Assessing the effect of soil texture and slope on sediment yield of Marl units using a portable rainfall simulator

A case Study : Qezel-Ozan watershed of Zanjan province, Iran

Parviz Abdinejad[1], Sadat Feiznia[2], Hamid Reza. Pyrowan[3], Faraj Olah. Fayazi[4] and Amir Ali. Tbakh Shabani[5]

1.Department of Geology, Science and research branch, Islamic Azad University, Tehran, Iran.
E- Mail: prz_abdi@yahoo.com
2. Faculty of Natural Resources, University of Tehran
3. Faculty of Soil Conservation and Watershed Management Research Institute
4. Faculty of Natural Resources, University of Teacher Training in Tehran
5. Faculty of Iranian Geological Institute

Abstract: Fine grained, saline, alkaline and erodible Tertiary marly formations are exposed in many geological zones and they play an important role in the formation of present landform structures. Marly formations as one of the most critical sediment resources, will always pose special problems on watershed management. Due to special mineralogical and geological formulation of these formations, they are intolerant to erosion and their minerals contents affects their behavior from the view point of erosion and sediment production which are important factors on land degradation. Investigating the causes of soil erosion is difficult in natural conditions owing to the presence of other factors. Without simplifying the experimental conditions, studying soil behavior regarding its numerous factors such as vegetation cover, topography, and rainfall is not impossible but difficult. The application of simulation approaches is therefore necessary to simplify the prototype. In this research, the effects of some physical soil factors such as texture along with land slope were evaluated in the Qezel-Ozan watershed of Zanjan province, Iran, using a rainfall simulator and soil erosion plots. For this purpose, a 89 × 120 cm rainfall simulator producing 60 mm/h rainfall intensity of 30 min duration, as a common condition of the study area, was used at 64 locations over soil erosion plots with dimensions of 95 × 125 cm. Plots had slope classes of 5 and 20 percents, and different soil textures. It was found that for 60 mm/h rainfall intensity, the correlation coefficient of 0.047 between sand and sediment yield for 60 mm/h rainfall intensity indicate very low correlation. Percentages of slope, clay and silt content had correlation coefficients of 0.689, 0.329 and -0.233 respectively at the 99% confidence level with sediment yield. The correlation coefficients of 0.861 in equations indicate their high potential in simulating sediment yield.

[Parviz Abdinejad, Sadat Feiznia, Hamid Reza. Pyrowan, Faraj Olah. Fayazi and Amir Ali, Tbakh Shabani. **Assessing the effect of soil texture and slope on sediment yield of Marl units using a portable rainfall simulator**. Journal of American Science 2011;7(10):617-624]. (ISSN: 1545-1003). http://www.americanscience.org.

Key Words: Rainfall simulator, Soil erosion, Soil physical parameters, Qezel-Ozan watershed, Iran

1. Introduction

Soil erosion is one of the most important environmental problems in developing countries including Iran which has destructive effect on all natural ecosystems being managed by human. Erosion not only causes land degradation and decreasing fertility, but also by producing and accumulation of sediments, decreases reservoirs and dams capacity. To decrease the impacts of soil erosion, soil conservation and sediment control measures are needed. To put these plans into practice, information about the relative importance of sediment sources is required. In Iran fine–grained, saline, alkaline and erodible Tertiary marly formations are exposed in many geological zones and play important role in the formation of present landforms. They also play important role in degradation of water resources and soils as diffuse sources; they are the main sources of suspension loads of many rivers and are endless sources of sediments for sand dunes. These marly formations are present in Zagros, Central Iran, Alborz and Kopeh – Dagh Geological Zones and consists of different geological formations such as Gachsaran, Mishan and Razak Formations (in Zagros), Lower Red and Upper Red Formations (in Central parts of Iran) and Neogene Red Beds (in Albors and Kopeh-Dagh) (Zakikhani. et al, 2009). Marly formations pose problems on watershed management and they are one of the most critical sources of sediment. Due to their special mineralogical and geological formulations, these marly formations are very erodible and the type of their mineral contents affects their erodibility behavior and sediment yield, which are important factors in land degradation. Marly formations have high distribution in Qezel-Ozan watershed of Zanjan province.

