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Assessment of soil particle erodibility and sediment trapping using check dams in small semi-arid catchments

Ali Reza Vaezi[a,*], Mohammad Abbasi[a], Saskia Keesstra[b], Artemi Cerdà[b,c]

[a] *Department of Soil Science, Agriculture Faculty, University of Zanjan, 45371-38791, Zanjan, Iran*
[b] *Soil Physics and Land Management Group, Wageningen University, Droevendaalsesteeg 4, 6708NX Wageningen, The Netherlands*
[c] *Soil Erosion and Degradation Research Team, Departament de Geografia, Universitat de València, Blasco Ibàñez 28, 46690 Valencia, Spain*

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ABSTRACT

Check dams can be used as a source of information for studies on sediment characteristics and soil particle erodibility. In this study, sediment yield and grain size distribution (GSD) were measured in twenty small catchments draining into a rock check dam in NW Iran for different runoffs during 2010–2011. Significant correlations were found between sediment yield and slope steepness, vegetation cover and soil erodibility factor (K) of the catchments. The erodibility of soil particles was determined using the comparison of GSD between sediment and original soil. Clay was the most erodible soil particle which showed 2.05 times more percentage in sediment than the original soil. The erodibility of soil particles were strongly affected by the rainfall erosivity (EI_{30}). Check dams showed more effectiveness in trapping coarse particles (sand and gravel). The effectiveness of check dams in trapping coarse particles enhanced with increase in the remaining capacity of check dams.

1. Introduction

Semi-arid areas cover about 24% of the world's surface and are characterized by limited rainfall, annual precipitation ranges from 300 to 600 mm, and periodic droughts that restrict rainfed crop production (Araya et al., 2011). In these areas, soils are usually shallow, poorly structured and low in organic matter content, and vegetation cover is often inadequate to protect the surface, especially when agricultural practices of crop cultivation and grazing further reduce this cover (Cammeraat et al., 2010). They are considered to be one of the most vulnerable areas to the impacts of water erosion processes, and this is why restoration strategies are applied (Keesstra et al., 2016; Prosdocimi et al., 2016). Soil erosion is the most important factor in land degradation or desertification in these areas (Ligonja and Shrestha, 2015; Zhou et al., 2016).

Soil erosion by water is the major factor controlling sediment production in all catchments in semi-arid areas (Wang et al., 2016; Ochoa et al., 2016). Total sediment outflow from a catchment, measurable at a point of reference and for a specified period of time is defined as sediment yield (Vanmaercke et al., 2014). It can be expressed in absolute terms ($\mathrm{Mg\ year^{-1}}$) or per unit area ($\mathrm{Mg\ km^{-2}\ year^{-1}}$) (Jain and Das, 2010). The sediment yield of a catchment represents only a part of the total soil erosion within the catchment, as often-important masses of sediment are deposited before they reach the outlet (Lee and Yang, 2010; Masselink et al., 2016). It is dependent on all variables that control erosion and sediment delivery in a catchment, and determine the connectivity of the system (Baartman et al., 2013; Marchamalo et al., 2016). Sediment delivery is influenced by catchment characteristics, regional climate, and reservoir characteristics (Syvitski et al., 2005). Thus, sediment yield can be controlled by the environmental conditions of the watershed, such as climate, soil, topography, land use and its spatial distribution, vegetation cover, drainage network characteristics, and various forms of human disturbances (Syvitski et al., 2005; Boix-Fayos et al., 2007; Shi et al., 2012; Naden et al., 2016). The determination of sediment yield and the factors controlling it is of essential importance for sustainable management of catchments (Akrasi, 2011).

