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Stochastic soil erosion risk modelling and simulation using Fournier Index

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ABSTRACT

Approximately 280 million tons of cereal crop is lost from 108 million hectares of croplands through soil erosion. This study aimed to (i) monitor soil erosion hazard over 48 year- long precipitation time series, (ii) determine if changes exist for informed decision making and (iii) provide management stakeholders with relevant and scientifically sound information for effective proactive disaster management. Fourier index data was computed annually, and for four seasons; spring, summer, autumn and winter, for the years 1967 to 2014. Each series was fitted to a suitable distribution and then, based on the fitted distributions, marginal probabilities were computed according Fournier index categories: <20, 20-40, 40-60, 60-80, 80-100 and >100. After some exploratory analyses trying out various distributions, the following distributions were fitted to the data: Gumbel, three-parameter Weibull and three- parameter log-normal. Q-Q plots were generated to assess the fit of the various distributions. Overall, the three-parameter log-normal distribution provided at least a reasonably good fit to all five data sets. In order to have a model (distribution) that fits reasonably well to all five data sets (rather than fitting possibly different distributions to the five data sets), and to have a model with a reasonably simple functional form, the three-parameter log-normal distribution was chosen. Based on the fitted three-parameter log-normal distributions the required probabilities were calculated. The greatest soil loss was detected in summer and autumn with 89% and 66% respectively. However, no significant loss of soil was found on annual basis.

Key words: *Disaster, Hazard, Statistical modelling, Environmental degradation risk, Fournier Index*

Introduction

Soil erosion is one of the most extensive forms of land degradation and adversely impacts on soil nutrients and increases desertification in semi-arid regions. Other impacts of this environmental hazard span agricultural sector production and contamination and quality of water resources (Mahamane, 2015). About 50% of the world's topsoil is estimated to have been eroded in the last 150 years. This phenomenon has resulted in; (i) longer ecosystem recovery time, (ii) loss of top soil and soil fertility, reduced native plants species, (iii) increased risks of flooding, (iv) negative impacts on aquatic ecosystems and species and (v)increased risk of desertification (Greentumble, 2016; UNEP, 2006). Soil erosion has become one of the most critical environmental hazards that have accelerated land degradation of modern time which in turn has left about 20 million hectares of land unproductive and uneconomic (Jackowski, n.d). Soil erosion is recently increasingly recognised as an environmental hazard that threatens ecosystems and food security especially in the mountain areas where community's livelihood depends on agriculture (Prasannakumar *et al.*, 2012). Water is the main cause of this phenom-

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enon across the globe and has attracted many scholars now and during the past century (Wei *et al*. 2010). These authors also assert that severe soil erosion deteriorate soil fertility, reduce soil water holding capacity, adversely affect biodiversity, increased eutrophication and lead to increased land degradation. Given the increase of human impact on environment, more especially in the form of agricultural intensification and varying changes in climate, there is a need to continually assess and monitor soil erosion (Le Roux and Sumner, 2013). Communities whose livelihood depends on rain-fed agriculture are at risks of soil erosion, which fails sustain crop production due to loss in its fertility. Some of the negative effects of climate change include increased droughts and floods in frequencies and intensities. On 22 December 2015, Lesotho was faced with vast climate change variability which resulted in the country being declared in drought disaster (MESA, 2015). The country appealed for help from international community. Due that same drought disaster, one in four people in Lesotho are faced food insecurity risks which are estimated to go throughout 2016. Currently over 377 000 people are in need of food and cash for livelihood due to the prevailing drought conditions (FAO, 2016). However, most agriculturally important part of Lesotho is the northwest with its favourable soil and climatic conditions (Moeketsi and Tongwane, 2014; Trillo-Figueroa, 2009). This region, particularly Leribe has the highest population of all districts in the country whose lives depend on income from agriculture, livestock production, manufacturing and remittances from migrant labour sources, which are the mainstay of the district's economy (Trillo-Figueroa, 2009). This implies that when this agriculturally economic area is affected, the whole country's economy and community are actually negatively affected. Of the many key drivers of land degradation, is lack appropriate policies. However, effective policies making requires well-articulated information gathering about a hazard in question (Vagena *et al.* 2015). An effective land management decision aimed at reduced negative impacts of soil erosion significantly depends on detailed information gathered with scientific methods (Zhang *et al*. 1998). Hlalele (2016a).