Many factors affect sediment detachment and redistribution such as rainfall characteristics, topography features, land use, soil texture and its organic matter content, soil moisture, soil management and tillage operations. Usually, the processes that determine the size distribution and velocity of the impacting rain drops are referred to as "erosivity processes", while the processes involved in determining the properties of the eroded surface (such as slope, land cover, soil moisture and roughness) are described as "erodibility processes" (Bakker et al., 2005). Information on properties of eroded sediment is important because soil biological, chemical and physical properties may change as a result of soil erosion and, in some cases, they may lead to reduction in crop productivity (Lal, 1987, 1988; Meyer et al., 1992; Larney et al., 1995; Fullen et al., 1996; Fenton et al., 2005; Foley et al., 2005; Montgomery, 2007). For instance, several authors have reported that the fine particles are the most detached during erosion because of their light mass, but many studies reported different and sometime contrasting results (Ampontuah et al., 2005). The particle size distribution (PSD) of the eroded sediment also affects chemical transport, since solutes are preferentially bonded to small particles of high surface area, usually comprised in the clay and silt range (Jin et al., 2009). In recent years, the soil erosion trend has increased significantly owing to improper land use changes. Pimentel et al. (1995) reported an annual rate of soil erosion of 30–40 ton/ha in developing countries of Asia, Africa and South America. On a global scale the annual loss of 75 billion tons of soil costs the world about US$400 billion per year, or approximately US$70 per person per year (Eswaran et al., 2001). FAO (Food and Agriculture Organization) (1994) has acknowledged that Iran is among nine South Asian countries in which agricultural and natural lands are under influence of severe erosion. Based on suspended sediment data from more than 200 sampling stations, the average annual suspended sediment yield in Iran is reported to be 2 ton/ha or 350 million ton (Arabkhedri, 2003). Assuming a sediment delivery ratio (SDR) of 17.1 to 21.6 (Ouyang and Bartholic, 1997) and the amount of bed load to be 20% of the amount of suspended load, the amount of soil erosion in Iran could be some 2 billion tons (2.7% of the world's soil loss). Owing to the removal of productive soil from the surface of the lands, valuable biological resources are wasted and this considerably decreases the crop yield from agricultural and range lands. It is obvious that soil erosion information helps planners to control the degradation of productive soils, decrease expenses caused by erosion, and optimize the benefits of precipitation. Estimating the rate and amount of soil erosion helps planning in land use management and sustainable development. Soil erosion depends on different factors like soil texture, permeability and antecedent moisture, rainfall intensity, land use and the type and density of the land vegetation cover and land slope. The primary energy causing erosion by water is gravity, acting through falling precipitation and water flow down a terrain slope. Raindrop splash and overland flow detach soil particles, which are then transported downward by the kinetic energy transferred from the water flow to the sediment (Canali, 1992). Warrington et al. (1989) noticed that an increase in the slope of unstable soils abated the runoff rate slightly. Furthermore, one of the reasons for unstable soil impermeability in semi-arid areas is the formation of surface sealing during rainfall. Thus, an increase in the slope leads to the erosion and removal of sealing and consequently the increase in the permeability rate and decrease in runoff. Ward and Bolton (1991) observed that the difference between the amount of runoff and sediment yield from forest and rangeland soil depends on antecedent soil moisture, organic matter and the percentage of silt. Karnieli and Been-Asher (1993) noted the soil erosion threshold in marls depends on the rainfall intensity and antecedent soil moisture when simulating the daily runoff of four watersheds in Arizona, USA. The same results were noted by Blum and Gomes (1999).

