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Analysis of sediment rating loops and particle size distributions to characterize sediment source at mid-sized plot scale

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ABSTRACT

Estimates of spatio-temporal variations of sediment concentration with discharge are needed for the assessment of aquatic ecosystems, estimates of contaminant export from catchments. The relationship between discharge and sediment concentration is available for different watersheds. However, elucidating flow discharge-soil loss-contribution area relationships under simulated controlled conditions has not been adequately considered for better understanding of soil erosion processes. The objective of this study therefore is to employ sediment rating loops and PSD to characterize erosion source contribution of a mid-sized plot subjected to different input driving forces of slope steepness (S = 5 to 25%) and rainfall intensity (I = 30 to 90 mm h^{-1}). A cause-and-effect conceptual approach was employed for investigating erosion by individual storm events. Results of the study showed that the interrelationships among variables varied as erosion processes developed owing to increasing slope or rainfall intensity. The sediment rating mainly followed downward linear or semi clockwise hysteretic loops except for slopes of 15 and 25%, and rainfall intensity of 30 mm h^{-1}. It was further found that the high rainfall intensity event under steep slope had limited contributing area and more contribution of coarse particles with lesser coefficient of variation. Understanding the relationships among runoff, sediment and PSD can greatly improve our understanding of sediment transport mechanisms and the contributing areas that facilitate better soil erosion modeling leading to proper planning of soil and water management measures.

1. Introduction

Water erosion of soil is a serious environmental problem in the world which threatens the future sustainable development. In this pursuit, proper understanding soil erosion processes are of crucial importance (Silva et al., 2015; Tian et al., 2017). In this regard, accurate estimation of sediment yield and sediment graph are needed for the design of impoundments and erosion control structures, river morphological computations, management of ecosystems, and evaluation of the effects of various land use management practices (Sun et al., 2016; Zhang et al., 2017; Zhao et al., 2017).

Monitoring of sediment concentration and particle size distribution (PSD) is important for improved understanding, modeling and management of sediment-related processes in natural aquatic systems, such as rivers, lakes, estuaries and seas, and at hydraulic schemes for hydropower, irrigation, flood protection and even tracing the fate of chemicals (Young, 1980; Walling and Moorehead, 1989; Parsons et al., 1991; Slattery and Burt, 1997; Thompson et al., 2016; Jomaa et al., 2017; Sadeghi et al., 2017). In this regard, the transport of sediment by runoff and its potential for subsequent deposition depend on its size distribution (Proffitt and Rose, 1991). Therefore, knowledge of the processes involved in the generation, transport and deposition of sediments, is clearly of fundamental importance to understand the associated changes in the sediments PSD during erosion phenomenon (Kiani-Harchegani et al., 2018). The size characteristics of eroded sediment can also be expected to vary, depending on which erosion process is predominant. Walling et al. (2000) and Williams et al. (2007) demonstrated that the particle size characteristics of sediments were of fundamental importance in understanding their role in a variety of environmental processes, such as contaminant transport. Some studies (e.g., Williams et al., 2007; Asadi et al., 2011; Sadeghi and Kiani-Harchegani, 2012; Shi et al., 2012; Wang and Shi, 2015; Sadeghi et al., 2017) have investigated sediment PSD of suspended sediment and verified the selective size distribution of the eroded particles through different soil erosion stages due to selectivity in entrainment or transport mechanisms. Pieri et al. (2009) analyzed runoff water, sediment yield and sediment mean diameter as a function of land cover, rainfall kinetic energy and stream power at experimental plots installed in the

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Apennines mountain range, northern Italy. Thompson et al. (2016) developed a model considering event-specific and site-specific factors and total suspended sediment particle size distribution, based on the data collected from laboratory small scale experiments using rainfall simulation on fourteen different soils from active construction sites and surface mining operations in Canada. Sadeghi et al. (2017) reported that PSD of the splashed sediment significantly varied depending on rainfall intensity, slope steepness and upward/downward direction of the splash cups.

Sediment concentration is controlled by the interaction among the processes of flow generation, transport capacity, sediment delivery from external sources, and the amount of fine sediment mobilized from internal sources varying over a wide range of temporal and spatial scales (e.g., Gomi et al., 2005; Perks et al., 2015; Thompson et al., 2016; Zhao et al., 2017). The variability of these processes is associated with the variability of precipitation characteristics, the connectivity of sediment sources, changes in contributing areas, and hydraulic boundary conditions (e.g., Nadal-Romero et al., 2008; Liu and Fu, 2016; Gran and Czuba, 2017). The above considerations indicated that sediment generation and transportation is a complex process, being influenced by many factors and has very important role for soil erosion research. Many experiments have been performed in plot scale to control factors affecting on fluvial behavior. Additionally, several studies (e.g., Jomaa et al., 2017; Asadi et al., 2011; Shi et al., 2012; Wang and Shi, 2015; Vilayvong et al., 2016; Zhang et al., 2016; Gran and Czuba, 2017; Kiani-Harchegani et al., 2018) investigated relationships between generation and transport of sediment with its PSD under different conditions. Many researches (e.g., Nadal-Romero et al., 2008; Saeidi et al., 2016) have focused on the relationship between sediment graphs (SGs) and hydrographs (HGs) at the watershed scale. The sediment rating loops (SRLs) between suspended sediment concentration and water discharge have also been developed (e.g., Nistor and Church, 2005; Gao and Pasternack, 2007; Fan et al., 2012; Gellis, 2013; Sun et al., 2016) to provide information on sediment yield processes. However, measurement of soil erosion and sediment characteristics associated with rain and soil conditions is tedious in practice and measurement data are therefore limited (Vilayvong et al., 2016). Cheraghi et al. (2016) investigated the hysteresis loop patterns of different sediment PSD versus discharge for time-varying precipitation rates from a 5 m × 2 m erosion plot. For an initially dry and ploughed soil, clockwise hysteresis loops in SG versus HG were generated for the total sediment concentration and finest PSD. In contrast, for the larger PSD, the hysteresis loops are narrower and have a more irregular shape.

