006). Although adequate results were achieved, this study was limited in its ability to produce valuable information on the relative importance of soil and landscape factors, only taking into account the local conditions of a single inland valley. Additionally, a limitation of the use of the Boolean logic in the overlay process was revealed in the occurrence of overlapping areas that featured a good suitability attribute on every cultivation system map. This requires a thorough analysis for discretizing the areas by defining the parameters boundary thresholds, in order to assign to the different parts the best suited cultivation system. Although, this analysis was beyond the scope of this study, it could be tested by using the fuzzy logic which permits partial memberships.

However, the methodology and the ensuing findings are useful and could be adopted for diverse studies under similar agro-climatological conditions, which should additionally account for currently omitted factors in the suitability evaluation, such as the percentage of coarse fragments and the soil depth. For the purpose of regionalisation, the similarity among inland valleys in the region with respect to landscape and soil and their nearness in the geographical space should be assessed first. And further, in the resulting clusters derivation process, the similarity measurement of values of the selected agro-ecological attributes should be performed carefully in consideration of the existent irrigation facilities and socio-economic factors.

7.5.2. Constraints and assets to optimising rice production within the inland valley

As the harvested rice fields were almost exclusively cultivated under natural flood conditions and lie within areas classified to be suitable for such a cultivation system, one would expect high values of actual rice yield, assuming that soil and landscape are not limiting conditions. However, the average grain yield measured within the inland valley was very low (1.4 ± 1 t/ha) in comparison with the potential yield obtained by Worou et al. (2013) who reported values from 3.81 to 4.36 t/ha on average over four wet seasons in the same region. In the study conducted by Worou et al. (2013), yields were investigated in rainfed lowland rice in a researcher-managed on-farm trial in order to evaluate the efficiency of bunding and fertiliser application for improving rice productivity in the upslope and downslope positions in inland valley (Worou et al., 2013). However, the yield gap in the areas of favourable physical conditions in the inland valley of Tossahou, in the present study, could mainly indicate an important influence of the social and economic environment as source of constraints that might affect farmers' decisions and result in the high restriction of the yield noted. Actually, land pressure is very low and not constraining in the village due to the low population, and the access to land is usually gained through lease, gift or inheritance following the agreement of the owners. Nonetheless, various difficulties were mentioned by the farmers during the interviews and could qualitatively be discussed for characterising the actual socio-economic constraints on rice production within the inland valley. In general, the farmers have no assured access to credit to buy seeds and fertilisers and no subsidies are currently acquired from the government. Moreover, the access to market is almost non-existent as only a small portion of the harvest could be sold during the local market day and the remaining part was used for subsistence or barter due to the lack of transportation means to reach more distant and larger market places. This state of affairs causes the farmers to become heavily indebted from one season to another. Gradually, they become discouraged from producing more rice and even refrain from adopting recommended and costly activities on their fields which are therefore cultivated to a lower extent. It has been reported that even for the few having some resources from another job, the labour costs were not affordable specifically for weeding as the weed pressure is very high in the valley bottom. The valley bottom was remarkably infested with weeds in many areas during the monitoring period, and the farmers have pointed out the strong competition of these weeds with the rice plants and the high labour-intensiveness of removing them, as only hand weeding was performed due to economic reasons, which, however, is rather good for protecting the environment from herbicide pollution.

Other existent constraints were mentioned during the post-processing of the paddy such as the lack of adequate threshing areas and materials for husking. In addition, the need has been highlighted for training in effective rice cultivation and acquisition of knowledge of high-yielding and stress-tolerant rice varieties. No selected varieties of rice are specifically used in the inland valley, and rice is directly seeded, which could also lead to a higher risk of yield losses due to weed competition (Chauhan, 2013; Ogban and Babalola, 2003). Chauhan (2013) have shown that weeds could cause yield losses of up to 50 % in direct-seeded fields even after one hand weeding (Chauhan, 2013).

In the light of all above, the yield gap could be closed if a favorable socio-economic environment is made accessible to the farmers.

7.6. Conclusions

This paper attempts to assess the climate, landscape and soil suitability in the inland valley of Tossahou in Benin, based on the FAO land evaluation guidelines and parameter method develop by Sys et al. (1991,1993) to map potential areas of favourable conditions for expanding and optimising rice production, using GIS techniques. Three rice cultivation systems were considered, namely, irrigated, bunded and cultivation under natural floods. The results reveal that more than half of the inland valley is of good suitability for irrigated system, whereas the cultivation under natural floods is best suited only for the central valley bottom. The low potential for rainfed bunded rice cultivation is mostly due to the sandy soil texture occurring throughout the inland valley. In general, the most-limiting physical factors are the precipitation, temperature, flooding, steep slopes and soil texture. However, we were limited by the absence of cultivated fields to validate the suitability maps for the irrigated and bunded cultivation systems.

The low grain yield recorded on fields of favourable physical land conditions sheds a light on the need to understand the constraining impact of the socio-economic environment on rice cultivation within the inland valley. Prior to the study, no methodological approach was applied in Benin to evaluate the land suitability for rice production. Thus, this approach can be adopted by researchers to conduct diverse studies in inland valleys under similar agro-climatological conditions, with a need to be improved for a detailed discretisation in the overlapping areas which proved to be suitable for all cultivation systems. Moreover, the findings should make an important contribution at local level for complementary and necessary socio-economic analyses which lie beyond the scope of this study, and are relevant for the yield improvement in the potential areas identified.

Chapter 8

General conclusions and recommendations

8.1. General conclusions and recommendations

The West African country of Benin has a large proportion of inland valley wetlands of high potential for agricultural production which are only developed to a small extent for food production. They constitute mainly an important asset for the rural poor in supplying them for hunting, fishing, forest, forage resources, and for their attractive lowlands suitable to rice intensification. However, 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. In addition, this involves the use of 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. The present research sheds a light on the matter by assessing the impacts of the management practices involved in rice intensification on water quantity in inland valleys in Benin. As most of the studies conducted in the region on evaluating future impacts of climate or land use change were carried out at larger spatial scales (e.g., Barthel et al., 2009; Bossa et al., 2012; Hiepe, 2008; Regh et al., 2014; Sintondji, 2005; Worou et al., 2013; Worou et al., 2012), this study is a valuable complement in analyzing the relative changes on water resources at such a small-scale.

Accordingly to the methodological approach applied, (1) three small headwater inland valleys characterized by different land cover and different agricultural intensification were selected in the commune of Djougou in central Benin such as Kounga, Tossahou and Kpandouga, (2) and were equipped for field data collection due to the limited availability of data sources; (3) the capacity of a spatially explicit hydrological model to capture water quantity and water quality processes in inland valley contributing watersheds was evaluated; (4) the hydrological response of inland valley to rice intensification under climate change during a projected period up to the year 2049 was examined; and (5) a land suitability analysis approach to assess areas for potential rice production in an inland valley was developed for yields improvement during intensification while reducing the possible environmental risks.

