

Modeling sediment yield in semi-arid pasture micro-catchments, NW Iran

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ABSTRACT

Modeling sediment yield is a complex task due to the nonlinearity of natural processes intervening at slope and basin scale. In this study slope steepness, vegetation cover, and soil properties along with sediment yield were studied in twenty pasture micro-catchments in a semi-arid region, NW Iran in order to understand and predict sediment yield. The micro-catchments included only one first-order gully and drain toward a rock check dam in the outlet. The sediment yield of each micro-catchment was calculated using the measurement of sediment mass in the check dams for a sixteen-year period (1994-2010). Relationships between sediment yield and drainage characteristics were analyzed using correlation matrix and multiple linear regression method. Based on the results, sediment yield in the micro-catchments varied from 0.29 Mg ha⁻¹ yr⁻¹ to 14.81 Mg ha⁻¹ yr⁻¹, with an average of 5.04 Mg ha⁻¹ yr⁻¹. It was significantly related to slope steepness, vegetation cover, and soil organic matter using a linear regression equation ($R^2 = 0.87$, $p < 0.001$). The slope, vegetation and soil organic matter explained about 44, 23 and 20% of total variance in sediment yield, respectively. The spatial validation of the model using data from eight different micro-catchments located nearby showed that the model efficiency is 0.94. Therefore, the model can be used for predicting sediment yield in this and similar study area, with a high degree of accuracy.

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INTRODUCTION

Soil erosion by water is the most serious form of land degradation in many areas of the world particularly in arid and semi-arid regions (IPCC, 2008; Sarah & Zonana, 2015; Turgut, 2015; Laudicina et al., 2015; Ochoa et al., 2016; Prosdocimi et al., 2016a) where the soil formation rate is usually lower than the rate of soil erosion by water due to the accelerated soil erosion as a consequence of human misuse and abuse of the soils (Lieskovský & Kenderessy, 2014; Erkossa et al., 2015; Dai et al., 2015; Biswas et al., 2015; Seutloali & Beckedahl, 2015). This is why it is necessary to develop soil erosion control strategies such as organic farming (Keesstra et al., 2016), Mulch (Cerdà et al., 2016; Prosdocimi et al., 2016b), organic amendments (Yazdananah et al., 2016) or promote land abandonment to avoid high erosion rates in agricultural lands (Novara et al., 2016).

Approximately 40% of the world's land surface is classified as arid or semi-arid regions (IPCC, 2008). In these regions, soils with little or no vegetation cover are exposed to torrential precipitation events, which are characterized by short durations and high intensities (Ries & Hirt, 2008). About two third of the land surface of Iran (~ a million km²) can be classified to be arid to semi-arid. Water erosion is a serious problem in many catchments in these areas, with specific sediment yield rates ranging from 8 to 16 Mg ha⁻¹ yr⁻¹ (Mahdian, 2005). Overgrazing, land use change and improper cultivation practices are often the main factors triggering severe land degradation and soil erosion in many catchments in these regions (Heshmati, 2010). Gully erosion is the most evident form of water erosion and a major source of sediment in arid and semi-arid catchments in Iran and is the most visible and the most widespread factor of soil degradation in these catchments.

Observations of soil erosion and sediment load are lacking for rivers in many parts of the world, particularly in developing countries (Heng & Suetsugi, 2014). Thus, there is a need to determine sediment yield from upland areas through alternative sources of data, in order to estimate catchment total sediment yield (Palazón et al., 2014; Cortizas et al., 2014). Sediment yield is defined as the amount of sediment per unit area removed from a catchment by flowing water during a specified period of time (Griffiths et al., 2006). It is the sediment load normalized by the drainage area and is the net result of erosion and deposition processes within a catchment (Restrepo et al., 2006). Sediment yield is the integrated result of all erosion and sediment transporting processes operating in a catchment and is therefore of high value for environmental studies and monitoring purposes (Vanmaercke et al., 2011). It is controlled by several factors including climate, topography, vegetation cover, land use, drainage network characteristics, and soil properties (Hovius, 1998; Cerdà, 2002). The determination of sediment yield and the factors controlling it provides useful information for developing quantitative models of landscape evolution and geochemical and sediment mass balance studies, and for estimating net erosion intensities within river basins (Restrepo et al., 2006; Keesstra, 2007; Keesstra et al., 2009). One concept that recently has attracted a lot of attention in research is the concept of connectivity of water and sediment (Parsons et al., 2015). This concept is useful to look at the sediment dynamics in catchment from a holistic point of view. In this concept gives insight in the impact of geomorphology and land management (Baartman et al., 2013), but also can be used to assess the impact of climate, soil characteristics, land cover and soil- and land management on sediment yield (Masselink et al., in press).

The estimation of watershed sediment yield is critical in planning soil conservation and sustainable development of natural resources (Borah et al., 2008). Modeling sediment yield is a complex task due to the nonlinearity of natural processes intervening at slope and basin

scale (Mutua et al., 2006; Keesstra et al., 2014; Borrelli et al., 2015). The sediment volume accumulated in lakes and reservoirs can be used as an indirect validation method for modeling sediment yield at regional scale (Grauso et al., 2008). Recently, sediment volumes stored in water-retention dams have also been used for distributed mathematical model validation, as shown in previous researches (De Vente et al., 2008; Alatorre et al., 2010; Bussi et al., 2014; Rodríguez-Lloveras et al., 2015; Mekonnen et al., 2015b). Not only large reservoirs can be used for sediment yield estimation, but also smaller reservoirs like check dam reservoirs, irrigation and water supply ponds, etc., can be in a similar way, a source of information (Verstraeten & Poesen, 2002). Check dams are relatively small, temporary engineering structures constructed across a gully or small river channel which are used to reduce the velocity of concentrated water flows, a practice that helps to reduce erosion, control sediment transport (Khonkaen & Jie-Dar, 2011), and stabilize channel slopes. These conservation structures can be used to determine sediment yield, particularly in micro-catchments (Boix-Fayos et al., 2007). The dams contribute to change the hydrological and erosional system (Marchamalo et al., 2015; Poepl et al., 2015) but still little is known about the impact on the landscape of the dams from the point of view of the connectivity of the water and sediment discharge within the watershed and basins (Baartman et al., 2013; Parsons et al., 2015), although better understanding of the sink and source are found on slopes (Cerdà, 1997; Bochet, 2015; Stavi et al., 2016).

In North West Iran, a large number of check dams have been built on ephemeral gullies to prevent or reduce sediment inputs into perennial streams during the rainy seasons. This area is a semi-arid region with a mean annual precipitation between 250 and 500 mm. Vegetation cover, which often consist of rangelands and agricultural lands, is usually sparse and allows raindrop impacts during high-intensity storms to destroy soil structure, enhance sheet and rill erosion and transport a large amount sediments into gullies. In this condition, most of check

dams which were constructed in high order gullies were filled by sediment a short time after construction.

