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Estimation of soil erosion using USLE and GIS in Awassa Catchment, Rift valley, Central Ethiopia

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ABSTRACT

In central part of the Main Ethiopian Rift, population increase is forcing farmers to expand their land by clearing forests, bushes and scrubs for crop cultivation, construction purposes and for fuel as energy source. Thus, loss of agricultural lands is increasing in the catchment. Therefore, estimation of soil erosion in Awassa catchment, Ethiopia is very important to make sound environmental management strategies and land use planning. In this context, Universal Soil Loss Equation (USLE) has been adopted to estimate soil erosion for sheet, rill and inter-rill. All these thematic layers were prepared in a Geographical Information System (GIS) using various data sources and data preparation methods. The soil erosion map was prepared by GIS layers over lapping method which ultimately estimated soil erosion rate of study area. The study revealed that 97% of the study area is characterized by 0–10 t ha^{-1} year^{-1} soil erosion rate, whereas 3% of the study area is characterized by 10–202 t ha^{-1} year^{-1} soil erosion rates. When estimated for soil erosion, it was found that out of the whole catchment, 30 km^2 was under high to extremely high soil erosion rate (91–202 t ha^{-1} year^{-1}). The outcome of research also showed that the study areas having six ordinal classes of soil erosion risk zone, e. g., extremely high risk (91–202), extreme risk (55–91), very high risk (30–55), high risk (10 — 30), moderate risk (5–10) and low risk (0–5) with corresponding percentage of area falling, 0.18, 0.26, 0.43, 1.62, 2.68, and 94.83, respectively. From the level of soil tolerance limits, it appears that the amount of soil loss is tolerable at its current situation.

1. Introduction

Soil erosion assessment has gained attention because it can be used as a base for developing effective soil and water conservation plans. In this regard, there has not been a locally developed soil erosion model for erosion risk assessment in Ethiopia. Soil erosion is the major form of land degradation in Ethiopia (Hurni, 1993). El-Swaify and Hurni (1996) found Ethiopia to be among the most degraded lands in Africa. According to FAO (1986) average annual soil loss is about 2 billion tons of the whole country; of which about 10% crosses the national boundary. Considering the redeposit, soil loss on crop lands is close to 100 t ha^{-1} year^{-1}. Another study by Hurni (1993) estimated the average soil removal to be around 1493 million tons per annum. An earlier study estimated erosion rates of 42 t ha^{-1} year^{-1} from cultivated land, whereas soil regeneration rate estimated was 3–7 t ha^{-1} year^{-1} (Hurni, 1988). Hurni (1993) on these bases, predicted the loss of 0.5 million ha of cropland and 5.7 million ha of pastures in near future.

The studies conducted by Ethiopian Highland Reclamation, showed that over 14 million ha in the highland were seriously eroded and 1900 million tons of soil were annually eroded from the highlands, which is equivalent to an average net soil loss of 100 tons ha^{-1} varying between 50 and 170 tons ha^{-1}. The Highlands Reclamation Study also estimated that erosion would result in a reduction of crop production by 2.6 million tons in near future; Sutcliff (1993) also predicted similar trends. Other observation showed that soil erosion lead to productivity loss of 1 to 2% per annum (Hurni, 1993). Use of crop residues and dung for fuel production has contributed to biological degradation of soil. This in itself further increased the decline of agricultural productivity by 1% per annum. Land degradation due to soil erosion is in fact overwhelming and affects many facets of life. In order to address the problem of land degradation three steps are needed: (i) assessment, (ii) monitoring, and (iii) implementation of mitigating technologies (Mati and Veihe, 2001) However, the effectiveness of any measure to prevent land degradation is influenced by the type and quality of information.

Soil erosion problem in Ethiopia, is more severe due to steep topography, overgrazing and its long cultivation history coupled with outdated technology (Nyssen et al., 2004), formation of gullies (Nyssen et al., 2006), nutrient loss by way of runoff and sedimentation (Haregeweyn et al., 2006, 2008). Recently large number of process based soil erosion

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models (Gete, 1999, Haregeweyn and Yohannes, 2003; Hengsdijk et al., 2005, Jetten et al., 2003) have been used to assess the sheet and rill erosion in Ethiopia. Consequently sheet, rill and inter-rill erosion has been estimated using the widely applied USLE model (e.g. Laflen and Moldenhauer, 2003), known as Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978), and modified by Hurni (1985) for Ethiopian highlands. The USLE parameters measures only sheet, rill and inter-rill erosion, therefore the overall soil erosion rate especially in the areas where deep gullies are observed, could be much higher than predicted by the USLE. However, other similar studies have calibrated the USLE model parameter for Ethiopian condition (Nyssen et al., 2004, 2009, Gebremichael et al., 2005; Haregeweyn et al., in press). USLE allows prediction of annual soil loss based on the product of six factors. It is represented by $\mathbf{A = R * K * L * S * C * P}$; Where, **A** is Computed spatial average soil loss and temporal average soil loss per unit area, expressed in the units selected for k and for the period selected for R. Usually expressed in t ha^{-1} $year^{-1}$; **R** is runoff from snowmelt. It is expressed in joules m^{-2}; the **K** represents soil erodibility factor. The soil loss rate per erosion index unit for a specified soil as measured on a standard plot is defined as a 72.6 ft. (22.1 m) length of uniform 9% slope in continuous clean tilled fallow. It is expressed in t-s m^{-2}. The **L** i.e. slope length factor is the ratio of the soil loss from the field slope length to soil loss from a 72.6 ft. length under identical conditions. The slope gradient factor (**S**) is the ratio of soil loss from the field slope gradient to soil loss from a 9% slope under otherwise identical conditions whereas, **C** denotes cover management factor. It is the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow. And, finally **P** is support practice factor, is the ratio of soil loss with a support practice like contouring, stripping, or terracing to soil loss with straight-row farming up and down the slope. The last four factors are dimensionless. To predict the mean annual soil loss in tonnes per hectare per year [t ha^{-1} $year^{-1}$] of a certain area, all erosion factors were surveyed before their calculated numerical values were multiplied.