The Soil and Water Assessment Tool (SWAT) has successfully been used across the world and in the research area to assess the impact of land management and climate on water and nutrients transports. For analyzing the performance in small watersheds, the HRU-based interface (ArcSWAT2012) and the grid-based setup (SWATgrid) were applied to assess water quantity and quality within the three inland valley watersheds. However, apart from climatic data, the preparation of the model requires some spatial details on soil and land use which were relevant for this study but not available at such a small scale. Hence, the physical properties of the soils were determined. A soil map was created for each watershed and a land use map derived from a supervised classification of a SPOT6-image. Moreover, additional information was collected on the shallow groundwater table level along transect at upstream, in midstream and at downstream where water discharge and water quality measurement were also undertaken. The ArcSWAT interface was used for calibration and validation of SWAT in order to assess the hydrological characteristics of the inland valley watersheds, to predict nitrates loads, and to investigate the future changes of water availability impacted by rice intensification and climate change. The SWATgrid interface was applied for evaluating the ability of both hydrological models to capture the hydrological processes within the watersheds with respect to their differing spatial discretization schemes. Two climate scenarios (A1B and B1) of the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Paeth et al., 2009), were simulated to project future changes in temperature and precipitation and assessing the impacts of climate change on the watersheds water availability for the period from 2019 to 2049. The rice intensification was simulated in terms of lowland conversion to rice fields and change in management practices. Thus, the following land use change scenarios were simulated: (1) lowland conversion into rice fields at 25 %, and (2) lowland conversion into rice fields at 75 %. The management scenarios included the current rice cultivation system and the rainfed-bunded rice cultivation system based on two treatments described as with or without fertilizers inputs. To evaluate land suitability, different quantitative and qualitative approaches were developed from recent studies integrating remote sensing or a multi-criteria evaluation, coupled with GIS, and combining layers of factors such as climate, hydrology, landform, land use, soil, topography and vegetation, etc. (e.g. Halder, 2013; Krishna and Regil, 2014; Liu et al., 2006; Martin and Saha, 2009; Mokarram and Aminzadeh, 2010; Singh, 2012). In this study, a GIS-based approach was applied at the inland valley of Tossahou as a case study, which evaluates and combines biophysical factors such as climate, hydrology, soil and landscape, following the FAO parameter method and guidelines for land evaluation (FAO, 1976; Sys et al., 1993; Sys et al., 1991). Soil and landscape suitability was assessed namely for three different rice cultivation systems: rainfed bunded, cultivation under natural flooding, and irrigated cultivation.

Throughout this work, we were able (1) to assess the dynamics of hydrological processes, (2) to reveal the impacts of climate change and rice intensification on water resources in the selected inland valleys, and (3) to determine the suitable areas and the limiting factors for rice cultivation in Tossahou. Consequently, the different research questions as stated in the general introduction were addressed as follows:

(1) How accurately can a physically based and spatially distributed model describe the hydrological behavior of an inland valley as affected by its contributing watershed properties?

Satisfactory SWAT model performance was obtained from calibration and validation of daily discharges, but not for nitrate loads due to the difficulties in modelling complex nitrogen processes within the inland valleys, the discontinuous nature of the observations, and the insufficient amount of water samples collected on a weekly basis. Although the results indicate that evapotranspiration requires more than 50% of the precipitation, the ability of the model to account for the contributing watersheds properties was revealed to the extent that runoff is of the highest value in Kounga with the highest proportion of cultivated areas, followed by Tossahou, and lowest in Kpandouga which is dominated by natural vegetation and has the smallest proportion of agricultural land use. However, beyond the conceptual model and the inherent non-uniqueness of parameter combinations, a large range of uncertainty is reflected in the predictions due to possible errors in the spatial representation of patterns related to rainfall, soil, land use and topography, and to the quality of the discharge data used for validation. This implies that a good performance of the model is achievable if the applied methods for accurately classifying land use and soil units are improved. More rain gauges should be installed at every site for accounting the high spatial and temporal variability of rainfall and the resolution of the DEM (30 m) should be improved to accurately account for the topography. The TanDem-X mission could be an alternative which has to be investigated (Krieger et al., 2007). Nonetheless, the results of the SWAT model will still be limited by the potential uncertainties induced by the highly dynamic human activities that occur within the inland valleys, and which might not be considered or acceptably parameterized. Comparing ArcSWAT and SWATgrid, the simulated discharge was not significantly influenced by the discretization schemes. However, the modifications that affect the distribution and composition of land use, soil and topography have an impact on water balance components in the grid-based setup resulting in reduced surface runoff, percolation and water yield at all sites. SWATgrid is an effective tool because it accounts for lateral fluxes between grid cells but would require a spatial calibration in order to perform a quantitatively detailed spatial analysis of hydrological processes.

(2) What are the spatial and temporal changes on water availability in inland valleys under rice intensification?

Temporal changes were successfully analyzed using the calibrated and validated ArcSWAT model in spite of the uncertainties related to the model parametrization and the downscaled precipitation and temperature data used. It was revealed that the effects of land use change involved during intensification within all inland valleys are overwhelmed by the dominant impacts of climate change. Hence, a severe water shortage is projected downstream for agricultural land as the streamflow will significantly decline due to the decreased precipitation. Although the hydrological processes within all watersheds will be affected by a pronounced lowland development, the changes on streamflow will be insignificant with marginal increase in Kounga and Kpandouga and decline in Tossahou. Thus, climate change was inferred to be the crucial threat for water availability within the inland valleys during intensification.

Through this study, the spatial changes caused by rice intensification on water availability within the inland valleys could not be assessed because of the insufficient number of gauging station (only one station downstream at the outlet of each watershed) for discharge measurement.

(3) How to determine fields suitable for rice growing for aiding small-scale farmers in improving their production and sustaining their life?

It was revealed that more than half of the inland valley of Tossahou is of good suitability for irrigated system, whereas the cultivation under natural floods is best suited only for the central valley bottom. Moreover, due to the sandy soil texture occurring throughout the inland valley, the potential for rainfed bunded rice cultivation is very low. As no irrigation schemes are implemented in the inland valley, it can be inferred that the local farmers would currently benefit more from the cultivation of rice under natural floods. However, localizing a land of favorable biophysical properties was revealed to be not enough for ensuring a high production because measured rice yields were low on the fields located in the areas actually identified to be suitable. The level of rice production was found to be mainly restrained by social and economic constraints prevailing in the inland valley such as the limited access to credits and markets, and the costly maintenance of the rice fields. Thus, dealing with these constraints in addition to the determination of the suitable areas would effectively help in improving the livelihood of the small-scale farmers considerably.

