Development of an empirical equation to predict runoff in dry-farming lands of a semi-arid region in NW Iran

Abstract

The process of transformation of rainfall into runoff over an area is very complex, so quantification of the runoff generation is very difficult. Determination of factors controlling runoff in the area is the first step to quantify runoff. Soil properties have important role in determining the runoff generation behavior**.** This study was conducted to develop an empirical equation on the basis of some soil properties for predicting runoff. Thirty six dry-farming lands under follow conditions in a semi-arid agricultural zone in Hashtroud, NW Iran were considered to installation of the unit plots. Runoff volume was measured at the plots under natural rainfall events during a 2-year period from March 2005 to March 2007. Soils were mainly clay loam having 36.7% sand, 31.6% silt and 32.0% clay, and calcareous with about 13% lime. Runoff generation in 41 rainstorms was largely associated with the erosivity index, EI_{30} ($R^2= 0.81$, $p< 0.001$). Annual runoff was significantly ($p< 0.001$, $R^2= 0.74$) related to the final infiltration rate and aggregate stability. To easily quantify annual runoff generation, it was considerably ($p< 0.001$, $R^2= 0.64$) related to coarse sand, organic matter and lime as the easily-measurable soil properties. Lime like to organic matter enhanced the aggregate stability and infiltration rate, and consequently decreased soil sealing and runoff generation. An empirical linear equation was developed based on the easily-measurable properties to predict runoff generation in semi-arid regions with the soil and rainfall properties similar to the study area.

Key-Words: Runoff; Lime; Aggregate stability; Infiltration; Sealing

1. Introduction

Runoff occurs only when the rate of rainfall on a surface exceeds the rate at which water can infiltrate the soil (Schwab et al., 1993). Runoff more commonly occurs in the arid and semi-arid regions, where rainfall intensities are high and the soil infiltration capacity is reduced because of surface sealing, or in paved areas. Runoff generation is an important factor in soil loss (Le Bissonnais et al., 2005) and nutrient movement from soil surface (Lal, 1998; Simard et al., 2000; Ng Kee Kwong et al., 2002), and consequently declining soil productivity and crop yield, particularly in dry-farming lands of semi-arid regions. Over the last two decades, a large body of knowledge has been built up about the hydrological processes such as runoff in semi-arid areas (Yair and Lavee, 1985; Abrahams et al., 1988). These studies showed that the runoff-controlling factors in semi-arid catchments are different from those which regulate the hydrology of wetter environments (Lavee et al., 1998; de Wit, 2001). In semi-arid catchments, surface conditions, such as soil crusting and rock pavement (Sole´-Benet et al., 1997) are the most relevant factors. Runoff generation in semi-arid regions is dominated by an infiltration excess mechanism with a short time to final infiltration rates and a fast response due to steep hillslopes with shallow soils, exposed rocks and lack of vegetation (Wheater, 2002; Greenbaum et al., 2006).

The process of transformation of rainfall into runoff over a catchment is very complex, highly nonlinear, and exhibits both temporal and spatial variability (ASCE, 2000a). There is a strong demand to develop an accurate and easily-used model that can appropriately model the runoff generation process (Lin and Wang, 2007). Recently many models have been developed to simulate this process. These can be categorized as empirical black box, conceptual, and physically based distributed models (ASCE, 2000b). Modeling runoff in semi-arid areas is also a challenging task because, many of the hydrological models developed for more humid areas are tuned to a saturation excess mechanism and not to the infiltration excess mechanism that often dominates in dry regions (Faures et al., 1995). In these regions, runoff is formed when the rate of rainfall exceeds the rate at which water can infiltrate the soil. The rate of infiltration of water into the soil depends on several soil properties, particularly physical characteristics of the soil (Ghawi and Battikhi, 1986). Thus, determining the soil properties influencing infiltration rate and controlling runoff is necessary to quantify the runoff generation in the area (Schwab et al., 1993).

Factors affecting runoff may be divided into those factors associated with the rainfall properties i.e. duration and intensity, and those with the watershed characteristics (slope, shape and surface storage) and soil properties (Schwab et al., 1993). Soil physicochemical properties have important role in determining the runoff generation behavior (Abrahams et al., 1988; Martı´nez-Mena et al., 1998). In a definite area with different soils, the runoff generation was directly affected by soil physicochemical properties. It has been proven that soil parameters responsible for runoff generation e.g. infiltration capacity, soil moisture, and aggregate stability are highly variable over space and time (Seeger, 2007). In semi-arid areas spatial variability of soil infiltration capacities is mainly attributed to the physical and chemical properties of the soil surface and rainfall characteristics (Lavee and Yair, 1987).

