Araştırma Makalesi / *Research Article* Iğdır Üni. Fen Bilimleri Enst. Der. / *Iğdır Univ. J. Inst. Sci. & Tech.* 2(2,Ek:A): 105-112, 2012

Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi
Iğdır University Journal of the Institute of Science and Technology

Runoff and Erosion as Affected by Soil Spatial Variation and Temporal Conditions

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ABSTRACT: Soil loss by overland flow in agricultural lands or watersheds is a severe problem worldwide. Agricultural fields usually exhibit a complex spatio-temporal variability related to soil characteristics, and hence variable sources of sediment and pollutant, and hydrologically sensitive areas. We have studied and quantified, in a systematic manner, the contribution of soil spatial variation/properties and temporal conditions on runoff and soil erosion from numerous soils. The soil properties and conditions included: (1) soil texture classes and other properties; (2) predominant clay mineralogy (kaolinitic, illitic and smectitic); (3) organic matter content; (4) antecedent moisture contents (from dry to full saturation); (5) rain kinetic energy (KE, 0-22 kJ/m^3); (6) wetting rates of soil by rainfal or irrigation water; (7) tillage type (conventional and minimum tillage); (8) water quality (rain, fresh, effluent or saline irrigation water); (9) use of soil amendments (polymer, gypsum and manure).

Runoff and erosion were highly affected by clay mineralogy, and increased exponentially with the increase in rain KE, rate of soil wetting and soil sodicity. Rain KE and water quality played a predominate role in determining infiltration, runoff and soil loss in medium- and coarse-textured soils, and wetting condition played a predominate role in fine-textured soils. Soils from semi-arid regions, having moisture content in the range between wilting point and field capacity were less susceptible to runoff and soil loss. Effects of minimum-tillage depend on soil texture and irrigation water quality. However, effects of minimum-tillage were lower than conventional one. Application of a small amount of polymer in combination with gypsum may effectively decrease runoff and soil loss by 2-4 times relative to the control.

The presented data on runoff and soil erosion may significantly assist in improving our understanding and modelling of the changes in the degree of runoff and erosion in arid and humid zone soils.

Keywords: Runoff, erosion, spatial variation, intrinsic properties and temporal condition

Toprak Mekansal Varyasyonu ve Zamansal Koşullarla Etkilenmiş Yüzey Akış ve Erozyon

ÖZET: Tarım arazileri veya su havzalarında toprağın yüzey akış ile kaybı tüm dünyada ciddi bir sorundur. Tarım alanları, genellikle, toprak özellikleri, değişen sediment yükü, kirleticiler ve hidrolojik hassas alanlar nedeniyle karmaşık bir uzaysal-zamansal değişkenlik gösterebilir. Bu çalışmada, toprağın mekansal değişimi/özelliklerinin ve zamansal koşulların yüzey akış ve toprak erozyonuna etkisi, çok sayıdaki toprak örnekleri üzerinde sistematik bir şekilde araştırılarak değerlendirilmiştir. Değerlendirmede kullanılan toprak özellikleri ve koşulları şunlardır: (1) toprak yapısı sınıfları ve diğer özellikleri; (2) baskın kil mineraloji (kaolinitik illitic ve smectitic), (3) organik madde içeriği, (4) nem içerikleri (kurudan tam doygunluğa kadar); (5) yağmur kinetik enerjisi (KE, 0-22 kJ m^{-3}); (6) yağmur veya sulama suyu ile toprak ıslanma oranları; (7) tarım şekli (konvansiyonel ve minimum toprak işleme), (8) su kalitesi (yağmur, taze, atık veya tuzlu sulama suyu); (9) toprak düzenleyicilerin kullanımı (polimer, jips ve gübre).