Nonetheless, during the application of the FAO parameter method and guidelines for land evaluation, the validation of the suitability maps for the irrigated and bunded cultivation systems was limited by the absence of cultivated fields. Thus, defining some others ways for validation is valuable to improve this methodological approach.

In conclusion, this work is of a substantial contribution to researchers and water management decision makers for predicting future impacts of rice intensification on inland valleys water availability and rice production in the region. Because of all uncertainties, the application of other future climate change scenarios and hydrological models for comparison would be useful while planning adaptation strategies for climate change and policies for sustainable watershed management. For future works, this study could be improved by increasing the number of discharge and water quality observations to properly validate the model for accurate water quantity and quality assessment. Thereby, future studies are recommended to be focused on assessing the long-term effect on water quality for determining the likely environmental impacts of rice intensification on water resources. Another improvement would be to include more spatial input data for conducting a spatial calibration of the grid-based version SWATgrid and performing an effective quantitative evaluation of spatially distributed hydrological processes. Regarding the evaluation of the inland valleys suitability, complementary socio-economic analyses are required to provide knowledge necessary for increasing the yield in the potentially suitable areas.

References

Abbaspour, K.C., 2014. SWAT-CUP 2012: SWAT Calibration and Uncertainty Programs – A user manual, Swiss Federal Institute of Aquatic Science and Technology (EAWAG), Zurich, Switzerland.

Abe, S. S., Buri, M. M., Issaka, R. N., Kiepe, P., Wakatsuki, T.,2010. Soil fertility potential for rice production in West African lowlands. Japan Agric. Research Quart. 44, 343–355.

Achenbach, H., 1994. Die agraren Produktionszonen der Erde und ihre natürlichen Risikofaktoren. In: Geogr. Rundschau. 46, 58–64.

Acres, B.D., Rains, A.B., King, R.B., Lawton, R.M., Mitchell, A.J.B., Rackham, L.J., 1985. African dambos: their distribution, characteristics and use. Zeitschrift für Geomorphologie Supplementbände. 52, 63–86.

Adetonah, S., Coulibaly, O., Sessou, E., Padonou, S., Dembele, U., Adekambli, S., 2010. Contribution of Inland Valleys Intensification to Sustainable Rice/vegetable Value Chain Development in Benin and Mali: Constraints, opportunities and profitable cropping systems. AgEcon Search.

AFD, 2013. Rainfed Food Crops in West and Central Africa: Points for Analysis and Proposals for Action. Available at http://recherche.afd.fr.

Amadou, T., Rodenburg, J., Saito, K., Sylvester, O., Futakuchi, K., Gumedzoe, D., Huat, J., 2011. Cultivar and weeding effects on weeds and rice yields in a degraded upland environment of the coastal savanna. Weed Science Society of America. Weed tech. 25, 322–329.

AMMA-CATCH Database., 2015.available at: http://bd.amma-catch.org/amma-catch2/main.jsf (last access: 10 May 2015).

Andriesse, W., Fresco, L.O., 1991. A characterization of rice-growing environments in West Africa. Agric. Ecosyst. Environ. 33, 377-395.

Andriesse, W., Fresco, L.O., Van Duivenbooden, N., Windmeijer, P.N., 1994.Multi-scale characterization of inland valley agro-ecosystems in West Africa. Netherlands J. Agric. Sci.42, 159-179.

App, A., Santiago, T., Daez, C., Menguito, C., Ventura, W., Thriol, A., Po, J., Watanabe, I., De Data, S.K., Roger, P., 1984. Estimation of nitrogen balance for irrigated rice and the contribution of phototrophic nitrogen fixation. Field Crops Res. 9, 17–27.

Arheimer, B., Lidén, R., 2000. Nitrogen and phosphorus concentrations from agricultural catchments – influence of spatial and temporal variables. J. Hydrol. 227, 140–159.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modelling and assessment part I: model development. J. Am. Water Resour. Assoc. 34 (1), 73–89.

Arnold, J., Allen, P., Volk, M., Williams, J., Bosch, D., 2010. Assessment of different representations of spatial variability on SWAT model performance. T. ASABE. 53, 1433–1443.

Arnold, J. G., Kiniry, J. R., Srinivasan, R., Williams, J. R., Haney, E. B., Neitsch, S. L., 2013. Soil Water and Assessment Tool Input/Output Documentation Version 2012, TexasWater Resources Institute, College Station, Texas, USA.

Bada, B.V., Ndiaye, M. A. A., 2010. Long-term of continuous cropping of irrigated rice on soil and yield trends in the Sahel of West Africa. Spr. Sci. Busi. Med. B.V. DOI 10.1007/s10705-010-9355-7.

Balu L. Bumb and Carlos A. Baanante, 1996. World trends in fertilizer use and projections to 2020. Int. Food Policy Res. Ins. 2020 Brief 38.

Banai, R., 1993. Fuzziness in geographical information systems: contributions from the analytic hierarchy process. Int. J.Geog. infor. Sys.74, 315–329.

Bandyopadhyay, K. K., Sarkar, M. C., 2005. Nitrogen Use Efficiency, 15N Balance, and Nitrogen Losses in Flooded Rice in an Inceptisol. Division of Soil Science and Agricultural Chemistry, Indian Agricultural. Res. Ins. New Delhi, India. The Fertilizer Association of India, New Delhi, India. Communications in Soil Sci. and Plant Anal. 36, 1661–1679.

Barthel, R., Sonneveld, B.G.J.S., Götzinger, J., Keyzer, M.A., Pande, S., Printz, A., Gaiser, T., 2009. Integrated assessment of groundwater resources in the Ouémé basin, Benin, West Africa. Phys. Chem. Earth. 34, 236–250. doi:10.1016/j.pce.2008.04.001.

Becker, M., Johnson, D.E., 2001. Improved water control and crop management effects on lowland rice productivity in West Africa. Kluwer Academic Publishers. Nutrient Cycling in Agro-ecosystems. 59, 119–127.

Beven, K., Binley, A., 1992. The future of distributed models: model calibration and uncertainty prediction. Hydrol. Process. 6 (3), 279–298.

Bossa, A.Y., Diekkrüger, B., Giertz, S., Steup, G., Sintondji, L.O., Agbossou, E.K., Hiepe, C., 2012. Modeling the effects of changing crop patterns and management practices on N and P loads to surface water and groundwater in a semi-humid watershed (West Africa). Agric. Water Manag. 115, 20-37.

Bossa, A.Y., 2012b. Multi-scale modeling of sediment and nutrient flow dynamics in the Ouémé watershed (Benin) – towards an assessment of global change effects on soil degradation and water quality. PhD-Thesis University of Bonn, http://hss.ulb.uni-bonn.de/2012/ 2983/2983.htm.

