

Full Length Research Paper

The effect of polyacrylamide (PAM) applications on infiltration, runoff and soil losses under simulated rainfall conditions

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One of the major causes of soil degradation throughout the world is water erosion. Anionic polyacrylamide (PAM) application to soils is an effective soil conservation practice for reducing runoff and soil losses caused by erosion. It also increases the infiltration rate of soils. The objective of this study was conducted to determine effects of different application rates of PAM (0 (control), 1.667, 3.333 and 5.000 kg.ha⁻¹) on infiltration rate, runoff and soil losses. Polyacrylamide was sprayed on the surface of the experimental soils with different textures. The PAM treated soils were introduced to simulated rainfall at 61 mm/h intensity for an hour. The results indicated that, PAM applications significantly reduced surface runoff and soil losses, but increased infiltration rates. The effectiveness of PAM was higher in clay and clay loam soils than that of sandy clay loam soil. The most effective applications rates of PAM on reducing surface runoff and soil losses and increasing infiltration rates were found to be 3.333 and 5.000 kg.ha⁻¹. By considering the price and application cost of PAM, it was suggested that 3.333 kg.ha⁻¹ PAM is the most suitable application rate. As compared with the control, it was obtained that PAM application with a rate of 3.333 kg.ha⁻¹ reduced surface runoff and soil losses by 23.1 and 18.5%, respectively and increased infiltration rate by 24%.

Key words: Polyacrylamide (PAM), soil erosion, soil loss, runoff, infiltration rate, simulated rainfall.

INTRODUCTION

Soil and water conservation is essential for sustaining food production and preserving the environment (Graber et al., 2006). Therefore, agricultural lands should be managed in a sustainable fashion and used according to land use capability classification. One of the major threats for sustainable land management is soil erosion. Erosion is a major type of human-induced land degradation (Ingram et al., 1996). It is a very widespread phenomenon and is usually irreversible. Soil degradation is a significant problem throughout the world (Green and

Stott, 2001; Ben-Hur, 2006). Oldeman et al. (1991) suggest that, about one-six of the world's usable land has already been degraded by water or wind erosion. Soil erosion can also cause off-site environmental problems such as increased dust in the air (Stetler et al., 1994; EPA 1990), increased transport of sediments to river and lakes (Rabinson, 1979).

Our future ability to feed ourselves and live in an unpolluted environment depends on our ability to reduce the rates at which our soils are currently eroding (Poesen et al., 1996). Use of synthetic organic polymer as soil conditioners, including anionic polyacrylamide (PAM), is one of the many options for protecting soil resources against the erosion. Synthetic organic polymers have been explored by many researchers in the past. But, the high application rates recommended in the past studies made their use in agriculture economically unfeasible.

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Recent studies showed that small rate of synthetic organic polymers, including anionic polyacrylamide (PAM), can improve soil structure and aggregate stability (Terry and Nelson, 1986), bonding between adjacent aggregates and clay flocculation (Graber et al., 2006), decrease soil crusting (Shainberg et al. 1990; Fox and Byran, 1992) increase infiltration thus, reducing runoff and soil erosion (Wallance and Wallance, 1986; Smith et al., 1990; Lentz and Sojka, 1994; Levy and Agassi, 1995; Chan and Sivapragasam, 1996; Ben-Hur and Keren, 1997; Sojka et al., 1998a; Green et al., 2000; Bjorneberg and Aase, 2000; Peterson et al., 2002). Polyacrylamide (PAM) can stabilize soil structure but does not remediate poor soil structure (Cook and Nelson, 1986; Green and Stott, 2001). For agricultural uses, soil with good infiltration and stable aggregation is imperative. As infiltration decreases, runoff and erosion increase, thus, degrading the soil. Good aggregation associated with high aggregate stability helps maintain adequate pore space for infiltration (Green and Stott, 2001). Raindrop can impact the soil with great force, compacting the soil and creating a structural crust. Additionally, the impact of the rain and the rapid wetting of the soil cause slaking and dispersion of clay, thus, disrupting the integrity of the soil aggregate. Once the soil aggregate has slaked and dispersed into smaller particles, the small particles can clog the pore spaces of the soil matrix. When this occurs, a thin seal develops which when dry, becomes a hardened surface crust (McIntyre, 1958; Shainberg and Singer, 1985; LeBissonnais, 1996). Runoff amount will increase due to surface crust hardened that reduce infiltration of majority of precipitation into soil. In addition to increase in runoff water, soil losses will increase as well. Preventing of degradation of soil surface aggregates and also increasing formation of stable aggregates are necessary to reduce runoff water and soil losses. Thus, anionic polyacrylamide (PAM) is suitable for these purposes. Polyacrylamide (PAM) for erosion control is an effective soil conservation practice used on about a million hectares worldwide (Wallance and Terry, 1998; Sojka et al., 1998b).