Studies on sediment yield for small catchments are very important for understanding linkages between upstream soil erosion and the amount of sediment transported in large rivers (Verstraeten et al., 2003). Several attempts have been made to explain factors influencing sediment yield and to develop models in semi-arid regions (Tamene et al., 2006; Bouchnak et al., 2009; Bussi et al., 2013). Nevertheless, limited information is available on sediment yield and the factors controlling it for semi-arid micro-catchments. Considering that there are no field data on sediment production in many catchments, check dams can provide valuable information about the sediment production and subsequent sediment yield in micro-catchments. Therefore, the objectives of this study were to determine sediment yield of pasture micro-catchments and to quantify the relationship between sediment yield and characteristics of these drainage areas in a semi-arid region in NW Iran.

MATERIAL AND METHODS

2.1. Study area

The study was carried out in the Taham Chai Catchment, one of the main catchments of the Zanzanroud Watershed, located between latitudes $34^{\circ} 46'$ and $36^{\circ} 53'$ N and longitudes $48^{\circ} 17'$ and $48^{\circ} 37'$ E, in the north of Zanzan Province, NW Iran (Fig. 1). The Taham Chai catchment includes the Taham River, which drains into the Taham reservoir dam. The elevation ranges from 1800 m in the west to over 2677 m in the northeastern of the hilly area. The catchment has an area of 228.2 km². The lithology mainly consists of volcanic rocks including andezite, and sedimentary rocks of shale and sandstone. The average annual temperature and precipitation for a 50-year period (1960-2010) are 10°C and 378 mm, respectively. Precipitation mostly occurs as snow in winter (35.9%), and as rain in spring (37.25%). Range lands and rainfed agricultural lands are the main land uses in the area,

which include about 62% and 32% of the catchment area, respectively. Soils in the area are usually calcixerepts according to the Soil Taxonomy classification system (Soil Survey Staff, 2010).

Field observation showed that soil erosion by water has been severely accelerated in the uplands due to overgrazing in the rangelands, change of rangelands to agricultural lands, and tillage in slope direction. Most of the gullies formed on unprotected slopes and some of them reached depth of 4 m, especially where steep slopes have been cut away due to agricultural practices. Gully erosion affects more than 71% of land surface area in the catchment (Zanjani Jam et al., 2013) and act as main source of sediment production in the catchment. It is estimated that about 21 Mg of sediment per year is transported by gullies toward the Taham River and finally deposited behind the Taham reservoir dam.

Over 140 cement rock check dams along with several loose rock dams were constructed by the Zanjan Watershed Management Organization in the Taham-Chai catchment between 1993 and 1995. These small reservoir structures, as reported by Verstraeten and Poesen (2002), can be used for studying sediment yield in the area for a specific period. The small rock dams (in general less than 5 m high) were constructed in first order gullies to stabilize the channel, reduce soil erosion, and prevention of sediment transport into the reservoirs. In some cases, several cement rock check dams were constructed sequentially downstream in perennial gullies. Generally, the cement rock check dam holds several drainage tubes (outlets) and a trapezoidal/rectangular spill way for releasing excess flood water (Fig. 2). These structures have successfully controlled sediment transported into gullies, especially in areas where soil erosion has been accelerated by overgrazing, land use change and improper tillage practices.

2.2. Selection of micro-catchments and assessment of their characteristics

Twenty micro-catchments with pasture as main land use which were drained by cement rock check dams constructed in first order gullies were selected to investigate the sediment yield and factors controlling it. The micro-catchments include only one first-order gully and drain toward a cement rock check dam in the outlet, where part of the eroded material is deposited. These small catchment units were selected to have the lowest drainage area to minimize the effect of waterway characteristics in controlling sediment delivery ratio (De Vente & Poesen, 2005). The drainage area, which was determined by GPS field survey on the water divide lines, was less than 3 ha. The smaller drainage units typically are less restricted by sediment-transport limitations such as channel storage and transmission losses, which are characteristic of larger, more topographically complex drainage basins (Lane et al., 1997). In this condition, sediment yield can be affected based on only a selection (sheet-, rill-, ephemeral gully erosion) of erosion processes (Merritt et al., 2003; De Vente et al., 2013). Additionally, the micro-catchments should produce a sediment volume smaller than the corresponding check dam capacity after the construction period. Field observations showed that the check dams were filled with sediment up to about 70-90% of their storage capacity within 16 years (1994-2010). Mean annual precipitation in the area during the sedimentation period was 362 mm. The slope steepness of the micro-catchments was determined by the ratio of the difference between the highest and the lowest elevations along the gully and the root of the drainage surface area. The micro-catchments are mostly covered with sparse grass and sometimes with rainfed plants. Vegetation cover was determined using the GSA image analyzer in 2D photos taken in the plot scale (1m× 1m) (Acosta et al., 2015) from three locations with three replicates in each micro-catchment as:(1) the farthest point along the channel, (2) right side of the channel, and (3) left side of the channel. The GSA Image Analyzer is a program for the scientific evaluation of 2D images of Photographic objects (Kaladhar et al., 2010).

Soil properties were determined in samples taken from similar locations with vegetation cover in each micro-catchment. The soil bulk density (BD) was determined using a steel cylinder with a diameter and height of 5 cm at three points in the mentioned locations (Blake & Hartge, 1986). The soil infiltration rate (Ks) was determined on-site by double-ring infiltrometer (Bouwer, 1986) at three replications in each point. Three 2-kg samples were also collected from 0-30 cm depth of soil surface in each location and accordingly a composite sample of each location was taken to the laboratory analysis. The soils samples were left to air-dry before being sieved to 2 mm for subsequent analysis. The gravel content was determined using proportion of gravel mass (2-8 mm) and total soil mass. The samples were analyzed for particle size distribution (PSD) of the <2-mm fraction by the Bouyoucos hydrometer method (Gee & Bauder, 1986). Exchangeable sodium percentage (ESP) was obtained based on the Na extracted by 1 M NH_4Ac (Sumner & Miller, 1996). The organic matter content (OM) was determined by Walkly & Black (1934) method, and Bernard's calcimet method was used to determine calcium carbonate equivalent (CCE). To evaluate structure stability in the soil samples, dry and wet mean weight diameters (MWD) of aggregates in a 100 g sample with 6-8 mm in diameter were determined by using dry and wet sieving methods, respectively. By placing the aggregates on the top of sieves set and shaking for 3-min with 500 rotations in min (Klute, 1986), the MWD of dry-stable aggregates (MWD_d) was determined. Also, the MWD of water-stable aggregates (MWD_w) obtained by moving of the aggregates in a water cylinder (Angers & Mehuys, 1993) for 1 min with 20 rotations in min.

