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Soil erosion risk associated with climate change at Mantaro River basin, Peruvian Andes

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ABSTRACT

Soil degradation by water erosion has been accelerated by human activities. This process is aggravated in the Andes region due to steep slopes, sparse vegetation cover, and sporadic but high intensity rainfall, which together with a shallow soil depth, increases soil erosion risk. The objective of this study was to analyze the soil erosion risk, associated with A1B climate change scenario over the twenty-first century, for the Mantaro River basin (MRB), Peruvian Andes. The temporal analyses revealed maintenance of current soil erosion risk along the twenty-first century in almost all the MRB, whose current risk is either "very severe" or "extremely severe". At the sub-basin level, for those located in the center and northern MRB, progressive increases were observed in the average erosion rate by the end of this century, increasing the soil erosion risk. In sub-basins under greater influence of the Andes, this risk was classified as "moderate" and remained this way throughout the century, despite the increase in rainfall erosive potential simulated for these. In annual terms, there was a significant trend of decreasing rainfall erosivity and increasing the concentration of rainfall simulated based on A1B climate change scenario. Because the A1B scenario affects rainfall erosivity mainly during the rainy season, this causes a risk to the environmental sustainability and future agricultural activities.

1. Introduction

According to the German Council on Global Change (WBGU, 1994), water erosion, is the most important type of soil degradation worldwide, covering approximately 1.1 billion hectares (56% of the agricultural areas of the world). In addition, the international scientific community recognizes that soil erosion is a serious environmental problem; however, it is difficult to determine its magnitude as well as the economic and environmental consequences, especially under possible future climate changes.

According to Benites et al. (1993), soil erosion in Argentina, Bolivia, Brazil, Chile, and Paraguay is responsible for an average of 46% of the total extent of degraded soils by different erosion agents. According to the Agricultural Land Development Agency of Japan (JALDA, 2003), agricultural productivity in South America has been decreased due to soil erosion, which has been accelerating the degradation of natural resources in this region. The population of South America does not exceed 10% of the world population, but according to FAO/UNESCO (1990), it is one of the richest regions in terms of natural resources, possessing 14% of arable land, 46% of tropical forests, 31% of water resources, and 50% of flora and fauna, worldwide.

"The Andes Cordillera" is located in the western South America, consisting of rugged mountains and very steep relief plateaus. The "Inter-Andean Valleys" are located among these mountains where agricultural activity has been concentrated. Water erosion in these areas has become a complex problem causing decrease on topsoil fertility. The present study was conducted at Mantaro River basin, one of the most productive Peruvian "Inter-Andean Valley" zones. According to the Geophysical Institute of Peru (IGP, 2005), the Mantaro River is considered one of the most important rivers of the Peruvian Andes, due to its capacity for electricity generation, and agricultural and livestock production.

According to Amézquita et al. (1998), Peru is one of the Andean countries that have presented various problems associated with erosion, wherein the first attempt to assess its occurrence was done by Morales et al. (1977). Since then, there were the studies from Alegre et al. (1990) to Romero (2005); however, there has been a scarcity of research aimed at evaluating the character of soil erosion in the country.

Accelerated climate change has been recorded in recent decades. According to the IPCC (2013), the last three decades have been

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successively warmer regarding the average global surface temperature. The increase on temperature has been verified across the planet and has been greatest at higher latitudes of the Northern Hemisphere. This warming trend from 1956 to 2005 (0.13 [0.10–0.16] °C per decade) is nearly twice that presented in the last 100 years (1906–2005). This indicates a clear temperature increase trend in recent decades, with 2014 claiming to be the warmest year since weather records began.

Climate changes are causing more warming at more elevated regions than at the lower ones due to snow cover loss, which leads to a reduction in albedo and increase in solar radiation absorption at the surface (Giorgi et al., 1997). Thus, according to Bradley et al. (2006) and Ramirez et al. (2001), several modeling and projections studies indicate that many glaciers in lower altitudes of the Andes can disappear completely in the next 20 years, with the 0 °C point displacement to higher altitudes. This situation places Peru in a highly vulnerable condition, considering that 70% of the tropical mountain glaciers in the world are located in Peru.

The Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith (1978), was a pioneer model in an attempt to predict soil erosion, to produce soil erosion risk mapping, and for supporting soil conservation practices. Despite the empirical structure used in this model and in its revised version (RUSLE), the model has been applied to basins or regions that have database restrictions for calibration and validation with other models which are process based type (Beskow et al., 2009; Oliveira et al., 2014; Durães and Mello, 2014; Li et al., 2014; Tang et al., 2015).

The RUSLE model contains significant improvements in the estimation of the passive factors associated with soil erosion, especially the topographic factor, and has been applied to study the climate change impacts on soil erosion (Segura et al., 2014; Mello et al., 2015). RUSLE is a parametric and empirical model, based on the most relevant variables for the water erosion process (Renard and Freimund, 1994). This model has been already tested and validated in various soil, climate, and agronomic management conditions (Mitasova et al., 1996; Tiwari et al., 2000; Amore et al., 2004; Beskow et al., 2009; Segura et al., 2014; Li et al., 2014; Oliveira et al., 2014; Tang et al., 2015; Ochoa et al., 2016). Most of these studies have shown reasonable performance in the qualitative characterization of the soil erosion risk, especially when it is integrated into a Geographic Information System (GIS), enabling consistent improvements in its performance. Despite of limitations with RUSLE, it is possible to highlight a methodological evolution associated with the topographic factor estimates and the use of a map algebra tool to overlay the layers of the equation factors (Lu et al., 2004; Zhou et al., 2008; Kouli et al., 2009; Beskow et al., 2009; Parveen and Kumar, 2012; Rodriguez and Suarez, 2012; Segura et al., 2014; Tang et al., 2015).