Yüzey akış ve erozyon kil mineralojisinden oldukça etkilenmekte; yağışın KE, toprak ıslanma oranı ve toprak tuzluluğu katlanarak artmaktadır. Yağışın KE ve su kalitesi, orta ve kaba bünyeli topraklarda, ıslanma koşulları ise kil dokulu topraklarda infiltrasyon, yüzeysel akış ve toprak kaybının belirlenmesinde, baskın bir rol oynamaktadır. Solma noktası ile tarla kapasitesi arasında nem içeriğine sahip yarı-kurak bölgelerdeki toprakların yüzey akış ve toprak kaybına daha az duyarlı olduğu görülmüştür. Minimum toprak işleme etkileri, toprak yapısı ve sulama suyu kalitesine bağımlıdır. Ancak, minimum toprak işlemenin etkileri geleneksele göre daha düşük bulunmuştur. Küçük miktarda polimerin jips ile kombinasyonu, kontrol denemelerine göre, yüzey akış ve toprak kaybını etkili bir şekilde 2-4 kat azaltabilmektedir. Yüzey akış ve toprak erozyonu üzerine sunulan veriler kurak ve nemli bölge topraklarının yüzey akış ve erozyon derecelerinin modellenmesi ve anlaşılmasında önemli ölçüde yardımcı olabilir.

Anahtar kelimeler: Yüzey akış, erozyon, mekansal değişimi, içsel özellikleri ve zamansal durumu

Cilt: 2, Sayı: 2, Ek:A Sayfa: 105-112, 2012
Volume: 2, Issue:2,Sp:A,pp: 105-112, 2012

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Geliş tarihi / *Received:* 29.12.2011
Kabul tarihi / *Accepted:* 16.04.2012

INTRODUCTION

The loss of soil from the agricultural field or watershed, the breakdown of soil structure, the decline in organic matter and nutrient, the reduction of the available soil moisture as well as the reduced capacity of rivers, and its water pollution, and the enhanced risk of flooding and landslides all are erosion processes which generally depend on spatio-temporal variation of soil properties and cultivation history (e.g. soil inherent properties and extrinsic conditions). In many semi-arid lands runoff is initiated or enhanced by seal formation at the soil surface. Seal formation in soils exposed to rain or overhead irrigations systems results from two complementary mechanisms (Agassi et al., 1981): (i) physical disintegration of surface aggregates and their compaction by the impact of the waterdrops, and (ii) a physico-chemical dispersion and movement of clay and other fine-sized particles down the profile to 0.1–0.5 mm depth, where they may accumulate and clog water conducting pores.

Generally, soil interril erosion by water involves two main processes: (i) detachment of soil material from the soil mass by waterdrop (commonly raindrops) impact and/or runoff shear, and (ii) transport of the resulting sediment by waterdrop splash and/or flowing runoff water. Raindrop detachment is greater than flow shear detachment because kinetic energy of raindrops is much higher than that of surface flow. However, movement of detached soil down slope by rain splash is minimal, and most of the sediments are removed from the interrill area by runoff flow (Hudson, 1971). However, under certain conditions (disturbed or sodic soil, hill slope, dispersion, etc.), runoff flow may be sufficient for soil detachment and transport (Levy et al., 1994; Mamedov et al., 2002).

Results from a large body of soil erosion research suggest that sediment detachment and transport is quiet substantial during high rain-intensity events. Usually, only a portion of the watershed generates erosion and contributes sediments to the streams. The transport processes that control sediment and dissolved pollutants are different, but linked; the latter are also susceptible to transport whenever runoff water flows through or from an area loaded with pollutants (Qui et al., 2007). Moreover, agricultural fields usually exhibit a complex spatio-temporal variability related to soil characteristics, and hence variable sources of sediment and pollutant, and hydrologically sensitive areas (Walter at al., 2000). Little is known about real erosion rates and the spatial and temporal production of sediment from land surfaces. Calculating erosion rates, which contains serious misconception, is usually done by redistributing the stream sediment load uniformly over the area of the watershed to give a regional erosion rate.

Most of the currently used management practices and risk assessment models, can not adequately handle the complexity of the conditions prevailing in the field, probably due to lack of understanding of how soil properties and conditions affect runoff generation (e.g. crusting, etc.) in a watershed, and the subsequent transport of sediments and/or chemicals (Sharply et al., 2006; Mamedov et al., 2006). There is, therefore, an urgent need to assess the combined effects of soil permanent properties and time dependant conditions on runoff generation and erosion, so that suitable management practices can be developed to minimize loss of sediments and/or transport of nutrients having a significant pollution potential.