Many studies have been performed on the relationship between runoff generation and rainfall parameters (Rajurkar et al., 2004; Anctil et al., 2006; Boughton, 2006; Jacquin and Shamseldin, 2006; Al-Qurashi et al., 2008; Bahat et al., 2009), and on the importance of physical and hydrological parameters of the watershed in producing runoff (Parsons et al., 1997; Wainwright et al., 2000; Onda et al., 2006). Studies on the effect of soil parameters in the runoff generation have been mainly associated with the influences of antecedent soil moisture (Fitzjohn et al., 1998; Meyles et al., 2003; Castillo et al., 2003; Wei et al., 2007) and soil management systems (Martı´nez et al., 2006; Go´mez et al., 2009) on the runoff generation. Soil surface structure is one of the main factors controlling runoff and subsequent water erosion in cultivated soils and is, as such, a major threat to sustainable agriculture (Farres, 1987; Lecomte et al., 2001). The first few millimeters of the topsoil strongly affect infiltration rates and runoff generation (Auzet et al., 2004). Importance of soil surface seal properties as a main responsible factor in infiltration process and runoff generation has been well known (Bohl and Roth, 1993; Bradford and Huang, 1994). An increase in particle fraction of the soil increases the crust strength and decline runoff generation (Skidmore and Layton, 1992). Runoff generation may be decreased with an increase in coarse particles of soil (Adekalu et al., 2007) and ground cover (Costin, 1980; Lang, 1979). Adding organic matter to soil results a low surface runoff due to an increasing in soil water infiltration capacity (Zehetner and Miller, 2006; Zeiger and Fohrer, 2009). Some soil salts such as $CaCO_3$ (lime) and $CaSO_4$ (gypsum) influence on clay dispersion, infiltration and runoff (Roth and Pavan, 1991).

Almost 39 percent of Iran (642797 km^2) has a semi-arid climate condition, with an annual precipitation between 200 and 500 mm (Alizadeh, 2003). In these regions about 33% of the annual precipitation loss as surface flows (Rafahi, 1996). Farming is mostly done in dry condition and crop production is wholly dependent on water storage of rainfalls in soil. Prevention of runoff generation in these areas is an essential issue to conserve soil productivity and water supply for crop production. Thus, determining soil properties that influence runoff in dry-farming lands is the first step in the choice of a strategy to control runoff. More studies have focused on the effect of land use change on runoff generation (Sadeghi et al., 2004; Saadati et al., 2006), application of the hydrological model in estimating runoff (Rostamian et al., 2008), and modeling runoff based on geomorphologic properties (Abdollahi et al., 2003) in Iran. Some studies showed that the runoff generation can be affected by soil particles (Raeesiyan, 1996) and surface gravel (Javadi et al., 2004). However, there is no quantitative study to predict runoff in dry-farming lands of the semi-arid regions in Iran. Therefore, the objective of this work is to quantify the influence of soil physicochemical properties on runoff generation in order to develop an empirical equation to predict runoff in dry-farming lands of semi-arid regions.

2. Materials and Methods

2.1. Study area

The study was carried out in a semi-arid area of NW Iran located in Hashtroud township (southern part of East Azarbyjan province) from March 2005 to March 2006. The study zone was 900 km^2 in area located between 37° 18' 49" and 37° 35' 0" N latitude, and 46° 46' 5" and 47° 6' 5" E longitude (Fig. 1). The climate is semi-arid with an average annual precipitation of 322 mm, mostly falling in the winter, autumn and spring and a mean annual temperature of 13°C. Agricultural soils located mostly in 5-15% slopes and mainly are utilized for wheat dry-farming. The soils have low organic matter (about 1%) and are mainly calcareous with a moderate value of total carbonates (Hakimi, 1986). First observations in the area showed that cultivation in slope direction is a main factor in producing surface runoff and so declining crop productivity in dry-farming lands.

Fig. 1

2.2. Field study

To measurement of surface runoff, plots were installed in 36 square grids with a dimension of 5 km × 5 km in the study area. In each grid, a dry-farming land located in a south slope 9% and under fallow condition was considered. Study lands were plowed in slope direction and harrowed to provide a smooth uniform (Rejman et al., 1998) on February 2005. Three unit plots with 1.83-m wide and 22.1-m long (Wischmeier and Smith, 1978) with 1.2 m spacing were installed in each land on March 2005 (Fig. 2). Runoff-collecting installations consisted of gutter pipes, pipes and 70-1 tanks (Rejman et al., 1998) were established at the lower parts of the plots (Fig. 3). After each natural rainfall producing runoff at each plot, total runoff volume generated in the collecting tank was measured. Runoff was then mixed thoroughly and a 0.5 kg sample was taken to determination of water mass (Hussein, 2007). In the laboratory, the runoff samples were weighed and evaporated on a hot plate then weighed again to determine sediment concentration (Guy, 1975) and accordingly water mass. Water loss of each plot was determined based on multiplying total runoff volume of the tank by mass percentage of water in the sample. Annual surface runoff was also computed from summation of total surface runoffs produced in different natural rainfall events for each year. Runoff coefficient (runoff factor) of each plot was also obtained from proportion of runoff depth (mm) per unit of rainfall depth (mm).

Fig. 2

Fig. 3

2.3. Determination of rainfall properties

Rainfall data were taken from five rainfall gauges stations located in the study area (Fig. 1). Four standard rainfall gauges located in the grids 2, 10, 27 and 30 were used to manually measure the depth of rain after each runoff event at the plots. An automatic rain gauge belonging to Irrigation Office of Hashtrood located in the grid 17 was also used to determine intensity of rainfall events. On the basis of recording rain gauge data of the meteorological station in grid 17, the rainfall intensity and I_{30} (the maximum 30-minute intensity), and rainfall energy of rainfall events was obtained for a 2-year period. The rainfall energy computed using the energy equation as follow (Wischmeier and Smith, 1978):

$$KE = 210.3 + 87 \log_{10} I \qquad (1)$$

where I is the rainfall intensity (cm h^{-1}) and KE (J $m^{-2}cm^{-1}$) is kinetic energy per unit rainfall height (cm). The kinetic energy, E (J m^{-2}) was obtained by multiplying KE into the rain depth (cm). Rainfall erosivity index (EI_{30}) which is a major causal factor of soil erosion (Angulo-Mart´ınez et al., 2009) was obtained by multiplying E into I_{30} (mm h^{-1}) and was accordingly calculated as MJ mm ha^{-1} h^{-1} unit. The annual rainfall erosivity factor or R (MJ mm ha^{-1} h^{-1}) was ultimately calculated by the summation of the EI_{30} values of different rainfall events occurred in the first and second years.