The objective of this research is to determine the effectiveness of polyacrylamide (PAM) on soil and runoff losses and infiltration rate at different agriculture soils under simulated rainfall in laboratory conditions.

MATERIALS AND METHODS

The study was conducted on four various soil types (Alfisol (SC:1), Entisol (SC:2 and 5), Inceptisol (SC:3), Mollisol (SC:4)) having three different texture (clay, sandy clay loam, and clay loam) in laboratory conditions. Five soil samples were collected from the upper soil layer (0 to 30 cm) of cultivated agricultural lands in different sites of Bursa, Turkey. The samples were transported to the laboratory within large bags, air-dried and crushed gently. A small portion of soil samples were sieved from a 2 mm sieve and used for determining physical and chemical soil analyses and the rest were passed through a 8 mm sieve for using in the PAM

experiment.

The particle size distribution was determined using the hydrometer method (Gee and Bauder, 1986). The pH and electrical conductivity (EC) of the soils were measured in 1:2.5 soil:water suspension (Nelson, 1982). CaCO₃ content was determined using a Scheibler calcimeter (McLean, 1982) and organic matter by the Walkley-Black method (Nelson and Sommers, 1982). The moisture content of soil samples at field capacity (-0.033 MPa soil water pressure) and at the permanent wilting point (-1.5 MPa soil water pressure) were determined with a pressure plate apparatus (Klute, 1990). Hydraulic conductivity of soils was measured by the constant-head method in saturated samples (Klute and Dirksen, 1990). Aggregate stability was determined by the wet sieving analysis using a modified Yoder type sieving machine (Yoder, 1936). Exchangeable cations (Na, K, Ca and Mg) were extracted with ammonium acetate at pH 7.0 (Pratt, 1965) and were determined by the Eppendorf Elex 6361 model flame photometer.

A 5 cm thick layer of air-dried soils passed through a 8.0 mm sieve, were packed over a 7 cm thick layer of sand placed on the bottom of the 30 × 45 × 15 cm sized experimental trays with drainage holes. Soil surface in experiment tray (Figure 1) was smoothed. The experiment tray was sloped at a rate of 9% and placed under the rainfall simulator with a nozzle type of Veejet 80100 (Figure 2). A collector container was placed under the outlet of the experimental tray for measuring eroded soil particles and runoff water during rainfall applications.

Anionic polyacrylamide (PAM) was used as soil conditioner in the research. PAM was prepared by free radical polymerization of acrylamide in benzene with azoisobutyronitrile as initiator at 70°C for 24 h in a nitrogen atmosphere. PAM in the form of white powder was dried in a vacuum oven at 50°C. The average molecular weight of PAM (Mw), measured by gel permeation chromatography was 25.000 g/mol.