The soil erosion plot and rainfall simulator are two soil erosion research facilities widely used by scientists around the world. Rainfall simulation experiments are used to study erosion and contaminant transport in overland flow (Sharpley and Kleinman, 2003). Meyer and Harmon (1984) used a rainfall simulator to investigate the effect of slope and soil texture on the amount of soil erosion, runoff and the size of sediment particles for plots with row vegetation cover. They found the amount of soil erosion increases with slope steepness and the sediment particle size changes with soil texture. Duiker et al. (2000) used a rainfall simulator with 60 mm/h intensity over 0.75 m2 plots on 30% slopes in southern Spain to evaluate the permeability and erodibility of the predominant soils. The results showed that alluvial soil had the greatest erodibility rate of 985 among clay, shallow hilly, alluvial and colluvial soils, in dry conditions. The rate of permeability in fluvial soils was the highest. In addition, the amount of soil erosion has high correlation (r = 69%) with the amount of silt and very fine sand. Lasanta et al. (2000) measured the amounts of runoff and sediment on overgrazed terraces of a watershed in Spain with a rainfall simulator to examine their relationships with the severity of livestock grazing. The results showed that the velocity and intensity of the hydrologic reactions and erosion increase owing to the overgrazing of plots, which decreases the vegetation cover. Barthes and Roose (2002) measured the amounts of runoff and erosion in 1 and 2 m plots using a rainfall simulator. They stated that the results of these experiments had high similarity with the results of field studies. Within 30 min rainfall, runoff discharge and the amount of soil erosion did not show any relation with the organic carbon content. However, continuing rainfall resulted in significant correlations between runoff discharge and sediment yield and organic carbon content. Shekl Abadi et al. (2003) used a portable rainfall simulator 1 and m2 plots to determine the relative soil erodibility of geological formations and to find its relation with physical and chemical characteristics of soils in the Golabad basin, Isfahan. The results suggested that using a rainfall simulator not only decreases the required research period while giving reasonable results and precision, but also makes changing the intensity, duration and frequency of rainfall possible. Marques et al. (2007) studied the erosive power of frequent light rainfalls. Field experiments of simulated rainfall were conducted over eight USLE plots with a slope of 10%. Runoff and sediments amounts were negligible in covered plots and this revealed the efficiency of vegetation cover. Scientists are working on numerous ways to introduce appropriate methods to mitigate soil erosion. Most watersheds in developing countries have not been equipped by water and sediment measurement devices. However, the necessity for information about the rate and trend of erosion and the importance of different factors for erosion is inevitable.

The main objective of this research is to compare the effects of soil texture, climate, land slope, Runoff, and Runoff coefficient on sediment discharge and introduce equations to predict sediment yield using a rainfall simulator in the Marl units of Qzel-Ozan watershed, Zanjan, Iran, which is the representative of the vast area of the south-west Alborz mountains.

2. Material and Methods

a. Study area

This study was conducted within the Qzel-Ozan watershed located in Zanjan Province. It lies off the north-west of Iran, say 300 km. away from Tehran, the capital. The study area is bordered by the upstream of Sefidrood dam, in the southern part of the Alborz Mountains. The study area extends between 35° 35' and 37° 13' N latitude and 47° 13' and 49° 25' E longitude and covers an area of 1906400 ha. The average annual precipitation is 319 mm. within the climate zone of arid and semi-arid. Figure 1 shows the location of the Qzel-Ozan watershed.

b. Rainfall simulator

A portable non-pressurized rainfall simulator was employed in this research which was developed at the Soil Conservation and Watershed Management Research Institute, Iran. The basic unit of the simulator is a Plexiglas container with two plates, 1.2 m long and 0.84 m wide, at the top and bottom connected with a frame of 0.04 m height as shown in Figure 2. The lower raindrop-former plate contains 216 nozzles of 0.5 mm diameter, which are spaced 0.07 m apart. The oscillating mechanism of the simulator works with a drive motor to produce a uniform distribution of raindrops across the plot. The system equipped with an upper tank of 11.28 liters with an overall capacity of 51.6 liters, four adjustable legs each 1.5 m in height, that help to mount the system horizontally on various land slopes. Drops form by gravity and atmospheric pressure controlled by a tube connecting the basic unit to the outside within the upper tank. This gives a 3.6 mm median drop size and a nozzle exit velocity of 10 to 80 m/s. Figure 3 shows the mounted rainfall simulator operational (Vahabi and Nikkami, 2008).

