Catena 172 (2019) 324–334

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Spatio-temporal variation in rainfall-runoff erosivity due to climate change in the Lower Niger Basin, West Africa

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ARTICLE INFO

Keywords:
Rainfall-runoff erosivity
GCMs
RUSLE
Soil erosion
Niger-basin
Climate change

ABSTRACT

Spatio-temporal variation in rainfall-runoff erosivity resulting from changes in rainfall characteristics due to climate change has implications for soil and water conservation in developing countries. Understanding past and future variations in rainfall-runoff erosivity and its implication, in tropical areas where there are limited continuous daily rainfall records, is important. The present study attempted to (i) quantify the nature of spatio-temporal variability of erosivity from rainfall amount using Global Circulation Models (GCMs), and (ii) evaluate the implications of changes in rainfall-runoff erosivity in the Lower Niger Basin, West Africa. The GCMs scenarios (GFDLCM3, HADCM2, MIROC5, and MPIESMLR) were statistically downscaled using the delta method for three-time slices (the 2030s, 2050s, and 2070s). World climate data was used as the current baseline climate since it is the source of the future precipitation simulation. The R factor from the Revised Soil Loss Equation (RUSLE) was used to determine erosivity, while the RUSLE model was used to ascertain the implications of changes in erosivity. Observation data (1970–2013) from 20 meteorological stations were used to validate the erosivity model. The result indicates that there is an increasing trend in the annual rainfall-runoff erosivity from the baseline climate up to the GCMs, for all the GCMs, with an average change in rainfall-runoff erosivity of about 14.1%, 19%, and 24.2% for the 2030s, 2050s, and 2070s respectively. There was a concomitant increase in soil loss of 12.2%, 19.3% and 20.6% from the baseline for the 2030s, 2050s, and 2070s respectively. Though the combined average annual rainfall and erosivity show steady increases, some of the models (GFDLCM3-2.6 and HADCM2-2.6) reveal a likely decrease in annual rainfall and erosivity for the 2070s. Higher precipitation amounts were the major drivers of increasing spatial and temporal rainfall-runoff erosivity. More studies should be performed to include other important factors that exacerbate increases in erosivity, especially future changes in land use.

1. Introduction

Intense soil erosion arising from increasing rainfall-runoff erosivity is a critical issue in many basins around the globe (Angulo-Martínez and Beguería, 2012; Mondal et al., 2016; Vrieling et al., 2014). Rainfall-runoff erosivity relates to the climatic parameter of rainfall (Yang et al., 2003), and the powerful kinetic energy of falling raindrops often detach soil particles and transport them together with surface runoff. This phenomenon has been demonstrated by Wischmeir (1968) with a raindrops-particle detachment relationship proposed by Govers (1991) that became the most commonly used index for quantifying rainfall erosivity as presented in the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) or its revised-RUSLE (Renard, 1997). Erosivity does not have a linear relationship with soil erosion, as

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https://doi.org/10.1016/j.catena.2018.09.003
Received 12 October 2017; Received in revised form 17 August 2018; Accepted 2 September 2018

erosion largely depends on raindrops, rainfall intensity, and duration (Salles et al., 2002). High-magnitude rainstorm events have some degree of control over rainfall erosivity (González-Hidalgo et al., 2009) and may increase with high rainfall intensities. Doetterl et al. (2012) reported that rainfall erosivity together with slope gradient explains about 75% of soil erosion variability. These factors represent triggers for runoff and soil erosion due to changes in precipitation.

Climate change may determine the nature of rainfall through the alteration of trends and patterns in rainfall in sub-Saharan Africa (Serdeczny et al., 2017), especially in the Niger basin area (Badou et al., 2017; Oyerinde et al., 2015). The climatic parameter of rainfall has been used to detect trends in rainfall-runoff erosivity using past and future climatic data in many basins (Gupta and Kumar, 2017; Panagos et al., 2017) and also in various sub-basins of the Lower Niger Basin (Fagbohun et al., 2016; Salako, 2010; Salako et al., 1995). Quantifying the effects of past and future climate-induced rainfall-runoff erosivity is essential in identifying key areas prone to erosion under a changing climate in West Africa, especially in the lower Niger Basin.

The mean precipitation change over West Africa shows a less evident trend and mostly oscillates between −10 and 10% where changes in climate cause more precipitation variability with greater amplitudes (Sylla et al., 2016). According to (IPCC, 2013), the range of precipitation trend varies from negative to positive values (mostly between −30 and 30%), indicating that projected precipitation is highly uncertain over the region. This uncertainty increases correspondingly with Representative Concentration Pathways (RCPs) forcing with the highest one found in the Sahel area. From a spatial perspective, most of West Africa experiences no changes, and a significant precipitation decrease of about 5–40% prevails in the West Sahel for the RCP4.5 to RCP8.5 and the time period shifts from 2036–2065 to 2071–2100 (Sylla et al., 2016). It fluctuates, and further experiences increase below the West Sahelian zone. These precipitation characteristics are controlled by the migration of a tropical frontal system, the Inter-Tropical Convergence Zone (ITCZ), a band of clouds over the tropics formed by the convergence of humid southeast trade winds and the dry Northeast tradewinds (Oyerinde et al., 2016).