PAM solutions were applied to dry soil surfaces at concentrations of 0, 250, 500 and 750 mg L⁻¹ (0 (control), 1.667, 3.333 and 5.000 kg ha⁻¹, respectively). The trays were exposed to simulated rainfall with a 61 mm/h intensity for a period of 1 h after the 24 h from PAM applications. Tap water with an electrical conductivity of 0.34 dS.m⁻¹ was used in rainfall application. Thereafter, the collector container was taken from the outlet and left to sedimentate soil particles for 24 h. Runoff water in the collecting container was separated from soil by sucking the water by means of a hose at the end of that time. Runoff data were obtained by measuring runoff volume. Soil loss data were obtained by weighting of soil particles that dried at 105°C in oven. Infiltration rate data was obtained by subtracting the total amount of runoff from the total amount of precipitation fallen on the soil surface during to 1 h time.

The experimental design was a completely randomized design with three replications. All data were subjected to analysis of variance for each variable using MINITAB (Version 14, University of Texas at Austin, TX) and MSTAT-C (Version 2.1, Michigan State University, 1991) softwares. The statistical significance among of various soil types and different application rates of anionic PAM on soil loss, runoff and infiltration rate occurring in examined soils were determined at the 0.05 and 0.01 probability levels using appropriate F-values. The LSD test was used for multiple comparisons (Steel and Torrie, 1980).

RESULTS AND DISCUSSION

Characteristics of soils

Soils with different textures (clay, sandy clay loam, and clay loam) were chosen for this experiment to determined the effectiveness of PAM applications in various soil



Figure 1. Experiment trays for PVA application.

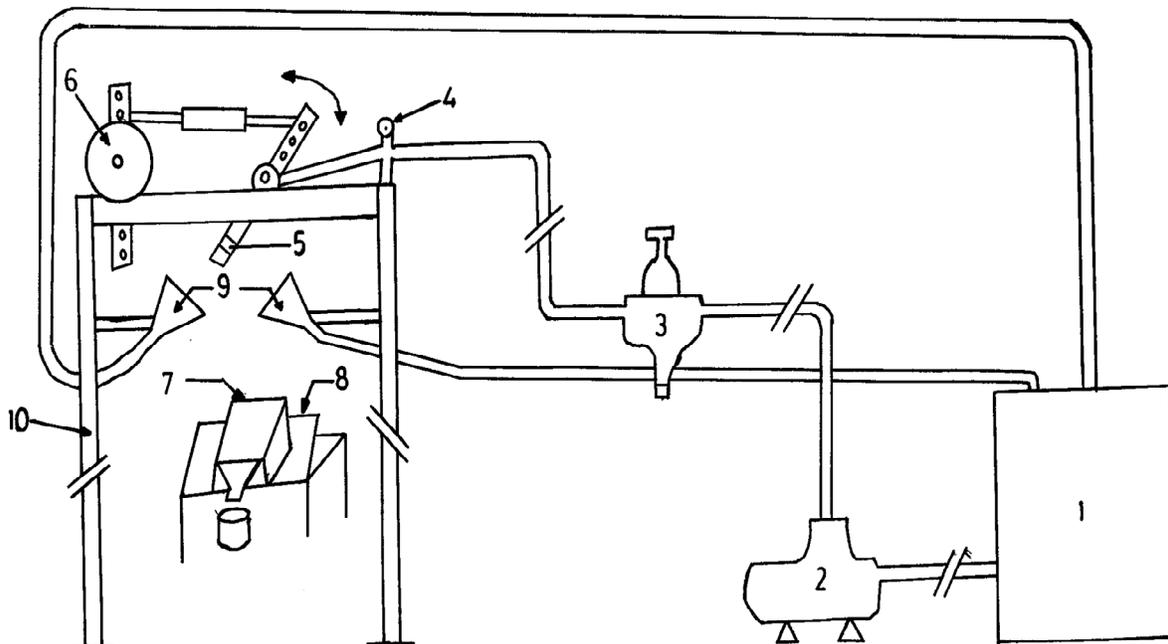


Figure 2. Schematic structure of the rainfall simulator and its parts ((1) water reservoir; (2) pump; (3) regulator; (4) pressure gauge; (5) nozzle; (6) electric motor and variator; (7) erosion tray; (8) sloped table; (9) excess water collectors; (10) main frame).

types (Alfisol (SC:1), Entisol (SC:2 and 5), Inceptisol (SC:3), Mollisol (SC:4)). Clay soils had the highest water-

stable aggregate stability, water content at field capacity and permanent wilting point and hydraulic conductivity

Table 1. Some physical and chemical characteristics of the soils.

