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Identification and prioritization of critical erosion areas based on onsite and offsite effects

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ABSTRACT

Accelerated soil erosion is considered as one of serious agro-environmental threats to sustainable development all over the word. Tolerable erosion concept is a tool for awareness and assessment of soil erosion status and its economic, social, and environmental hazards. This study was conducted to design a framework for evaluating and identifying spatial patterns of erosion hazard in Haji-Ghushan watershed, based on tolerable erosion concept, by using the SWAT model. The framework was consisted of two parts: the erosion tolerance index (ETI), and the sediment-phosphorous index (SPI) for evaluating onsite and offsite effects of soil erosion, respectively. Four hazard levels were defined for each index. The results of sediment simulation indicated that the maximum rate of erosion belonged to agricultural lands located on steep slopes in the central part of the watershed, and the minimum rate was from forest lands, despite their steep slopes. The map of spatial distribution of erosion hazard showed that, in terms of both onsite and offsite effects, a major part of the watershed (around 65%) had experienced an erosion rate lower than the erosion tolerance threshold; hence, these areas were not faced with erosion hazard. The spatial distribution of the areas exposed to the onsite erosion hazard, however, was differed from those confronted by the offsite erosion hazard. Identified high hazard areas based on the erosion offsite impacts were mainly located in sub-basins close to the watershed outlet where the sediment and phosphorous yield was high due to the high sediment-phosphorous delivery ratio. High hazard areas with high risk of soil degradation and productivity reduction are distributed throughout the watershed, depending on the magnitude of the erosion rate. These findings revealed that, in addition to erosion rate, sediment delivery ratio is also an important parameter in evaluating soil erosion hazard. For achieving the sustainable agro-environment, it is necessary to consider both the onsite and offsite effects of soil erosion to identify the high hazard areas. Also the results showed that the designed framework was capable of identifying the high hazard and hot spot areas well. The findings of this study are useful for officials and policy makers of soil conservation and environmental protection agencies in the region.

1. Introduction

Globally, about 75 billion Mg of soil are eroded from agricultural lands (Pimentel et al., 1995) and around 0.3% of the agricultural production value is lost due to erosion each year (Den Biggelaar et al., 2003), which directly affects rural livelihood (Kerr, 1997; Lal, 1985) and challenges the achievement of the goal of food security (Pimentel and Burgess, 2013). Of the 75 billion Mg of soil lost worldwide, approximately two-thirds become deposited in lakes and rivers (Pimentel, 1997), which impacts aquatic resources (Bilotta and Brazier, 2008; Eggermont and Verschuren, 2003; Clark, 1987), lake/river sediment dynamics (Kelley and Nater, 2000; Walling, 2000), global carbon cycling (Lal, 2003), aquatic and terrestrial biodiversity (Alin et al., 2002; Harrey and Pimentel, 1996) and ecosystem services and soil quality (Lal, 2001; Pimentel and Kounang, 1998). Sediments also reduce water storage capacity, increase the maintenance cost of the dams, and shorten the life of the reservoirs (Pimentel et al., 1995).

Research has shown that the intensity of soil erosion has increased considerably in Iran in the past few decades (Emadodin et al., 2012; Emadodin and Bork, 2011; Ahmadi et al., 2003; FAO, 1994) because of

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incorrect use of soils, land-use changes, and mismanagement and that, if this current trend continues, this soil erosion will be a serious threat to the food security and the environment of this country. It has been estimated that about 500 million Mg of fertile soil are lost from the 16 million ha of agricultural lands in Iran every year (Emadodin et al., 2012). This means that the average annual intensity of soil erosion in these areas is about 32 Mg per ha. Moreover, studies on sediments yield in the watersheds of Iran indicate that storage capacity of the dams in the country declines by about 0.2 billion m^3 per year (Emadodin et al., 2012). In other words, every year a relatively large dam like the Karaj Dam is filled up due to erosion. Based on the report published by Emadodin et al. (2012), losses caused by sedimentation at dams in Iran amount to about 0.6 billion U.S. dollars per year.

