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

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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 (Mg year^{-1}) or per unit area (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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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

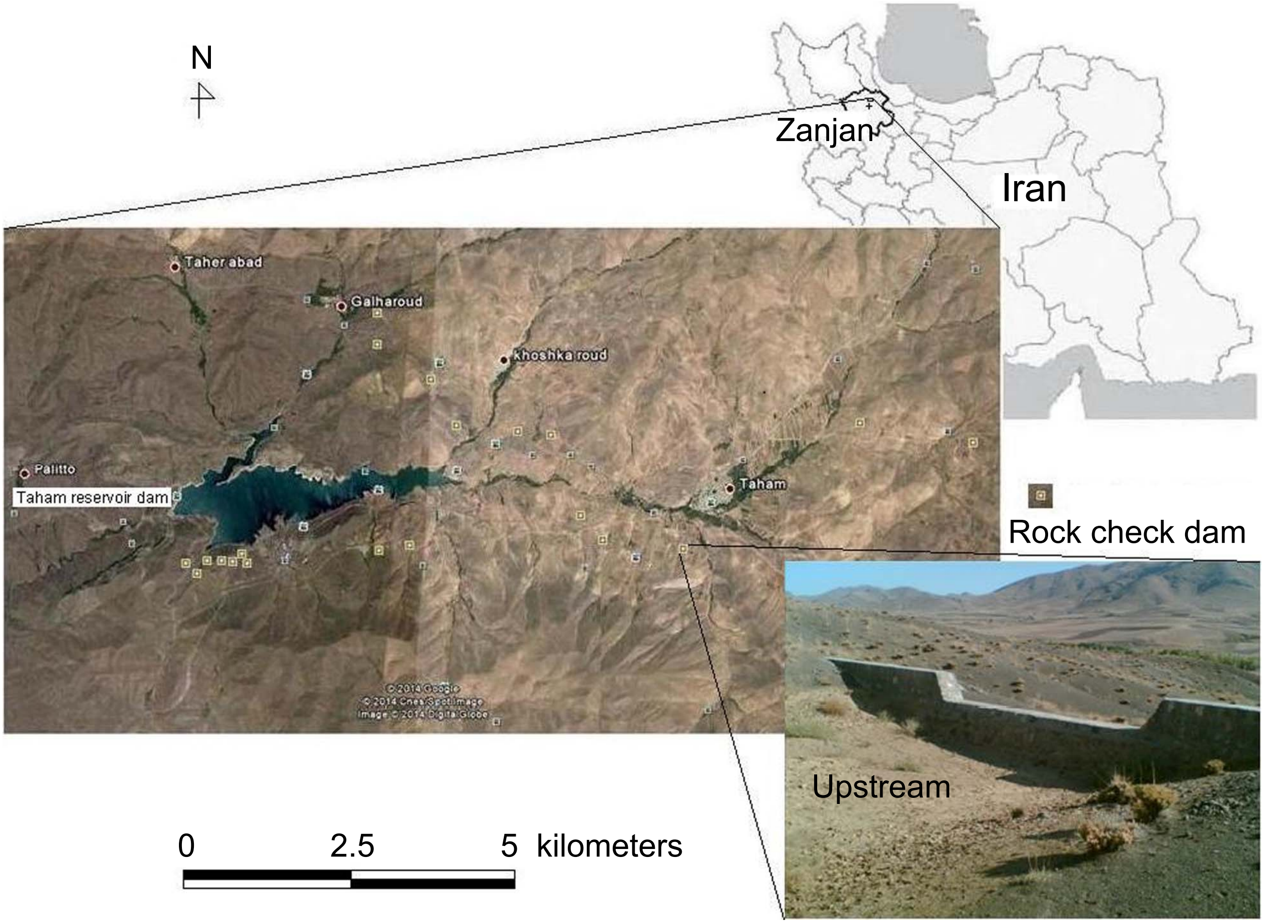

Fig. 1. Location of the cement rock check dams constructed in the first order gullies in the Taham Chai catchment, NW Iran.

Inceptisols and Entisols according to the Soil Taxonomy classification system (Soil Survey Staff, 2010). Soil erosion is severe in the area, particularly in rainfed agricultural areas where plowing is usually done perpendicular to the slope contour lines. Sheet, rill and gully erosion are the most common types of soil erosion in the area which transports large amounts of sediment to the Taham Chai river (Fig. 2b). Gullies are most often developed in steep areas that are dominated by highly erodible soils and have low densities of vegetation cover. Soil conservation practices are essential to reduce soil erosion and sediment, and protect soil productivity in the area.

2.2. Study catchments

Various check dams including cement rock check dams and loose rock check dams have been constructed in the for preventing floodwater and trapping sediment in 1994. The cement rock check dams form about 85% of the conservation structures in the area. These conservation structures are generally composed of several drainage tubes and a trapezoidal spillway for releasing excess flood. This type of check dams similar to concrete dams are almost impermeable, contain holes through which sediments can pass, especially when they are not totally consolidated (Romero-Díaz et al., 2012). Some check dams were constructed consecutively along permanent gullies or valleys where sediment production rates are very high (Fig. 3a). Field observation shows that the sediment retention performance of check dams is high in early spring when rainfall is frequent and erosive (Vaezi and Abbasi, 2012). Some of these structures, which were installed in agricultural areas, have rapidly been filled by eroded soil particles from upland

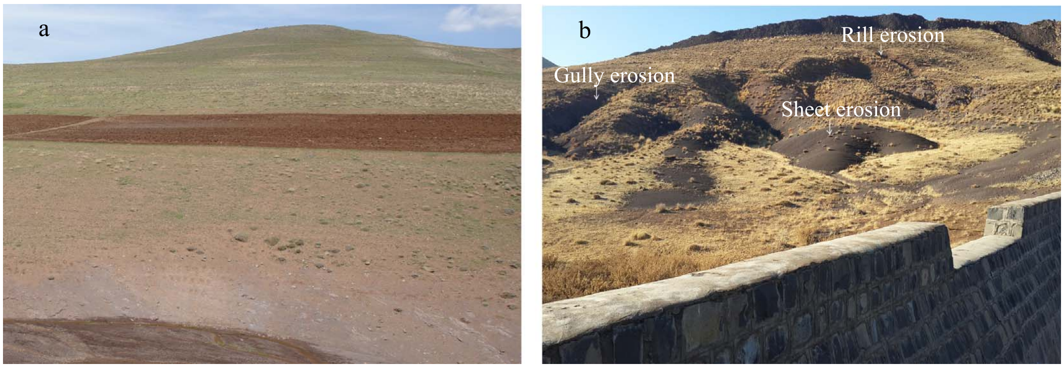

Fig. 2. The pasture catchment with weak vegetation cover and under agricultural land use change (a) and different soil erosion types in the uplands of the check dam (b) in the Taham Chai catchment, NW Iran.