SC	Particle size distribution (%)			TC	WAS (%)	MC (%)		HC (cm/h)	pH	EC (dS/m)	CaCO ₃ (%)	OMC (%)	Exchangeable cations (cmol. kg ⁻¹)			
	Sand	Silt	Clay			FC	PWP						Na ⁺	K ⁺	Ca ⁺⁺	Mg ⁺⁺
1	36.12	22.03	41.85	C	70.3	22.2	17.4	15.01	7.6	0.27	1.38	0.47	0.21	1.39	14.0	16.7
2	53.12	26.31	20.57	SCL	15.4	14.8	9.8	1.54	7.5	0.23	0.40	1.84	0.09	0.86	7.0	2.5
3	46.37	20.90	32.73	SCL	28.1	21.3	16.4	4.51	8.1	0.19	5.14	1.53	0.17	0.64	22.0	5.4
4	43.36	28.90	27.74	CL	29.5	21.7	15.6	3.55	7.9	0.21	5.53	4.29	0.52	0.51	21.7	2.6
5	28.39	19.28	52.33	C	53.3	22.7	19.2	15.05	8.1	0.22	18.37	2.17	0.18	1.03	22.2	8.6

SC: Soil sample coding (1:Alfisol, 2:Entisol, 3:Inceptisol, 4:Mollisol, 5:Entisol), C: clay, SCL: sandy clay loam, CL: clay loam, TC: soil texture class, WAS: water-stable aggregate stability, MC: moisture content, FC: field capacity, PWP: permanent wilting point, pH: soil reaction, EC:electrical conductivity, HC: hydraulic conductivity, OMC: organic matter content.

Soil losses

The amounts of soil losses from the experimental trays under simulated rainfall conditions varied among soils (Figure 3). Soils with SCL texture (SC:2 and 3) had higher rates of soil loss than the others and the lowest soil erosion rate was obtained for clay-textured (SC:1 and 5) soils. It was determined that sand content, aggregate stability and hydraulic conductivity of soils were the most effective soil properties on the amount of soil lost (Figures 4, 5 and 6).

A significant relationship ($r^2:0.84$) was observed between sand content and soil loss (Figure 4). Soils with high sand contents (SC:2 and 3) had higher amounts of soil losses than those of low sand contents (SC:1, 4 and 5) (Table 1 and Figure 3). Similar results were also reported by some other researchers. Miller et al. (1998) reported that, PAM efficiency as a soil conditioner may depend on soil texture rather than on soil clay mineralogy. Luk (1979) and Wischmeier and Mannering (1969) reported that, soil with high content of fine sand and silt were more susceptible to erosion than others. Since the particle size of sand is much greater than the clay and specific surface area of sand is much less than that of clay, contact surface area among sand

particles is very small. Thus, sufficiently strong binding bridge among sand particles could not be created by spraying PAM solution to soil. Therefore, the integrity of soil aggregates on soil with high sand content were readily disrupted by rapid wetting of soil and impulse effect of fallen raindrops. Consequently, the higher soil loss was occurred due to the transport of soil aggregates that were dispersed into smaller particles through sloped soil surface (9% slope) by the impact of high simulated rainfall intensity (61 mm h⁻¹).