2.3. Determination of sediment yield

To determine the amount of sediment accumulated behind each check dam, some physical characteristics of check dams and sedimentation area were measured. Length and surface of the sedimentation area were determined by GPS. The sedimentation area was distinguished from the surrounding hillslopes based on changes in grain size of the sediments, changes in vegetation cover or a change in the longitudinal gradient (Castillo et al., 2007). The slope of longitudinal profile and the cross-sectional shape of the gullies were also estimated. Other basic characteristics of the check dams measured within this study were the depth of the sedimentation deposit, the top width (width of the dam at the sedimentation surface) and the bottom width (width of the dam in gully bed). Since all gullies had a V-shape in cross section, the lower width of the check dams was approximately negligible. The mean width of the check dams was assumed as average of the upper and lower width. The volume of sediment stored behind the check dams was computed as a prismatic channel with triangular cross section (May & Gresswell, 2003, Eq. 1):

$$V = \frac{1}{2} (W_s + L_s H) = \frac{1}{2} S H \quad (1)$$

where, V is the volume of the sediments (m^3), H is the height of the sediments measured from the basis of the dam (m), and W_s is the average width of sediment wedge (m) defined as S / L_s , with S the surface area of sediment wedge (m^2) and L_s is the longitudinal length of the surface area of sedimentation (m).

The sediment mass (kg) retained behind the check dams was calculated multiplying the sediment volume (m^3) by the sediment bulk density ($kg\ m^{-3}$). To determine the sediment bulk density, three sediment samples were taken using a steel cylinder with a diameter and height of 5 cm from three sedimentation locations: at the beginning, middle and end of sedimentation surface. Since part of the sediment transported is not trapped by the check

dam, the trap efficiency (TE) was determined using the ratio of sediment deposited behind the check dams and total sediment load entering the check dams (Verstraeten & Poesen, 2002) for all events from March 2010 to March 2011. Total sediment load for this one-year period was calculated using the sum of sediment deposited behind the check dams and sediment passed through the outlets. The sediment volume behind the check dams was determined using the change of sedimentation depth in ten points on the sedimentation area. The sediment volume passed through the check dams was obtained using sediment collected in a silting basin in front of the check dams. The trap efficiency calculated for a one-year period was extended for the past sixteen sedimentation periods and finally, the mean annual sediment mass (SM) was computed for each micro-catchment (Mg yr^{-1}). Since TE usually varies from event to event (Verstraeten & Poesen, 2002; Bussi et al., 2013), an average value of TE was considered to determine total sediment mass (SM) for each micro-catchment. The sediment yield of the micro-catchments was computed by dividing SM by the drainage area ($\text{Mg ha}^{-1} \text{yr}^{-1}$) (i.e., as done in Romero-Díaz et al., 2012).

2.4. Data analysis

The micro-catchment characteristics and sediment yield values were characterized using statistical parameters such as mean, standard deviation, skewness, and kurtosis and were assessed for normality using Shapiro and Wilk statistic. Pearson's pair-wise correlation was used between all pairs of both dependent and independent variables to establish whether variables are related linearly. Spearman's correlation coefficient as a non-parametric test was also used to determine linear relationship between the variables under the lack of normality. The sediment yield was related to the correlated micro-catchment variables using multiple regression analysis method to develop an equation for predicting the sediment yield for nearby ungauged micro-catchments. The collinearity which affects the results in multiple regression analysis was tested to detect the effect of inter-correlation among

predictors/factors by using the variance inflation factor (VIF). To validate the model, eight other micro-catchments were randomly selected in the area (Fig. 1). The validation micro-catchments also include only first order gullies. Each validation micro-catchment was drained by a cement check dam which was installed at the same time as the observed check dams. Physical characteristics including drainage area, slope gradient, and canopy cover along with soil properties were determined in the micro-catchments. Sediment volume, bulk density and sediment mass were determined to compute mean annual sediment yield in the micro-catchments for a sixteen-year period (1994-2010). The accuracy of the model to estimate the sediment yield was evaluated by comparing predicted and observed sediment yield values using the model efficiency (ME) and fitting a 1:1 line (Verstraeten & Poesen, 2001; De Vente et al., 2008; Haregeweyn et al., 2008). The ME, which compares the variance of the model error with the variance of observations, was determined as following equation (Nash & Sutcliffe, 1970):

$$ME = 1 - \frac{\sum_{i=1}^n (Q_{pre,i} - Q_{obs,i})^2}{\sum_{i=1}^n (Q_{obs,i} - \bar{Q}_{obs})^2} \quad (2)$$

where, n is the total number of observations; $Q_{obs,i}$ is the i^{th} observed runoff depth; \bar{Q}_{obs} is the mean of observed (measured) runoff depth; $Q_{pre,i}$ is the i^{th} predicted runoff depth. The ME can range from $-\infty$ to 1 and indicates the proportion of the initial variance accounted for by the model (Restrepo et al., 2006). A 95% probability level was used in the statistical analyses. Data were analyzed using SPSS version 20.

RESULTS

3.1. Characteristics of the micro-catchments

Drainage area, slope steepness and vegetation cover values of twenty micro-catchments are shown in Table 1. The drainage area of the micro-catchments varied from 1.04 to 2.87 ha. Mean slope steepness in the micro-catchments was relatively high, with an average of 21.35%. The vegetation cover was found to be poor, ranging from 9.08% to 13.40%. The micro-catchments' soils were entirely calcareous having about 18.2% calcium carbonate equivalent, on average (Table 2). The amount of organic matter in the soils was relatively low (1.64%, on average) and aggregates were mostly characterized to be unstable in water ($MWD_w = 1.54$ mm for 1-min). Bulk density varied from 1.5 to 1.66 g cm⁻³ and showed the lowest variation coefficient, (CV=0.03) among the soil properties, whereas ESP showed the highest CV (0.46). The soil final infiltration rate showed a large variation in the micro-catchments, ranging from low (0.95 cm h⁻¹) up to rapid (7.13 cm h⁻¹). All micro-catchment variables except BD, MWD_{wet} and SM showed normal distribution, as evaluated using the Shapiro-Wilk test. These variables were analyzed using Spearman's correlation coefficient.