Asserts that most African countries manage their disasters reactively with little or no policies put in place. In order for such decisions to be made, research on modelling of such disasters must be conducted. Given the current drought disaster conditions in Lesotho, it is imperative that efforts are not focused on drought alone, but to also other climate related risks which may just follow after the current drought. This will ensure proactive measures to be taken way before other cascading risks evolve. The present study therefore proposes a proactive move to be taken against possible soil erosion risks that may just after the current drought disaster, through an assessment of soil erosion risk using Fournier index. Environmental monitoring is essential for properly managing our natural resources. This monitoring provides all authorities and relevant stakeholders with scientifically-based, quantitative information that enables them to make environmentally sound, informed planning decisions and to set appropriate goals for environmental management and rehabilitation given the current rapid climate change conditions. This is however in response to information gaps and needs identified by (LVAC, 2012) where there was lack of monitoring of drought and climate change condition in Lesotho.

Soil erosion effects

Soil erosion risks by water are some of the major environmental challenges in Africa, particularly in the developing countries that regenerate both physical and socio-economic implications (Kefi and Yoshino, 2010). The loss of natural nutrients and possible fertilizers directly affect crop emergence, growth, and yield. Seeds can be disturbed or removed and pesticides can be carried off. The soil quality, structure, stability, and texture are also affected, which in turn affect the holding capacity of the soil (Nkonya, 1999; GEI Works, 2016). This phenomenon has been identified as a major environmental hazard in the world, threatening plants and animal sustainability. Similarly, South-Eastern parts of Nigeria suffer from the same detrimental effects of soil erosion risks (Abegunde *et al*., 2006). If poorly managed, soil leads to erosions and land degradations to have adverse impacts on man and environment (Tellest *et al*., 2013; Hlalele, 2016b). Lesotho is not an exception in soil erosion risks with her fragile ecosystems due to mountainous topography. The rain patterns have become very erratic and unpredictable with heavy short-duration downpours that results in massive soil movement (Ministry of forestry, range and soil conservation (Belle and Hlalele, 2015). The primary agent to soil erosion risks in Lesotho is rainwater induced gullies and sheet erosion. The main cause being poor management of the land over-cultivation and overgrazing by domestic animals (Ministry of forestry, range and soil conservation, 2015).

Solutions to soil erosion

Soil erosion is a major source of Earth's natural resource depletion leaving soils vulnerable to rainfall erosion risks (Hlalele *et al*, 2016) Rainfall is the most important natural condition to consider in soil erosion risks. However, these risks can be significantly mitigated through conservation practices to prevent the remaining vegetation cover from being eroded. Sustainable cultivation strategies also reduce soil erosion problems, these can include, no tillage practices which save residue, mulch and organic matter from the past growing seasons (Happ, 2014). Alberta department of Agriculture and Forestry (2016) concur with the above mentioned strategies and add the following strategies to control severe soil erosion; (i) Cross- section of a typical grassed waterway, (ii) Lined channels, (iii) Drop structures, (iv) Terracing, (v) Cross-section of one type of terrace and (vi) Grassed waterways. Figure 1 below shows severe soil erosion prevention strategies in the order given running horizontally from left.

According to Coetzee and Stroebel (2011) some of the cost effective strategies to prevent soil erosion and rehabilitate eroded areas are; (i) Hollows or pits, (ii) Erosion control Fences, (iii) Treating footpaths, (iv)Re-shaping donga systems, and (v) Using stone gabions. The above mentioned strategies are cost effective and require cheap and readily available materials. Hollows require only mulch and seed. The fences can be made using scrap wire and wire netting and old rusty and bent iron fencing standards cut up into short sections. It would not be cost-effective to purchase new standards, wire and wire netting material. The reshaping treatments require jute geotextile (Soilsaver) and mulch. The Soil saver is pinned to the ground, by hammering sharpened sections of old wooden fencing droppers into the material.

Study area description

Lesotho is small land surrounded fully by the Republic of South Africa with an average 30, 000 km2(Lesotho Meteorological Services, 2013: OnTheWorldMap, 2016). This land locked country consists of ten administrative districts. Leribe is one the ten administrative districts of this country that lays in the north eastern parts and covers three ecological zones namely, lowlands, foothills and mountains (Trillo-Figueroa, 2009: OnTheWorldMap, 2016). This district covers about 9.32% of the country's surface area with total estimated population of 298,352. Approximately 17% of this district arable land has severely shrunk due heavy soil ero-

Fig. 1. Severe soil erosion prevention strategies

Source: Alberta department of Agriculture and Forestry, 2016.

sion and land degradation(Trillo-Figueroa, 2009). Leribe is considered one of the major agricultural production areas in the country due to its fertile soils and large arable area. The majority of the communities in this district are dependent on subsistence agriculture and livestock for livelihood production. On the contrary, Leribe is faced with challenges of high unemployment rate, low levels of income, severe soil erosion and land degradation that restrain potential agricultural production. The map below as shown in Figure 2 shows the study areasand its position in Lesotho within African continent.