Bormann, H., Diekkrüger, B., 2003.Possibilities and limitations of regional hydrological models applied within an environmental change study in Benin (West Africa). Phys. Chem. Earth. 28, 1323–1332. doi:10.1016/j.pce.2003.09.008.

Bormann, H., 2005. Regional hydrological modelling in Benin (West Africa): Uncertainty issues versus scenarios of expected future environmental change. Phys. Chem. Earth. 30, 472–484.

Busche, H., Hiepe, C., Diekkrüger, B., 2005. Modeling the Effects and Land Use and Climate Change on Hydrology and Soil Erosion in a Sub-humid African Catchment. 3rd International SWAT Conference Proceedings, Zurich. http://www.brc.tamus.edu/swat/3rdswatconf/Bookofabstracts -3rdswatconf1.pdf

Burton, I. and Lim, B., 2005. Achieving adequate adaptation in agriculture. In: Climatic Change. 70, 191–200.

Casanova, D., Goudriaan, J., Catala Forner, M.M., Withagen, C.J.M., 2002. Rice yield prediction from yield components and limiting factors. European Journal of Agronomy. 17, 41–61.

CGR, 2004. La filière riz au Bénin : l'analyse du Comité de Concertation des Riziculteurs du Bénin.pp1. comite_riz_benin@yahoo.fr.

Chauhan, B., 2013. Management strategies for weedy rice in Asia. International Rice Research Institute. Los Baños.

Chien, H., Yeh, P.J., Knouft, J.H., 2013. Modeling the potential impacts of climate change on streamflow in agricultural watersheds of the Midwestern United States. J. Hydrol. 491, 73–88. doi:10.1016/j.jhydrol.2013.03.026.

Collins, M.G., Steiner, F. R., Rushman, M.J., 2001. Land-use suitability analysis in the United States: historical development and promising technological achievements. Environ. Manag. 285, 611–621.

Cornelissen, T., Diekkrüger, B., Giertz, S., 2013. A comparison of hydrological models for assessing the impact of land use and climate change on discharge in a tropical catchment. J. Hydrol. 498, 221–236. doi:10.1016/j.jhydrol.2013.06.016.

Cournac, L., Dubois, M.A., Chave, J., Riéra, B., 2002. Fast determination of light availability and leaf area index in tropical forests. J. Tropical Ecol. 18, 295-302.

Dahal, M., Sitaula, B.K., Sharma, S., Bajracharya, M., 2007. Effects of agricultural intensification on the quality of rivers in rural watersheds of Nepal Bed. J. Food, Agric. Environ. 5(1), 341-347.

Danvi, A., Jütten, T., Giertz, S., Zwart, S.J., Diekkrüger, B., 2016. A spatially explicit approach to assess the suitability for rice cultivation in an inland valley in central Benin. Agric. Water Manag. 177, 95–106.

Danvi, A., Giertz, S., Zwart, S.J., Diekkrüger, B., 2017. Comparing water quantity and quality in three inland valley watersheds with different levels of agricultural development in central Benin. Agric. Water Manag. Arcticle in press.

Dengiz, O., 2013. Land suitability assessment for rice cultivation based on GIS modeling. Turkish J. of Agric. and Forestry. 37, 326–334.

De Reu, J., Bourgeois, J., Bats, M., Zwertvaegher, A., Gelorini, V., De Smedt, P., Chu, W., Antrop, M., De Maeyer, P., Finke, P., Van Meirvenne, M., Verniers, J., Crombé, P., 2013. Application of the topographic position index to heterogeneous landscapes. Geomorphology. 186, 39–49.

De Wasseige, C., Bastin, D., Defourny, P., 2003. Seasonal variation of tropical forest LAI based on field measurements in Central African Republic. Forest Meteorol. 119, 181-194.

Djagba, J.F., Rodenburg, J., Zwart, S.J., Houndagba, C.J., Kiepe, P., 2013. Failure and success factors of irrigation system developments: a case study from the Ouémé and Zou valleys in Benin. Irrigation and Drainage. 63, 328–339.

Duku, C., Rathjens, H., Zwart, S.J., Hein, L., 2015. Towards ecosystem accounting : a comprehensive approach to modelling multiple hydrological ecosystem services. Hydrol. Earth Syst. Sci. 4377–4396. doi:10.5194/hess-19-4377-2015.

Dulal, K.N., Takeuchi, K., Ishidaira, H., 2007. Evaluation of the Influence of Uncertainty in Rainfall and Discharge. J. Hydraul. Eng. 51, 31–36.

Eckhardt, K., Haverkamp, S., Fohrer, N., Frede, H.G., 2002. SWAT-G, a version of SWAT99.2 modified for application to low mountain range watersheds. Phys. Chem. Earth. 27, 641-644.

Edame, G.E., State, C.R., Ekpenyong, B., Fonta, W.M., 2011. Climate Change , Food Security and Agricultural Productivity in Africa : Issues and policy directions . Int. J. Humanit. Soc. Sci. 1, 205–223.

FAO, 1976. A framework for land evaluation. FAO Soils Bulletin 32. FAO, Rome.

FAO Stat, 2011. Import commodities by country - Benin. http://faostat.fao.org/site/342/default.aspx/ (accessed: 15.07.14).

Fink, A.H., Christoph, M., Born, K., Brücher, T., Piecha, K., Pohle, S., Schulz, O.,Ermet, V., 2010. Climate. In: Speth, P., Christoph, M., Diekkrüger, B. (Eds.), Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer, Heidelberg, Germany.

Fujii, H., Gumma, M. K., Thenkabail, P. S., Namara, Regassa, E., 2010. Suitability evaluation for lowland rice in inland valleys in West Africa. Transactions of the Japanese Society of Irrigation, Drainage and Rural Engineering. 78, 47–55.

Garbrecht, J., Martz, L., 2000. Topaz User Manual: Version 3.1, Technical Report. Grazinglands Research Laboratory, USDA, Agricultural Research Service, El Reno, Oklahoma.

Garrity, D.P., Vejpas, C., Herrera, W., 1992. Percolation barriers increase and stabilize rain-fed lowland rice yield on well drained soils. In: Murty, V.V.N. and Koga, K. (Eds). Proceedings of the International Workshop on soil and Water Engineering for Paddy Field Management. Asian Institute of Technology, Rangist, Thailand. 413–421.

Giertz, S., 2004. Analyse der hydrologischen Prozesse in den sub-humiden Tropen Westafrikas unter besonderer Berücksichtigung der Landnutzung am Beispiel des Aguima-Einzugsgebietes in Benin. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.unibonn.de/diss_online/math_nat_fak/2004.

Giertz, S., Diekkrüger, B., Steup, G., 2006. Physically-based modelling of hydrological processes in a tropical headwater watershed (West Africa) – process representation and multi-criteria validation. Hydrol. Earth Syst. Sci. 10, 829-847.