The above discussion suggests that fluvial behavior of a watershed is complex and its proper study requires an appropriate experimental setup (Iserloh et al., 2013; Lassu et al., 2015; Gran and Czuba, 2017). Of fundamental importance are the processes of generation, transport, sink and sources, and sediment particle size distribution for unraveling soil erosion-related issues at different spatio-temporal scales. Considering the literature on SG and HG, and sediment PSD at the watershed scale, it seems that few studies have been conducted to comprehensively assess the HG, SG, sediment PSD and specifically SRLs in different slopes and rainfall intensities at the plot scale. The present study, therefore, employs SRLs and PSD to characterize erosion source contribution at mid-sized plot scale. This indoor study was conducted at plot scale in order to control the influencing factors and to monitor the processes (Malam Issa et al., 2006; Pieri et al., 2009; Vilayvong et al., 2016). Studying flow discharge-soil loss-contribution area relationships under simulated controlled conditions can help modelers and even decision makers consider scale dependency of soil erosion processes leading to better conceptualization and formulation of the rainfall-runoff-sediment characteristics relationships. Results of the study may constitute a basis for characterizing the fluvial behavior of a watershed pertaining to the physical properties of soil, rain and runoff that may lead to appropriate conceptual ion and modeling.

2. Material and methods

2.1. Experimental setup

Laboratory experiments, comprising a three-plot set of 6 m^2-mid-sized plots with dimensions of 6 (length) × 1 (width) × 0.5 (depth) m, were conducted in the Rainfall Simulation and Soil Erosion Laboratory of Faculty of Natural Resources, Tarbiat Modares University. Soil used in the experimental set-up was obtained from the Kojour Watershed in the degrading Hyrcanian Region of northern Iran. This silt loam soil collected from the top 20 cm of surface layer with respective bulk density, pH, electrical conductivity (EC), organic matter content and mean weight diameter (dry) of 1.46 g cm^{-3}, 7.65, 0.76 dS m^{-1}, 2.61% and 1.38 mm (Kiani-Harchegani et al., 2018). The soil was appropriately placed in the plots as per procedures followed by Kiani-Harchegani et al. (2018). The soil moisture volumetric content was set at about 12 ± 3%, similar to that reported for the soil in the research area (Kiani-Harchegani et al., 2018).

A set of experiments was carried out to investigate soil loss and size characteristics of sediment discharged under rainfall intensities (I) of 30, 60 and 90 mm h^{-1} with respective durations of 30, 15 and 10 min extracted from the intensity-duration-frequency curves for a return period of about 25 years which corresponded with watershed executive projects of the Kojour meteorological station located in the vicinity of the area (51°44′E; 36°24′N; elevation 1550 m above sea level) from where the experimental soil was sampled. The rainfall water was fed by a 4000 L-tank and 7 nozzles in line with the ability to simulate raindrops from 1.5 mm to 1.58 mm diameters for above the experimental rainfall intensities which corresponded with the greatest number of 1–2 mm raindrops reported by Abdollahi et al. (2013) for the same area. The slopes (S) of 5, 15 and 25% existing in the area were also considered for the experiments. All experiments were conducted with complete combinations of slope and rainfall with three replicates, and therefore a total 27 experiments were considered.

2.2. Measurements and analyses

In order to characterize the erosion source contribution, the interrelationships among HGs and SGs, and outflow sediment size characteristics relating to soil erosion processes were analyzed at plot scale (Asadi et al., 2011; Thompson et al., 2016). Water flow and suspended sediment concentration were volumetrically measured at 1-min intervals for each rainfall event at the outlet of plots for all experimental runs. The sediment concentration (SC) was determined through settling, decantation and oven drying at 105 °C (Kiani-Harchegani et al., 2016). The number of samples of water runoff and sediment concentration varied from 22 to 25, 12 to 13 and 8 to 9 for the rainfall intensity of 30, 60 and 90 mm h^{-1} in different replicates, respectively. The corresponding HGs and SGs were then depicted on the same coordinates. The SRLs were also developed, based on the relationship between SC and runoff to help understand the temporal variation of sediment hysteresis and recognize the temporal contribution of sediment in runoff (Lee and Yang, 2010; Megnounif et al., 2013) and also elucidate the contributing areas (i.e., lower part or whole plot) of the eroded soil reaching the plot outlet.

The soil and sediment samples were analyzed for PSD with the use of a Malvern Mastersizer 2000 laser diffraction device (Malvern Instruments, 2004). The PSD data were determined without any dispersion treatment to allow for measuring the effective sediment PSD (Walling et al., 2000; Martinez-Mena et al., 2002; Pieri et al., 2009). The main characteristics of sediment and original soil were calculated using the GRADISTAT software package (Blott and Pye, 2001). Simultaneously, the variability of average PSD of sediment for three replicates from each treatment were analyzed in comparison with original soil to determine the contribution of lower part of the plot with