Fig. 2. Lesotho showing study area location-(Leribe)
Source: On The World Map, 2016

Methodology

Data processing and quality control

All gaps identified in the data set were filled with Expectation Maximum (EM) using IBM SPSS V.24. A non-parametric Cochran's Q test for outliers was used in the precipitation totals to depict outliers that would influence time series analysis. All the detected outliers were removed and gaps estimated back from Expectation Maximum using SPSS v. 24.

Methods and Materials

A 48 year long precipitation time series data was collected over Leribe district provided by Lesotho Metrological Services in Maseru. Fournier index was calculated on two time steps, annual and seasonal. Each of the four series was subjected to a homoscedasticity.Homoscedasticity is a term used in defining examining variance disturbance over the time series. If residuals are homoscedastic, their variances are stable (Huang *et al.* 2015: Kanaya, 2011). For this reason, a non-parametric Pettitt's test for homoscedasticity was deployed to determine if all four (annual, winter, autumn, summer and spring) time series were mean-variance invariant over time. Non variance-stable time series imposes negative influences on the behavioural properties of the time series as well as spurious regressions (Anon, 2016). All series were then fitted to suitable probability distribution functions.Marginal probabilities were then computed according to Fournier index classification to identify the mostly likely class over the study region. To further extract further information from the two time step series, a Mann-Kendal's trend test was applied to determine which of the series had a statistically significant trend.

The following equation was used to compute Fournier index (Climatic index);

$$Cp = P2max/P \quad .. (1)$$

Where;

Cp is the Fournier index

P is the total annual/seasonal precipitation (mm) and

Pmax is the rainfall amount in the wettest month/season

Table 1 below shows classes of rainfall erosion risk based on Fournier index (Cp)

Limitations and delimitations of the study

According to Hassan (2011) soil erosion risks are constituted by a number of factors. These are included in a Universal Soil Loss Erosion (USLE) as;

$$A = R.K.L.S.C.P \quad .. (2)$$

Where **A** is the average annual soil loss (Mg ha^{-1} yr^{-1})

R is the rainfall erosivity index

K is the soil erodibility factor

L is the slope length factor

S is the slope gradient factor

C is the vegetation protection cover and

P is the conservation protection factor

All the above factors are considered in the soil loss equation computation. However, due to the major contribution made by rainfall in soil erosion, especially in the mountainous areas, the study considered this factor only which possesses a limitation.

Results and Discussion

Table 2 above shows homogeneity test results

Table 1. Rainfall erosion risk classification based on Fournier index

Class no.	Fournier index (Cp)	Soil loss (tons/ha/yr	Soil erosion risk
1	<20	<5	Very low
2	21-40	5-12	Low
3	41-60	12-50	Moderate
4	61-80	50-100	Severe
5	81-100	100-200	Very severe
6	>100	>200	Extremely severe

Source: Hassan, 2011

Table 2. Homogeneity test results (Pettitt's test)

Pettitt's test resulst	Time step				
	Annual	winter	spring	Summer	Autumn
p-value (two tailed)	0.722	0.124	0.857	0.192	0,232
Risk of rejection	72.17%	12.37%	85.7%	19.24	23.2%
Homogeneity results	homogeneous	homogeneous	homogeneous	homogeneous	homogeneous

(Pettitt's test) obtained using XLSTAT. The annual and spring time series showed to be more homogeneous than all other times. However, the most important results were that in all time steps, the series results were homogeneous indicating that no spurious regression results would be expected in the further analysis.

Mann-Kendall's trend results

No trend pattern was detected in the annual time step series, an alternative hypothesis that a trend existed was rejected at a p-value of 0.441. No trends patterns were found in all seasons. The null hypothesis that there is no trend in the time series was accepted at the following p-values; Winter (p-value = 0.169), Spring (p-value = 0.72.7), Summer (p=value = 0.419) and Autumn (p-value = 0,463).

