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Research article

Hydrological responses to land degradation in the Northwest Benin Owena River Basin, Nigeria

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ABSTRACT

Adequate insights into how land degradation alters the hydrology of river basins will help forecast the hydrological impacts of land cover change dynamics, thereby providing unique information required for sustainable river basin management. This study attempts to utilize a multi-dimensional methodology involving the application of the physically based Soil and Water Assessment Tool (SWAT) hydrological model and Partial Least Square regression (PLSR) statistical model to evaluate the response of the hydrological components within the Northwest Benin Owena River Basin (NWBORB) in Nigeria to land degradation. Using the historic land cover maps of 1986, 2002, and 2015, covering the basin, the SWAT model was employed to simulate the hydrological components for each historic year. The PLSR model was utilized to establish a response relationship between land cover changes and hydrological component modification within the basin. Results showed that between 1986 and 2015, 18.56% of the forest was lost, with a major portion (16.19%) gained by plantation. Consequently, annual water yield and surface runoff increased by 18.28% and 17.26% respectively, while annual base flow and actual evapotranspiration decreased by 22.58% and 21.72% respectively. The reduction in forest is strongly correlated with an increase in plantation (−0.833), surface runoff component (−0.723) and water yield (−0.532). Also, expansion of plantation land is strongly correlated with surface runoff components (0.877) and negatively correlated with base flow component (−0.573). Variable Importance of the Projections (VIP) from the PLSR model showed forest (VIP = 1.23), Plantation land (VIP = 1.02) as the most important land cover variables altering the basins' local hydrology. The study clearly shows that forest preservation plays an important role in the regulation of water resources within a river basin. This methodology can be replicated for poorly gauged river basins provided the land cover maps and stream discharge data are available.

1. Introduction

An assessment of the impacts of land degradation as a result of anthropogenic land cover alteration on hydrology is crucial for sustainable river basin development and management (Ahiablame and Shakya, 2016). Land degradation, the gradual process of decline in forest biomass, species composition, and soil quality, alters the process of conversion of rainfall to runoff by modifying key hydrological components i.e. evapotranspiration, water yield, infiltration and surface runoff (Costa et al., 2003; Luo et al., 2016; Orewole et al., 2016; Ott and Uhlenbrook, 2004) within a river basin. However, as a result of the complex and dynamic interactions occurring between land cover alterations, climatic variables, and hydrological processes in a river basin, a more intimidating problem of quantifying these changes is presented (Yatheendradas et al., 2008).

Widely utilized methodologies for the assessment of land cover alteration on river basin hydrology includes paired catchments, hydrological modelling and multivariate statistics (Esterby, 1996; Khoi and Suetsugi, 2014; Watson et al., 2001). However, amongst these methodologies, the application of physically based hydrological models to the assessment of the impact of land degradation on hydrology is the most utilized. This is because of the capability of hydrological models to directly establish a relationship between model parameters and land surface properties (Legesse et al., 2003), and also unambiguously characterize the spatial variability inherent within these properties (Akbari and Singh, 2012; Wijesekara et al., 2012). A summary of the processes involved includes the examination of hydrological responses to land cover maps of different time scales, evaluation of the calculated basin-wide hydrological responses at different temporal scales, and a comparison of stream flow with land cover maps of different time scales

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(Ahmad et al., 2015; Cui et al., 2007; Gumindoga et al., 2014a, 2014b; Luo et al., 2016; Niraula et al., 2015; Olivera and DeFee, 2007; Rafiei Emam et al., 2017; Weng, 2014). In achieving these, several watershed models such as CLS (Todini and Wallis, 1977), Stanford modelling system (Crawford and Linsley, 1966), MIKE-SHE (Refsgaard, 1997), PRMS (Leavesley et al., 1983), HEC-HMS (Chu and Steinman, 2009), and (SWAT) (Arnold and Allen, 1996; Baker and Miller, 2013; Garg et al., 2017; Memarian et al., 2014; Neitsch et al., 2005; Öztürk et al., 2013; Uniyal et al., 2015) have been applied. Utilizing these models, several studies have attempted to investigate the hydrological response of basins to land degradation at different spatio-temporal scales (Ayeni et al., 2014; Garg et al., 2017; Hlásny et al., 2015; Kundu et al., 2017; Li et al., 2007; Ott and Uhlenbrook, 2004). However, these studies could not accurately identify and present the individual contributions of land degradation components (i.e. land cover classes) to the responses of different hydrological components within these basins. In the North West Benin Owena River Basin (NWBORB), relatively similar studies on the hydrology of the basin (Ayeni et al., 2014; Ikhile, 2007) neither considered the changes in land cover classes nor attempted to relate these changes to alterations in the hydrological components of the basin. According to Nie et al. (2011), studies without these information could lead to the overestimation, underestimation or misinterpretation of information on hydrological changes within the basin. Furthermore, no information exists about the hydrological response of the NWBORB to land degradation. To address to this knowledge gap, this study attempts to utilize the SWAT hydrological model and Partial Least Square Regression (PLSR) approach (Giri et al., 2016; Woldesenbet et al., 2017; Yan et al., 2013) to evaluate the responses of hydrological components to land degradation within the NWBORB. This would provide vital information on how simultaneous land cover changes as a result of land degradation influence hydrological components within the basin; whilst advancing the forecast of hydrological consequences of land cover changes, a requirement for sustainable river basin development and management. In view of these, the objectives of this study include the evaluation of the effect of land cover changes on the hydrology, and quantification of the changes in each land cover class to the key hydrological components within the NWBORB.