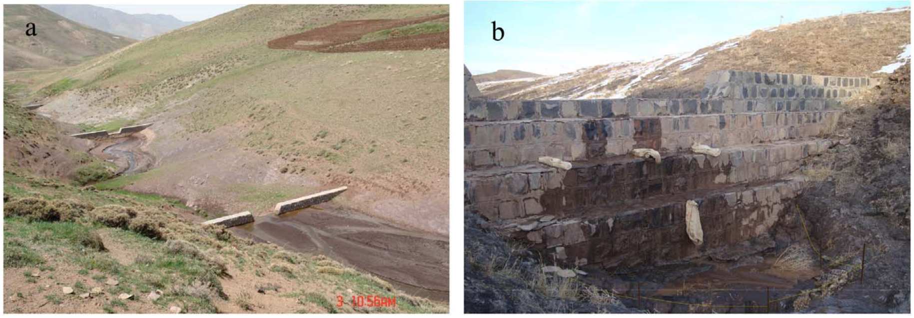

Fig. 3. The cement rock check dams constructed consecutively along the channel (a) and cement rock check dam equipped with the sacks and stilling basin to collect passed sediment (b) in the Taham Chai catchment, north west of Iran.

erosion and gully development.

Twenty cement rock check dams constructed in the first order gullies were selected to investigate the soil particle erodibility and the ability of check dams to retain sediment material. The location of the check dams was georeferenced by a GPS (Fig. 1). Each check dam covered a small drainage surface ranging from 1.04 to 2.87 ha which was mapped by GPS. The GPS was moved in water divide lines from upland of each check dam. The process of sediment deposition behind a check dam can directly indicate sediment yield in the drainage area of the check dam (Mouri et al., 2013). The drainage area of a check dam can be regarded as a catchment system (Mouri et al., 2013). In these small catchments, limited factors such as slope steepness, vegetation cover and soil type contribute to sediment transport while in the large scale, these factors along with other factors, including mass movements, riverbank erosion and characteristics of surface drainage network affect the sediment yield (de Vente et al., 2013; Zhang et al., 2015). Thus, the study on the sedimentation process on a small scale can give reliable information about the type of eroded material and the dominant factors controlling soil erosion in this catchment. The selection of the check dams was heterogeneous, based on the drainage surface area, slope steepness, vegetation cover, and soil properties. Additionally, check dams must contain less sediment material than their maximum storage capacity, mostly about 80% to be able to trap sediment materials in the monitored flood events. Slope steepness of each catchment was obtained by the proportion of the height difference of the maximum and the minimum elevation along the gully (ΔH) and the root of the catchment area ($A^{0.5}$). In order to determine vegetation cover, three locations including: the most upstream point of the gully, and right and left side of the gully were considered in each drainage area and the GSA image analyzer (Acosta et al., 2015) was used to analyses vertical photos of the surface vegetation cover (grasses and wheat) in small vegetation plots 1 m × 1 m with three replicates (Molina et al., 2008) (Fig. 4). The vegetation plots were also used to provide soil samples and field measurements of soil infiltration rate. Soil infiltration rate was measured using the one-dimensional water flow into the soil per unit time by double-ring infiltrometer (Bouwer, 1986). Soil bulk density (BD) was determined in the undisturbed sample collected by a steel cylinder with 5 cm in diameter and depth at the vegetation plots in the field. Three 2 kg disturbed soil samples were collected from 0 to 30 cm depth and left to dry in the air before being sieved to 2 mm for laboratory soil analysis. Also, three 2 kg undisturbed soil samples were collected using the steel cylinder from the soils to determine soil structure characteristics in the lab.

2.3. *Field measurements of sediment*

In order to evaluate the effectiveness of the cement rock check dams in trapping sediment, sedimentation was monitored before and after the check dams in different flood events over one year from April 2010 to April 2011. The sediment yield for each catchment (Mg ha^{-1} $year^{-1}$), was determined using the sum of sediment mass passed over the check dams and deposited behind the check dams per the catchment area (ha) and year (Verstraeten and Poesen, 2002):

$$SY = \frac{SSM}{A \cdot Y} = \frac{SM_d + SM_p}{A \cdot Y} \tag{1}$$

where, SY is sediment yield (Mg ha^{-1} $year^{-1}$), SSM is the incoming sediment in the check dam which equal to the sum of sediment mass deposited behind check dam (SM_d) and sediment mass passed over the check dam (SM_p), A is catchment area (ha) and Y is age of the check dam (years). The sediment mass passed over the check dams was determined using sediment collected in both sacks closed to the outlet tubes and the stilling basin. The stilling basin was a hydraulic structure designed at the downstream side of the check dam to the reducing the flow velocity to the acceptable/nonerosive limit resulting in sediment deposition. It was surrounded to filter sediments and deposit them in the stilling basin (Fig. 3b). The SM_d was also determined using multiplying the sediment volume, SV (m^3) by the average dry bulk

Fig. 4. Vegetation cover at plots 1 m × 1 m from a pasture land (a), and rainfed wheat land (b) from a drainage area in the Tahahm Chai catchment to use for the GSA image analyzer (Acosta et al., 2015).

density of the deposited material, $\overline{BD}$ (Mg m^{-3}):

$$SM_d = SV \cdot \overline{BD} \tag{2}$$

In order to determine SV, the change of sedimentation depth was measured in ten points on the sedimentation area behind the check dam in each event. These points were selected systematically in the sedimentation area behind the check dam with 2 m and 3 m intervals in width and in length, respectively. The volume of sediment deposition (m^3) was calculated using multiplying sedimentation area (m^2) and the depth average of deposited sediment (m). $\overline{BD}$ was obtained by the average of dry bulk density of undisturbed sediment samples taken using the steel cylinder (Molina et al., 2008) in ten sedimentation points. Trap efficiency (TE) which represents the ratio of deposited sediment behind the check dam to the total incoming sediment in the check dam for a given period (Verstraeten and Poesen, 2002) was determined using the ratio of SM$_d$ and SSM for all events during the study period:

$$TE = \frac{SM_d}{SSM} \tag{3}$$

where TE is the trap efficiency (Mg Mg^{-1}) and SM$_d$ is sediment mass deposited behind the check dam (Mg) and SSM is the incoming sediment in the check dam (Mg).

The cylinder sediment samples taken from the behind check dams were used to determine the GSD of stored sediment. The sediment materials collected in the sacks and the stilling basin were sampled and a composite sediment sample was taken from the two to determine the GSD of sediment passed from the check dams. Runoff data was essential to interpret the variation of sediment production and grain sized distribution at the event scale. Since the installation of runoff equipment in the gullies was usually expensive and hard, there was no possibility to collect runoff and measurement in each flood event. So, the rainfall erosivity index (EI$_{30}$) related to each flood was used to interpretation of flood characteristics. The EI$_{30}$ is the characteristics of rainfall which reflects the potential ability of rainfall to cause soil erosion by water (Wischmeier and Smith, 1978). This index was calculated using the kinetic energy of each rainfall, E (J m^{-2}) and the maximum 30-min rainfall intensity, I$_{30}$ (mm h^{-1}). The E was computed using the multiplying rainfall height by the KE. The KE was determined using following equation (Wischmeier and Smith, 1978):

$$KE = 11.8 + 8.73 \mathrm{Log}_{10} I \tag{4}$$

where KE is the kinetic energy per unit area and rainfall height (J m^{-2} mm^{-1}) and I is the rainfall intensity (mm h^{-1}). Data of the recording rain gauge located in Zanjan was used to compute I and I$_{30}$ in each event.