Efficiency of PAM's application is depend on, firstly, soil textural classification, primarily the percentage of clay in soil and its type, secondly the molecular weight and charge density of PAM and application method. The effectiveness of the polyacrylamide was found to be related to clay content of the soils by many researchers (Wallance and Wallance, 1990, Seybold, 1994, Vacher et al., 2003). On the other hand, aggregate stability and hydraulic conductivity of soils had significant effects on soil losses. With increases in aggregate stability and hydraulic conductivity, soil losses declined (Figures 5 and 6). Significant relationships were found between aggregate stability and soil loss and between hydraulic conductivity and soil loss (Figures 5 and 6). The amount of soil lost was lower in soils with

clay texture (SC: 1 and 5) due to higher aggregate stability and hydraulic conductivity when compared with the others.

The results clearly indicated that, PAM applications to soil had significant effect on reducing soil losses by limiting physical disintegration of soil aggregates (Figure 7). Many researchers reported that PAM applications to soils reduced soil loss and sediment entrainment (Peterson et al., 2002; Vacher et al., 2003; Abu-Zreig, 2006b). Based upon the mean values, it could be concluded that the amounts of soil lost in samples treated by 500 and 750 mg L⁻¹ PAM were lower than these of the control (0) and 250 mg L⁻¹ PAM treated samples. However, no significant difference in the amounts of soil lost by erosion in the samples treated by 500 and 750 mg L⁻¹ PAM has been obtained (Figure 8). When compared with the control, it was determined that soil losses were reduced by the application of PAM at 250, 500 and 750 mg L⁻¹ (1.667, 3.333, 5.000 kg ha⁻¹ PAM) with the rates of 3.34, 23.14 and 18.0%, respectively. These results agreed with the results reported by Abu-Zreig (2006a).

Reduced soil loss from higher rates of PAM applications (500 and 750 mg L⁻¹) compared with lower rates of PAM applications, can be attributed to its positive effect in improving soil aggregate

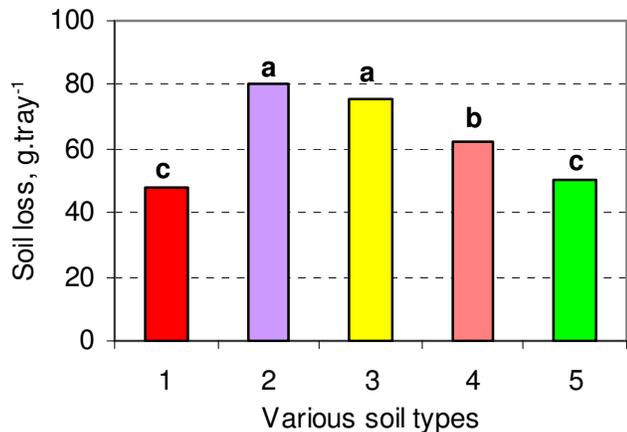


Figure 3. Soil loss for various soil types as a function of PAM applications. Columns labeled by the same letter do not differ significantly at the 0.05 probability level.

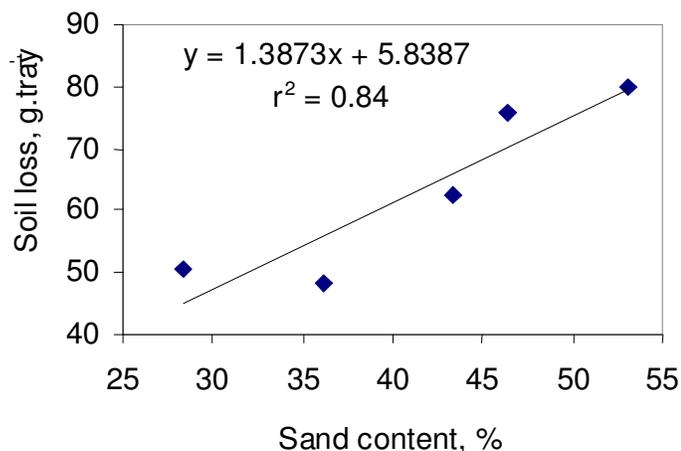


Figure 4. Relationship between soil loss and sand content.

stability, reducing dispersion of soil particles, conservating soil surface roughness and increasing infiltration of rainfall into the soil matrix.