2.4. Determination of soil properties

To determination of soil properties influencing runoff, soil properties consisted of independent properties (mineral particles, gravel, organic matter, lime, and potassium) and dependent properties (initial and final infiltration rate, and aggregate stability) were determined in the study soils. Soil samples (0-30 cm depth) were taken randomly from three locations within each plot before plowing to determine the independent soil properties. Then, the samples of each plot were mixed together and a representative sample was provided. After being dried, the soil samples were grounded to pass a 2 mm sieve and stored in sealed polyethylene bags in a cool and dry place until the chemical analysis in the laboratory. The particle size distribution consisted of coarse sand (0.1-2 mm), very fine sand (0.05-0.1 mm), silt (0.002-0.05) and clay (<0.002 mm) was determined by the Robinson's pipette method (SSEW, 1982). Gravel (2-8 mm) was determined using the weighting method (Gee and Bauder, 1980). The total soil organic carbon was measured by the Walkley–Black wet dichromate oxidation method (Nelson and Somers, 1982) and converted to organic matter through multiplying it by 1.724. To determine lime amount, the total neutralizing value (TNV) on the basis of calcium carbonate was measured using acid acetic volume consumed to neutralizing carbonates (Goh et al., 1993). The available potassium content was also measured with the ammonium acetate extraction method (Knudsen et al., 1982). The aggregate stability and infiltration rate were determined in the soil plots immediately after plowing. The aggregate stability was determined using the wet-sieving method based on the mean weight diameter (MWD) as proposed by Angers and Mehuys (1993). The water-stable aggregates were determined by placing 100 g aggregates with diameter larger than six mm on the top of sieves set and moved up to down in a water cylinder for one minute. The initial and final infiltration rate was determined by measuring the one-dimensional water flow into the soil per unit time by double-ring infiltrometer (Bouwer, H. 1986) at four to six replications in the plots. The infiltration measurements were carried out at the end of the dry season (in July 2005) in order to exclude the influence of different initial moisture contents as described by Turner and Summer (1978). Immediately after measuring the aggregate stability and infiltration rate, plowed state the plots in testing places was adjusted.

2.5. Statistical analysis

Data were assessed for normality using the Kolmogorov-Smirnov test. Factors influencing runoff was extracted based on bivariate correlation matrix built between runoff and soil properties (dependent and independent) using Pearson's method (Soka and Rohlf, 1981). A stepwise multiple regression analysis was utilized to formulate an equation to predict runoff generation based on the soil properties.

3. Results

3.1. Rainfall properties

Ninety seven natural rainfalls occurred in the study area during the 2-year study period. Table 1 shows the mean characteristics of the rainfall events from March 2005 to March 2007. Out of 97 rainfall events, 41 rainstorms produced runoff and sediment (soil loss) at the unit plots in the area (Table 2). The rainfall erosivity index (EI_{30}) varied from 1.077 to 73.402 MJ mm ha^{-1} h^{-1}, with an average of 15.444 MJ mm ha^{-1} h^{-1}. The mean annual erosivity factor (R) was also identified to be 334.543 MJ mm ha^{-1} h^{-1} $year^{-1}$. The mean depth of rainfalls causing runoff in the rain gauge stations located in grids 2, 10, 17 and 30 were 7.22, 6.59, 6.98 and 6.84 mm respectively. There was no significant difference among the rainstorms depth values in different rain gauge stations (F=0.027, P-value=0.994).

Table 1

Table 2

3.2. Runoff production

The results are summarized in Table 3. Mean surface runoff produced in 36 lands was varied from 3.39 (33.90 m^3 ha^{-1} yr^{-1}) to 11.92 mm yr^{-1} (119.20 m^3 ha^{-1} yr^{-1}) with an average of 8.09 mm yr^{-1}(80.89 m^3 ha^{-1} yr^{-1}). Runoff coefficient of the plots was ranged from 0.02 mm mm^{-1} to 0.08 mm mm^{-1} with an average of 0.06 mm mm^{-1}. Runoff generation at the plots in different rainstorms varied due to differences of the rainfall properties. As shown in Fig. 4 despite a significant correlation between average runoff produced in the study area with the rainfall depth (R^2= 0.73, $p< 0.001$), maximum 30-minute intensity of rainfalls (R^2= 0.73, $p< 0.001$), runoff generation strongly affected by rainfall erosivity index, EI_{30} (R^2= 0.81, $p< 0.001$). With an increasing in the erosivity index, runoff volume remarkably increased. There was no significant correlation between runoff and rainfall intensity (R^2= 0.41).

Table 3.

Fig. 4.