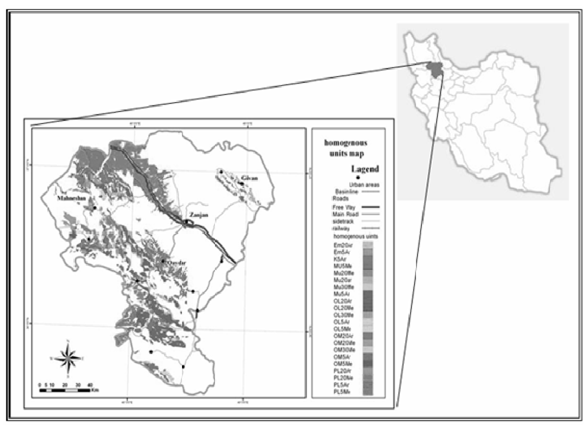

Figure 1. Position of Zanjan province in Iran

c. Plots locations

To specify the locations of the plots, slope (scale 1:50000), marl units map (using geology maps (scale 1:100000), climate map (scale 1:50000), soil texture and TM satellite imagery were used. The slope map with its two most common slope classes of 5–10 and 10–30 per cent, without vegetation cover conditions, and climate map with its two classes arid, semi-arid and very humid Mediterranean were overlaid using ILWIS software, as a result 20 different categories were obtained. The locations of the experimental plots were considered to be well distributed in the watershed (Figure 4).

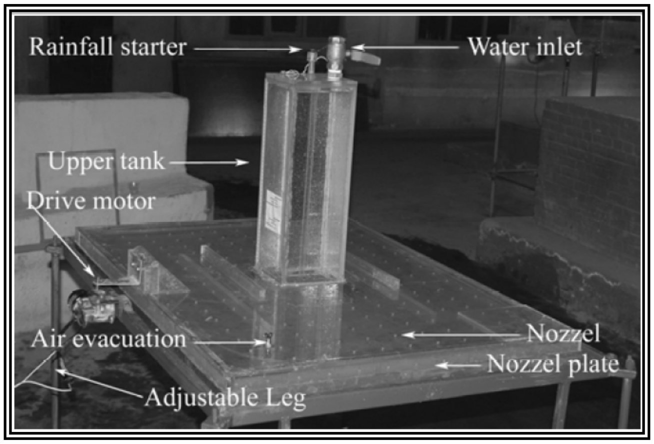

Figure 2. Rainfall simulator and its different parts (adapted from Vahabi and Nikkami, 2008)

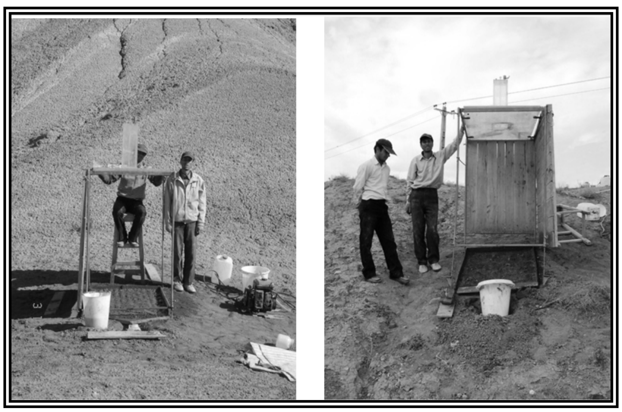

Figure 3. Mounted rainfall simulator

Figure 4. A photograph of upper red formation of marl unit in Chahre Abad of Zanjan province, Iran

d. Data acquisition

Rainfall data from Joestan synoptic meteorological station at the middle of the Qzel-Ozan watershed were collected to study rainfall intensities. One rainfall intensity of 60 mm/h within ±2 mm/h and having 30 min duration for this experiment was selected. Rainfall intensity was incorporated as a base criterion in the rainfall simulator and each treatment had three replications. Antecedent soil moisture in all plots was not measured. This experiment was performed in period of time where no occurrences of rainfall were recorded since 2 months before as well as during the study. There was no vegetative cover and fine gavel was absolutely scarce as well.