The particle/grain size distribution of sediment (GSD) can be used as additional information to evaluate the soil particles susceptibility to water erosion in the catchment scale. Soil particles are different in their potential to be eroded by water. The susceptibility of soil particles to different erosion processes; detachment, transport and deposition can be defined as the soil particle erodibility. This term is different from the soil erodibility concept developed for soils, which reflects the soil's susceptibility against erosive forces (Wischmeier and Smith, 1978; Vaezi et al., 2016). The soil particle erodibility can be influenced by both inherent soil particle characteristics (size, mass/weight, shape etc.) and the transport mechanism (surface runoff, concentrated runoff,

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[*] Corresponding author.
E-mail address: vaezi.alireza@znu.ac.ir (A.R. Vaezi).

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etc.) which can be affected by various factors such as rainfall intensity, slope steepness and vegetation cover. The size of particle affects the soil erosion processes such as entrainment, transport and deposition (Pye and Blott, 2004; Rienzi et al., 2013). Thus, the soil particle erodibility can be strongly affected by the particle size. In past studies, which have been done in the plot scale using the simulated rainfall, the movement of soil particles by the raindrop impact (Legout et al., 2005; Ma et al., 2014) and surface runoff (Zhang et al., 2011; Shi et al., 2012; Wang and Shi, 2015) has been investigated. Some of these studies provide evidence of size-selective erosion, transport, and deposition and demonstrated that consideration of both effective and ultimate particle size distribution of sediment can provide an improved understanding of the size selectivity of erosion and sediment delivery processes (Shi et al., 2016). The ultimate particle size distribution of sediment can be determined in the samples after chemical and mechanical dispersion. The ratio between the ultimate particle size composition of the transported sediment and that of the parent soil provided a measure of the particle-size selectivity of the transported sediment (Martínez-Mena et al., 2000). Beside the studies at the plot scale, in many studies, measurements of suspended sediment and particle size distribution in rivers have been performed (Abedini et al., 2012; Mouri et al., 2013; Gamvroudis et al., 2015). However, information on soil particle erodibility and factors influencing on larger scales such as the catchments is limited. Knowledge of sediment sorting will improve understanding of erosion and sedimentation processes, which in turn will improve modeling soil erosion by water (Shi et al., 2012). Moreover, sediment selectivity during transport may provide basic information for evaluating on-site and off-site impacts of soil erosion (Wang and Shi, 2015). The soil particle erodibility can be used as a measure for determining the soil's susceptibility to produce sediment. It is also crucial for designing soil conservation practices on the hillslopes as well as at the catchment outlet. The conservation structures should sufficiently trap the erodible soil particles that eroded from the uplands. For this purpose, it is necessary to acquire information about the amount and grain size of sediment produced in catchments.

Smaller reservoirs like check dam reservoirs provide an opportunity to acquire information on the amount of sediment and grain size distribution (Verstraeten and Poesen, 2000; Sougnez et al., 2011; Zhao et al., 2016). This information is similar to those of large reservoirs (Verstraeten and Poesen, 2002; Molina et al., 2008; Norman and Niraula, 2016) and similarly the trapping efficiency of these structures is variable (in space and time) and needs to be assessed to allow good interpretation of the data (Getahun et al., 2015). Check dams are the most important engineering structures which are constructed across the gullies to reduce the velocity of concentrated water flows, a practice that helps reduce erosion, control sediment (Castillo et al., 2014), and stabilize gullies (Mekonnen et al., 2015). They are especially useful in semi-arid areas due to the degraded state of the vegetation cover and the torrential nature of rainfall which, together, make such areas susceptible to erosion (Romero-Díaz et al., 2012; Polyakov et al., 2014). Effectiveness of check dams in sediment retention can be associated to different factors such as check dam characteristics (location, height, spillway, porous degree, etc.), gully characteristics (cross section shape, slope, vegetation cover, etc.), and water flow (flood) conditions (Parsons et al., 2015).