Giertz, S., Hiepe, C., Steup, G., Sintondji, L., Diekkrüger., B., 2010. Hydrological processes and soil degradation in Benin. In: Speth, P., Christoph, M., Diekkrüger, B. (Eds.),Impacts of Global Change on the Hydrological Cycle in West and NorthwestAfrica. Springer, Heidelberg, Germany.

Giertz, S., Steup, G., Schönbrodt, S., 2012. Use and constraints on the use of inland valley ecosystems in central Benin: Results from an inland valley survey. Erdkunde. 66, 239–253. doi:10.3112/erdkunde.2012.03.04.

Gorban, A.N., Pokidysheva, L.I., Smirnova, Tyukina, E.V., 2010. Law of the minimum Paradoxes. Bulletin of Mathematical Biology. 73, 2013–2044.

Grebmer, K. V., Fritschel, H., Nestorova, B., Olofinbiyi, T., Pandya-Lorch, R., Yohannes, Y., 2008. The Challenge of Hunger 2008: Global Hunger Index. Washington DC, International Food Policy Research Institute.

Gruber, I., Kloos, J.,Schopp, M., 2009. Seasonal water demand in Benin's agriculture. Journal of Environmental Management. 90, 196–205.

Gumma, M., Thenkabail, P., Fujii, H., Namara, R., 2009. Spatial models for selecting the most suitable areas of rice cultivation in the inland valley wetlands of Ghana using remote sensing and geographic information systems. J. of Applied Remote Sensing. 3, 1–21.

Gupta, H. V., Sorooshian, S., and Yapo, P. O., 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration, J. Hydrol. Eng. 4, 135–143.

Haefele, S.M., Nelson, A., Hijmans, R.J., 2014. Soil quality and constraints in global rice production. Geoderma. 235-236, 250-259.

Halder, J. C., 2013. Land Suitability Assessment for Crop Cultivation by Using Remote Sensing and GIS. J. of Geography and Geology. 5, 65–74.

Havlin, J.L., Tisdale, S.L., Nelson, W.L., Beaton, J.D., 2013. Soil fertility and fertilizers. 8th eds. Pearson, New York.

Hiepe, C., 2008. Soil degradation by water erosion in a sub-humid West-African watershed a modelling approach considering land use and climate change in Benin. Doctoral thesis, University of Bonn, Bonn. http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2008/ hiepe_claudia.

Igué, A.M., 2000. The use of soil and terrain database for land evaluation procedures: Case study of Central Benin. Hohenheimer Bodenkundliche Hefte 58. University of Hohenheim. Stuttgart, Germany.

IMPETUS, 2007. IMPETUS Geonetwork, http://www.impetus.uni-koeln.de/geonetwork-daten/klimadiagramme-benin.html?no cache=1 (accessed 03.04.14.).

IPCC .2007. IPCC Fourth Assessment Report. Rome, Italy, Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar4/ (accessed : 12.04.2017).

Ishikawa, M., Tabuchi, T., Yamaji, A., Nakajima, J., 1992. Field test of water quality purification using under drain—study of water quality purification by soil layer in paddy field (I), Trans. Japanese Society of Irrigation, Drainage, and Reclamation Engineering (JSIDRE). 159, 81–89.

IVC (Inland Valley Consortium), 2005. Summary Report of Presentations and General Discussions. Annual Workshop of the Inland Valley Consortium – IVC, held at Cotonou, Benin 4th to 8th April 2005.

Janssens, M., Deng, Z., Mulindabigwi, V., Röhrig, J., 2010. Agriculture and food. In:Speth, P., Christoph, M., Diekkrüger, B. (Eds.), Impacts of Global Change on theHydrological Cycle in West and Northwest Africa. Springer, Heidelberg.

Jenness ,J., Brost, B., Beier, P., 2013. Land Facet Corridor Designer. http://www.corridordesign.org.

Judex, M., Röhrig, J., Linsoussi, C., Thamm, H.-P., Menz**.,** G**.**, 2010. Vegetation cover and land use change in Benin. In: Speth, P., Christoph, M. and B. Diekkrüger (eds.).2010., Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer, Heidelberg. 257-273.

Kaneki, R., 1989. Effect of purification by recycling use of water to Biwa Lake, Jour. JSIDRE , 57(7), 39–44.

Kemp, M.J., Dodds, W.K., 2001. Spatial and temporal patterns of nitrogen concentrations in pristine and agriculturally influenced prairie streams. Biogeochemistry.53, 125–141.

Kiefer, R.W., 1965. Land evaluation for land use planning. Building Science. 1, 109–125.

Kihoro, J., Bosco, N.,Murage, H., 2013. Suitability Analysis for Rice Growing Sites Using a Multicriteria Evaluation and GIS Approach in Great Mwea Region, Kenya. SpringerPlus. 2, 265. **DOI:** 10.1186/2193-1801-2-265.

Kinkingninhoun-Medagbe, F. M., Diagne A., Biaou, G., 2015. Impact of use of credit in rice farming on rice productivity and income in Benin. International Association of Agricultural Economists. No 211635, 2015 Conference, August 9-14, 2015, Milan, Italy.

Knippertz, P., Fink, A.H., 2006. Synoptic and Dynamic Aspects of an Extreme Springtime Saharan Dust Outbreak. Q. J. Roy. Meteor. Soc. 132, 1153-1177.

Kotze, D.C., 2011. The application of a framework for assessing ecological condition and sustainability of use to three wetlands in Malawi. Wet. Ecology and manag. 19, 507-520.

Krieger, G., Moreira, A., Fiedler, H., Hajnsek, I., Werner, M., Younis, M., Zink, M., 2007. TanDEM-X : A Satellite Formation for High-Resolution SAR Interferometry. IEEE Trans. Geosci. Remote Sens. 45, 3317–3341.

Krishna, G.V.T., Regil, R., 2014. Agricultural land suitability analysis of a river basin area using remote sensing and GIS. Int. J. Geo. Eng. and Tech.1, 37–42.

Kuhn, A., Gruber, I., Heidecke, C. 2010. Economy and infrastructure. In: Speth P, Christoph M, Diekkruger B (eds) Impacts of Global Change on the hydrological Cycle in West and Northwest Africa. Springer, Heidelberg, Germany.

Kuria, D., Ngari, D.,Waithaka, E., 2011. Using geographic information systems (GIS) to determine land suitability for rice crop growing in the Tana delta. J. Geogr. and Reg. Pla. 4, 525–532.

Kyaw, K.M., Toyota, K., Okazaki, M., Motobayashi, T., Tanaka, H., 2005. Nitrogen balance in a paddy field planted with whole crop rice (Oryza sativa cv. Kusahonami) during two rice-growing seasons. Biol. Fertil. Soils, published online, http://www.springerlink.com/content/x3418573025222m3/fulltext.htm.