3.2. Trap efficiency and sediment yield

About 356 mm precipitation occurred in the area during the one-year field experiment (from March 2010 to March 2011). Eleven flood events were recorded in the check dams during this period. The average remaining capacity was about 23.2% of the original check dam capacity, equivalent to 13.7 m³. The trap efficiency (TE) during the flood events considered in this study varied from 56% to 82%. The first flood events appeared the higher TE. It was significantly related to the remaining capacity of the check dams ($R^2 = 0.83$, $p < 0.001$) (Fig. 3). The lower values of TE in Fig. 3 are for the final flood events. The trap efficiency (TE) in twenty check dams varied from 54% to 88% (Table 1). These data were used to determine the

sediment yield in each check dam for the sixteen sedimentation periods. Significant relationship was found between TE and the ratio between the check dam capacity and the micro-catchment area ($R^2 = 0.79$, $p < 0.001$) (Fig. 4). Larger micro-catchments showed higher SM in the area, with exception of the largest micro-catchment (2.87 ha), which has low slope steepness (16%) and high canopy cover (12.80%). The sediment yield ranged from $0.29 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ to $14.81 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, with an average of $5.04 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. In general, high values of sediment yield were attributed to high values of slope steepness and low values of vegetation cover (Table 1).

3.3. Correlation matrix of micro-catchment variables

Results of the correlation matrix (Table 3) indicated that the sediment yield of the micro-catchments was significantly correlated with slope steepness ($r = 0.83$, $p < 0.001$), vegetation cover ($r = -0.70$, $p < 0.01$), and some soil properties including gravel ($r = -0.69$, $p < 0.01$), clay ($r = -0.52$, $p < 0.05$) and organic matter ($r = -0.54$, $p < 0.01$). A significant correlation was observed between sediment mass (SM) and drainage area ($r = 0.45$, $p < 0.05$). With an increase in the drainage area, SM significantly increased. Nevertheless, no significant correlation was found between sediment yield and drainage area ($r = 0.12$). Soil particles (sand, silt and clay) showed contrasting effects on the sediment yield in the micro-catchments considered in this study. Clay negatively affected the sediment production potential in the upland soils ($r = -0.52$, $p < 0.05$). No significant correlation was found between the sediment yield and silt fraction. The sediment yield was also negatively linked to gravel percentage ($r = -0.69$, $p < 0.01$). Organic matter (OM) showed a negative effect on sediment production potential of the micro-catchments. Although OM exhibited a positive correlation with vegetation cover ($r = 0.38$), this was not statistically significant. Despite calcium carbonate equivalent (CCE) having a positive correlation with aggregate stability, no significant correlation was found

between CCE and sediment yield. Soil infiltration rate (Ks) did not show a considerable effect on the sediment yield in the catchments.

3.4. Modeling sediment yield

Stepwise multiple regression analysis was used to distinguish the catchment characteristics with a statistically significant contribution to predicting sediment yield. Such method has been used to model sediment yield for areas around the world using the diverse explanatory variables (Verstraeten & Poesen, 2001; Tamene et al., 2006; Haregeweyn et al., 2008; Molina et al., 2008; De Vente et al., 2013; Vanmaercke et al., 2014). Following this method, three variables, namely slope steepness, vegetation cover and organic matter (OM), which had no significant correlation with each other, were selected from all the considered variables (Table 4). Clay and gravel had no significant effect on the sediment yield when used in the multiple regression analysis along with three mentioned variables (slope steepness, canopy cover and OM). The independent predictors could explain 87% of the variance in the sediment yield from the micro-catchments in the area. With an increase in slope steepness and a decline in both vegetation cover and OM, sediment production in the micro-catchments considerably increased.

The resulting regression equation is the following:

$$SY = 6.525 + 0.594SS - 0.995VC - 1.927 OM \quad R^2 = 0.87, \quad p < 0.001 \quad (3)$$

where SY is the sediment yield for the micro-catchment containing first order gully ($\text{Mg ha}^{-1} \text{ yr}^{-1}$), SS is slope steepness (%), VC is vegetation cover (%) and OM is soil organic matter (%). The variance inflation factor (VIF) was found to be close to one for all predictors (SS, CC, and OM), suggesting no inter-correlation (collinearity) between the predictors.

3.5. Validation of model

The validation micro-catchments have similar characteristics to the calibration micro-catchments: drainage area between 0.99 ha and 2.63 ha, slope gradient from 16% to 27%, vegetation cover from 11.4 to 12.3%. Organic matter content varied from 0.97% to 1.87% and its average was 1.43%. The validation of the model by comparing predicted and observed values of sediment yield for eight micro-catchments during the sixteen-year period showed that the model obtained a very good performance, especially for low and medium values of sediment yield, while the model overestimated sediment yield for high values ($> 6.56 \text{ Mg ha}^{-1} \text{ yr}^{-1}$) (Fig.5). A strong correlation was found between observed sediment yield and model-based predictions ($R^2 = 0.97$). The ME appeared to be 0.94, indicating a very efficient model for predicting the sediment yield in the area (Restrepo et al., 2006).

DISCUSSION

4.1. TE in check dams and flood events

TE was significantly related to the ratio between check dam capacity and micro-catchment area. Larger micro-catchments showed higher sediment production, so that a positive correlation was found between sediment mass and the drainage area ($r = 0.45$, $p < 0.05$). Similarly to these results, Haregeweyn et al. (2013) observed a significant positive correlation between sediment production (Mg yr^{-1}) and catchment area in Ethiopia ($r = 0.86$). However, in the micro-catchments which had the higher check dam capacity, most of sediment material was deposited behind the check dam. So, with an increase in the ratio between check dam capacity and drainage area, TE also strongly increased. TE decreased also from flood to flood due to decrease in the remaining capacity of check dam. Bussi et al., (2013), among others, noted that the trap efficiency varies depending on the flood magnitude and the reservoir capacity, which changes in time due to reservoir filling. SM of the twenty micro-catchments

resulting from upland soil erosions (rill, interrill erosion and gully erosion) for the 16-year period was between 0.40 Mg yr^{-1} and 24.46 Mg yr^{-1} .