Land management is certainly the key important factor to minimize a wide range of damaging effects of soil erosion. To implement best management practice, we need to determine soil loss tolerance, and identify and prioritize vulnerable and high-risk zones. Soil loss tolerance, which is introduced in order to give a measurement of how much soil should society allow to be eroded before experiencing excessive damage (Verheijen et al., 2009), has been recommended as an ultimate indicator in controlling onsite and offsite erosion effects (Li et al., 2009; Bhattacharyya et al., 2008; Sparovek and Jong van Lier, 1997 and it must be determined in a scientific and workable manner. Soil loss tolerance is one of the most fundamental and at the same time the most complex topics in studies on soil erosion. McCormack et al. (1982) proposed numerous criteria that should be considered in evaluating soil loss tolerance, including rate of weathering, changes in soil quality, impact on water quality, etc. Considered at a more pragmatic level, soil loss tolerance is equal to the rate of soil formation that is affected by changes in rainfall amount, average temperatures, water infiltration rate, type of soil cover and other environmental or anthropic factors (Jenny, 1941). The available data on soil formation rates are disperse and rare and the low rate of the process combined with the difficulty of its measurement at the soil-rock border makes the precise establishment not possible (Alewell et al., 2015; Sparovek and Jong van Lier, 1997). Furthermore, recent research has shown that the rate of soil production has an inverse relationship with soil depth (Dahms et al., 2012; Humphreys and Wilkinson, 2007), which means deep soils have lower thresholds of soil loss tolerance compared to shallow soils. Therefore, another criterion is proposed which limits the soil erosion to a specified range with an acceptable degree of risk associated with a soil type and social and political issues (Bazzoffi, 2009; Cole and Higgins, 1985). Soil productivity, defined as the capacity of a soil to produce a certain yield of crops or other plants with a specified system of management (Soil Science Society of America, 1997), and/or economic issues usually are a basis for determining this criterion (Lobo et al., 2005; Lal, 1998; Pierce, 1991). In a more recent study, Duan et al. (2017) developed a new method to calculate soil loss tolerance as a function of the soil productivity index (PI) for farmland on basis of the Skidmore (1982) equation. They defined T1 and T2 as lower and upper limit of the soil loss tolerance, respectively and stated that to maintain sustainable soil productivity, the soil productivity level should be higher than a threshold. In India country, a quantitative bio-physical model has been employed as a methodological approach for assessment of permissible soil loss based on soil resistance to erosion and soil depth (Mandal and Sharda, 2011; Mandal et al., 2010, 2006).

Nowadays, considering increasing environmental concerns and pollution of water resources, some scientists have suggested that more than one criterion be determined for soil erosion tolerance (Bazzoffi, 2009; Li et al., 2009; Skidmore, 1982). Sparovek and De Maria (2003) expressed the view that the acceptable erosion level was a multi-dimensional problem that could prove successful only through a comprehensive natural process of thinking. Li et al. (2009) believed that the real soil erosion tolerance was an erosion level at which no decline or reduction happened in one or more soil functions. To calculate this soil loss tolerance all soil functions are need to be quantified, first, and the relationship between each of these functions and soil erosion must be determined. Therefore, scientists hope that in the near future they will be able to include all aspects of erosion in the concept of soil erosion tolerance.

One of the most common limitations of existing method to determine the soil loss tolerance is that the offsite effects of soil erosion are not considered simultaneously. Therefore, the main objectives of the study were to assess the soil loss tolerance in relation to soil productivity as a main onsite impact and sediment and phosphorus delivery as a main offsite effects of erosion. The working hypothesis for this study was that estimated soil loss tolerance based on soil productivity may not be enough to control the destructive impacts of erosion from an environmental-economic perspective, and therefore another index is required.

2. Materials and methods

2.1. Site description

This investigation was carried out in Haji-Ghushan, as Boustan dam drainage basin, that is a part of the large Gorgan-roud watershed, east of Golestan province between 37° 24′ and 37° 5′ N latitude and 55° 29′ and 56° 04′ E longitude with 1560 km^2 area (Fig. 1). Golestan is one of the most important provinces for agricultural production in Iran. But, most of croplands located on steep lands that suffer high degree of erosion damages. The soils of the study area originated mainly from loess materials which are usually erodible because of silt particles abundance, low permeability and absence of cement materials between the particles. Accordingly, there are serious erosion problems in this area. The watershed's complex topography is characterized by mountainous, steep hillslopes and deep valleys in which two main branches of Gorgan-roud river flow down. The elevation varies from 100 m at the basin outlet to 2100 m at the highest point in the southeast of area. The climate is characterized as semiarid in north, and semi-humid in south, with average annual precipitation of 450 and 590 mm, respectively by De-Martonne classification system (Kazemi et al., 2015). The common land use of area includes cropland, rangeland, and forest land approximately 37, 32 and 29%, respectively.

2.2. Soil sampling

Field surveys were employed to characterize the study watershed in terms of different soil, land use and topography based on maps, areal image and field observations. On the basis of such soil sampling zones, the watershed divided into 54 zones consisting of combinations of two slopes (2–12% and 12–25%), three land uses (cropland, rangeland and forestland) and nine soils. For each zone, representative soil profiles were described and soil samples (disturbed and undisturbed) were obtained from the 0–20, 20–40, 40–70, 70–100 cm depth intervals. Undisturbed soil samples were taken in cores (100 cm^3 steel cylinders) from each layer (n = 3) for analysis of water holding capacity (WHC) and soil bulk density (BD). Initially, these soil samples were saturated from the bottom using a 0.01 M $CaCl_2$ solution for 24 h and then placed in a pressure plate apparatus for determining WHC by the difference between soil moisture content at field capacity and wilting point, which estimated from soil samples equilibrated at a pressure of 33 and 1500 kPa on a pressure plate, respectively (Romano and Santini, 2002). In the next step, samples were weighed before and after oven drying at 105 °C to determine the soil's bulk density. The disturbed soil samples were air-dried and passed through a 2-mm sieve to determine selected soil physicochemical properties such as particle size distribution (Gee and Or, 2002), organic matter (OM) content (Nelson and Sommers, 1982) and soil phosphorus (P) concentration (Olsen and Sommers, 1982). In addition these soil samples, 350 recently collected topsoil samples from the soil quality monitoring project by Agriculture Organization of Golestan Province (unpublished report) were indepen-