Kyei-Baffour, N., Ofori, O., Mensah, E., Agyare, W.A., Atta-Darkwa, T., 2013. Modelling groundwater flow of the besease inland valley bottom in Ghana. G.J.B.A.H.S. 2(1), 52-60.

Lal, R., 1990. Soil erosion in the tropics. In: Principles & Management. McGraw-Hill, Inc., New York, 580.

Lam, Q.D., Schmalz, B., Fohrer, N., 2010. Modelling point and diffuse source pollution of nitrate in a rural lowland catchment using the SWAT model. Agric. Water Manag. 97, 317–325. doi:10.1016/j.agwat.2009.10.004.

Li, Y.H., Yu, F.,1999. Improved irrigation management of paddy fields for sustainable increase in water productivity. 2nd, Inter-regional conference on environment-water. 99, 13.

Liew, M.W. Van, Feng, S., Pathak, T.B., 2012. Climate change impacts on streamflow , water quality , and best management practices for the shell and logan creek watersheds in Nebraska. Int J Agric Biol Eng. doi:10.3965/j.ijabe.20120501.003.

Lightfoot, D., Mavlyanov, N., Begimkuloy, D., Comer, J., 2009. Reliability of interview data for monitoring and mapping groundwater. Proceedings of the Kampala Conference, June 2008. International Association of Hydrological Sciences (IAHS) Publication. 334, 40–43.

Liu, Y., Wang, J., Guo, L., 2006. GIS-Based assessment of land suitability for optimal allocation in the Qinling Mountains, China. Pedosphere. 16, 579–586.

Liu, Y., Yang, W., Qin, C., Zhu, A., 2016. A Review and Discussion on Modeling and Assessing Agricultural Best Management Practices under Global Climate Change. J. Sustain. Dev. 9, 245–255. doi:10.5539/jsd.v9n1p245.

Lohou, F., Kergoat, L., Guichard, F., Boone, a., Cappelaere, B., Cohard, J.M., Demarty, J., Galle, S., Grippa, M., Peugeot, C., Ramier, D., Taylor, C.M., Timouk, F., 2014. Surface response to rain events throughout the West African monsoon. Atmos. Chem. Phys. 14, 3883–3898. doi:10.5194/acp-14-3883-2014.

MAEP, 2010. Stratégie nationale pour le développement de la riziculture au Benin. 26.

Martin, D., Saha, S.K., 2009. Land evaluation by integrating remote sensing and GIS for cropping system analysis in a watershed. Current Science. 96, 569–575.

Maruyama, T., Tanji, K.K., 1997. Physical and chemical processes of soil related to paddy drainage. Shinzansha Sci. and Technol. Publ. Co., Inc., 229.

Masiyandima, M.C., Giesen, N. Van De, Diatta, S., Windmeijer, P.N., Steenhuis, T.S., 2003. The hydrology of inland valleys in the sub-humid zone of West Africa : rainfall-runoff processes in the M'b´e experimental watershed. Hydrol. Process. 1225, 1213–1225. doi:10.1002/hyp.1191.

Masoud, J., Agyare, W.A., Forkuor, G., Namara, R., OFORI, E., 2013. Modeling inland valley suitability for rice cultivation. ARPN J. Eng. and Applied Sci. 8, 9–19.

Matson, P. A., Parton, W. J., Power, A. G., Swift, M. J., 1997.Agricultural Intensification and Ecosystem Properties. Science. 277, 504-509.

McDonald, R.I., Green, P., Balk, D., Fekete B.M., Revenga, C., 2011. Urban growth, climate change and freshwater availability. Proc. National Acad.Sci., 108, 6312-6317. DOI: 10.1073/pnas.1011615108.

Misawa, S., 1987. Mechanism of the water quality change in paddy field, Trans. JSIDRE. 127, 69–78.

Mokaram, M., Aminzadeh, F., 2010. GIS-based multicriteria land suitability evaluation using ordered weight averaging with fuzzy quantifier: A case study in Shavur Plain, Iran. Joint International Conference on Theory. Data Handling and Modelling in GeoSpatial Information Science. 38, 508–12.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., Veith, T. L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. T. ASABE. 50, 885–900.

Mulindabigwi, V., 2005. Influence des systèmes agraires sur l'utilisation des terroirs, la séquestration du carbone et la sécurité alimentaire dans le bassin versant de l'Ouémé supérieur au Bénin, PhD-Thesis University of Bonn. http://hss.ulb.uni-bonn.de/2006/0784/0784.pdf.

Mustafa, A.A., Singh, M., Sahoo, R.N., Ahmed, N., Khanna, M., Sarangi, A., Mishra, A.K., 2011. Land suitability analysis for different crops : A multi criteria decision making approach using remote sensing and GIS. Water Tech. 3, 61–84.

Nagasaka, T., Horino, H., Watanabe, T., Maruyama, T., 1998. Actual phenomena of agricultural pond and evaluation of it by principal analysis. Trans JSIDRE., 195,125–131.

NASA, USGS, 2011. METI and NASA Release Version 2 ASTER Global DEM. https://lpdaac.usgs.gov/about/news_archive/meti_and_nasa_release_version_2_aster_ global_dem/(accessed 09.10.2014).

Nash, J. E., Sutcliffe, J. V., 1970. River flow forecasting through conceptual models: Part 1. A discussion of principles. J. Hydrol. 10, 282–290.

NCA, 2014. Climate change impacts in the United States: The third national climate assessment. U.S. Global Change Research Program. http://s3.amazonaws.com/nca2014/high/NCA3_Climate_Change_Impacts_in_the_United%20States_HighRes.pdf (accessed: 12.04.2017).

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., and Williams, J. R., 2009. Soil and Water Assessment Tool, Theoretical Documentation, Grassland, Soil and Water Resources Laboratory, Temple, TX, USA. http://swat.tamu.edu/media/99192/swat2009-theory.pdf (accessed: 30.03.2017).

Nisar Ahamed, T., Gopal Rao, K., Murthy, J.S., 2000. GIS-based fuzzy membership model for crop-land suitability analysis. Agric. Sys. 63, 75–95.

NRDS, 2011. Natural report data series report. https://www.nature.nps.gov/publications/nrpm/nrds.cfm. (accessed: 30.03.2017).

Ogban, P.I., Babalola, O., 2003. Soil characteristics and constraints to crop production in inland valley bottoms in southwestern Nigeria. Agric. Water Manag. 61, 13–28.

Orthmann, B., 2005. Vegetation ecology of a woodland-savannah mosaic in central Benin (West Africa) : Ecosystem analysis with a focus on the impact of selective logging. PhD-Thesis University of Rostock. http://rosdok.uni-rostock.de/metadata/rosdok_disshab_000000000005.