4.2. Sediment yield and drainage area

There was no significant correlation between sediment yield and drainage area in the micro-catchments. In the studies carried out in larger basins ($>30 \text{ km}^2$) a negative relationship has been found between sediment yield and drainage area (Lane et al., 1997; Dedkov & Moszherin, 1992; Romero-Díaz et al., 2012; Vanmaercke et al., 2014). However, the relationship between sediment yield and drainage area is dependent on the basin scale (De Vente & Poesen, 2005). For example, in a study about sediment yield and its scale dependence in Europe, Vanmaercke et al. (2011) found no clear negative relationships between sediment yield and catchment area. One of the reasons for this case was that sediments may originate from various sources, such as gullies, riverbanks and landslides, and not only from topsoils (i.e. through splash, sheet and rill erosion). In different basin scales, the relative contribution of rill and interrill erosion to sediment yield is very different from that of gully erosion. In the studies by Lane et al. (1997) and Griffiths et al. (2006), very small drainage basins ($< \text{km}^2$) have been described as supply-limited, controlled by sediment production processes such as sheet wash and rill erosion, which result in an increase in sediment yield with drainage area. In this study, different types of soil erosion mechanisms, such as rill, interrill and gully erosion, were detected. With an increase in the drainage area, sediment production resulting by rill, interrill and gully erosions significantly increased. In particular, the relative contribution of gully erosion to total sediment yield increases as the drainage area increases. Poesen et al. (1996) measured rill and gully volumes for areas between 0.20 and 10 ha, 10 years after arable land abandonment, and showed that with increasing area the sediment yield generally increased up to about $12 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ at a

drainage area of 10 ha. They showed that the contribution of rill erosion to total sediment yield remained at a relatively low value (about 2 Mg ha⁻¹ yr⁻¹) within the area of the studied slope (i.e. 0.2–10 ha). Poesen et al. (2003) and De Vente et al. (2008) reported that the contribution of gullies to sediment yield at the catchment scale can amount up to 80%, especially in semi-arid environments. De Vente and Poesen, (2005) showed that only from a contributing area of approximately 0.03 km² did the contribution of gully erosion result in a strong rise in sediment yield. However, this threshold of 0.03 km² for incipient gully formation is dependent on slope as well, as was shown by Vandekerckhove et al. (2000). This strong correlation between the sediment yield and the presence of gullies in a catchment is due to the high connectivity from the sediment source to the outlet of the catchment system. The sediment is generated in the drainage system and has no possibility to be deposited before reaching the outlet of the catchment, while sediment generated on the hillslopes with processes like splash erosion, sheet erosion and rill erosion is in many cases deposited along the pathway in the catchment. Features like surface roughness, vegetation patches and small man made obstructions in the landscape can have a large influence on the connectivity of the hillslope towards the drainage network (Okin et al.,2015).

4.3. Sediment yield and slope steepness

The slope steepness showed the highest correlation with sediment yield as compared to other catchments characteristics. Similarly, Verstraeten and Poesen (2001) showed that a positive correlation exists between sediment yield and mean slope ($r = 0.43$, $p < 0.05$) in small cultivated catchments. Tamene et al. (2006) analyzed factors determining sediment yield in 11 catchments upstream reservoirs and showed that terrain form, gully erosion, surface lithology, and land cover explain most of the variability in sediment yield among the catchments ($R^2 = 0.96$, $p < 0.05$). In contrast with our result, they indicated that mean slope

had not a very strong correlation with the sediment yield. This observation suggested that the role of slope is masked due to its association with dense surface cover and less erodible lithology. Zhang et al (2015) investigated the relationships between sediment yield and the characteristics of 29 selected watersheds in the Loess Plateau in China and showed that the slope as a relief parameter along with watershed shape has large influence on sediment yield. Slope steepness can also affect the type of gully erosion in the catchments. Head-cut and sidewall–floor erosion are two dominant types of soil loss in gullies. The contribution of each of the two erosion types in gullies in return is affected by slope steepness. Bouchnak et al. (2009) investigated the sediment yield of first order gullies in a semi-arid catchment and concluded that sidewalls–floor erosion contributed more than head-cut to total gully sediment yield.

4.4. Sediment yield and vegetation cover

Sediment yield appeared to be relatively high in some catchments where vegetation cover percentage is also low. It is well known that natural vegetation has a high filtering capacity by intercepting rainfall and promoting infiltration, and lowers the water table through transpiration (Rey & Burylo, 2014; Lieskovský et al., 2014; Mekonnen et al., 2015a). The clearance of natural vegetation reduces the resistance of land surfaces and enhance the effectiveness of flow on sediments, thus increasing sediment yield, particularly in steeper slopes (Gessesse et al., 2014; Berendse et al., 2015). Similarly, findings by Molina et al. (2008) in a tropical mountain basin showed that vegetation cover exerts the strongest influence on sediment yield and has the highest predictive power ($R^2=0.57$), compared to other catchment characteristics. Shit et al. (2014) found also a very significant relationship between vegetal cover and sediment concentration ($R^2=0.91$, $p<0.001$).

4.5. Sediment yield and soil properties

Sediment yield was significantly affected by some soil properties including clay, gravel and organic matter. Negative correlation between SY and clay percentage could be explained by the fact that clay is more difficult to erode because of its better aggregation capacity (Morgan, 2005). Although silt is a major factor in increasing soil erodibility, it was not an important factor in sediment production in the micro-catchments. This result can be attributed to low content of silt particles in the micro-catchment soils (27.2%, on average). As reported by Yang and Chapman (2006), only soils having a high percentage of silt particles are easily detached, as they tend to crust and produce high rates of runoff and sediment. Gravel was also appeared negative correlation with SM as well as SY. As reported by Descroix et al. (2001) and Cerdà (2001) for stone fragment, soil surface features, such as gravel, protect the top soil against raindrops and overland flow kinetic energy and lead to reduce runoff and soil loss in the catchments. Similarly, a negative correlation was found between OM and SM or SY. The role of organic matter as a binding agent in increasing flocculation of soil particles, improving aggregate stability and consequently declining soil erodibility in the semi-arid regions has been well known (Vaezi et al., 2008; Saygın et al., 2011). Contrary to the expectations, there was no significant correlation between OM and vegetation cover. On the gentle slopes, where vegetation cover is usually higher than the steeper slopes, pastures are severely grazed in early spring. Thus, turnover of crop residues in soil which control soil organic matter content is relatively low. However, Molina et al., (2008) and Salari Nik et al. (2015) indicated a positive correlation between soil organic matter content and vegetation density in the rangelands. Although the importance of calcium cation (Ca^{2+}) in increasing water-stable aggregates and declining soil erodibility in semi-arid regions has been well documented (Vaezi et al., 2008; Habel, 2013), it did not appear to be an important factor in controlling the SY in the micro-catchments. However, it seems that other soil structure

characteristics such as size and percentage of water-stable aggregates have a stronger influence on controlling the sediment yield in this area. SY was not affected by soil infiltration rate (K_s) in the micro-catchments. However, it is usually considered to be an important factor controlling runoff and sediment production (Joshi and Tambe, 2010). Nevertheless, in semi-arid regions, soils are often unsaturated during the year and runoff and soil erosion mostly occurs when rainfall intensity or soil moisture content are high. Thus, K_s alone cannot explain the soil potential for runoff production and soil erosion in this area.