When assessing erosion risk at a district or regional level, the use of Geographical Information systems (GIS) becomes an important and powerful tool. According to Mati and Veihe (2001), the application of GIS has increased in the last decade with the availability of digital data, cheaper and more user-friendly software and the need to handle large spatial database. Multi-temporal, high-resolution, remotely sensed data and GIS have been used extensively to monitor environmental changes and to map land cover changes on the local, regional and global scales (Berberoglu, 2003, Ali and Tesgaya, 2010; Meshesha et al., 2014). These have helped land use planning and sustainable management of resources (Evrendilek and Doygun, 2000, Wali et al., 2002). Interpretation of remote sensing data in conjunction with sufficient real ground information greatly help to identify and outline various ground features such as geological structures, geomorphic features and hydraulic characteristics (Ali, 2000, Ali and Piresteh, 2004; Iqbaluddin. and Ali, 1983 and 1984, Piresteh and Ali, 2004). Additionally, morphometric study further supplements the evaluation by measuring various stream properties (Ali et al., 2003a,b, Ali and Piresteh, 2005; Pirasteh et al., 2007). The analysis involves measurement of linear, aerial and relief aspects of the basin and slope contribution (Ali, 1988, Ali and Khan, 2013a,b).

2. Materials and methods

2.1. Location and accessibility

The study area is located in the lakes region, in main Ethiopian rift, 275 km south of Addis Ababa, located in and around the Awassa town of SNNPR region. The study site (Fig. 1) lies between 6°49′N–7°15′N latitude and 38°17′E–38°44′E longitude. The area is accessible through the paved road, which goes from Addis Ababa to Moyale, and the surrounding area is accessible by all-weather road and seasonal gravel roads.

2.2. Data collection

Landsat ETM^{+} digital images of path 168 and row 55 were used in this study. Interpretation and classification was carried out via false colour composite (FCC). Before conducting the image classification the digital satellite data was rectified using Survey of Ethiopia topographic map on a scale of 1:50,000. Rainfall data (10 years) was obtained from National Meteorological Services stations, and the soil map was obtained from the Soil Conservation Research Programme stations, Hurni (1985). The ERDAS Imagine 9.1 software was used for mosaicing and geo-referencing scanned topographic maps. Arc GIS 9.1 was used for screen digitizing of the topographic maps and further used for implementing USLE factors and ENVI 4.0 for image processing.

2.3. Methodology

2.3.1. USLE factor calculation

The soil erosion rate is calculated in the proposed region by employing USLE on the basis of six parameters. The actual estimation of soil loss was carried out by map overlays, pixel by pixel. This enabled the multiplication of USLE parameters accurately.

2.3.2. Rainfall erosivity (R factor)

The erosivity is an interaction between kinetic energy of raindrops and soil surface (Hudson, 1971, Wischmeier and Smith, 1978). It explains the detachment and down slope transport of soil particles according to the amount of energy and intensity of rain in the similar soil, topographic conditions and soil cover. Rainfall erosivity (R) is computed as total storm energy multiplied by the maximum 30 min intensity (Renard et al., 1997); which is expressed as, $R = EI_{30}$; where R, E and I_{30} represent, rainfall erosivity factor in metric factor, rainfall kinetic energy in J m^{-2} and 30 min rainfall intensity in mm hr^{-1} respectively.

The application of this formula is limited in Ethiopia partly because of the absence of data on rainfall kinetic energy and rainfall intensity. The calculation of the rainfall erosivity factor used the modified method for Ethiopian condition as recommended by Hurni (1985). The formula thus used is represented as $\mathbf{R = -8.12 + (0.562 * P)}$; where **P** is mean annual precipitation (mm), and R is Rainfall erosivity factor. Rainfall data of five stations Awassa, Wondogenet, Shashemene, Yirba Dibancho and Haisa Witto were used. Mean annual rainfall data of ten years i.e., from 1993 to 2002 was considered. Stations having incomplete data were filled by the available nearest neighborhood interpolation technique. The R factor calculated on this basis using modified method has been summarized in Table 1 and represented spatially with 100 m grid cell using Arc GIS 9.1 (Fig. 3A).

2.3.3. Soil erodibility (K factor)

The soil erodibility which is a measure of the susceptibility of a given soil to erosion by rainfall and runoff was determined separately (Table 2). Eleven different soil types were identified in the study area (Fig. 2). The soil types were assigned K factor values to reflect the Ethiopian condition based on FAO soil classification (Hurni, 1985). After assigning K factors the resulting map was converted to a grid map of 100 m cell size (Fig. 3B).

2.3.4. Slope gradient factor (S factor)

The digital elevation model (DEM) was developed for the study area using 1:50,000 scale topographic maps with contour intervals of 20 m after on screen digitizing of the topographic maps on Arc GIS 9.1 environment. The slope map of 100 m grid cell size was generated from the DEM and reclassified to 8 slope classes. S factor values were assigned to each slope gradient class. About half of the study area had slope gradient of 0–1% (Table 3). The spatial distribution of slope gradient in percent and the slope gradient factors are shown in Fig. 3C and D.