2.4. Laboratory analysis

In the undisturbed soil samples aggregate size distribution was determined using a set of sieves (12.7, 9.75, 5.6, 4.75, 2 and 0.25 mm) and the mean weight diameter (MWD) of aggregate fractions was computed accordingly. In order to determine aggregate stability, MWD of water-stable aggregates (MWD$_{wet}$) was computed in a 100 g 6–8 mm aggregate sample by moving of the aggregates in a water cylinder (Angers and Mehuys, 1993) with 20 rotations in min for 1 min (Vaezi and Akbari, 2015). In the disturbed soil samples, exchangeable sodium percentage (ESP) was obtained based on the Na$^+$ extracted by 1 M NH$_4$Ac. Organic carbon content was determined by Walkly and Black (1934) method and the multiplied by 1.72 to determine organic matter content. Additionally, soil erodibility factor (K) as one of factors controlling soil erosion in the catchment was estimated using the USLE (Universal Soil Loss Equation) procedure. The multiregression equation was applied to estimate K for each sampling point in the catchments (Wischmeier and Smith, 1978):

$$K = 2.8 \times 10^{-7} M^{1.14} (12 - a) + 4.3 \times 10^{-3} (b - 2) + 3.3 \times 10^{-3} (c - 3) \tag{5}$$

where K is soil erodibility factor in Mg h MJ^{-1} mm^{-1}, M is [(100-% clay) × (% very fine sand + % silt)], a is % organic matter content, b coefficient is structure code and c is infiltration rate class. The b coefficient was determined using the size and the shape of soil aggregates and the c coefficient was obtained using the measurement of infiltration rate by double rings method (Vaezi et al., 2008).

In order to understand the soil particle erodibility and determine the effectiveness of check dams in trapping soil particle, grain size distribution (GSD) was determined in the soil and sediment (passed and stored) samples. Toward this, gravel was determined by weighing of 2–7.5 mm fragments (Gee and Bauder, 1986) and size distribution of the < 2 mm fraction consisting sand (2–0.05 mm), silt (0.05–0.002 mm) and clay (< 0.002 mm) was determined by the Bouyoucos hydrometer method (Gee and Bauder, 1986) in the samples. The GSD was determined using the percentage of oven-dried mass of given grain in a 100-g soil/sediment sample.

2.5. Determination of soil particle erodibility and check dam effectiveness

Most of sediment transported to the out let of the catchment (check dam) was originated from eroded soil on the hillslopes. This part of sediment was transported by surface runoff and delivered to the gully and eventually transported to the check dam. The proportion of particle percentage in the sediment and in the original soil was used as a measure of soil particle erodibility. According this measure, the erodibility of each soil particle varies with the variation of the grain size distribution (GSD) in sediment. When the particles percentage are the same in the original soil and sediment shows that the erodibility of all soil particles in the catchment are the same. The effectiveness of the check dams in sediment trapping was also assessed using comparison of the GSD between sediment stored behind check dams and sediment passed the check dams. The remaining capacity of each check dam shows the capability of a check dam to trap sediment material. This capacity was determined by assessing the difference between the initial check dam volume and total sediment volume stored behind the check dams since the time of construction.

2.6. Data analysis

Normality assumption for all data was evaluated using the Sahapiro-Wilk test (Shapiro and Wilk, 1965) before comparing the means of dependent variables. Catchment area, slope steepness, vegetation cover, and soil erodibility factor were analyzed as variables which may affect sediment yield and the erodibility of soil particles in the catchments. The Pearson correlation matrix (r) was used to obtain the dependency of the sediment yield or the erodibility of soil particles on these drainage characteristics. The Duncan's test was also used for the analysis of variance to compare the GSD between the original soil and sediment in the drainage areas. A 95% probability level was used in the statistical analyses. All data analysis was performed using SPSS version 22.

3. Results

3.1. Characteristics of drainage areas

Table 1 shows some characteristics of the drainage areas in the Taham Chai catchment. The drainage areas have relatively high slope steepness ranging from 15 to 32%. Vegetation cover (grasses and wheat) is sparse, varying from 9.08 to 13.40%. The soil erodibility factor (K) ranged from 0.023 to 0.044. Table 2 shows mean soil properties of twenty drainage areas in the Taham Chai catchment. The soils are mostly sandy loams with 52.8% sand, 27.2% silt, and

Table 1
Some characteristics of the catchments in the study area.

Check dam no.	Drainage area (ha)	Slope steepness (%)	Vegetation cover (%)	Soil erodibility factor (Mg h MJ^{-1} mm^{-1})	Trap efficiency (Mg Mg^{-1})	Sediment yield (Mg ha^{-1} year^{-1})
1	1.242	24	12.33	0.033	0.56	3.987
2	1.038	15	11.42	0.039	0.54	0.799
3	1.413	22	12.5	0.042	0.82	3.850
4	1.103	20	13.07	0.030	0.61	2.962
5	2.293	24	9.11	0.037	0.82	8.629
6	1.942	20	10.28	0.043	0.65	4.910
7	1.361	18	11.06	0.035	0.54	0.310
8	2.081	25	10.96	0.032	0.85	6.391
9	1.961	20	11.71	0.025	0.68	1.370
10	2.070	22	9.43	0.042	0.81	7.439
11	2.334	20	10.67	0.0366	0.75	3.504
12	2.281	24	10.23	0.040	0.79	6.196
13	2.866	16	12.8	0.031	0.66	0.612
14	1.220	19	13.4	0.034	0.54	1.969
15	1.233	23	9.42	0.044	0.77	8.983
16	1.194	24	11.07	0.030	0.81	6.254
17	1.182	21	11.23	0.023	0.63	2.200
18	1.876	16	10.04	0.031	0.66	1.880
19	1.335	20	10.4	0.037	0.74	8.098
20	1.651	32	9.08	0.039	0.88	14.242

Table 2
Soil physicochemical properties of the catchments in the study area.

Soil property	Mean ± StD	Shapiro-Wilk test
Sand (%)	46.52 ± 14.75	0.33
Silt (%)	23.92 ± 8.39	0.80
Clay (%)	17.54 ± 7.37	0.88
Gravel (%)	12.01 ± 3.35	0.29
BD (g cm^{-3})	1.59 ± 0.05	0.04
MWD of aggregate size distribution (mm)	2.20 ± 0.36	0.21
MWD of water-stable aggregates (mm)	1.54 ± 0.62	0.01
Saturated hydraulic conductivity (cm h^{-1})	3.57 ± 1.51	0.84
Organic matter (%)	1.64 ± 0.50	0.27
Calcium carbonate equivalent (%)	18.23 ± 6.18	0.44
ESP	4.81 ± 2.21	0.24

20.0% clay. The soils are calcareous with calcium carbonate equivalent (CCE) contents ranging from 7.6 to 30.9% and pH ranging from 7.9 to 8.3. Soils have low amounts of organic matter (about 1.64%) and moderately saturated hydraulic conductivity (3.6 cm h^{-1}, on average). Aggregates were relatively instable in water with a MWD_{wet} of 1.54 mm, which make them prone to breakdown by raindrops impact. Bulk density was relatively high (1.59 g cm^{-3}) which can be related to higher percentages of coarse fractions such as grave (13.7%) and sand and lower aggregation rate. All data except BD and MWD_{wet} showed normal distribution as evaluated using the Shapiro-Wilk test (Table 2). Normality assumption was confirmed for BD and MWD when their data were transformed using the square and inverse transformation, respectively.

