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

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ABSTRACT

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

1. Introduction

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

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

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

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

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

2. Materials and methods

2.1. Research area

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

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

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