2. The study area

The study area of this research is the North-western part of the Benin Owena River Basin located in south-western Nigeria. Ecologically, the basin is a part of the tropical rainforest zone of Africa that strides the equator, and extends to 5° and 10° on either side (Fig. 1A). It lies within latitudes 6°52′10″N - 7°26′32″N and longitudes 4°50′0″E – 5°13′35″E, and covers an area of 1942.46 km^2. Major settlements within the basin include Erinjiyan Ekiti, Ilawe Ekiti, Ogotun, Igbara odo, Olori oko, Ikeji, Owena, Igbara oke, Ilara mokin, Ibule, Ipogun, Ibasoyin, Aponmu, amongst others (Fig. 1B).

This zone is characterized by tropical ever and semi-evergreen rainforest. The NWBORB falls within the tropical ever green category of this zone (Salami, 1999). Tall, lush, closely spaced diverse tree species with heights between 50 and 60 meters form a dense and extensive multi-layered forest canopy consisting of Iroko (*Milicia excelsa*), Kolanut (*Kola acuminata*), Palm-trees (*Elaeis guineensis*), and Cocoa trees (*Theobroma cacao*). Geologically, the basin is characterized by ancient crystalline basement rocks, with petrologic units consisting of migmatite-gneiss complex (undifferentiated granite gneiss and migmatite), the metasediments/meta-igneous rocks (Quartzite), and the pan African older granitoids (Charnockite, medium coarse grained biotite granite, fine grained biotite granite, and coarse porphyritic biotite/biotite hornblende granite) (Aladejana et al., 2016; Fagbohun, 2018; Fagbohun et al., 2017). The soil association within the basin (Fig. 1C) reveals a close correlation with the weathered parent basement rocks, thus making them a major determinant of the basin soil morphology (Smyth and Montgomery, 1962). It is drained mainly by the Owena River, a major source of water in the basin. This river is perennial, originating from three major tributaries with both dendritic and parallel drainage patterns flowing in the North-South direction. The first, second and third tributaries originate from distances and directions of 23.74 km, 109.40°; 14.92 km, 91.62°; and 23.20 km, 47.07° respectively from Ogotun village. The first and second tributaries join at about 2.06 km, 248.58° from Ogotun village while the third major tributary joins them at 5.79 km, 254.35° from Ogotun village, to flow southwards as a major river. The NWBORB falls under the Koppen A_f Wet Equatorial Rainforest climate (Smyth and Montgomery, 1962). This climatic condition is controlled by the influence of two major wind currents, the hot and dry one from the north east, and the warm and moist one is from the southwest. The interaction of these winds gives rise to the Inter-Tropical Convergence Zone. Subject to annual fluctuations, this interaction produces a wet and dry season over the basin area (Adedokun, 1978). Hence, a short dry season is experienced from November to March with an average temperature of 30 °C, while the wet season extends from April to October with an average temperature of 26 °C (Asseez, 1972). Furthermore, a mean total rainfall varying between 1382.87 and 1522.53 mm is occurs within the basin (Fig. 1D). At the peak of the rainy season, temperatures may fall to as low as 23 °C (Smyth and Montgomery, 1962). The land cover classes within the NWBORB include the native forest, plantation, built-up, rock outcrop and water body. Driven by rain-fed, subsistent agriculture, the major food crops planted by the locals include plantain (*Musaceae* spp.), yam (*Dioscorea* spp.), cassava (*Manihot* spp.), mango (*Mangifera indica*) and cashew (*Anacardium occidentale*). All of these make up the plantation cover class within the basin.

3. Methodology

The methodology employed in this study involves modelling to simulate the hydrological components for each land cover map of the NWBORB in three time steps (1986, 2002, and 2015), and the performance of PLSR analysis to evaluate the contribution of changes in land cover classes to hydrological components within the basin.

3.1. Modelling to simulate basin hydrological components

3.1.1. The Soil and Water Assessment Tool (SWAT)

The SWAT model was employed for the hydrologic modelling of the NWBORB. Being a distributed, continuous, daily time-step, and physically based hydrological model, it possesses the capacity to effectively characterize, evaluate and measure the key hydrological components (Arnold et al., 1998) at play within the NWBORB. The model operates on the basis of breaking down crucial elements of the river basin into smaller parts (basin to sub-basins to hydrological response units (HRUs)) based on similar properties (land cover, soil and slope), simulating the hydrological components for these elements, and re-aggregating them back to sub-basins. Majorly, these components include evapotranspiration (ET), surface run-off, percolation, lateral flow, groundwater flow (return flow), and transmission losses (Arnold et al., 1998).

These components are derived based on Eq. (1).

$$SW_t = SW_o + \sum_{i}^{t} (P_{day} - Q_{sur} - ET_p - W_{seep} - Q_{gw}) \tag{1}$$

SW_t and SW_0 = final and initial soil water content; P_{day} = precipitation; Q_{sur} = surface runoff, ET_P = evapotranspiration; W_{seep} = percolation; Q_{gw} = return flow (all measured in mm).

Surface runoff for the basin is derived through the adjustment of the SCS Curve Number (CN), and calculated from precipitation, land cover, and the antecedent soil moisture (USDA, 1986). According to (Lenhart et al., 2002), Eq. (2) enunciates the rainfall-runoff relationship