Data fitting

All the five data sets were fitted with SAS software. Figure 3 depicts the Q-Q plots for the final fitted lognormal distributions for all the five data sets.

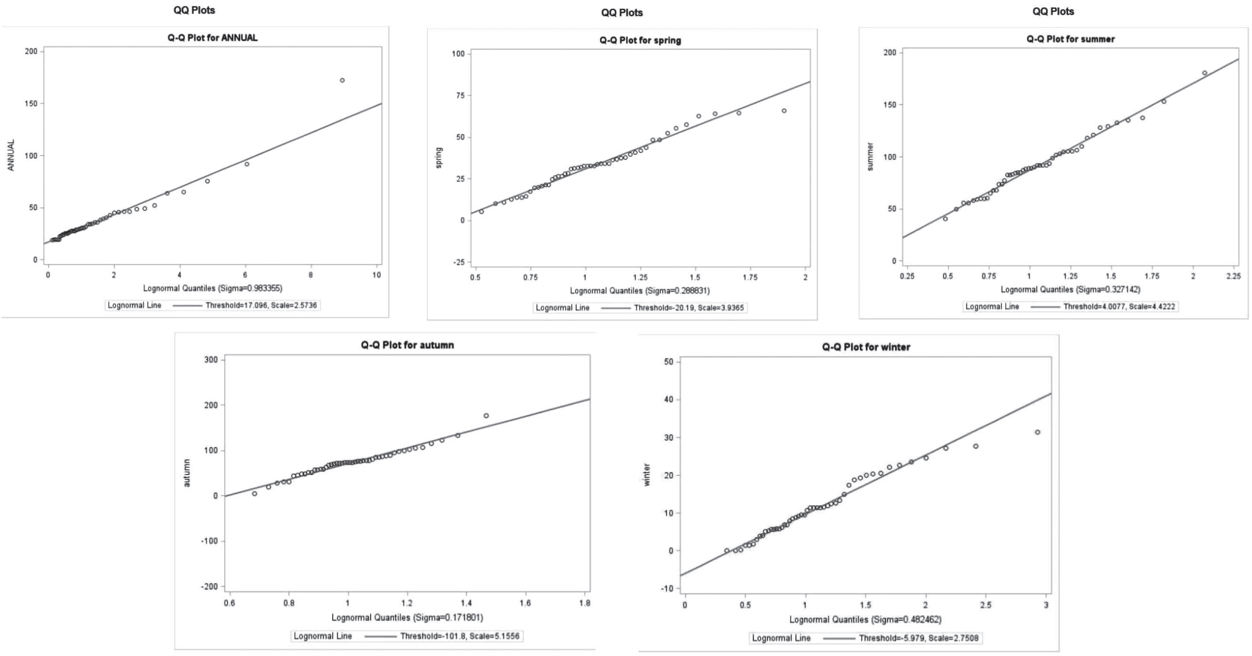

Fig. 3. Q-Q plots

Table 3. Estimated probabilities according to Fournier Index classification

Season	Theta	Zeta	Sigma	<20	20<Cp<40	40<Cp<60	60<Cp<80	80<Cp<100	>100	P(Cp>61)
Annual	17,096	2,57363	0,98336	0,06265	65,20%	17,13%	5,86%	2,50%	3,04%	11%
Spring	-20,189	3,93651	0,28883	0,20017	51,12%	22,82%	5,04%	0,86%	0,16%	6%
Summer	4,008	4,42216	0,32714	0	0,52%	10,73%	27,73%	27,82%	33,20%	89%
Autumn	-101,784	5,15562	0,1718	0,01985	10,08%	22,26%	26,50%	20,30%	18,88%	66%
Winter	-5,979	2,75078	0,48246	0,85311	13,41%	1,13%	0,12%	0,02%	0,00%	0%

Table 3 shows estimated probabilities calculated according to Fournier index classification. Starting from the severe Fournier index level, the annual time series result in lower soil loss. The greatest soil loss is attributed by summer autumn seasons.

Conclusion

Over 80% of the population of Lesotho's livelihood is dependent on rain-fed agriculture (Belle and Hlalele, 2015). Leribe district is one the most productive areas in the country with fertile soils. It is therefore important areas like this to be protected against risks of soil erosion that impact adversely on the country's food security. The current study has provided the authorities with solid scientific information upon which they can base the interventional strategies to curb soil erosion risks. Soil erosion in this area is not seen on annual basis but significant in summer and autumn temporal scales.

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