3.3. Soil properties

Since there was no significant difference in rainfall properties (depth) among the rain gauge stations, the spatial rainstorm distribution was uniform. Thus, difference in runoff generation at the unit plots was directly depended on the soil properties. As shown in Table 4, soil textures were mainly clay loam having 36.7% sand, 31.6% silt and 32.0% clay. Soils had low organic matter (1.1%) and were calcareous (limy) containing 13% equivalent calcium carbonate (lime). Mean values of gravel and potassium in the study soils were 10% and 315 $mg.kg^{-1}$, respectively. Soil aggregates were mainly granular with a mean diameter of 5 mm. The water-aggregate stability of the soils was very low with the mean weight diameter (MWD) value ranged between 0.27 and 1.91 mm. The soil permeability (infiltration capacity) value on the basis of the final infiltration varied between 1.4 and 5.8 cm h^{-1} with an average value of 3.5 cm h^{-1}. Initial infiltration rate were ranged between 60 and 81.3 cm h^{-1}. Statistical distributions of the different soil properties data were normal.

Table 4

3.4. Relationship between runoff and soil properties

Mean annual runoff values at the study plots were between 137.12 and 482.07 liter, with an average of 327.16 liter for a 2 -year period. Factors influencing runoff extracted from correlation matrix was presented in Table 5. Based on the results, the final infiltration rate/ the soil permeability and aggregate stability were the dependent soil properties that strongly declined the annual runoff with an R^2 of 0.77, 0.47 and 0.38, respectively. The stepwise multiple regression analysis showed that the annual runoff significantly ($p< 0.001$, $R^2= 0.74$) related to the final infiltration rate and aggregate stability (Table 6). With a increasing in these soil properties, the runoff generation considerably decreased. The soil permeability was significantly affected by coarse sand ($p< 0.01$), silt ($p< 0.05$), organic matter ($p< 0.01$) and lime ($p< 0.05$). Silt contrary to coarse sand and organic matter decreased the soil permeability. The aggregate stability was considerably influenced by very fine sand ($p< 0.01$), clay ($p< 0.001$), organic matter ($p< 0.05$) and lime ($p< 0.01$). Clay and organic matter opposite with very fine sand enhanced the aggregate stability.

Table 5

Table 6

Soil independent properties consisted of mineral particles, gravel, organic matter, lime and potassium that significantly correlated with the soil permeability and aggregate stability, controlled generation of the runoff. Since measurements of the infiltration rate and aggregate stability were relatively difficult and consuming time, there was a need to estimation of runoff using easily-measurable soil properties. As shown in Table 5 the annual runoff significantly correlated with coarse sand ($p< 0.01$), silt ($p< 0.05$), organic matter ($p< 0.01$) and lime ($p< 0.05$), while its relationship with very fine sand, clay, gravel and potassium was not significant. Multi-regression analysis of the relationship between runoff and these soil properties showed that runoff was significantly ($p< 0.001$, $R^2= 0.64$) related to coarse sand, organic matter and lime (Table 7). In fact, these easily-measurable soil properties could explain 64% variations of runoff in the study area. Coarse sand, organic matter and lime at the statistical level of 0.001, 0.01 and 0.01 negatively influenced runoff in the study area, respectively.

Table 7

Therefore an empirical equation was extracted from the multiple regression analysis as fallows:

$$R= 174.812 - 1.842CS - 36.566OM - 1.524Li \tag{2}$$

Where R is the runoff volume ($m^3\ ha^{-1}\ yr^{-1}$), CS is coarse sand (%); OM is organic matter (%) and Li is lime/total carbonates as calcium carbonate (%) in soil surface sample.

4. Discussion

Runoff coefficient of the plots in forty one rainstorms was 0.06 mm mm^{-1}, on average, which confirms the high infiltration capacity of soils in comparing to rainfall intensities (Kao et al., 1998; Augeard et al., 2005). Hensley et al. (2000) and Botha et al. (2003) also showed that in semi-arid areas with fine textured soils, runoff can vary between 8% and 49% of the annual rainfall depending on the prevailing conditions. Analysis of rainstorms caused runoff at the plots indicated that out of the rainfall parameters (depth, intensity, maximum 30-minute intensity and erosivity index), the rainfall erosivity index (EI_{30}) had the highest correlation with runoff generation in the study area. In fact the composition of the maximum 30-minute intensity (I_{30}) and energy (E) of the rainfalls gave a better index (EI_{30}) to explain runoff generation potential of the rainfalls in the study area. The rainfall erosivity index (EI_{30}) is also considered as one of the most important factors in soil loss estimation using universal soil loss equation (USLE) (Wischmeier and Smith, 1978) and its revised version (RUSLE) (Renard et al., 1997). This index can present capability of a rainfall in detachment of soil particles and their transportation. Transportation of soil particles is mainly supplied by the runoff movement. Disruption of soil surface structure and crust formation that leads to a decrease in the soil hydraulic conductivity of the top layer and generation of the runoff is strongly affected by rainfall properties (intensities, duration and kinetic energy) (Fohrer et al., 1999). Thus, The EI_{30} can be used as a runoff producing index of the rainfalls. This result accords with Onda et al. (2007), who found that surface runoff has a good correlation with the rainfall energy. Studies by Morin and Cluff (1980) also showed that rainfall intensity is one of the most important factors influencing runoff in semi-arid areas.