Surface runoff

The amounts of surface runoff from the experimental trays under simulated rainfall conditions varied among soils (Figure 9). The amount of surface runoff was the lowest (2.79 L.tray⁻¹) for the clay-textured soil (SC:5), but the highest for sandy clay loam textured soils (SC:2 and 3).

PAM applications generally reduced the amount of runoff and its transport capacity (Figure 10). A significant relationship ($r^2=0.87$) between PAM applications and runoff was found (Figure 11). Shainberg et al. (1990) noticed that, the effectiveness of PAM reduced by time but soil crusting and surface sealing have been con-

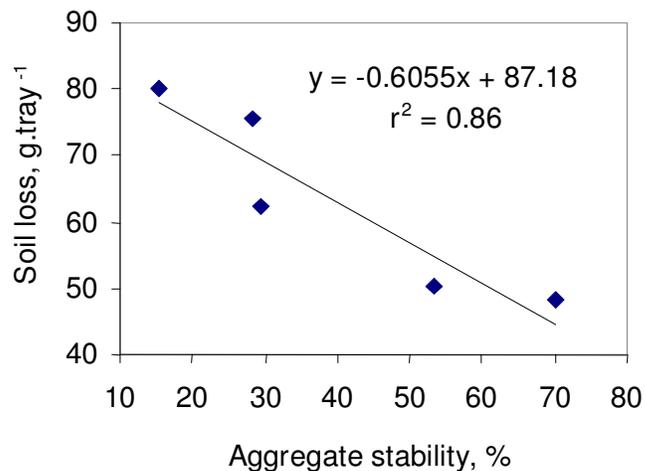


Figure 5. Relationship between soil loss and aggregate stability.

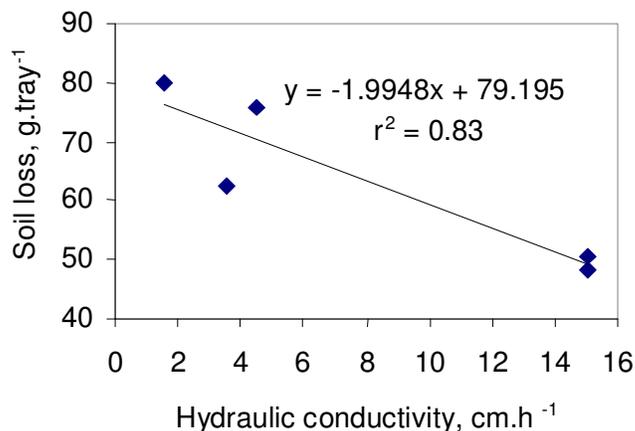


Figure 6. Relationship between soil loss and hydraulic conductivity.

trolled. Runoff has been significantly reduced in field plot by spraying PAM on dry soil surfaces prior to sprinkler irrigation (Levy et al., 1991; Ben-Hur, 1994; Zhang and Miller, 1996). Based upon the mean values, it could be concluded that the amounts of surface runoff from the control and the sample treated by 250 mg L⁻¹ PAM were higher than these of the samples treated with 500 and 750 mg L⁻¹ PAM. However, no significant difference in the amounts of runoff from the samples treated by 500 and 750 mg L⁻¹ PAM has been obtained (Figure 10). As compared to the control, it was determined that the amounts of surface runoff were reduced by the application of PAM at 250, 500 and 750 mg L⁻¹ (1.667, 3.333, 5.000 kg ha⁻¹ PAM) with the rates of 7.74, 18.49 and 17.46%, respectively. Comparatively, Sepaskhah and