3.2. *Sediment yield in the drainage areas*

Trap efficiency of the check dams ranged from 54% to 0.88%. Sediment yield in the drainage areas ranged from 0.31 to 14.24 Mg ha^{-1} year^{-1} with an average of 4.73 Mg ha^{-1} year^{-1} (Table 1). Result of the normality test for the sediment yield data showed that S—W test was equal to 0.12 ($p > 0.05$) indicating the sediment yield data was normally distributed and so the data could be used directly to compare means among the catchments. Results of mean square of sediment yield revealed that a significant difference exists among the catchments in the sediment yield ($p < 0.001$).

The results of the correlation matrix for sediment yield and the catchments characteristics indicated that the relationship between sediment yield and the catchments area was statistically insignificant ($r = 0.32$) (Table 3). Sediment yield was positively correlated with slope steepness ($r = 0.80$, $p < 0.001$), vegetation cover ($r = -0.75$, $p < 0.01$), and soil erodibility factor ($r = 0.47$, $p < 0.05$). In other words, soil erosion was higher in the catchments where slopes were steep, soils were erodible, and vegetation cover (grasses and wheat) was

Table 3
Pearson correlation matrix of sediment yield, soil particle erodibility, and the catchment characteristics in the area.

Variable[a]	SA	SS	VC	EF	SaE	SiE	ClE	GrE	SY
SA	1								
SS	− 0.01	1							
VC	− 0.25	− 0.41	1						
EF	0.07	0.18	− 0.42	1					
SaE	− 0.01	− 0.37	0.32	− 0.44*	1				
SiE	0.21	0.49*	− 0.09	0.01	− 0.48*	1			
ClE	0.15	0.56**	− 0.30	0.36	− 0.48*	0.75**	1		
GrE	− 0.12	− 0.43	− 0.23	0.18	0.05	− 0.39	− 0.13	1	
SY	0.32	0.80***	− 0.75**	0.47*	− 0.53*	0.44*	0.52**	− 0.24	1

[a] SA: surface area; SS: slope steepness; VC: vegetation cover; EF: soil erodibility factor (K); Sae: sand erodibility (proportion of sand in sediment to original soil); SiE: silt erodibility (proportion of silt in sediment to original soil); ClE: clay erodibility (proportion of clay in sediment to original soil); GrE: gravel erodibility (proportion of gravel in sediment to original soil): SY: sediment yield.

* Significant at $p < 0.05$.

** Significant at $p < 0.01$.

*** Significant at $p < 0.001$.

Table 4
Multiple linear regression analysis for factors controlling sediment yield in the catchments.

Variable	Unstandardized coefficients	Standardized coefficients	*p*-Value
Constant	− 3.267	–	0.544
Slope steepness	0.622	0.672	0.000
Vegetation cover	− 0.860	− 0.317	0.008
Soil erodibility factor (K)	120.874	0.200	0.045

also poor. The three variables can also be defined as the major characteristics of a catchment in controlling soil erosion by water (Bonilla and Johnson, 2012). Multiple linear regression analysis was used to assess the variables and determine the major factors controlling sediment yield in the studied catchments (Table 4). Sediment yield was significantly related to the slope steepness, vegetation cover and soil erodibility factor (K) ($R^2 = 0.89$, $p < 0.001$). These catchment variables could explain 58%, 25% and 17% of the variance of sediment yield in the catchments, respectively.

3.3. Short term variation in sediment yield

Eleven runoff events were recorded in the catchments during the study period. This data in combination with the rainfall data available, enabled the study of how the sediment yield varies over a short time frame. Mean rainfall erosivity (EI_{30}) for the events was 5.65 MJ mm ha^{-1} h^{-1}. Sediment yield was strongly varied from each runoff event to the other. A significant positive relationship was found between the sediment yield of a runoff event and the EI_{30} ($R^2 = 0.88$, $p < 0.01$) of the corresponding rainfall event (Fig. 5).

3.4. The erodibility of soil particles in the catchments

Fig. 6 shows the result of grain size distributions, GSD (sand, silt, clay, and gravel) of total sediment eroded from the catchments (deposited behind check dams and passed over the check dams) and original soil. With regarding higher sediment connectivity in the catchments, the grain size distribution (sand, silt, clay, and gravel) of sediment (GSD) was compared to their distribution in original soil. On average, the sediment transported downstream had higher percentage of fine particles (35% silt and 34.85% clay) while having a lower content of coarse particles (sand and gravel, which is 30.2% of GSD of transported sediment). The soil particle erodibility was evaluated using the proportion of each particle percentage in the sediment to its percentage in the original soil (Fig. 7a). Romero-Díaz et al. (2012) also used this proportion as a measure to explore the movement of the different fractions from the source soils to the check dams. The catchments showed large differences in the GSD of the sediment compared to the original soil (Table 5). The sediment delivered to check dam had 1.46 more times silt and 2.05 more times clay than the original soil. Significant relationships were found between the rainfall erosivity (EI_{30}) and the erodibility of sand ($R^2 = 0.71$, $p < 0.01$), silt ($R^2 = 0.59$, $p < 0.05$), clay ($R^2 = 0.59$, $p < 0.05$) and gravel ($R^2 = 0.69$, $p < 0.01$) (Fig. 8). With an increase in the EI_{30}, the coarse particle erodibility i.e. sand and gravel was strongly increased.

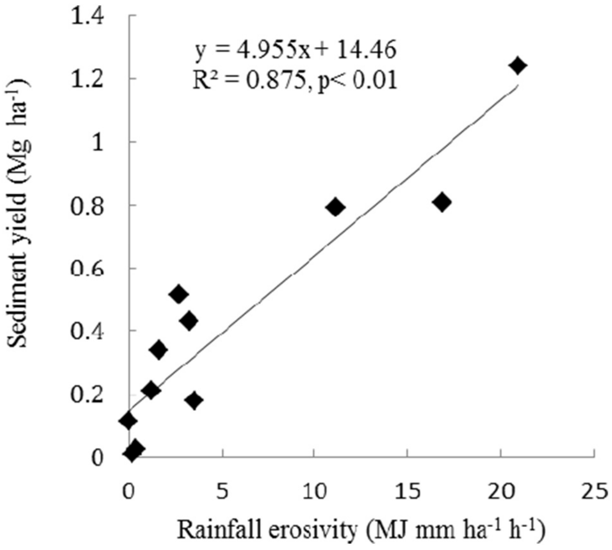

Fig. 5. Sediment yield versus event rainfall erosivity (EI_{30}) in the studied catchments.

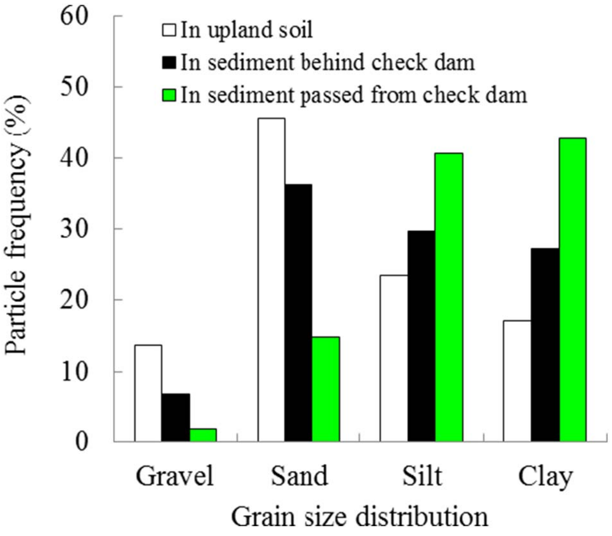

Fig. 6. Mean particle frequency of original soil, sediment deposited behind the check dam and passed over the check dam in twenty drainage areas.