4.6. Sediment yield and micro-catchment characteristics

Slope steepness (SS), vegetation cover (VC), and soil organic matter (OM) explained about 44%, 23%, and 20% of the total sediment yield variance respectively. In fact, slope steepness was recognized as the most important variable determining sediment yield in the micro-catchments. Although vegetation cover showed lower variability (about 4 %), it was a major factor controlling sediment yield in the area. *Astragalus* spp and *Alhagicomelorum* are dominant grass species in the area which cover completely soil surface and reduce sediment production by binding the soil mechanically and reducing the speed of the surface runoff. This shows the importance of good management in the region. The system in terms of erosion processes due to low vegetation cover is very close to the threshold condition in which large scale gully erosion is initiated. Since the construction of check-dams was estimated to be more expensive and effective only for a restricted time period (Quiñonero-Rubio et al., 2016), protection of vegetation cover through the management of grazing and prevention of land use change can be the effective management practices in controlling soil erosion and sediment yield in the micro-catchments (Cerdà & Lavee, 1999; Novara et al., 2013; Liu et al., 2014; Palacio et al., 2014; Palacio et al., 2014; Sarah & Zonana, 2015; Costa et al., 2015). This result proved the significance of vegetation cover to curb soil erosion and it may help the planners and managers to take proper decision for the conservation of soil (Shit et al., 2014).

With regarding to the highest rainfall intensities in the area often occur in early spring when there is very poor vegetation cover on the soil surface, prevention of grazing, implementation of conservation tillage, and crop management should be taken into consideration to control soil erosion and decrease sediment production. The result of this study can be used to assess the level of grazing that can be allowed in these areas to prevent large scale land degradation.

4.7. Accuracy of sediment yield model

The model could not explained 13% of the total variance. This may be either due to presence of some unknown controlling variables of the micro-catchments such as other slope factors (length, orientation, and shape), catchment shape characteristics (compactness, circularity, elongation, etc.), and surface roughness, as reported by Restrepo et al. (2006). However, the model provided a high ME, suggesting high capability for predicting the sediment yield in the micro-catchments. The high robustness of the model can be related to the small extension of the catchments, which limits sediment sources and sediment delivery complexity. Additionally micro-catchments include only one first-order gully and so sediment production was not affected by differences in the stream network. In other words, as the drainage area surface increases, other major sediment sources such as gully erosion, bank erosion or mass movements may become dominant (De Vente et al., 2013). The different land degradation statuses of the micro-catchments in terms of the extent of gully erosion may also be a reason for the difference between the observed and simulated values of SY. Sediment generated in gullies is immediately available for transport as it is already in the drainage network and therefore very well connected to the catchment outlet. The developed model can be used as a tool to estimate total sediment yield with a high degree of accuracy in micro-catchments in this and similar semi-arid regions. However, the developed model cannot be used to estimate soil erosion potential and the sediment delivery ratio on a cell-by-cell basis in the catchment.

CONCLUSIONS

Sediment yield, SY in twenty micro-catchments varied from 0.29 to 14.81 Mg ha⁻¹ yr⁻¹ with an average of 5.04Mg ha⁻¹ yr⁻¹. Various catchment properties, such as drainage area, slope steepness, vegetation cover and soil properties were analyzed in order to understand the large variation in sediment yield. Multiple linear regression analysis showed that SY was significantly related to slope steepness, vegetation cover and soil organic matter ($R^2= 0.87$, $p< 0.001$). The slope steepness was the most important factor determining sediment in the area, and could explain 44% of the total sediment yield variance, whereas vegetation cover and soil organic matter (OM) explained about 23% and 20% of the sediment yield variations in the micro-catchments, respectively. Since turnover of crop residues in soils on the gentle slopes is relatively low due to over-grazing in early spring, no significant correlation was found between vegetation cover and OM. A multiple regression model was developed to estimate the sediment yield in similar catchments, based on catchment properties. The validation of the model showed that the model provided good results, with a model efficiency of 0.94. Therefore, the model can be used for predicting sediment yield of micro-catchments in this and similar study area, with a high degree of accuracy.

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Table 1. Geographical coordinates of twenty micro-catchments along with their characteristics and sediment data in the Taham-Chai catchment, NW Iran

Geographic coordination		Drainage area (ha)	Slope steepness (%)	Vegetation cover (%)	Sediment			
Latitude	Longitude				Bulk	Trap	Sediment	Sediment yield
					density	efficiency	mass	(Mg ha ⁻¹ yr ⁻¹)
					(g cm ⁻³)	(%)	(Mg yr ⁻¹)	
36°47'	48°34'	1.24	24	12.33	1.64	0.56	4.43	3.56
36°49'	48°31'	1.04	15	11.42	1.74	0.54	0.87	0.84
36°48'	48°31'	1.41	22	12.50	1.69	0.82	7.97	5.64
36°48'	48°32'	1.10	20	13.07	1.53	0.61	3.10	2.81
36°48'	48°32'	2.29	24	9.11	1.95	0.82	24.38	10.64
36°47'	48°32'	1.94	20	10.28	1.64	0.65	9.69	4.99
36°48'	48°35'	1.36	18	11.06	1.81	0.54	0.40	0.29
36°47'	48°33'	2.08	25	10.96	1.60	0.85	15.64	7.52
36°46'	48°29'	1.96	20	11.71	1.68	0.68	2.71	1.38
36°46'	48°30'	2.07	22	9.43	1.77	0.81	17.36	8.39
36°47'	48°30'	2.33	20	10.67	1.48	0.75	8.05	3.45
36°47'	48°33'	2.28	24	10.23	1.48	0.79	13.41	5.88
36°47'	48°29'	2.87	16	12.80	1.47	0.66	1.77	0.62
36°47'	48°31'	1.22	19	13.40	1.64	0.54	2.40	1.96
36°47'	48°29'	1.23	23	9.42	1.56	0.77	10.23	8.29
36°47'	48°30'	1.19	24	11.07	1.60	0.81	7.30	6.11
36°48'	48°36'	1.18	21	11.23	1.53	0.63	2.43	2.06
36°49'	48°31'	1.88	16	10.04	1.62	0.66	5.24	2.79
36°48'	48°32'	1.33	20	10.40	1.65	0.74	11.69	8.76
36°47'	48°32'	1.65	32	9.08	1.52	0.88	24.46	14.81
StD ^a		0.52	3.85	1.31		0.11	7.29	3.82
Ske		0.59	0.81	0.26	0.12			
						-0.15	0.99	0.89
Kur		-0.62	2.04	-0.86	0.92			
						-1.34	0.25	0.60
SW test		0.07	0.13	0.48	1.07			
						0.12	0.03	0.15
					0.20			