Table 1. Plots specifications and sediment yield for Marl units within Qzel-Ozan watershed

working polygons	Slope (%)	Clay (%)	Silt (%)	Sand (%)	runoff thresh[1]	Runoff (liter)	Infeltr. depth (cm)[2]	Sedi yield (g/lit)[3]
EM5Ar 1	5	38	60	2	3	19.4	3.3	20.8
EM5Ar 2	5	38	60	2	3	19.5	3.3	23.5
EM5Ar 3	5	38	60	2	3.5	19.2	3.5	23.8
EM20Ar1	20	38	60	2	5	16.5	4	52.3
EM20Ar2	20	38	60	2	5	17	3.5	47.6
EM20Ar3	20	38	60	2	5.15	15	4.3	50.7
Mu5Ar1	5	40	46	14	2.5	16.9	2.8	27.2
Mu5Ar2	5	40	46	14	4.4	17.2	2.5	24.3
Mu5Ar3	5	40	46	14	5	18.5	2.5	23.8
Mu20Ar1	20	40	46	14	2	19.8	2.5	88.1
Mu20Ar2	20	40	46	14	3	18	3	96.7
Mu20Ar3	20	40	46	14	3	20.5	2	83.2
Mu5me1	5	40	46	14	5	15	3	69.5
Mu5me2	5	40	46	14	5.5	14	3	78.7
Mu5me3	5	40	46	14	6	13	3	74.6
Mu20me1	20	40	46	14	4.5	17	3	164.2
Mu20me2	20	40	46	14	5.3	19	2.7	156.3
Mu20me3	20	40	46	14	6	20	2.5	160.5
OL5Ar1	5	36	56	8	4.5	18	4.5	19.8
OL5Ar2	5	36	56	8	5.2	17.5	4.7	20.9
OL5Ar3	5	36	56	8	6	17	5	20.3
OL20Ar1	20	36	56	8	2.3	17.2	5	50.2
OL20Ar2	20	36	56	8	2.4	16.5	5.3	55.7
OL20Ar3	20	36	56	8	3	15.5	5.5	52.6
OL5Me1	5	28	56	16	3	18.3	2	32.5
OL5Me2	5	28	56	16	3	18.5	2	31
OL5Me3	5	28	56	16	4.45	19	2	31.3
OL20Me1	20	28	56	16	3	16.2	2.7	84.3
OL20Me2	20	28	56	16	4	15	2.9	92
OL20Me3	20	28	56	16	5	14.2	3	88.5
OM5Ar1	5	26	56	18	8	4.8	9	17.6
OM5Ar2	5	26	56	18	8	6	7	20.5
OM5Ar3	5	26	56	18	8.5	5.3	8	19.8
OM20Ar1	20	26	56	18	10	2.8	8.5	38.4
OM20Ar2	20	26	56	18	11	1.4	10	41.9
OM20Ar3	20	26	56	18	12	2.5	9	40.4
OM5me1	5	36	48	16	10	5.5	10	41.5
OM5me2	5	36	48	16	11.5	5	10	41
OM5me3	5	36	48	16	13	4.8	10	40.7
OM20me1	20	36	48	16	9	6	7	91.4
OM20me2	20	36	48	16	11	3.5	7.5	95.6
OM20me3	20	36	48	16	11	5	10.5	92.8
PL5A1	5	20	36	44	16	1.3	10	34.5
PL5A2	5	20	36	44	19	1.2	11.3	26.1
PL5A3	5	20	36	44	21	1.1	12.5	31.8
PL20Ar1	20	20	36	44	15	1.3	12	65.8
PL20Ar2	20	20	36	44	16	1.1	12.5	70.1
PL20Ar3	20	20	36	44	17	1	13	69.7
PL5Me1	5	28	42	30	18	1.2	9	31.7
PL5Me2	5	28	42	30	18	1.25	9	30.6
PL5Me3	5	28	42	30	20	1	9.5	29.8
PL20Me1	20	28	42	30	6	4	10	63.7
PL20Me2	20	28	42	30	7	3.2	10	59.4
PL20Me3	20	28	42	30	7.5	2.2	9	61.5