Paeth, H., 2004. Key factors in African climate change evaluated by a regional climate model. Erdkunde 58, 290-315.

Paeth, H., Capo-Chichi, A., Endlicher, W., 2008. Climate change and food security in tropical West Africa - A dynamic-statistical modelling approach. Erdkunde 62, 101–115. doi:10.3112/erdkunde.2008.02.01.

Paeth, H., Born, K., Girmes, R., Podzun, R., Jacob, D., 2009. Regional climate change in tropical Africa under greenhouse forcing and land-use changes. J. of Climate. 22, 114–132.

Pathak, B.K., Kazama, F., Toshiaki, I., 2004. Monitoring of nitrogen leaching from a tropical paddy field in Thailand, Agricultural Engineering International the CIGR Journal of Scientific Research and Development, vol VI, manuscript LW 04 015, 13.

Pervez, S., Henebry, G.M., 2015. Journal of Hydrology : Regional Studies Assessing the impacts of climate and land use and land cover change on the freshwater availability in the Brahmaputra River basin ☆. J. Hydrol. 3, 285–311.

Pohlert, T., Huisman, J.A., Breuer, L., Frede, H.-G., 2005. Modelling of point and diffuse source pollution of nitrate with SWAT in the river Dill, Germany. Adv. Geosci. 5, 7–12.

Qiao, L., Zou, C., Will, R., Stebler, E.,2015. Calibration of SWAT model for woody plant encroachment using paired experimental watershed data. J. Hydrol. 523, 231–239.

Quyen, N.T.N., Liem, N.D., Loi, N.K., 2014. Effect of land use change on water discharge in Srepok watershed, Central Highland , Viet Nam. Int. Soil Water Conserv. Res. 2, 74–86.

Rathjens, H., Oppelt, N., 2012. Advances in Geosciences SWAT model calibration of a grid-based setup. Adv. Geosci. doi:10.5194/adgeo-32-55-2012.

Rathjens, H., Oppelt, N., Bosch, D.D., Arnold, J.G., Volk, M., 2014. Development of a grid-based version of the SWAT landscape model. Hydrol. Process. doi:10.1002/hyp.10197.

Rawls, W.J., Brakensiek, D.L., 1985. Prediction of soil water properties for hydrological modelling. In: Jones, E., Ward, T.J. (Eds.), Proceedings of the symposium watershed management in the eighties, Denver. 293–299.

Refsgaard, J.C., Knudsen, J., 1996. Operational validation and intercomparison of different types of hydrological models. Water Reso. Res. 32, 2189-2202. Doi:10.1029/96WR00896.

Regh, T., Bossa, A.Y., Diekkrüger, B., 2014. Scenario-based simulations of the impacts of rainfall variability and management options on maize production in Benin. African J. Agric. Res. 9, 3393–3410. doi:10.5897/AJAR2014.8757.

Rocha, J., Roebeling, P., Rial-rivas, M.E., 2015. Science of the Total Environment Assessing the impacts of sustainable agricultural practices for water quality improvements in the Vouga catchment (Portugal) using the SWAT model. Sci. Total Environ. 536, 48–58.

Rode, M., Arhonditsis, G., Balin, D., Kebede, T., Krysanova, V., van Griensven, A., van Der Zee, S.E.A.T.M., 2010. New challenges in integrated water quality modelling. Hydrol. Process. 24, 3447–3461.

Rodenburg, J., Zwart, S.J., Kiepe, P., Narteh, L.T., Dogbe, W., Wopereis, M.C.S., 2014. Sustainable rice production in African inland valleys: Seizing regional potentials through local approaches. Agric. Syst. 123, 1–11.

Roel, A., Firpo, H., Plant, R.E., 2007. Why do some farmers get higher yields? Multivariate analysis of a group of Uruguayan rice farmers. Computers and Electronics in Agriculture. 58, 78–92.

Saito, K., Dieng, I., Toure, A.A., Wopereis, M.C.S., 2015. Rice yield trend analysis for 24 African countries over 1960-2012. Global Food Security. 5, 62–69.

Sakaguchi, A., Eguchi, S., Kasuya, M., 2014. Soil Science and Plant Nutrition Examination of the water balance of irrigated paddy fields in SWAT 2009 using the curve number procedure and the pothole module

Examination of the water balance of irrigated paddy fields in SWAT 2009 using the curve number. Soil Sci. Plant Nutr. 60, 551–564. doi:10.1080/00380768.2014.919834.

Sakané, N., Alvarez, M., Becker, M., Böhme, B., Handa, C., Kamiri, H.W., Langensiepen, M., Menz, G., Misana, S., Mogha, N.G., Möseler, B.M., Mwita, E.J., Oyieke, H.A., van Wijk, M.T., 2011. Classification, characterization, and use of small wetlands in East Africa. Wetlands. 31, 1103–1116.

Schilling, K.E., Jha, M.K., Zhang, Y., Gassman, P.W., Wolter, C.F., 2008. Impact of land use and land cover change on the water balance of a large agricultural watershed : Historical effects and future directions. Water Res. Res. 44, 1–12. doi:10.1029/2007WR006644.

Schmitter, P., Zwart, S.J., Danvi, A., Gbaguidi, F., 2015. Contributions of lateral flow and groundwater to the spatio-temporal variation of irrigated rice yields and water productivity in a West-African inland valley. Agric. Water Manag. 152, 286–298.

Schuol, J., Abbaspour, K.C., Srinivasan, R., Yang, H., 2008. Estimation of freshwater availability in the West African sub-continent using the SWAT hydrologic model. J. Hydrol., 352, 30-49.

Sicat, R.S., Carranza, E.J.M., Nidumolu, U.B., 2005. Fuzzy modeling of farmers' knowledge for land suitability classification. Agric. Sys. 83, 49–75.

Singh, S., 2012. Land suitability evaluation and landuse planning using remote sensing data and geographic information system techniques. Int. J. of Geology, Earth and Environ. Sci. 2, 1–6.

Sintondji, O.L., Zokpodo, B., Ahouansou,D.M., Vissin, W.E., Agbossou,E.K., 2014. Modelling the water balance of Ouémé catchment at the Savè outlet in Benin : contribution to the sustainable water resource management. 4, 74–88.

Sintondji, L., 2005. Modelling the rainfall-runoff process in the Upper Quémé watershed area (Terou) in a context of climate change: extrapolation from the local to the regional scale. Doctoral thesis, University of Bonn, Bonn.

Spektrum,1999. Lexikon der Biologie-Minimumgesetz. <http://www.spektrum.de/ lexikon/biologie/minimumgesetz/43184> Last access: 25.09.2014.

Speth, P., Christoph, M., Diekkruger, B., 2010. Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer Heidelberg, Germany. doi:10.1007/978-3-642-12957-5.