Various studies have evaluated the impacts of check dams on controlling soil erosion and retention of sediment (Romero-Díaz et al., 2012; Castillo et al., 2007; Bussi et al., 2013; Quiñonero-Rubio et al., 2016). Some studies however, have focused on the ability of check dams to retain eroded particles at the watershed larger scale. Toward this, Liu (1987) indicated that the sediment deposited behind check dams might be derived from the upstream channel during flood events and that the coarse material did not move downstream continuously. Takeuchi (2004) estimated that suspended sediment production in the world is about 20 × 109 t year^{-1} of which over 25% is trapped in large dams constructed around the world. Boix-Fayos et al. (2007) studied sediment size distribution in 58 check dams mostly filled along the river channel (10.5 km) and found that the D50 downstream of most of the dams is between 20 and 200 times coarser than upstream of the dams. Ran et al. (2008) showed that check dams are the most effective soil conservation measures to rapidly reduce the amount of coarse sediment (grain size $d \geq 0.05$ mm) entering the major rivers. Hassanli et al. (2009) found that the portion of clay and silt trapped by porous check dams decreased from the downstream sections toward the upstream sections. The check dams located at the far downstream sections were more efficient at trapping fine sediment than those located at the middle sections and the upstream sections. Romero-Díaz et al. (2012) concluded that the sediment materials retained by check dams generally have a higher percentage of sand and silt compared to the soils in the contributing catchment.

Most studies on the impact of dams had carried out on the influence of large dams, but less attention has been paid to the efficiency of small check dams (Castillo et al., 2007). Rock check dams are a small dam type (in general < 5 m high), which are commonly constructed in small drainage areas where erosion and sedimentation intensities are usually high. They have been used for centuries to control erosion and increase local soil moisture and in consequence support subsistence agriculture in many areas around the world (Nichols et al., 2012). A given check dam give useful information on factors influencing sediment production particularly in smaller drainage areas, while taking into account the restrictions as mentioned above. It can provide evidence on the kind/size of transported material through upland erosion defined as soil particle erodibility, kind/size of trapped material in each runoff event. It represents also a rather novel way to approach the sediment delivery problem in the context of making use of check dams. There is a need for reliable information on the physical processes within small catchments such as the rates of soil loss, and an improved understanding of sediment transport and storage in small catchments to provide a basis for implementing improved erosion and sediment control strategies particularly in semi-arid regions. Therefore, this study was conducted to determine factors influencing sediment production, determine the soil particle erodibility characteristic, and evaluate the effectiveness of rock check dams for trapping soil particles using the sediment yield analysis and grain size distribution in semi-arid small catchments at the flood-event scale.

2. Materials and methods

2.1. Study area

The study was carried out in the Taham Chai catchment with 228.2 km^2 in an area located between 34° 46′–36° 53′ N latitudes and 48° 17′–48° 37′ E longitudes in the province of Zanjan, NW Iran (Fig. 1). The Taham Chai is the major river of the catchment with an average discharge of 1.19 m^3 s^{-1} and is poured into the Taham Reservoir Dam which has been constructed to supply drinking water in 2003. The catchment is mountainous with a dominant slope gradient between 20 and 40% and an elevation varying from 1480 m to 3100 m. It mainly consists of sandstone, shale, and andesite. The climate is semi-arid and average annual temperature annual precipitation is about 10 °C and 378 mm, respectively. Rainfall intensities vary from 5 to 100 mm h^{-1} for 3 to 90-min duration (Vaezi and Rostami, 2017). Rainfall mostly occurs in early spring and has a maximum intensity of 82 mm h^{-1}. About 69% of land surface area is covered with pastures with a sparse vegetation cover. The dominant grass species consist of *Astragalus* spp., *Ziziphora tenuoir*, *Hypericum perforatum*, and *Alhagi comelorum*. About 32.7% of the area is occupied by rainfed agricultural land which is dominantly used for winter wheat production (Vaezi and Abbasi, 2012). The change of pasture area to agriculture lands accelerates water erosion processes and sedimentation in the catchment (Fig. 2a). Flow discharge in the Taham Chai river varies from 0.01 m^3 s^{-1} in March to 2.58 m^3 s^{-1} in September (Vaezi and Rostami, 2017). The soils are