1- runoff threshold(Minute) 2- infeltraion depth(cm) 3- Sediment yield(g/lit)

All data related to 120 runoffs and sediments produced were collected and measured in the laboratory and recorded. The correlation matrix and multi-variable regression method were further applied to determine the degree and type of correlation exists between variables using SPSS software. For this purpose, slope, vegetative cover, sand content, clay content, silt content and antecedent soil moisture were considered as independent variables and sediment yield as the dependent variable.

3 Results

Table 1 shows plot specifications such as slope, clay content, silt content, sand content and sediment yield for rain intensity of 60 mm/h. Table 2 shows a correlation matrix between sediment yield and all independent variables and the degree and type of the relation. This study suggested that variables such as slope, clay content, sand content, antecedent moisture, and silt content were critical. Owing to a sufficient number of experiments, all available variables were accepted by stepwise and backward methods and one model was presented for independent variables and sediment yield, respectively.

Equation 1, with a determination coefficient of 0.816 ($p < 0.001$), was selected as an appropriate model to predict sediment yield produced by 60 mm/h rainfall intensity.

Sy=3.033S+3.770Cl+1.7Sa-135.718 (Equation 1)

Here, SY is the amount of sediment yield (g/m2), S is the slope (%), Cl is the clay (%), Sa is the amount of sand (%) in soil samples. Tables 4 and 5 give the variance analysis and regression coefficient of the model, respectively.

As table 2 shows, dominant soil texture among marl units was silt-clay or silt-clay-loam, in which percentage of silt content is high, i. e. nearly all marl units especially upper red marl units (Mu), Qom marl unit (OM), lower red (OL), and Eocene marl (EM) silt content comprises a larger proportion in soil texture than two other particles - clay and sand. This could be regarded as one of the most important reasons that led to produce sediment within these marl units. The more silt content the more erosion prone soil. Silt grains has not considerable stickiness, hence as they get wetted soil grains easily will broke up and silt grains will become separated and transported, consequently more sediment will be produced. On the other hand, sand particles have larger sizes so resistant to movement and fine clay particles as the result of their stickiness are resistant to disjointing (Faiznia et al., 2007). This result is supported by findings of other researchers including Canga et al. (1999), Mispolinus et al. (1998), Cary and Evans (1974).

Table2. Coefficient of correlation matrix of sediment yield and independent variables

Parameter	CLAY	SILT	SAND	Slope	SEDM
Pearson Correlation	.329(**)	-.233	-.047	.689(**)	1
Sig. (2-tailed)	.008	.064	.714	.000	.
N	64	64	64	64	64

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Table 3. Descriptive statistics of the selected model

R	R Square	Adj. R Sq[1]	Std. Erro2	Change Statistics				
				R Square Change	F Change	df1	df2	Sig. F Change
.816 (a)	.665	.648	20.50	.665	39.742	3	60	.000

a Predictors: (Constant), SAND, SLOPE, CLAY
1- Adjusted R Square 2-Std. Error Of the Estimate

Table 4. Variance analysis

	Sum of Squares	df	Mean Square	F	Sig.
Regression	50109.061	3	16703.020	39.742	.000(a)
Residual	25216.910	60	420.282		
Total	75325.971	63			

a Predictors: (Constant), SAND, SLOPE, CLAY
b Dependent Variable: SEDM

Table 5. Coefficients of sediment yield

Parameter	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B		Correlations			Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
Constant	-135.718	27.331		-4.966	.000	-190.389	-81.047					
SHIB	3.033	.343	.663	8.852	.000	2.347	3.718	.689	.753	.661	.995	1.005
CLAY	3.770	.646	.711	5.839	.000	2.478	5.061	.329	.602	.436	.376	2.658
SAND	1.700	.385	.537	4.415	.000	.930	2.471	-.047	.495	.330	.377	2.650