Objective. Our objective was to evaluate in a systematic manner the contribution of both soil inherent properties and extrinsic conditions prevailing in the field on soil susceptibility to erosion, so as to gain a better insight into this complex topic. Hence, the current paper summarizes results (mostly published) of studies on soil erosion mainly from semi-arid regions in Israel and the USA.

MATERIALS AND METHODS

The contribution of soil inherent properties and extrinsic conditions on soil erosion was studied in many cases using laboratory rainfall simulators. A detailed description of the experimental setup can be found in various studies (e.g., Agassi et al., 1981; Mamedov et al, 2000). Soil inherent properties that were studied include: (1) soil texture (4-6 typical textural classes from sandy to heavy clay); (2) predominant clay mineralogy and (3) organic matter content (tillage). Extrinsic conditions that were evaluated include: (1) 4-5 levels of rain kinetic energy (KE, 0-22 kJ/m3); (2) 3-4 wetting rates (WR) of dry soil by rainfall and irrigation water; (3) water quality (rain, fresh, waste or saline water); (4) 4-8 antecedent moisture contents (from dry to full saturation) combined with different aging durations between two wettings; (5) tillage intensity (conventional and minimum-tillage); and (6) soil sodicity, and use of soil amendments (polymer, gypsum).

RESULTS AND DISCUSSION

Rain kinetic energy (KE)

Runoff and interrill erosion increase exponentially with an increase in rain KE (Mamedov et al., 2000), however the magnitude depend on soil texture (Fig. 1). Mamedov et al. (2000) noted that changes in rain KE lead to changes in runoff mainly in the low to moderate rain KE range, whereas for interrill erosion this change took place in the medium to high rain KE range. This observation highlights the intricate relationship between runoff and soil loss. The phenomenon where by interrill erosion increases with the increase in rain KE while changes in runoff level are negligible, suggests that seal formation is already completed at medium rain KE (~12.4 kJ m^{-3}) and therefore the contribution of runoff in facilitating transport for the entrained material is only secondary to the role of soil detachment in determining interrill erosion (Mamedov et al., 2000).

Soil texture

Total runoff and soil loss depended on clay content and wetting conditions by rain or irrigation water (Levy et al., 1997; Mamedov et al., 2001). The soils with intermediate clay content (20-40% clay) were the most susceptible to seal formation (Fig. 2). The rate at which the soil was wetted (WR) prior to being exposed to raindrop impact had a marked affect on soil loss, showing that the use of slow WR is effective in decreasing runoff and erosion in soils exposed to high KE rain. The effect of WR on seal formation increased noticeably with an increase in clay content (Fig. 2).

Seal formation and runoff production have been found to depend on rain KE in medium- and fine-textured soils while in heavy-textured soils (> 40 % clay) sealing and runoff mostly depend on wetting condition or WR. A positive linear relation was found between soil loss and runoff data, which indicates that most of the eroded soil was generated and transported by runoff water. Enrichment of the eroded material by clay-size particles relative to parent soil material and its dependence on WR and hence on the degree of aggregate slaking under rainfall, emphasizes the importance of protecting surface soil aggregates from breaking down during rainstorms (Levy et al., 1997; Mamedov et al., 2001; Shainberg et al, 2003a; Warrington et al., 2009). It should be noted that for predominantly kaolinitic soils, the effects of soil texture and wetting condition on soil structure and hence soil loss were not consistent (Norton et al., 2006; Mamedov et al., 2010).

Clay mineralogy

Clay mineralogy was recognized as a dominant factor in controlling soil structure stability, hydraulic properties, and hence formation of seal and erosion (Stern et al., 1991, Norton et al., 2006; Reichert et al., 2009; Mamedov et al., 2010). Rainfall simulation studies showed that loss of sediments from smectitic soils was up to 3 to10 times higher than from kaolinitinc soils, not containing smectite or kaolinitic mixed soils containing smectite or illite (Fig. 3).