3.5. Relationship between soil particle erodibility and drainage area characteristics

Univariate relationships between the soil particle erodibility and drainage area characteristics (slope steepness and vegetation cover) were also analyzed using the Pearson correlation matrix (Table 3). Based on the results, positive correlations were found between slope steepness and the silt erodibility ($r = 0.49$, $p < 0.05$) and clay erodibility ($r = 0.56$, $p < 0.01$). Negative correlation was observed between slope steepness and the gravel erodibility ($r = -0.43$, $p < 0.05$), while than that one for sand was no statistically significant ($r = -0.37$). Out of the soil particles, just the erodibility of sand was significantly correlated to the soil erodibility factor (K) ($r = -0.44$, $p < 0.05$). In the other words, catchments having erodible soils appeared to be less susceptible to the loss of sand. Drainage surface area and vegetation cover did not show significant correlation with the soil particle erodibility. However, clay, silt and gravel contrary to sand showed negative correlations with the vegetation cover.

3.6. Performance of check dams in trapping sediment materials

The GSD of sediment before and after check dam was used to determine the effectiveness of the check dams on trapping sediment and settling sediment material (Fig. 7b). Table 6 shows GSD of sediment deposited behind the check dams and sediment passed the check dams, and the comparison between the two in twenty drainage areas. The results indicated that the sediment deposited behind check dams was coarse–grained, with 36.11% sand and 6.97% gravel, while sediment that passed the check dams showed to be including less coarse particles

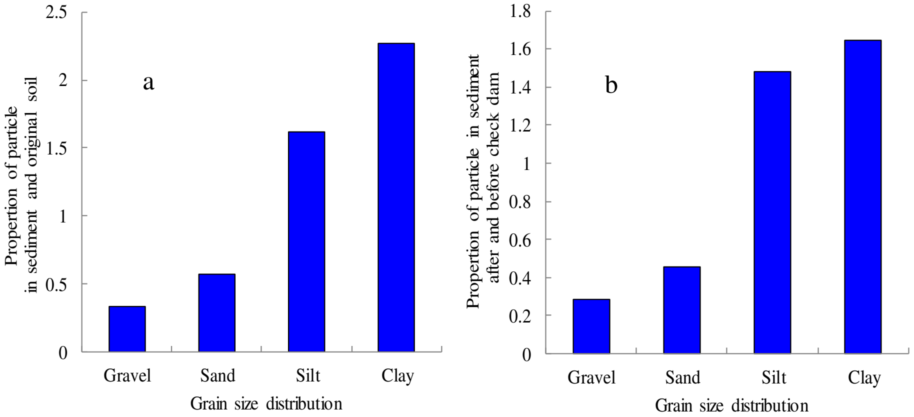

Fig. 7. Evaluation of soil particle erodibility (a) and effectiveness of check dams (b) using the comparison of grain size distribution in twenty drainage areas.

Table 5
Grain size distribution (GSD) of total sediment eroded from the catchments and the analysis of variance for comparing GSD between sediment and original soil in the catchments.

Variable	In total sediment eroded from the catchments		Analysis of variance for sediment and original soil	
	Mean ± StD	Shapiro-Wilk test	*F*	Mean square
Sand (%)	25.73 ± 6.35	0.65	61.37	5562.69***
Silt (%)	35.00 ± 4.87	0.61	15.33	880.26***
Clay (%)	34.81 ± 4.06	0.50	58.49	2054.67***
Gravel (%)	4.46 ± 1.29	0.14	102.13	253.51***

*** Significant at $p < 0.001$.

(14.84% sand and 1.93% gravel). In return, fine particles i.e. silt and clay showed to be dominant in the sediment that passed the check dams, about 40.55% and 42.68%, respectively. The sediment that passed the check dams had about 59% sand and 72% gravel less and 137% silt and 157% clay more than the sediment deposited behind the check dams. All the sediment GSD differences between behind check dams and passed the check dams were found to be statistically significant ($p < 0.001$). As shown in Fig. 9, the check dams provide a good selection of coarse particles from concentrated flows/floods in the gullies. The trap efficiency was used to evaluate the effectiveness of check dams in trapping incoming sediment. There was no significant relationship between the trap efficiency and the remaining capacity of check dam ($R^2 = 0.14$) (Fig. 10a). The trap efficiency is dependent on the characteristics of the inflowing sediment and the retention time of the water in the pond, which in turn are controlled by pond geometry

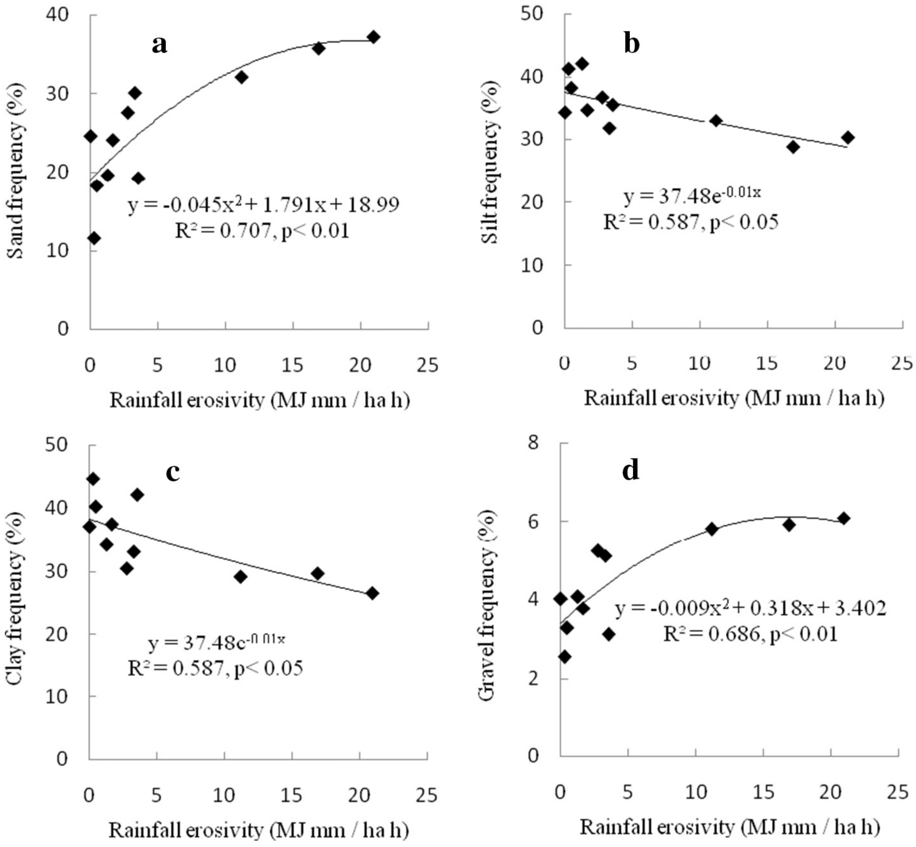

Fig. 8. Relationship between the rainfall erosivity and the frequency of sand (a), silt (b), clay (c) and gravel (d) in total sediment eroded from the catchments.

Table 6
Grain size distribution (GSD) of sediment deposited behind check dams and sediment passed over check dams, and the analysis of variance for comparing GSD between the two in the catchments.