The use of GCMs has revealed that changes in rainfall patterns will impact soil erosion through several pathways, including changes in rainfall-runoff erosivity (Plangoen et al., 2013). Several studies have investigated, in isolation, changes in erosivity (Almagro et al., 2017; Plangoen and Babel, 2014), and a combined study of erosivity and soil erosion (Maeda et al., 2010; Segura et al., 2014) in different parts of the world using GCMs. Changes in erosivity have been directly linked to climate change effects on soil erosion (Nearing, 2001) because erosivity rates are expected to change in response to climate change.

Globally, rainfall patterns vary in time and space with expected increases in rainfall amounts in the tropics and subtropics. Separate researches by Salako et al. (1995) and Fagbohun et al. (2016) have shown that the tropical climate like the lower Niger basin, with its high rainfall intensity, has the highest mean erosivity. Vrieling et al. (2014) have evaluated the importance of the spatial and temporal variability of rainfall erosivity across Africa using the *R* factor in the RUSLE. The power with which soil particles are detached and carried by rain can be determined by changes in erosivity due to increased rainfall. Since a relationship has been established between rainfall characteristics and erosivity, an understanding of the spatiotemporal variability of rainfall erosivity is important. Thus, it is of significance to decipher whether the decreasing or increasing trend in rainfall amounts (climate change), for past and future climates in the Lower Niger Basin (LNB), will have any implication for rainfall erosivity.

Climate change is expected to impact erosivity in the LNB and other parts of the world. Temporal and spatial prediction of future rainfall-runoff erosivity under a changing climate has not been well documented in the LNB. The evaluation of rainfall erosivity and its implications can help practitioners and scientists to formulate better soil conservation practices and improve dam construction and agricultural management. The outcome of this kind of research is generic and may reflect the kind of changes to be expected in other parts of the globe (e.g., the tropics and subtropics) and not necessarily confined to the study area. Therefore, the objectives of this study were to (i) quantify the nature of spatial and temporal variability of erosivity from rainfall amount using World climate data[1] and predicted rainfall from different GCMs (GFDLCM3, HADCM2, MIROC5, and MPIESMLR) for RCP 2.6 and 8.5 scenarios respectively, and (ii) evaluate the implications of changes in rainfall-runoff erosivity using RUSLE.

2. Site description

With a length of 4200 km, the Niger Basin houses the third longest river in Africa—the River Niger. It stretches from the mountains of Guinea through the Sahara Desert to the Gulf of Guinea, and is located between Longitude 11°30′ W and 15° 00′ E and Latitude 22°00′ N and 5°00′ N. The basin occupies areas with different climatic characteristics and is divided into four sub-basins based on differing hydrological and topographical features: the Upper, the Central Delta, the Middle and the Lower Niger Basins. The present research concentrates on the Lower Niger Basins. It covers about 528,000 km^2: 81% in Nigeria, 12% in Cameroon and 7% in the Benin Republic. The basin is located in different ecological zones, passing through the Savannas (Sudan, Guinea, Derived), to the Humid forest and then the Freshwater forest, where the river flows into the Atlantic Ocean via a deltaic mouth. Rainfall varies spatially (Fig. 1a) within the basin with mean annual rainfall decreasing from south to north averaging 750 mm to over 2000 mm. Temperature is generally hot all-year-round, ranging from 25 °C to 32 °C, and the mean annual temperature range increases from 2.5 °C in the south of the basin, along the coast, to nearly 10 °C in the north, at the fringes of the Sahara Desert. Agriculture is the main source of livelihood, and it is predominantly rain-fed.

3. Materials and methods

3.1. Global climate data

Compared to the CMIP3, the CMIP5 is a significant model improvement and utilises a new set of emission scenarios referred to as RCPs. Global climate data from 4 GCMs (Table 1) under the RCP2.6 and RCP8.5 scenarios were used (Taylor et al., 2012) in this study. The GCMs were selected because of their (a) relative independence and good performance in precipitation simulation (Yan et al., 2015); (b) representativeness of the broader range of models and (c) satisfactory performance for the African continent (McSweeney et al., 2015). In the evaluation of future changes in rainfall erosivity and possible implications, projected climate data (precipitation), for the 2030s (2020–2039), 2050s (2040–2069), and 2070s (2060–2099) were obtained from the Climate Change Agriculture and Food Security (CCAFS)[2] portal. The data were statistically downscaled to a 30 arc-second (1 km^2) horizontal resolution using the delta method (Ramirez-Villegas and Jarvis, 2010). The delta data, with respect to the baseline climate, WorldClim 2.0, were used to derive daily and monthly precipitation. Anomalies were then interpolated using a thin plate spline interpolation technique (Ramirez-Villegas and Jarvis, 2010). These datasets, for monthly precipitation, were used as input data for this research.

3.2. Changes in rainfall-runoff erosivity

To better understand the implications of changes in the rainfall-runoff erosivity, the *R* factor from the Revised Universal Soil Loss

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[1] World Climate data, http://worldclim.org/version2, Accessed July 2017.

[2] GCMs, http://www.ccafs-climate.org/data/, Accessed July 2017.