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Grid-cell based assessment of soil erosion potential for identification of critical erosion prone areas using USLE, GIS and remote sensing: A case study in the Kapgari watershed, India

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A B S T R A C T

Estimation of soil erosion is of paramount importance due to its serious environmental and societal concern. Soil erosion would have impact on fertility of agricultural land and quality of water. The major objective of this study was to investigate the spatial heterogeneity of annual soil erosion on the grid-cell basis in a small agricultural watershed of eastern India. The study watershed has a drainage area of 973 ha and is subdivided into three sub-watersheds namely: KGSW1, KGSW2 and KGSW3, based on the land topography and drainage network. Average annual soil erosion was estimated on 100 m × 100 m grid-cells by integrating universal soil loss equation (USLE) model with GIS for subsequent identification of critical erosion prone areas. It was found that 82.63% area of the total watershed falls under slight-erosion-class (0–5 t-ha^{-1}-yr^{-1}), 6.87% area lies under the moderate-erosion-class (5–10 t-ha^{-1}-yr^{-1}), 5.96% area is under high-erosion-class (10–20 t-ha^{-1}-yr^{-1}), 3.3% area of watershed lies under the very-high-erosion-class (20–40 t-ha^{-1}-yr^{-1}) and 1.24% area falls under "severe-erosion-class" (40–80 t-ha^{-1}-yr^{-1}). The study revealed that the sub-watershed KGSW3 is critical due to the presence of the highest number of critical erosion prone grid-cells. The sediment delivery ratio (SDR) was also estimated to analyze the contribution of sediment yield at the sub-watershed level. Lowest SDR for the whole watershed as compared to sub-watersheds indicates that most of the eroded soil got deposited in rice crop check-basins before reaching the outlet. The reported results can be used for prioritizing critical erosion prone areas and for determining appropriate soil erosion prevention and control measures.

1. Introduction

The soil erosion has increased during 20th century, and has become a worldwide issue of significant environmental and societal concern (Angima, Stott, O'Neill, Ong, & Weesies, 2003). India has a total geographical area of 329 Mha out of which 175 Mha (53%) is suffering from the land degradation problem. It has been assessed that nearly 5334 Mt soil erosion occurs yearly in India, due to various reasons of which about 10% settle down in the reservoirs, and 29% reaches the sea and significantly reduce the storage capacity (Narayana & Babu, 1983). The prevention of soil erosion and sediment deposition are important due to their direct impact on fertility of agricultural land and quality of water. About 85% of land degradation globally is due to by soil erosion, causing decline in crop yield up to 17% (Oldeman, Hakkeling, & Sombroek, 1990). Reduction in fertility of agricultural land as a consequence of soil erosion increases the expenses on fertilizers initially but afterward may lead to land abandonment (Pimentel, Harvey, Resosudarmo, & Sinclair, 1995). On the other hand the sedimentation at downstream area decreases the storage capacity of streams and retention ponds, which increases the possibility of flooding and reduces the designed life of water resources structures (Boardman, Ligneau, de Roo, & Vandaele, 1994; Verstraeten & Poesen, 1999). Deterioration of the drainage systems in agricultural watersheds has severe effect on soil erosion, which increases the water logging and salinity in agricultural fields (Valipour, 2014). The sediment is also a pollutant due to agro-chemicals adsorption, which can raise the nitrogen and phosphorus levels in water bodies and result in eutrophication (Sibbesen, 1995; Steegen et al., 2001).

Soil erosion may be more severe in near future due climatic change across various parts of the world (Amore, Modica, Nearing, & Santoro, 2004). The soil erosion will aggravate further with increasing population pressure, over-utilization of natural resources, faulty land and water management practice (Jena et al., 2015). There is a need for soil conservation to reverse the process of land abandonment and enhancement in agricultural production to

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ensure food security and sustainability. Hence, there is a necessity for identifying critical erosion prone areas at watershed scale to provide pre-requisite information for effective watershed management, including soil conservation strategies.

Appropriate watershed management plans for sustainable development need reliable long-term soil loss information at various parts of the watershed. Thus, many hydrological models such as: empirical, lumped conceptual and physically based models are being utilized for decades for assessment of soil erosion potential (de Vente & Poesen, 2005; Lal, 2001). Investigation in the past revealed that empirical models are relatively simple, robust in structure and have significant importance in assessment of soil erosion potential under scarcity of field data (Zhu, 2015).