Variable	In sediment deposited behind check dams		In sediment passed over check dams		Analysis of variance for sediment passed over check dams and deposited behind check dams	
	Mean ± StD	Shapiro-Wilk test	Mean ± StD	Shapiro-Wilk test	*F*	Mean square
Sand (%)	36.11 ± 12.51	0.17	14.84 ± 2.57	0.65	50.08	6655.63***
Silt (%)	29.68 ± 7.74	0.76	40.55 ± 6.16	0.98	18.30	890.01***
Clay (%)	27.24 ± 6.04	0.24	42.68 ± 4.51	0.99	73.48	2701.26***
Gravel (%)	6.97 ± 2.10	0.10	1.93 ± 0.73	0.07	133.69	863.18***

*** Significant at $p < 0.001$.

Fig. 9. The effectiveness of a cement rock check dams on trapping coarse particles from concentrated flow occurred along a gully in early spring.

and runoff characteristics (Verstraeten and Poesen, 2000). It is clear that for a given inflow rate, the trap efficiency decreases temporally with the reduction in check dam capacity due to deposited sediment. Sedimentation within reservoirs and in consequence decreasing the trap efficiency is a problem as it makes the structure less efficient (Verstraeten and Poesen, 2000). Significant relationships were found between the remaining capacity of check dam and the amount of trapped sand ($R^2 = 0.29$, $p < 0.05$), silt ($R^2 = 0.23$, $p < 0.05$), and clay ($R^2 = 0.21$, $p < 0.05$) while for gravel it was not statistically significant. The trapping of fine particles (silt and clay) shows an opposite trend with sand and decreased with increasing in the remaining capacity of check dam.

4. Discussion

4.1. Sediment yield and controlling factors

The ranges of sediment yield in the drainage areas were high as compared to regional datasets (Haregeweyn et al., 2008; Parehkar et al., 2013). Similarly, Polyakov et al. (2010) showed that in small semi-arid watersheds in southern Arizona, sediment yields were highly variable, ranging from 0.85 Mg ha^{-1} year^{-1} to 6.69 Mg ha^{-1} year^{-1}. Also Warrick and Mertes (2012) found that in a semi-arid basin, suspended-sediment yields varied by approximately an order of magnitude (7.4-53 Mg ha^{-1} year^{-1}). The higher sediment yield values in our study can be attributed to higher soil erosion rates and sediment delivery in the catchment. Various factors play a role in this: i.e. (1) the high intensities of erosive factors (raindrop impacts, and surface and concentrated flows) that are related to soil erosion factors such as slope steepness, poor vegetation cover, and higher soil erodibility factor (2) the small size of the catchments and hence less probability for sediment deposition before it reaches the stream network (Verstraeten and Poesen, 2002; Haregeweyn et al., 2008).

There was no significant correlation between sediment yield and drainage area. Inversely, Griffiths et al. (2006) noted that in 27 small drainage basins (< 1 km^2), the drainage area is one of the characteristics that can explain a part of the variation in sediment yield. Sediment yield from most basins generally decreased as the drainage area increased. In most sediment studies performed at the basin scale, it was found that sediment yield decreases as basin area increases (Avendaño Salas et al., 1997; Romero-Díaz et al., 2012; Vanmaercke et al., 2014). Similarly, Vanmaercke et al. (2011) found no clear negative relationships between sediment yield and catchment area in Europe. It seems, this relationship can be affected by more than only the catchment scale (de Vente et al., 2013). Since the drainage surface area of catchments is very small, with steeper slopes and poor vegetation cover, the system is well connected, and most eroded material can be delivered to the check dams and in consequence the surface area does appear to be more closely associated with erosion rates (Romero-Díaz et al., 2012). Thus, sediment delivery ratio (SDR) which indicates the ratio of sediment yield to gross erosion (Lane et al., 1997), in most catchments is relatively high, and catchments with larger drainage surface area could also produce relatively higher sediment. In some studies, positive correlation between specific sediment yield and the drainage area is associated with the channel erosion processes in the catchments (de Vente and Poesen, 2005, Verstraeten and Poesen, 2001; Haregeweyn et al. (2008).

Out of the variables controlling sediment yield, slope steepness and soil erodibility factor (K) were the important factors that could be considered constant in the short term. Slope steepness has important influences on precipitation retention, surface runoff and drainage rate in the catchments (Prasannakumar et al., 2011; Abu Salim, 2014). So, an increase in slope steepness increases the amount and velocity of the runoff and shear stress, which increases soil erosion and sediment load (Kinnell, 2012; Zhang et al., 2015). With an increase in the slope gradient, soil detachment may be enhanced through the increasing shear forces applied by the flow velocity and decreasing flow depth (Kinnell, 2012). The catchments with higher soil erodibility factor (K) appear to have also a higher potential to produce sediment. According the USLE, the higher K values occur when the soil has a higher percentage of erodible particles i.e. very fine sand and silt and lower percentage of organic matter content. Moreover, when the soil is weakly aggregated and has a lower permeability (Wischmeier and Smith, 1978; Vaezi et al., 2008). Out of the soil variables related to the K, clay and permeability had the highest variations among the catchments (42%) (Table 2). These two variables can be considered the major soil properties controlling K in the catchments. Increases in clay content and soil permeability decrease the soil's susceptibility to water erosion processes as well as sediment yield.

Vegetation cover was found to be the most important factor for decreasing sediment production in the catchments. It protects the soil surface from raindrop impact, improves the soil aggregation and infiltrability, increase the surface roughness, retain sediment and reduces runoff production (Pan et al., 2011; Rey and Burylo, 2014;