Soil clay mineralogy affects the physicochemical dispersion of the clay and the physical disintegration of soil aggregates, which is greater in soils with a predominantly smectitic clay mineralogy due to smectites having greater sensitivity to dispersion and aggregate breakdown during wetting. Kaolinitic and illitic soils

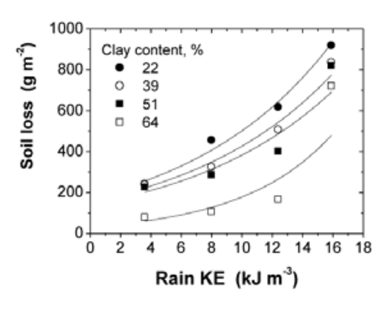

Figure 1. Effect of rain kinetic energy (KE) on interrill erosion (from Mamedov et al., 2000).

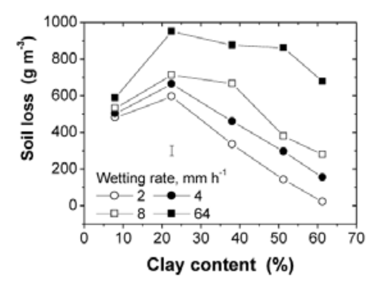

Figure 2. Soil loss as affected by clay content and wetting rate (from Mamedov et al., 2001).

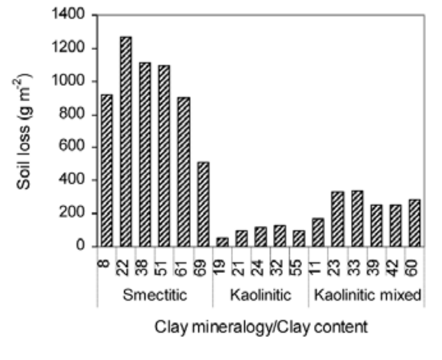

Figure 3. Clay mineralogy effects on soil loss (from Stern et al, 1991, Norton et al., 2006, and Mamedov et al., 2002).

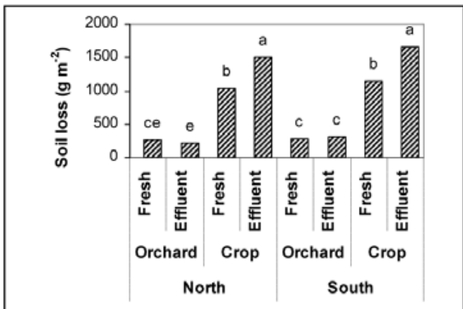

Figure 4. Soil loss as affected by tillage and water quality at two location with clay or sandy clay texture (from Shainberg et al. 2003b, Norton et al., 2006).

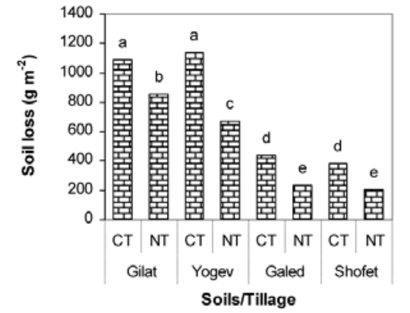

Figure 5. Effect of tillage (organic matter) on soil loss. Gilat is a loam, and other soils are sandy clay or clay soils (from Shainberg et al., 2003b).

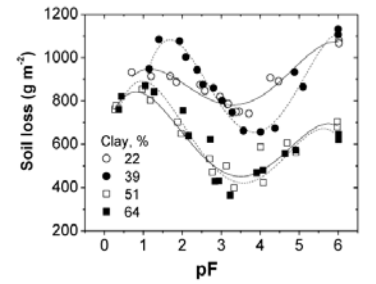

Figure 6. Effect of antecedent moisture content (pF) on soil loss in 3-7 day aging duration (from Mamedov et al., 2006).

which do not contain smectite are stable soils and are less susceptible to seal formation, and their structural stability is controlled mainly by other stabilizing agents such as organic matter and or oxides. However, kaolinitic and illitic soils that contain some smectitic impurities could be more susceptible to seal formation, but still more stable than smectitic soils (Lado and Ben-Hur, 2004; Norton et al., 2006). Consequently, based on clay mineralogy, soil ranking with respect to their sensitivity to erosion is in the following order: smectitic > illitic> kaolinitic soils (Fig. 3).

Tillage

Effects of tillage intensity (CT, intensive tillage – field crops, and NT, minimum tillage – field crop or orchards), water quality (fresh and effluent) and organic matter content on soil loss are presented in Figures 4 and 5. Organic matter content was significantly higher in the NT soils than the CT soils; however, the difference was smaller than 15%.