StD: standard deviation; Ske: skewness; Kur: kurtosis; SW test: Shapiro-Wilk test

Table 2. Some soil properties of the micro-catchments in the Taham-Chai catchment, NW Iran

Soil properties ^a	Min	Max	Mean	StD	Ske	Kur	SW test
Sand (%)	32.00	79.30	52.80	14.75	0.35	-0.97	0.33
Silt (%)	11.30	42.00	27.22	8.39	-0.21	-0.54	0.80
Clay (%)	7.70	34.00	20.02	7.37	-0.21	-0.55	0.88
Gravel (%)	8.06	18.58	13.74	3.35	0.09	-1.12	0.29
BD (g cm ⁻³)	1.50	1.66	1.59	0.05	-0.71	-0.68	0.04
MWD _d (mm)	1.28	2.72	2.20	0.82	-0.55	0.75	0.21
MWD _w (mm)	0.84	2.92	1.54	0.62	0.99	-0.09	0.01
Ks (cm h ⁻¹)	0.95	7.13	3.57	1.51	0.49	0.33	0.84
ESP	1.06	8.57	4.81	2.21	0.17	-1.17	0.24
OM (%)	0.87	2.51	1.64	0.50	0.30	-0.97	0.27
CCE (%)	7.61	30.96	18.23	6.18	-0.17	-0.32	0.44

^aStD: standard deviation; Ske: skewness; Kur: kurtosis; SW test: Shapiro-Wilk test

²BD: bulk density; θ_s : saturated moisture; MWD_d: mean weight diameter of aggregates; MWD_w: mean weight diameter of water-stable aggregates; Ks: final infiltration rate; CCE: calcium carbonate equivalent.

Table 3. Correlation matrix between the sediment yield and some micro-catchments variables in the Taham-Chai catchment, NW Iran

	DA ^a	SS	VC	Gr	Sa	Si	Cl	BD	MWD _d	MWD _w	K _s	ESP	OM	CCE	SM	SY
DA	1															
SS	-0.01	1														
VC	0.24	-0.43	1													
GR	0.14	-0.51*	0.40	1												
Sa	0.20	0.41	-0.17	-0.26	1											
Si	-0.21	-0.37	0.03	0.11	-0.94**	1										
Cl	-0.18	-0.39	0.30	0.40	-0.93***	0.75***	1									
BD	-0.16	-0.20	-0.04	-0.03	0.11	-0.17	-0.01	1								
MWD _d	-0.09	-0.32	-0.03	0.02	-0.35	0.37	0.27	-0.38	1							
MWD _w	0.29	0.03	0.15	0.30	-0.27	0.29	0.18	-0.82***	0.34	1						
K _s	-0.10	-0.01	0.33	0.41	-0.18	0.05	0.31	-0.21	-0.03	0.18	1					
ESP	0.21	0.16	0.12	0.14	0.43	-0.58**	-0.20	0.50*	-0.27	-0.36	-0.03	1				
OM	0.16	-0.29	0.38	0.44	-0.48*	0.46*	0.43	-0.44	0.19	0.44	-0.08	-0.13	1			
CCE	0.37	0.21	-0.24	-0.03	0.04	-0.04	-0.03	-0.50*	0.17	0.50*	-0.3	-0.27	0.10	1		
SM	0.45*	0.74**	-0.76**	-0.58*	0.29	-0.27	-0.42	-0.11	-0.20	0.07	-0.14	-0.08	-0.55*	0.44	1	
SY	0.10	0.83***	-0.70**	-0.69**	0.44	-0.3	-0.52*	-0.06	-0.25	-0.04	-0.20	0.03	-0.54*	0.19	0.94***	1

^a DA: drainage area; SS: slope steepness; VC: vegetation cover; Sa: sand; Si: silt; Cl: clay; Gr: gravel; BD: bulk density; MWD_d: mean weight diameter of aggregates; MWD_w: mean weight diameter of water-stable aggregates; K_s: final infiltration rate; CCE: calcium carbonate equivalent; SM: sediment mass;; SY: sediment yield.

*: Significant at p< 0.05, **: Significant at p< 0.01, ***: Significant at p< 0.001.

Table 4. The multiple linear regression analysis of the relationship between the sediment yield and controlling variables

Variable	Unstandardized coefficients		Standardized coefficients	T	<i>p</i> -value	Collinearity Statistics	
	B	Sd. E				Tolerance	VIF
Constant	6.525	4.562	-	1.430	0.172		
SS	0.594	0.100	0.599	5.938	0.000	0.799	1.252
VC	-0.995	0.304	-0.362	-3.273	0.005	0.744	1.344
OM	-1.927	0.749	-0.254	-2.571	0.021	0.837	1.195

SS: slope steepness; VC: vegetation cover; OM: organic matter.