The universal soil loss equation (USLE), is one of the most popular empirical models (Wischmeier & Smith, 1978) to estimate the long-term average annual rate of soil loss from small field having an average length of 22 m, a field slope of 9% based on rainfall pattern, soil type, topography, cropping system and management practices. In the last few decades, remote sensing (RS) technology and geographic information system (GIS) were used to precisely estimate the soil erosion precisely on the watershed and basin scale rather at a field scale (Chen, Niu, Li, Zhang, & Du, 2012; Cohen, 1960; Gelagay & Minale, 2016; Kouli, Soupios, & Vallianatos, 2009; Mhangara, Kakembo, & Lim, 2012; Millward & Mersey, 1999; Perovic et al., 2013; Wang, Yu, Shrestha, Ishidaira, & Takeuchi, 2010; Zhu, 2015). USLE has been widely applied at watershed and catchment scales (Baban & Yusof, 2001; Dickinson & Collins, 1998; Jain & Kothyari, 2000; Jain, Kumar, & Varghese, 2001) on the basis of lumped approach using RS and GIS. However, appropriate watershed management plans for sustainable development require prioritization of watersheds on the basis of micro-units, which contribute to maximum soil erosion. In this context, the past studies (Chowdary, Yatindranath, Kar & Adiga, 2004; Khan, Gupta & Moharana, 2001; Saxena, Verma, Chary, Srivastava & Barthwal, 2000; Sharda, Kumar, Venkataratnam & Rao, 1993; Welde, 2016; Yoshino & Ishioka, 2005) show that proper integration of USLE with RS and GIS techniques can be helpful for prioritization of erosion prone areas. It is also found from the past studies that integration of the USLE model with GIS on grid-cell basis would allow the analysis of spatially distributed soil erosion effectively (Bhattarai & Dutta, 2007; Onori, De Bonis, & Grauso, 2006; Onyando, Kisoyan, & Chemelil, 2005; Renschler, Diekkrüger, & Mannaerts, 1999). Recently, grid-cell based studies have been conducted to identify vulnerable areas in the watersheds and large catchments for the planning of conservation practices (Dabral, Baithuri, & Pandey, 2008; Pandey, Chowdary, & Mal, 2007; Wang et al., 2010, Perovic et al., 2013; Farhan & Nawaiseh, 2015).

USLE estimates the soil erosion caused by a rainfall event, but does not provide sediment yield at the outlet of the watershed. Vanoni (1975) reported the bulk of sediment deposits in-between sites, wherever the runoff water is inadequate to transport eroded soil to the watershed outlet. Thus, some portion of the eroded soils routing towards watershed outlet are responsible for the sediment yield. Hence, sediment delivery ratios (SDR) need to be determined for adjustment of soil erosion rate estimated by USLE to quantify the sediment yield at the watershed outlet. A reliable assessment of SDR is done by using observed sediment yield at watershed outlet and estimated soil erosion by USLE over the watershed (Ambika, Satoshi, & Okihiro, 2006; Weifeng & Bingfang, 2008). The modification was made on USLE in the form of MUSLE to estimate sediment yield more effectively under different conditions (Lal, 2001). Although, MUSLE performs better than USLE in estimating sediment yield, it does not provide an appropriate assessment of spatially distributed soil erosion (Wang, Hapuarachchi, Ishidaira, Kiem, & Takeuchi, 2009).

In the last decade, good amount of work has been done on soil erosion assessment in large catchments and at a regional scale by using lumped approaches and very few on micro-units and grid-cell basis. However, estimation of spatially distributed soil erosion on grid-cell basis has not been adequately addressed, in the agricultural watersheds, which has effect on fertility of agricultural land and quality of water. Therefore, the reported study is carried out with the following specific objectives: (i) Estimation of average annual soil erosion on 100 m × 100 m grid-cells basis by integrating the USLE model with GIS in a small agricultural watershed (ii) Classification of the estimated average annual soil erosion on grid-cell basis into different soil erosion classes (iii) Identification of the critical sub-watershed and critical erosion prone grid-cells that require urgent conservation measures and land management (iv) Estimation of sediment delivery ratio (SDR) for each hydrological unit to provide the proportion of the eroded soil reaching the outlet.

2. Material and methods

2.1. Study area

A small agricultural watershed namely Kapgari watershed (KGW), located in the eastern India was selected for the study. Geographically the watershed lies between 86°50' and 86°55'E longitude and 22°30' and 22°35' N latitude (Fig. 1) and has an area of 973 ha. The watershed was delineated into three sub-watersheds (Fig. 1) on the basis of the main drain and three sub-drains. The sizes of delineated sub-watersheds KGSW1, KGSW2 and KGSW3 are 280, 330 and 363 ha respectively. The climate of the study area is sub-humid subtropical and the average annual rainfall is 1370 mm. About 80% of the annual rainfall is concentrated during the rainy season from June to October. The daily average temperature varies from 24 °C to 40 °C and that of relative humidity from 59.4% to 94.3%. The major soil textural classes of the study watershed are sandy loam, silt loam, clay loam and loam; sandy loam soil being predominant. Erosion is the major problem of this agricultural watershed due to its undulating topography and unmanaged natural resources.

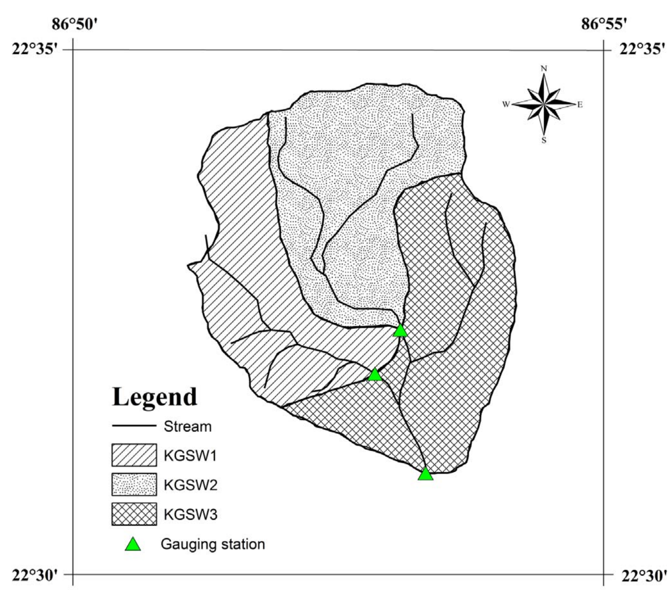

Fig. 1. Location map of Kapgari watershed.