Soil loss was similar for soils irrigated with fresh water and treated effluent in the samples taken from the orchard, thus suggesting that reduced tillage improves soil structure and enhances aggregate resistance to raindrop impact. Conversely, in samples taken from the field crop section, soil loss was greater in the effluent irrigated soil (and CT soil) than in the fresh water irrigated one (and NT soil) signifying that tilled soils have greater sensitivity to erosion. Furthermore, a lower level of soil loss was noted under limited tillage (orchard) than under intensively tilled soil (field crops), irrespective of irrigation water quality (Fig. 5)

Soil structure stability and thus erosion do not only depend on organic matter content, but also on the conditions that prevail in the field. Intensive cultivation affected soil erodibility and soil loss (Figs.4 and 5) through the periodically breaking of aggregates, decreasing of organic matter, deteriorating soil structure, yielding greater amounts of dispersed clay (i.e. more susceptible by raindrop impact) due to mechanical disruption and by affecting the microbial activity in the soil.

Antecedent moisture content

The effects and interaction of two different surface conditions, i.e., antecedent moisture content (AMC) and aging (timing after raining) duration, on erosion from 4 smectitic soils are presented in Figure 6. The results reveal the existence of an optimal range of AMC (matric potential, pF =2.4-4.2, between wilting point and field capacity) at which erosion levels are lower by up to 30%, than those obtained at AMC levels above or below the optimal range. Increasing aging duration (from 0 day to 7 day) resulted in a 15-30% decrease in soil loss at this optimal AMC range in comparison to no aging; effects of aging at optimal AMC on soil loss were of greater magnitude in clay soils (Fig. 6). A similar manner at which runoff and soil loss decreased with the increase in aging duration at the optimal AMC range was noted, thus indicating that, for the given experimental conditions, runoff was the main precursor for soil loss (Shainberg et al., 1996; Levy et al., 1997; Mamedov et al., 2006).

The combined favorable impact of AMC and aging on improving soil stability was associated with waterfilled pores that were of the size range belonging to the clay fabric (pF 2.4-4.2). Clay movement and reorientation have therefore been considered as key factors in the development of cohesive forces between and within soil particles during aging at optimal AMC levels (Mamedov et al., 2006). The results emphasize the importance of the role of surface conditions, and particularly that of AMC and aging, in determining soil surface structural stability and its resistance to seal development and soil loss production (Fig. 6).

Amendments

The effects of surface application of two anionic polyacrylamides (PAMs), varying in their molecular weight (MW, moderate-M and high-H), in combination with gypsum (PG), to that of PG alone and to no amendment at all, on seal formation, runoff, and soil erosion in 5 smectitic soils varying in clay (8-64%) content was studied by Mamedov et al. (2009). The two PAMs maintained runoff and soil loss levels (Fig. 7) that were lower, than those obtained in either the control or PG alone treatments. However, PAM (M) treatments yielded lower levels of soil erosion compared with the PAM (H) one, that were ascribed to its lower viscosity when in solution, which in turn, enhanced the ability of this solution to more uniformly and efficiently cover and treat the soil surface aggregates. The treated soil surface resisted soil aggregate breakdown and detachment yet it enhanced the deposition rate of eroded particles already present in the runoff water.

The observed advantage of medium- over high-MW PAM in controlling soil erosion was not in full agreement with previously published data where the effect of PAM MW was reported to depend on site-specific conditions and methods of PAM application (Levy, 1995; Yu et al., 2003). Further studies may verify whether or not PAM MW is an important factor for polymer application in a soil-specific management approach designed for controlling soil and water losses.

Water quality

Effects of irrigation water quality on soil loss (Fig. 8) under high KE rainfall simulation were tested on a silty clay soil irrigated for three years with either treated waste water (TWW), saline–sodic Jordan River water (JRW), or moderately saline–sodic spring water (SPW). Irrigation with TWW had a consistently more favorable effect on soil loss than irrigation with the saline–sodic JRW and SPW treatment. Hence, the results suggest that replacing saline–sodic irrigation water by TWW, with significantly lower salinity and sodicity levels, may prove beneficial in improving soil structural stability and could also mitigate problems associated with high levels of runoff and soil erosion, particularly in regions of low to moderate rainfall intensities (Mandal et al., 2008).