Runoff generation in thirty six study plots also was related to soil permeability (final infiltration rate). This result is in accord with Gómez et al. (2001), who found that approximately 50% of variability of runoff in fallow plots can be explained by the final infiltration rate. Many authors noted that closely related to the runoff generation mechanisms is the infiltration capacity of the soils. Indeed, infiltration capacity which was determined based on the final infiltration rate, is the most important factor controlling runoff in the soils (Brakensiek and Rawls, 1994; Roth, 2004). Morin and Cluff (1980) also noted that the final infiltration rate of the soil, which is greatly decreased by crusting, is the most important soil parameter influencing runoff in semi-arid areas.

Independent soil properties consist of mineral particles, organic matter and lime considerably influenced the runoff generation in the study area. Coarse sand, organic matter and lime contrary to silt positively affected soil permeability and consequently reduced runoff. So, variations of these parameters in soils could remarkably influence on the generation of runoff at the plots. Studies by Brakensiek and Rawls, (1994) and Maestre and Cortina (2002) indicated that spatial variability of the soil infiltration capacity is related to the high spatial variability of soil properties (structure, organic matter content, antecedent soil moisture, etc.) that affect the runoff generation in the hillslopes.

Aggregate stability as a dependent soil property was an important factor controlling runoff in the study area. This result agrees with Cammeraat and Imeson (1998), Barthès and Roose (2002) who confirmed that aggregate stability is a relevant indicator of runoff and soil susceptibility to water erosion in semi-arid environments. In this investigation, permeability of soils was obtained from the final infiltration rate in soil profile and so it was not affected by the aggregate stability of surface soil samples. Based on studies of Roth and Eggert (1994) no relationship was found between aggregate stability and infiltration parameters. In this study, the effect of the aggregate stability in decreasing runoff was not due to its influence in enhancing soil permeability, but it was due to its remarkable effect in enhancing initial infiltration rate. Soil structure disruption by raindrop impacts could be reduced due to a presence of the stable aggregates in soil surface and so water can enter to soil with a relatively high rate at initial times of starting rainfall. In this reason, increasing the aggregate stability of surface soil declined runoff generation without it could affect the final infiltration rate. This result accords with Lal and Shukla (2004) who noted that soils that have poor structure, leading to surface sealing of pores and crusting, and consequently less infiltration and high runoff. Augeard et al. (2007) showed that soil surface sealing drastically reduces infiltration in bare soils exposed to rainfall and subsequently affects runoff generation and soil erosion. Seal formation dynamics as proposed by Assouline and Mualem (1997) explicitly addresses the characteristics of both rainfall and soil.

Results showed that runoff is significantly influenced by soil particles i.e. coarse sand and silt. This result agrees with Malik et al. (1987) who found that runoff significantly related to soil texture. Effect of coarse sand in enhancing soil permeability and in consequence reducing runoff agrees with Santos et al. (2003) who found that in sandy soils due to presence of macro pores, rate of water enter to soil is higher than of fine textured soils and so generation of runoff is lower than them. Since silt particles have not strong cohesive property caused soil aggregate were easily disrupted by rain drop impacts. Aggregate disruption accelerated when previous rainfalls wetted them. So, during the rainfalls periods, the impact of raindrops induced the formation of the structural crust on the soil surface (Augeard et al., 2005). Despite clay particles can be absorbed on sand and silt fractions, and enhance strength and stability of aggregates (Lal and Shukla, 2004) but their effects on the runoff was not considerable due to its negligible role in the soil permeability. This result is not in line with Pepper and Morrissey (1995) who found that runoff is positively affected by clay. Particle size distribution especially clay particles play an important role in matric suction of the soil and improving water storage in the soil (Lal and Shukla, 2004), and in consequence speed up staring time of the runoff generation. Nevertheless enhancing aggregate stability and rising initial water infiltration rate caused that these particles did not positively influence the runoff generation. Effect of gravel on runoff also is not in accord with Mathys et al. (2005) who indicated that infiltration rate is increased by the gravel cover of soil surface in the Black Marls. Organic matter has been recognized as important binding and bridging agent in enhancing a soil's structural stability, infiltration capacity, and in consequence reducing runoff (e.g., Hartanto et al., 2003; Ferna´ndez er al., 2006; Zhang et al., 2007). Based on the results (Table 6) lime explained about 30 per cent of the runoff variations in soils of the study area. This result revealed that lime is an important factor controlling runoff in soils of semi-arid study area. In these soils, Ca^{2+} cation can bind soil particles and improves the aggregates stability in soil profile length. Williams (1935) and Peterson (1947) proposed Ca-linkage as a mechanism in the formation of water-stable aggregates, and increasing infiltration rate. This result accords with Pepper and Morrissey (1985) who found that runoff is negatively related to the exchangeable calcium percentage.

With considering importance of water conservation in the dry-faming lands to supply plant water requirement and keep soil productivity, quantify runoff is the first step in the choice of a strategy to control runoff. Although the final infiltration rate was the most important factor influencing runoff in the study soils, due to some difficult in its field measurements, developing a simple and practical equation to predict runoff in the area was necessary. Coarse sand, organic matter and lime were as the easily-measurable soil properties influencing infiltration and runoff that were used to establish a linear regression equation. Using this empirical equation can predict runoff generation from the dry-farming lands in the semi-arid regions where soil and rainfall properties are similar to them in the study area.