This study aims at offering unique contribution to Mantaro river basin, a typical basin located in the tropical Andes, whose glaciers are highly vulnerable to climate change. The basin is part of the headwaters of the largest river basin in the world, the Amazon River. Despite the difficulty recognized with some databases due to the lack of minimally investigative studies or hydro-climatic monitoring, the results of this study have significant potential to motivate further studies and to alert on the water erosion problem linked to climate change in one of the most sensitive regions of the world from both environmental and socio-economic points of view.

It is understood that the capacity of rain to generate erosion is the main factor affected by climate change, and its simulation shows a reasonable degree of acceptance (Nearing, 2001; Segura et al., 2014; Mello et al., 2015). In this context, the objective of this study was to assess the soil erosion risk, at the Mantaro river basin located in the Peruvian Andes.

2. Material and methods

2.1. General characteristics of the Mantaro River basin, Peruvian Andes

The Mantaro River basin (MRB) is located in central Peru, between the latitudes 10°34′30″S and 13°35′30″S and longitudes 73°55′00″W and 76°40′30″W, with most of its area included into the Peruvian Tropical Andes, making up part of the Amazon River basin (Fig. 1a). MRB has a total area of 34,544 km^2 and has the highest population density of the "Sierra of Peru" (IGP, 2005). The Mantaro River is of great importance for the country as it produces 35% of all electric energy as well as its potential for agricultural and livestock production.

In geomorphological terms, MRB is divided into agro-ecological regions, according to IGP (2005), whose names have origin in the Inca's language Quechua: "Janca" ("white" in reference to the permanent ice on the mountains), "Puna" ("evil that comes from the mountain"), "Suni" ("wide land"), "Quechua" ("temperate climate land"), "Yunga" ("hot valley") and "Selva Alta" ("high forest") (Fig. 1d). Throughout the text, we have chosen to use the names from the original Quechua language to avoid misunderstanding about their meanings. In addition to this agro-ecological division, MRB can also be divided into sub-basins, as shown in Fig. 1c. The analyses of the results will be presented on both spatial scales, agro-ecological regions and sub-basins, since different impacts may be caused given the different altitude conditions existing in MRB.

Correa (2015) described MRB as part of the Amazon River basin, whose main spring is in Lake Junín. The first river section flows from Lake Junín up to the "Pongo de Pahuanca". The second section flows from "Pongo de Pahuanca" to the mouth in the Apurimac River, forming the Ene River. In this section, we have the main Peruvian hydroelectric facilities ("Santiago Antunez Mayolo" and "Restitución"), known as the "Mantaro Complex".

2.2. Revised Universal Soil Loss Equation (RUSLE)

The Universal Soil Loss Equation (USLE) is an empirical model to predict the average annual soil loss generated by rainfall impact and shallow flow runoff. According to Farrish et al. (1993), the application of this equation in steep slope areas has limitations. According to Hoyos (2005); Durães and Mello (2014), Oliveira et al. (2014) and Mello et al. (2016) the RUSLE is a more suitable model for watersheds than USLE by providing fundamental revisions to characterize the LS topographic factor. Thus, the main advantage is related to adjust the topographic factor for various slope conditions, considering the contribution from upstream to downstream areas by means of a flow accumulation map.

The RUSLE is based on USLE equation, with reformulation of the topographic factor estimates according to Renard et al. (1997):

$$A = R \cdot K \cdot LS \cdot C \cdot P \quad (1)$$

where: A is the average annual soil loss ($t\ ha^{-1}\ yr^{-1}$), R is the average annual rainfall erosivity ($MJ\ mm\ ha^{-1}\ h^{-1}\ yr^{-1}$), K is the soil erodibility factor ($t\ h\ MJ^{-1}\ mm^{-1}$), LS corresponds to the dimensionless factors associated with slope-length and slope-steepness, respectively, C and P are factors of vegetation cover and soil conservation practices, both dimensionless.

The soil erosion risk was classified according to the criteria adopted by Li et al. (2014) and Tang et al. (2015), which is shown in Table 1.

2.3. Rainfall erosivity behavior over the twenty-first century at the Mantaro River basin, Peruvian Andes

In order to calculate rainfall erosivity (R-factor), precipitation data were simulated with a temporal resolution of 3 h and the average monthly rainfall were used, in a grid with a spatial resolution of 20 km covering the entire MRB, a total of 420 points (Fig. 1c). These datasets comprise the downscaling to 20-km resolution from the global HadCM3 A1B emission scenario. This is a dynamical downscaling done by the regional climate Eta-CPTEC model over South America (Chou et al., 2014) for the period of 1961–1990, considered as "present climate", and for the periods of 2011–2040, 2041–2070 and 2071–2099, known