Sodicity (salinity)

The combined effects of sodicity (ESP 2-20) and clay content on erosion are presented in Figure 9. Soil

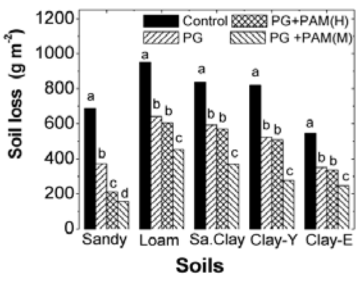

Figure 7. Total soil loss as a function of the treatments for the five soils (from Mamedov et al., 2009).

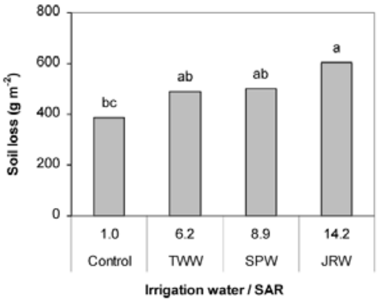

Figure 8. Total soil loss for the different water quality treatments: TWW, treated wastewater; SPW, spring water; JRW, River water (from Mandal et al., 2008).

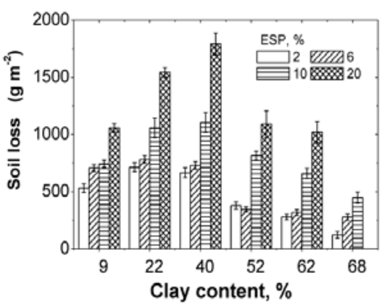

Figure. 9. Soil loss as affected by soil sodicity for the range of soil texture (from Mamedov et al.,2002).

loss increased exponentially with an increase in sodicity (ESP) with the magnitude of the effects depending on clay content. For sodic soils an exponential type relation between erosion and runoff was observed, whereas for non sodic soils this relationship was linear. This was ascribed in the sodic soils to the high runoff level and velocity that initiated rill erosion which supplemented detachment by raindrops in markedly increasing erosion (Levy et al., 1994; Mamedov et al., 2002).

CONCLUSIONS

Cultivated fields exhibit usually a complex spatio-temporal variability of soil characteristics, i.e. soil properties and conditions (formed by management, irrigation and rain water regime or characteristics, etc.). Little is known about real runoff and erosion rates and the spatial and temporal production of sediment from land surfaces. Our review of published literature suggests that factors and mechanisms controlling soil erosion are complex and depend on various processes.

Generally, runoff generation and soil erosion increased exponentially with the increase in rain KE and soil wetting condition and thus climatic zones. Rain KE and water quality played a predominate role in determining soil loss in medium- and coarse-textured soils (2-40% clay), while WR played a predominate role in fine-textured soils (40-70% clay). Soils from semi-arid regions, particularly clay soils, having moisture content in the range between wilting point and field capacity (pF 2.7-4.2), generate low levels of sediments. In soils with <20% clay, prevention of physicochemical clay dispersion (e.g., by gypsum application) is preferable for controlling soil erosion, whereas in clay soils, prevention of aggregate slaking during the wetting process of the soil could be more beneficial. Application of a small amount of polymer in combination with gypsum may effectively decrease soil loss by to 2-4 times relative to the control, mostly in smectitic soils.

The reviewed results indicate that effects of wetting condition on soil loss depended on soil clay content and mineralogy, thus making the task of predicting soil susceptibility to erosion even more complicated. In order to improve the prediction capabilities of models, soil conditions prior to erosive rainstorms should be considered. Whereas inherent soil properties cannot be changed, conditions prevailing in the soil such as soil moisture content, impact of drop kinetic energy, etc., can be manipulated by changing management practices (e.g., tillage intensity, irrigation water quality, use of amendments, manipulation of soil moisture level, etc.,) to arrive at conditions that decrease soil susceptibility to soil erosion. Our results can assist in understanding the changes in the degree of erosion, sediment and chemical transport, and thus potential water quality concerns in soils and could be useful for modeling efforts aimed at the prediction of soil erodibility.

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