5. Conclusions

Runoff volume was measured at the unit plots installed in thirty six dry-farming lands under natural rainfall events for a two-year study period. Runoff coefficient of the unit plots in forty one rainstorms was 0.06 mm mm^{-1}, on average, which confirmed the high infiltration capacity of soils in comparing to rainfall intensities. Runoff generation at the plots in different rainstorms was largely associated with the erosivity index of the rainstorms, EI_{30} ($R^2 = 0.81$, $p < 0.001$). Since the spatial distribution of rainstorms in the study area was uniform, difference in runoff generation at the plots was directly depended on the soil properties. The multiple regression analysis showed that the annual runoff significantly ($p < 0.001$, $R^2 = 0.74$) related to the final infiltration rate and aggregate stability. With a increasing in these soil properties, the runoff generation considerably decreased. Since measurements of the two soil - property were relatively difficult and consuming time, the annual runoff was considerably (p<

0.001, R^2= 0.64) related to coarse sand, organic matter and lime as the easily-measurable soil properties. Lime like to organic matter positively affected the aggregate stability and infiltration rate, and in consequence decreased soil sealing and runoff generation at the plots. An empirical linear equation was developed based on the easily-measurable soil properties to use in semi-arid regions with the soil and rainfall properties similar to the study area.

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Table 1

Mean characteristics of the natural rainfall events between March 2005 and March 2007

Rainfall characteristic	Mean	StD
Duration (h)	1.80	1.54
Depth (mm)	4.13	4.14
Intensity (mm h^{-1})	2.76	2.55
I_{30} (mm h^{-1})	4.88	4.99
EI_{30} index (MJ mm ha^{-1} h^{-1})	6.76	13.78

Table 2

Characteristics of the rainstorms lead to runoff at the plots between March 2005 and March 2007

Event No.	Duration (h)	Depth (mm)	Intensity (mm h^{-1})	Maximum-30 minutes intensity (mm h^{-1})	Erosivity index (MJ mm ha^{-1} h^{-1})
1	1.15	2.55	2.21	3	1.17
2	1.36	3.65	2.68	3.2	1.88
3	3.4	13.7	4.03	15.2	36.64
4	1	2.7	2.7	3	1.3
5	1.3	4.8	3.7	4.8	3.98
6	1.1	3.7	3.36	5.4	3.38
7	6.98	17.85	2.56	7.6	21.55
8	0.7	2.8	4	5.4	2.66
9	1.5	8.35	5.58	8.4	13.2
10	0.71	2	2.82	3.8	1.23
11	0.73	2.5	3.42	4.8	2.04
12	1.15	4.2	3.65	5	3.62
13	1.18	11.9	10.08	21.8	54.63
14	0.9	12.4	13.78	22.8	62.88
15	1.6	8.1	5.06	25	37.37
16	2.1	12.5	5.95	13	30.99
17	1.3	10.4	8	12.2	25.61
18	0.5	3.5	7	7	4.82
19	0.77	1.9	2.47	3.6	1.08
20	1.38	15.3	11.08	22.4	73.4
21	0.65	4	6.15	6.8	5.22
22	0.58	2.4	4.13	4.6	1.95
23	4	9.3	2.32	4.4	6.35
24	0.84	5.3	6.31	8.2	8.36
25	1.67	4.25	2.54	5.2	3.47
26	3.17	6.7	2.11	4.2	4.22
27	1.61	12.7	7.89	14.46	36.92
28	1.5	4.2	2.8	5	3.38
29	1.25	3.3	2.64	4	2.1
30	1.83	5.6	3.6	6	5.74
31	2.38	8.1	3.4	7.4	10.1
32	1.36	4	2.94	4.2	2.74
33	1.34	3.4	2.54	4	2.14
34	1.86	4.8	2.58	7.6	5.76
35	1.8	6.8	3.78	6.6	7.75
36	0.5	4.1	8.2	8.2	6.81
37	3.5	18.7	5.35	13	45.22
38	0.5	4.6	9.9	9.8	9.46
39	0.5	2	4	4	1.4
40	2.15	14.3	6.65	12.4	34.48
41	1.77	8.1	4.56	9.6	13.98

Table 3

Mean runoff generated by forty one rainstorms at the runoff plots in thirty six dry-farming lands in a 2-year study period from March 2005 to March 2007

Plot No.	Mean runoff ($mm\ yr^{-1}$)	StD	Runoff coefficient ($mm\ mm^{-1}$)
1	9.38	0.37	0.06
2	9.50	0.27	0.07
3	9.14	0.49	0.06
4	8.81	0.45	0.06
5	11.38	0.26	0.08
6	4.20	0.44	0.03
7	6.93	0.49	0.05
8	5.43	0.57	0.04
9	10.47	0.36	0.07
10	10.84	0.65	0.07
11	11.92	0.16	0.08
12	5.99	0.24	0.04
13	9.94	0.71	0.07
14	9.48	0.44	0.07
15	10.02	0.06	0.07
16	4.61	0.52	0.04
17	6.00	0.27	0.04
18	9.51	0.42	0.07
19	9.96	0.5	0.07
20	7.34	0.24	0.05
21	6.57	0.24	0.05
22	6.56	0.6	0.05
23	8.74	0.21	0.06
24	7.32	0.53	0.05
25	10.35	0.51	0.07
26	6.59	0.14	0.05
27	4.92	0.6	0.03
28	11.06	0.25	0.08
29	9.12	0.33	0.06
30	8.65	0.4	0.06
31	6.67	0.33	0.04
32	3.39	0.19	0.03
33	6.87	0.35	0.05
34	7.20	0.41	0.05
35	8.13	1.00	0.06
36	8.19	0.55	0.06