a Dependent Variable: SEDM

4. Discussion

In this research, clay and slope were recognized as the most efficient factors determining sediment yield and sand was noted as having a slight effect on sediment yield. This slight effect of land slope could be related to low frequency of sand in the soil of marl units. Coefficients of correlation of all variables except for sand content and silt were positive, which indicates positive effects of the slope and clay content, and negative effects of sand content and silt content on the sediment yield. The coefficient of correlation of 0.047 between sand and sediment yield for 60 mm/h rainfall intensity indicate very low correlation. Percentages of slope, clay content and silt content had coefficients of correlation of 0.689, 0.329 and -0.233 respectively at the 99% confidence level with sediment yield. The coefficients of correlation of 0.861 in Equations (1) indicate their high potential in simulating sediment yield.

Comparing the results of this research with those in literature shows its adaptation and conformity. Warrington et al. (1989) noted that an increase in the slope of unstable soils abated runoff rate slightly. The same result was noted by Nikkami et al. (2005) for shallow and sandy texture soils on greater slopes.

Warrington et al. (1989) noticed that an increase in the slope of unstable soils abated the runoff rate slightly. Furthermore, one of the reasons for unstable soil impermeability in semi-arid areas is the formation of surface sealing during rainfall. Thus, an increase in the slope leads to the erosion and removal of sealing and consequently the increase in the permeability rate and decrease in runoff.

Meyer and Harmon (1984) used a rainfall simulator to investigate the effect of slope and soil texture on the amount of soil erosion, runoff and the size of sediment particles for plots with row vegetation cover. They found the amount of soil erosion increases with slope steepness and the sediment particle size changes with soil texture. Duiker et al. (2000) used a rainfall simulator with 60 mm/h intensity over 0.75 m2 plots on 30% slopes in southern Spain to evaluate the permeability and erodibility of the predominant soils. The results showed that alluvial soil had the greatest erodibility rate of 985 among clay, shallow hilly, alluvial and colluvial soils, in dry conditions. The rate of permeability in fluvial soils was the highest. In addition, the amount of soil erosion has high correlation (r = 69%) with the amount of silt and very fine sand.

Shekl Abadi et al. (2003) used a portable rainfall simulator and 1 m 2 plots to determine the relative soil erodibility of geological formations and to find its relation with physical and chemical characteristics of soils in the Golabad basin, Isfahan. Clay usually decreases erodibility, as observed in studies in different parts of the world (Kemper and Koch, 1966; Imeson and Verstraten,1989; Dimoyiannis et al., 1998). Organic matter increases aggregate stability and resistance to erosion (Kemper and Koch, 1966). Other properties, which may influence erodibility, include finely divided calcium carbonate, iron and aluminum oxides, and parent material (Middleton, 1930; Lutz, 1936; De Meester and Jungerius, 1978; Trott and Singer, 1983; Goldberg et al., 1988; Cerda, 1996).

Cerda (2002) investigated the effect of parent material and season on water erosion in east of Spain. Yair, etal (1980) and Bryan and Yair (1980) believe that sediment yield of badland marly slopes are much higher than clayey and sandy slopes. They say that erosion rate on marls are very high and they produce the highest amount of sediment concentration and runoff coefficient. Erosion rate of clay and sand is 10 to 15 times lower than that of marls. Mathys et al. (2003) with calibrating rainfall runoff erosion model in experimental catchment of Draix in France, quantified erosion of marls. Arnaez et al. (2007) determined the effective factors on runoff and erosion by using rainfall simulator.

The results of this research altogether suggest that soil texture and slope have a highly effect on producing sediment from marl units and the regression equation of this factors for sediment yield will be used to anticipate the sediment amount in similar conditions within other marly areas. As well using the results of this research and similar studies can be used to enhance the determination of erosion rate of soils.

Acknowledgments

This paper is the result of a research project entitled ''Investigation on physico, chemical characteristics, erosion features and erosion rate of marl formation in Zanjan Province'' implemented by the Agricultural and Natural Resources Research Center of Zanjan,Iran. The authors acknowledge the financial support of this Center.

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10/19/2011