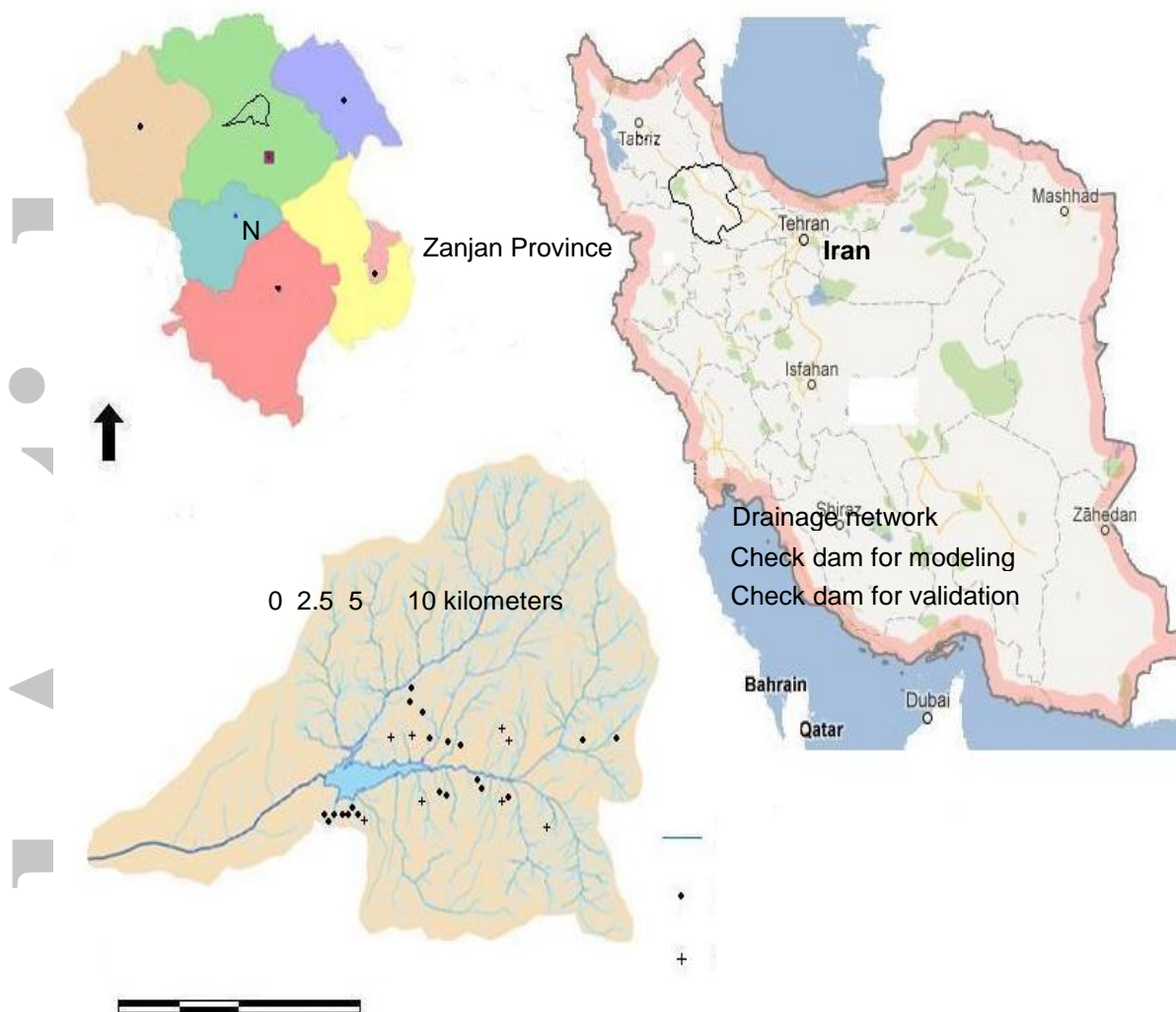


Fig. 1. Location of the Taham Chai (NW Iran) catchment and the twenty check dams considered in this study.



Fig. 2. A typical rock check dam with triangular cross section built on a first- order gully in the Taham Chai catchment.

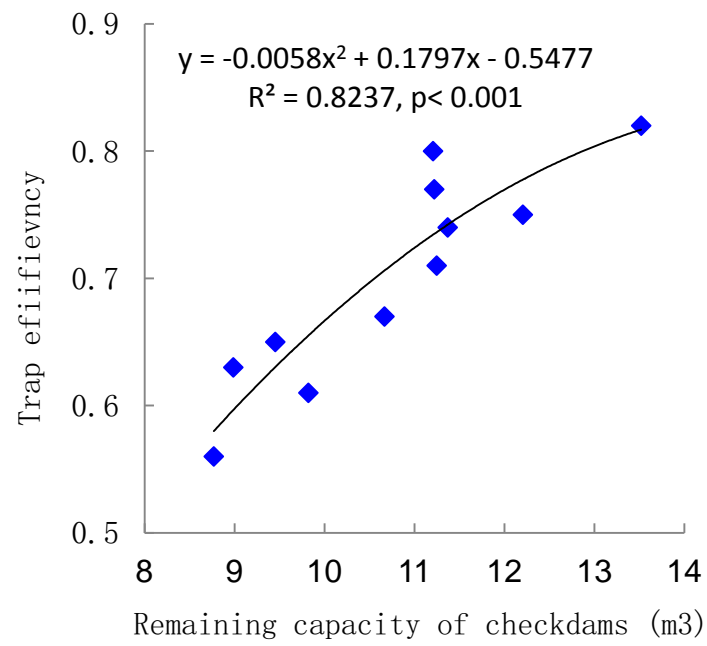


Fig. 3. Trap efficiency versus remaining capacity of the check dams in flood events.

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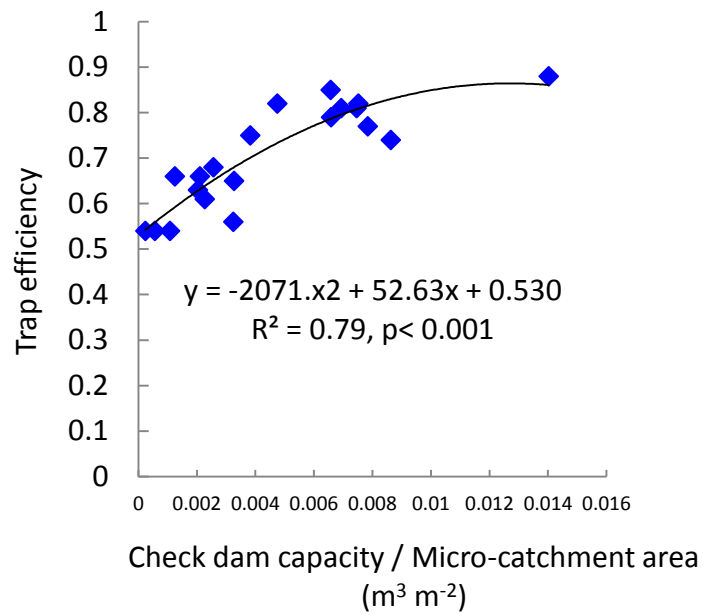


Fig. 4. Relationship between trap efficiency and the ratio between check dam capacity and micro-catchment area.

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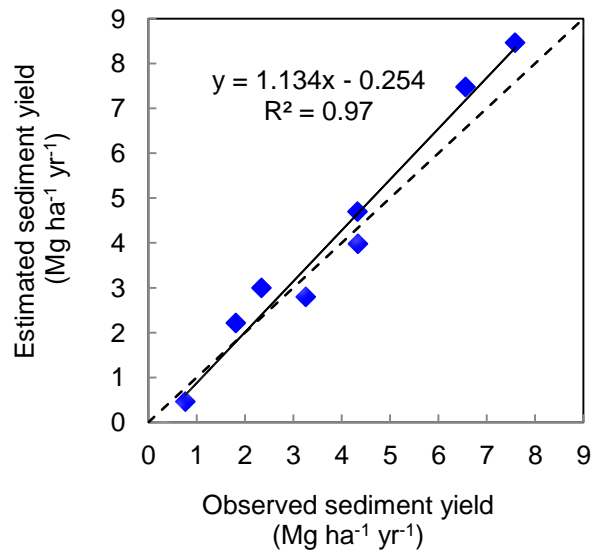


Fig. 5. Estimated sediment yield versus observed values in eight micro-catchments of the Taham-Chai catchment from 1994 to 2010.