Table 4

Physical and chemical soil properties in the study area

Soil property	Mean	StD
Coarse sand	18.9	5.3
Very fine sand	17.8	3.2
Silt	31.5	7.1
Clay	31.8	5.7
Gravel	9.9	2.4
Organic matter	1.1	0.2
Lime /Carbonates (%)	12.7	5.2
Potassium (mg kg^{-1})	314.7	25.4
Structure stability in Water, MWD (mm	1.13	0.44
Final infiltration rate (cm h^{-1})	3.5	1.2
Initial infiltration rate (cm h^{-1})	81.33	14.37

Table 5

The correlation matrix of runoff and physicochemical soil properties in the study area

	CS	VFS	Si	Cl	Gr	OM	Li	Pot	AS	Per	If	R
CS	1											
VFS	0.224	1										
Si	-0.742***	-0.197	1									
Cl	-0.179	-0.500**	-0.400*	1								
Gr	0.028	-0.007	0.024	-0.058	1							
OM	0.268	-0.307*	-0.228	0.208	0.165	1						
Li	-0.001	-0.558**	0.174	0.028	-0.030	0.046	1					
Pot	-0.072	-0.046	-0.177	0.309*	0.093	0.059	-0.092	1				
AS	-0.175	-0.670**	-0.123	0.705***	-0.091	0.293*	0.481**	0.217	1			
Per	0.761***	-0.047	-0.553**	-0.069	0.091	0.541**	0.295*	0.080	0.134	1		
If	-0.063	-0.340*	-0.058	0.410*	-0.359*	0.438**	0.321*	-0.063	0.614**	0.186	1	-0.384*
R	-0.558**	0.231	0.419*	-0.093	-0.088	-0.565**	-0.390*	-0.084	-0.467**	-0.777***	-0.384*	1

CS: coarse sand; VFS: very fine sand; Si: silt; Cl: clay; Gr: gravel; OM: organic matter; Li: lime (carbonates); Pot: potassium; AS: aggregate stability (mean weight diameter of stable aggregates in wet-sieving method); Per: permeability (final infiltration rate); If: initial infiltration rate; R: runoff

***. Correlation significant at $p < 0.001$; **. Correlation significant at $p < 0.01$; *. Correlation significant at $p < 0.05$

Table 6

The multi-regression analysis of relationship between runoff and some dependent soil properties

Model variable[a]	Unstandardized coefficients		Standardized coefficients	t-level	P-level
	Model coefficients	Standard error			
Constant	149.199	7.445		20.014	$p < 0.001$
Per	-13.454	1.664	-0.728	-8.084	$p < 0.001$
As	-17.971	4.382	-0.369	-4.101	$p < 0.001$

[a]. Per: soil permeability; AS: water-aggregate stability

Table 7

The multi-regression analysis of relationship between runoff and the easily-measurable soil properties influencing it

Model variable[a]	Unstandardized coefficients		Standardized coefficients	t-level	P-level
	Model coefficients	Standard error			
Constant	174.812	12.879		13.574	$p < 0.001$
CS	-1.842	0.461	-0.443	-3.994	$p < 0.001$
OM	-36.566	9.456	-0.429	-3.867	$p < 0.01$
Li	-1.524	0.440	-0.371	-3.465	$p < 0.01$

[a] . CS: coarse sand; OM: organic matter; Li: lime (carbonates)

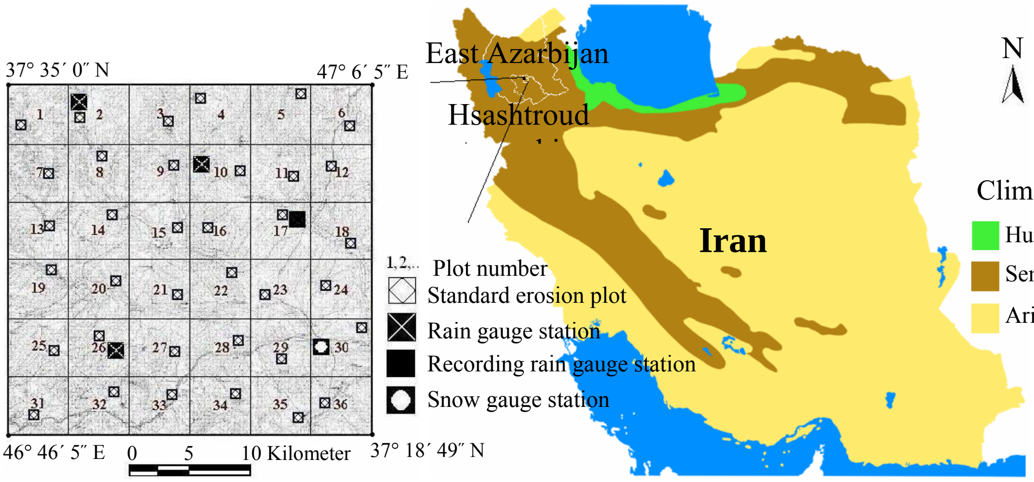

Fig. 1. Location of the study area, rainfall gauge stations and unit plots used for measuring surface runoff.