Speth, P., M. Christoph and B. Diekkruger, (Eds.), 2012. Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer Publisher. 675 p.ISBN: 978-3-642-12956-8.

Staudinger, M., Stahl, K., Seibert, J., Clark, M.P., Tallaksen, L.M., 2011. Comparison of hydrological models structures based on recession and low flow simulations. Hydrol. Earth Syst. Sci. 15, 3447-3459. doi:10.5194/hess-15-3447-2011.

Steiner, K.G., 1996. Causes of soil degradation and development approaches to sustainable soil management. GTZ report. Available at http://agriwaterpedia.info/images/c/c1/GIZ,_Steiner,_K.G._(1996)_Causes_of_soil_degradation_and_development_approaches_to_sustainable_soil_managament_Chapter_1_-_4.pdf (accessed: 30.03.2017).

Sun, M.T., Sun, G., Liu, C., Myers, J.A.M., McNulty, S.G., 2015. Future water budgets and water supply stress under climate change and urbanization in the upper Neuse River Basin, North Carolina, USA. Am. J. Environ. Sci. 11, 175–185. doi:10.3844/ajessp.2015.175.185.

Sundström, J.F., Albihn, A., Boqvist, S., Ljungvall, K., Marstorp, H., 2014. Future threats to agricultural food production posed by environmental degradation , climate change , and animal and plant diseases – a risk analysis in three economic and climate settings. Food Secur. 201–215. doi:10.1007/s12571-014-0331-y.

Sys, C., Ranst, E., Debaveye, J., 1991. Land Evaluation Part II - Methods in Land Evaluation. FAO Agricultural Publications. Brussels.

Sys, C., Ranst, E., Debaveye, J., Beernaert, F., 1993. Land Evaluation Part III – Crop Requirements. FAO Agricultural Publications. Brussels.

Tabuchi, T., 1986. Nitrogen outflow diagram in a small agricultural area, -Research on nitrogen outflow from an agricultural area (III). Trans JSIDRE. 124, 53–60.

Tabuchi, T., Takamura, Y., 1985. Flow out of nitrogen and phosphorus from basin, Tokyo University Publication Company, 34.

Tao, C., Chen, X.L., Lu, J.Z., Gassman, P.W., Sabine, S., José-Miguel, S.P., 2015. Assessing impacts of different land use scenarios on water budget of Fuhe River, China using SWAT model. Int. J. Agric. Biol. Eng. 8(3), 95—109.

Thenkabail, P.S., Nolte, C., 1996. Capabilities of Landsat-5 Thematic Mapper (TM) in regional mapping and characterization of inland valley agroecosystems in West Africa. Int. J. of Remote Sensing. 17, 1505–1538.

Tomer, M.D., Schilling, K.E., 2009. A simple approach to distinguish land-use and climate-change effects on watershed hydrology. J. Hydrol. 376, 24–33.

Totin, E., Stroosnijder, L., Agbossou, E., 2013. Mulching upland rice for efficient water management: A collaborative approach in Benin. Agric. Water Manag. 125, 71–80. doi:10.1016/j.agwat.2013.04.012.

Tuong, T.P., Bouman, B.A.M., 2003. Rice Production in Water Scarce Environments. In Water Productivity in Agriculture: Limits and Opportunities for Improvement. Kijne, J.W., Barker, R., Molden, D.J., Eds. CABI Pub: Oxon, UK/Cambridge, MA, USA, 53–67.

United Nations, 2013. World Statistics Pocketbook Country Profile: Benin. http://unstats.un.org/unsd/pocketbook/PDF/2013/Benin.pdf/(accessed 15.07.2014).

United States Department of Agriculture (USDA), 2013. GAIN Report Benin. Washington D.C.

United States Department of Agriculture, 2014. Soil Texture Calculator. http://www.nrcs.usda.gov/wpa/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167/(accessed 06.04.2014).

Van Ranst, E., 1991. Land Evaluation, Part I: Principles in Land Evaluation and Crop Production Calculations. International Training Centre for Post Graduate Soil Scientists. State University, Gent, Belgium. 274.

Verheye, W., Koohafkan, P., and Nachtergaele, F., 2009. The FAO guidelines for land evaluation. Verheye, W. (Ed): Land Use, Land Cover and Soil Sciences. Encyclopedia of Life Support Systems. FAO. Rome.

Vörösmarty, C. J., Sahagian, D., 2000. Anthropogenic disturbance of the terrestrial water cycle. BioSci. 50,753–765.

Wagner, P.D., Kumar, S., Schneider, K., 2013. An assessment of land use change impacts on the water resources of the Mula and Mutha Rivers catchment upstream of Pune , India. Hydrol. Earth Syst. Sci. 17, 2233–2246. doi:10.5194/hess-17-2233-2013.

Winchell,M., Srinivasan, R., Di Luzio, M., Arnold, J., 2013. ArcSWAT interface for SWAT2012 user's guide. http://www.brc.tamus.edu/swat/ArcSWAT.html.

Windmeijer, P.N., Andriesse, W., 1993. Inland Valleys in West Africa: An Agro-Ecological Characterization of Rice-Growing Environments. International Institute for Land Reclamation and Improvement Publication 52, Wageningen. http://library.wur.nl/WebQuery/wurpubs/fulltext/73431.

WMO, 2008. Guide to Hydrological Practices Volume I : Hydrology – From Measurement to Hydrological Information. WMO-No. 168.

Worou, O.N., Gaiser, T., Saito, K., Goldbach, H., Ewert, F., 2012. Simulation of soil water dynamics and rice crop growth as affected by bunding and fertilizer application in inland valley systems of West Africa. Agric. Ecosyst. Environ. 162, 24–35. doi:10.1016/j.agee.2012.07.018.

Worou, O.N., Gaiser, T., Saito, K., Goldbach, H., Ewert, F., 2013. Spatial and temporal variation in yield of rainfed lowland rice in inland valley as affected by fertilizer application and bunding in North-West Benin. Agric. Water Manag. 126, 119–124.

WRB, 2006. A framework for international classification, correlation and communication. World Soil Resources Reports No. 103. FAO, Rome.

Yang, J., Reichert, P., Abbaspour, K.C., Yang, H., 2007. Hydrological modelling of the Chaohe basin in China: statistical model formulation and Bayesian inference. J. Hydrol. 340, 167–182.

Yitbarek, T., Kibret, K., Gebrekidan, H., Beyene, S., 2013. Physical land suitability evaluation for rainfed production of cotton, maize, upland rice and sorghum in Abobo Area, Western Ethiopia. American J. of Research Com. 1, 296–318.

Zhang, X., Srinivasan, R., Hao, F., 2007. Predicting hydrologic response to climate change in the Luohe river basin using the SWAT model. Trans. Am. Soc. Agric. Biol. Eng. 50(4), 901–910.