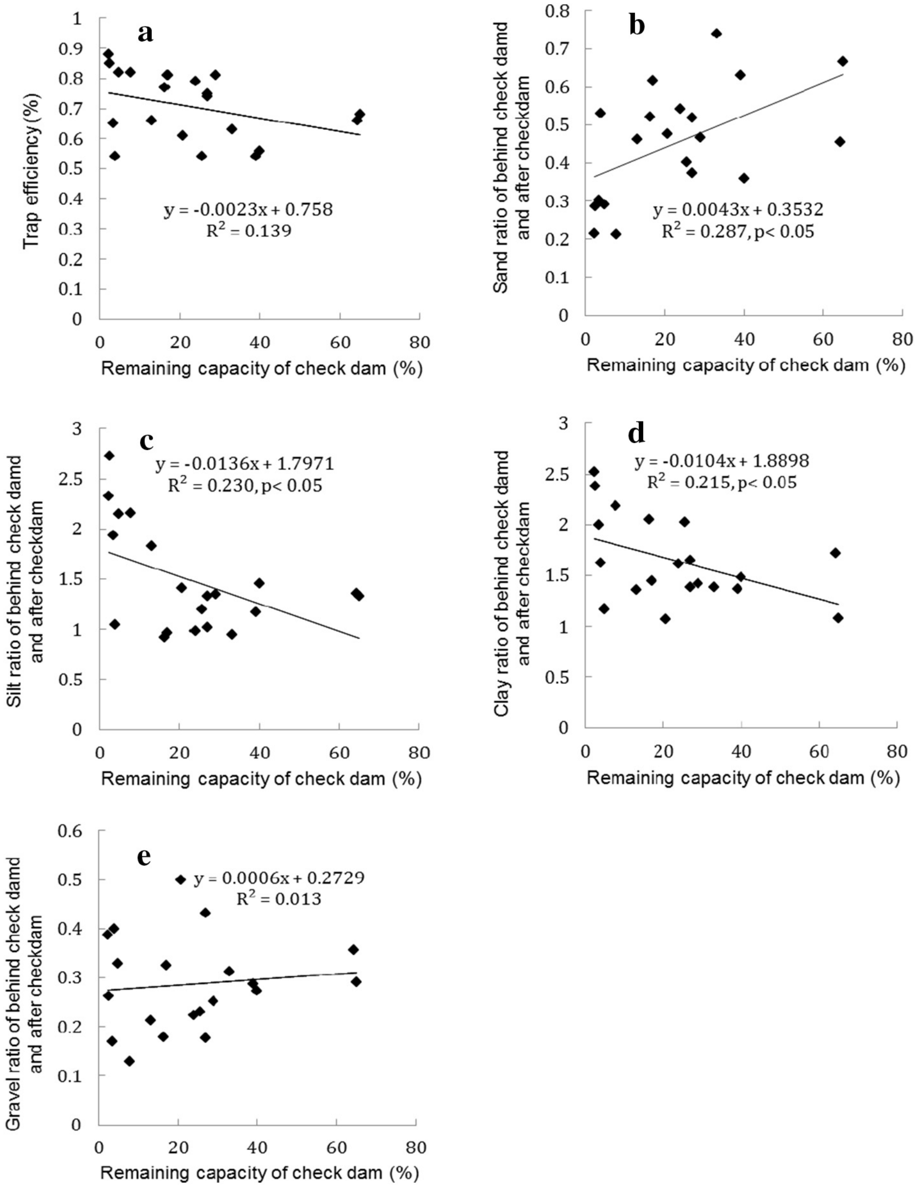

Fig. 10. Relationship between the remaining capacity of check dam and trap efficiency (a), sand ratio (b), silt ratio (c), clay ratio (d), and gravel ratio (e) of deposited sediment behind the check dams and passed sediment over the check dams.

Sun et al., 2016). Beside these, vegetation cover plays an important role in restoring sediment transport pathways (gullies) in catchments (Molina et al., 2009). Relatively small changes in vegetation cover can have major implications on sediment yield in the drainage areas, as vegetation cover exerts a non-linear control on the production and transfer of sediment (Chen et al., 2016; Quiñonero-Rubio et al., 2016). Additionally, at long time scale, the vegetation cover and related litter fall played a central role in the relation to hydrological characteristics and soil erodibility, and sediment load in the drainage areas (Peng and Wang, 2012; Shit et al., 2014). However the check-dams have a large and instantaneous impact on sediment yield over a restricted time period (Quiñonero-Rubio et al., 2016), while improving vegetation cover with prevention of the land use change and overgrazing can result important sustained effects at a lower economic cost.

Results revealed that the relative impacts of the factors controlling sediment yield in the semi-arid catchments were slope steepness > vegetation cover > soil erodibility factor, respectively. Findings by Ai et al. (2015) in the semi-arid loess area in China indicated that the relative impacts of the variables on sediment yield were soil > runoff > rainfall > topography > vegetation. In our study, steep steepness is the most important factor determining sediment yield in the catchments. The role of slope steepness or topography factor in sediment yield has been well known in the various studies (Verstraeten and Poesen, 2001; Warrick and Mertes, 2012; Zhang et al., 2015). An increase in slope steepness causes a decrease in the rainwater retention in the drainage area and leads to an increase in runoff volume and concentration which is the cause of sheet, rill and gully erosion in the catchments (Chamizo et al., 2012). The result of the vegetation cover analysis proves the significance of surface vegetation cover to decrease soil erosion and it may help the planners and managers to take proper decision for the conservation of soil (Shit et al., 2014). Thus, soil erosion can be controlled by maintaining natural pasture vegetation cover (grasses) and planting of various species of vegetation in the catchments both in the field as well as in the riparian zone of the drainage network (Garcia-Estringana et al., 2013; Zhou et al., 2016; Keesstra et al., 2016).

4.2. Event variation of sediment yield

Sediment yield in each runoff event was significantly affected by rainfall erosivity (EI_{30}) (Fig. 5). Higher sediment yields were likely the result of increased runoff events caused by intensive rainfall with higher EI_{30}. In accordance this, Lee and Yang (2010) estimated sediment yield during storms and concluded that with an increasing rainfall intensity, the maximum of the sediment production resulting from an instantaneous rainfall excess input increased and the time to peak decreased. Shin et al. (2013) studied the sediment and hydrological response to vegetation recovery in four sites with different vegetation cover in a small watershed. Their study showed that sediment yield from the watershed depended strongly on rainfall erosivity index. The greatest rainfall event with 113.5 mm h^{-1} of intensity generated an excessive sediment yield by landslide and debris flow. Robichaud et al. (2013) showed the largest maximum-10 min rainfall intensities produced the highest peak flow rate as well as sediment yield in the small catchments. In our study, the higher dependency of sediment yield on the rainfall erosivity in the runoff events might be explained by the connectivity of runoff (overland flow and concentrated runoff) and sediment in the catchments. The catchments are relatively small (< 3 ha) with higher slope steepness ($> 15\%$). Under this condition, sediment connectivity, i.e. the degree of linkage which controls sediment fluxes between sediment sources and downstream areas/out let can ensure an effective downstream transfer of sediment (Cavalli et al., 2013). Croke et al. (2005) noted two types of connectivity for sediment in the catchments: direct connectivity via gully, and diffuse connectivity as surface runoff. Sediment connectivity in the catchments depends on the intensities of the events that have occurred in the area as noted by Borselli et al. (2008). Since the rainfalls were relatively intensive (> 25 mm h^{-1}), flow connectivity as well as sediment connectivity could be occurred in the catchments. In a small rainfall event with lower EI_{30} value (< 5 MJ mm ha^{-1} h^{-1}), all generated sediment on the hillslope were redeposited before reaching the outlet and so SDR as well as sediment yield was very low. In a bigger storm ($EI_{30} > 10$ MJ mm ha^{-1} h^{-1}), the SDR was larger, and the sediment detached on the hillslopes was transported to the gully and exported to the outlet of the catchment (check dam). Additionally, the bigger storms occurred in early spring when the vegetation cover in the catchments was poor and some agricultural lands were ploughed for spring cultivations (Fig. 5). This result indicates that the maintenance of natural vegetation cover as well as declining agricultural practices in this period is advisable for minimizing runoff and soil erosion in the catchments (Molina et al., 2008; Shin et al., 2013). Destroying vegetation cover in the pasture through grazing and trampling by livestock therefore appear to cause deterioration of soil physical properties and to increase soil erodibility particularly in semi-arid region (Zhou et al., 2010). Cultivation practices are also known to increase the soil erodibility of semi-arid rainfed lands by declining soil organic matter, destroying the aggregates and decreasing soil infiltration rate (Vaezi and Bahrami, 2014).