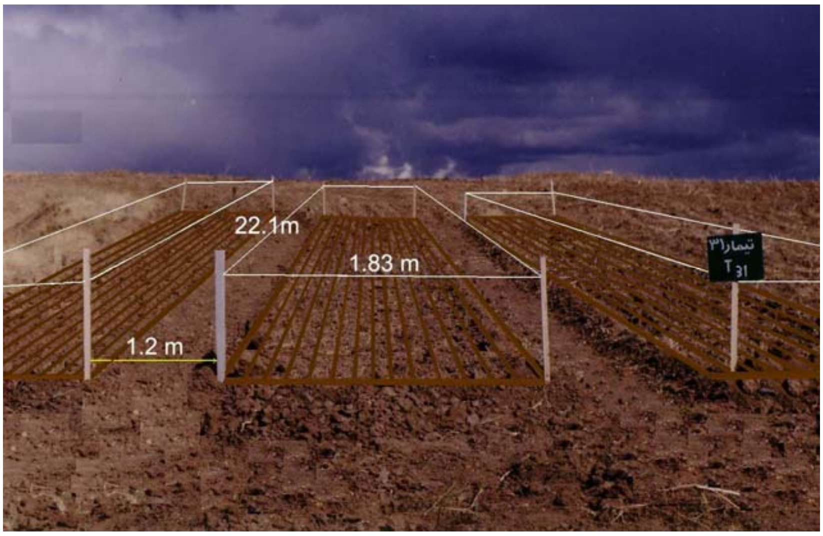

Fig. 2. Installation of three runoff plots with 1.83-m wide and 22.1-m long in a south land 9% under fallow condition.

Fig. 3. Runoff-collecting installations consisted of gutter pipes, pipes and 70-1 tanks at the lower part of the runoff plot

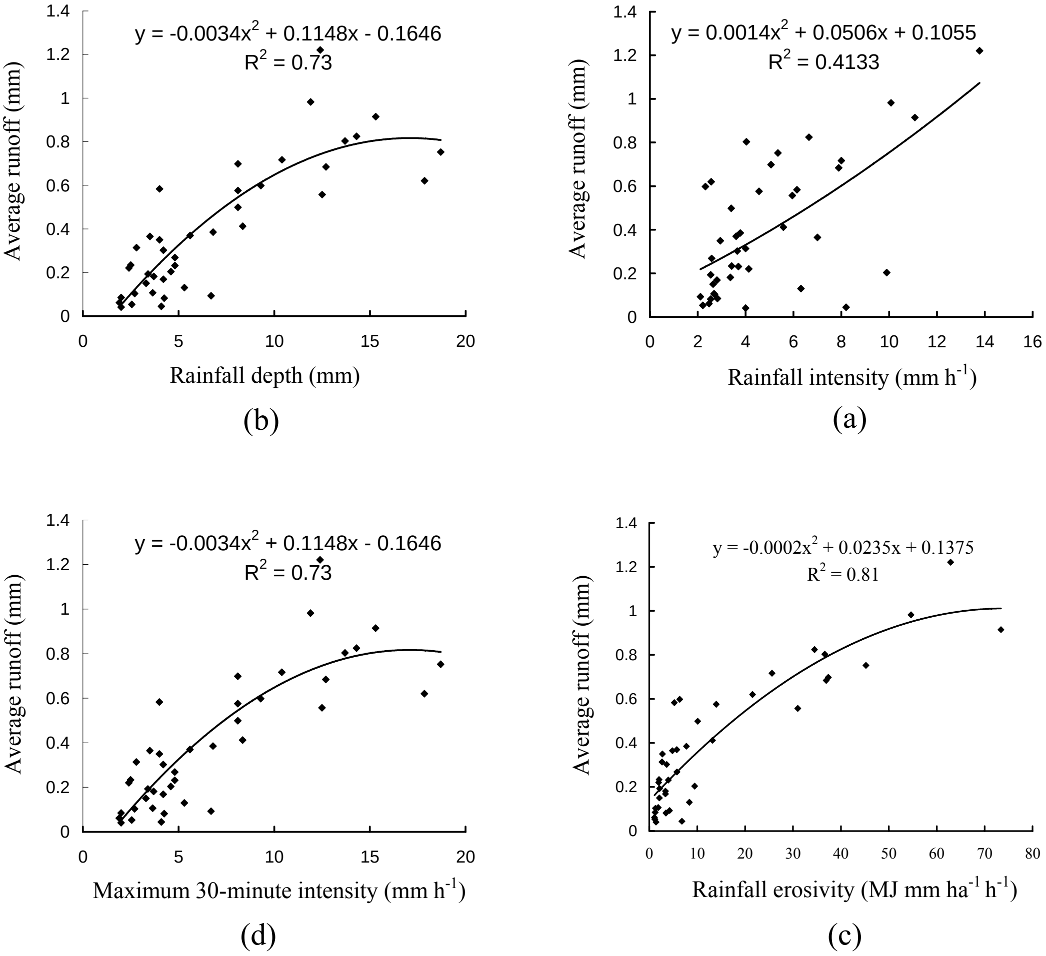

Fig. 4. Relationship between runoff and rainfall parameters for 41 rainstorms occurred during a 2-year study period in the study area.