4.3. Soil particle erodibility

Sediment eroded from the catchments was enriched by fine particles (clay and silt). Gilley et al. (2011) showed that both soil erosion and GSD of sediment can be strongly influenced by the runoff rate. Fine sediment, in contrast to coarse sediment, moves predominantly in suspension and can be transported by different types of transport processes in a catchment (overland flows and concentrated flows) while, coarse particles are usually transported only by means of concentrated flow (Toy et al., 2002). Concentrated flows can be mostly observed in rills when rainfall is intensive and retention capacity of the catchment is very low (Foster et al., 1995). These two factors are commonly the dominant mechanisms of water erosion following a disturbance on steep slopes or where the ground cover is sparse (Pierson et al., 2011). In various studies, the relationship between runoff and rainfall characteristics has been well known (Bahat et al., 2009; Vaezi, 2014). At the event scale, runoff rate in a catchment is mainly affected by the characteristics of the rainfall (Vaezi, 2014). It can affect the sediment production as well as GSD of sediment in a catchment. Although detachability of coarse particle size classes decreases with increasing particle size, which is associated with the increased physical mass (Farmer, 1973), in this study coarse particles (sand and gravel) were mostly eroded in the intensive rainfalls (with higher EI_{30}) in the catchments. Increase in the EI_{30} was due to the increases in both the rainfall intensity and rainfall duration (Wischmeier and Smith, 1978; Vaezi et al., 2016). In this condition, runoff coefficients could be high and the surface flows could be joined together quickly and form concentrated flows in the slope down area. Although these rainfall events were rare during the study period ($EI_{30} > 10$ MJ mm ha^{-1} h^{-1}), they were typically powerful and could transport coarse particles from the upland area to the drainage network.

The results indicated that clay is the most susceptible soil particle to water erosion processes in semi-arid catchments. Indeed selective transportation of fine particles through surface and interrill flows enriched the sediment yield in fine particles and enhanced coarse particles in the eroded soil relative to the original soil (Foster et al., 1995). This result is in contradiction to previous observations that showed that on plot scale, silt and very fine sand are the most susceptible soil particle sizes to be detached and transported by water erosion processes (Wischmeier and Smith, 1978, Bonilla and Johnson, 2012). Although, clay minerals mostly improve soil aggregation in the semi-arid regions (Vaezi and Akbari, 2015), most of aggregates in the area are generally unstable due to the very low organic matter content (Vaezi and Abbasi, 2012). Thus, the aggregates are easily broken down into primary particles by erosion processes particularly when soil surface is left unprotected due to the lack of vegetation cover (Moncada et al., 2014). Aggregate disruption leads to surface sealing during rainfall, causing increased runoff and consequently soil erosion in these areas (Canton et al., 2009). Accordingly, loose fine particles are easily washed from cultivated lands and sparsely vegetated pastures by surface runoff and are transported to gullies, where the eroded particles are transported quickly to the check dams. In accordance with this, Haregeweyn et al. (2008) found that sediment yield increase with increasing the finer soil particles in the catchments.

4.4. Factors controlling the soil particle erodibility

Catchments with higher slope steepness showed higher potential to transport fine particles to check dams. In contrast, Shi et al. (2012) showed that in steep slopes ($> 20\%$), large sediment sizes are easily transported due to the strong gravity and inertial forces in the direction of the slopes; rolling transport may increase with increasing slope gradients. Coarse particles were transported by rill fow, rather than by interrill fow, due to basic differences in the detachment and transport mechanisms (Schiettecatte et al., 2008; Shi et al., 2012). In this study, fine particles (clay and silt) are easily transported by surface flows on the catchment. The surface flows had higher magnitudes in sediment production than the concentrated flows in the catchments. Most of surface flows were produced on steep slopes especially when the rainstorms were not very intensive. The drainage surface area and vegetation cover did not appear to be important factors in the soil particle erodibility in the catchments. This result might be explained by the lower land surface and connectivity of flow system in the catchments. In these conditions, most of eroded particles easily could arrive to the out let. Results of correlation matrix showed a relative role of the vegetation cover in controlling both fine particles and very coarse particles (gravel) in the catchments. Martínez-Mena et al. (2000) evaluated the effects of vegetal cover on sediment particle size distribution at natural plots in a semiarid environment. Although vegetal cover reduced the energy available for soil erosion at the plots, no differences were found in particle size distribution after rainfall of varying intensities.

4.5. Effectiveness of check dams

The check dams in the area showed higher effectiveness in trapping coarse sediment (gravel and sand). Verstraeten and Poesen (2000) noted that the particle-size distribution of the incoming sediment is dependent on the soils in the catchment that are being eroded and on the sediment delivery processes. As mentioned above, the intensive rainfalls eroded higher coarse sediments (sand and gravel). The coarser material will have a higher settling velocity, and less time is required for it to be deposited. Very fine material, on the other hand, will need long retention times to deposit (Verstraeten and Poesen, 2000). According to this result, Abedini et al. (2012) found that the check dams are efficient in trapping coarser fractions (cobbles, gravel, and coarse sand) as the weight of sediment deposited behind the check dams increased from the first one to the last one. Romero-Díaz et al. (2012) concluded that out of 17 gabion and concrete check dams in three check dams, the clay fraction was higher than in the originating soils, while in six check dams, the silt fraction was higher and in eight check dams, the sand fraction was greater. Thus, in order to retain fine sediments behind check dams, closed check dams such as slit-check dams can be built in the downstream of gullies. These check dams do not allow finer sediment to pass through lower discharges. Moreover, the use of consecutive check dams along the gullies similar to Fig. 4, can be successfully to trap finer sediment in the catchments particularly where cultivation activities and over-grazing are intensive. The remaining capacity of check dam was an important factor in trapping sediment materials. The check dams with higher remaining capacity, incoming fine particles easily passed the check dams and in consequence the sediment deposited behind the check dams enriched by sand. Inversely, in the check dams with lower remaining capacity, sediment is mostly enriched with the fine particles. Since fine particles included the higher magnitude of sediment passed the check dams, trap efficiency decreased with increasing remaining capacity of check dam.

5. Conclusion

In this study, sediment yield, grain size distribution of sediment, and the soil particle erodibility were investigated by check dams installed in order one gullies in small catchments. The sediment yield for each catchment was determined using the measurement of sediment mass passed and deposited behind the check dams. Variation of sediment yield in the catchments was associated with large differences in slope steepness, vegetation cover and soil erodibility factor (K) among them. Surface vegetation cover was the major factor for preventing sediment production in the catchments. Sediment yield in the flood events was strongly influenced by the rainfall erosivity (EI_{30}). With an increase in the EI_{30}, sediment yield increased in the drainage areas. The analysis of grain size distribution (GSD) for sediment (deposited and passes) and original soil was performed to determine soil particle erodibility and effectiveness of check dams in trapping sediment material. The erodibility of soil particles was no affected by the land surface area and vegetation cover of the drainage area, whereas slope steepness was the major characteristic determine it in the catchment. The erodibility of clay and silt was positively correlated to slope steepness. Clay was the most erodible soil particles in the catchments. The check dams showed lower performance in retention of fine particles particularly clay, while they were more effective for trapping coarse sediment (sand and gravel). The effectiveness of check dams in trapping sediment was associated with the remaining capacity of check dams. The check dams with higher remaining capacity showed the lower trap efficiency particularly for fine particles (silt and clay). Therefore, in order to decline sediment yield of the catchments, the maintenance of natural vegetation cover (grasses) through minimizing both grazing and agricultural practices is essential in the area. Moreover, there is need the number of check dams along the gullies should be kept high to reduce the amount of sediment entering the river. The application of closed check dams such as slit-check dams can also help to trapping sediment especially fine particles.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.catena.2017.05.021. These data include the Google map of the most important areas described in this article.

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