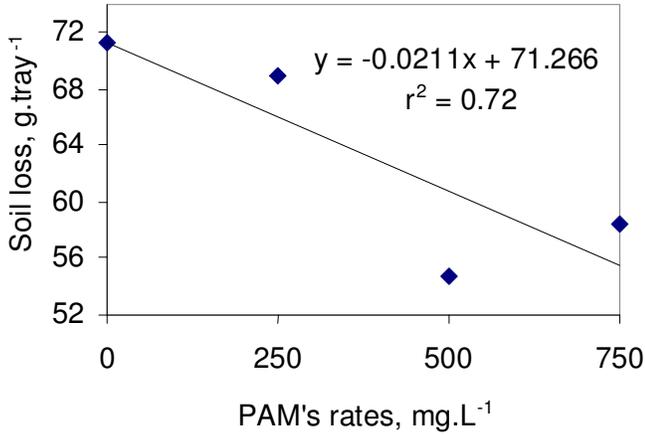


Figure 7. Relationship between soil loss and PAM application rates.

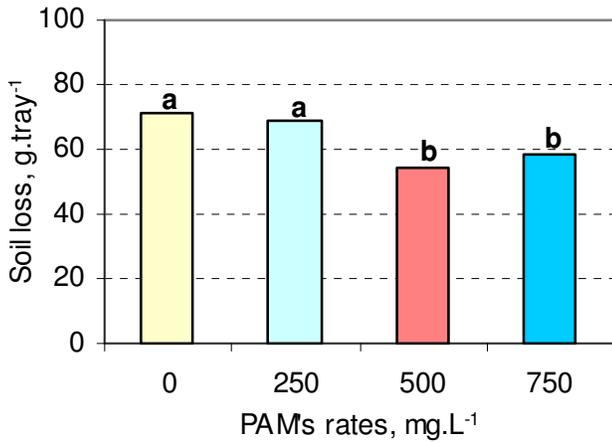


Figure 8. Soil loss for different application rate of PAM. Columns labeled by the same letter do not differ significantly at the 0.05 probability level.

Bazrafshan-Jahromi (2006) studied the effects of PAM application on runoff and soil loss in sloping lands under a rainfall simulator and found that, runoff losses were reduced up to 28%. They also emphasized that higher PAM application rates at steep slopes (up to 7.5%) are required to control runoff.

Interactions among the soil types and PAM application levels showed that different application levels of PAM decreased in varying amount of runoff depending on the soil types and application levels (Figure 12). The highest losses of runoff water occurred from the untreated and clay or sandy clay loam-textured soils. As it is seen in Figure 12, runoff in clay-textured soil (SC:1) was the highest at the control sample, but decreased sharply with increases in PAM doses. Runoff losses decreased 55% in the clay-textured and the highest dose PAM treated samples when compared with the control. However, PAM application on runoff losses did not show similar effects in

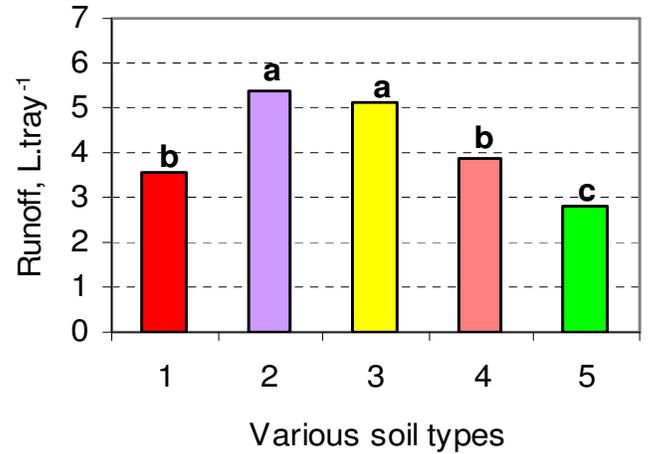


Figure 9. Runoff water from various soil types after PAM applications. Columns labeled by the same letter do not differ significantly at the 0.05 probability level.

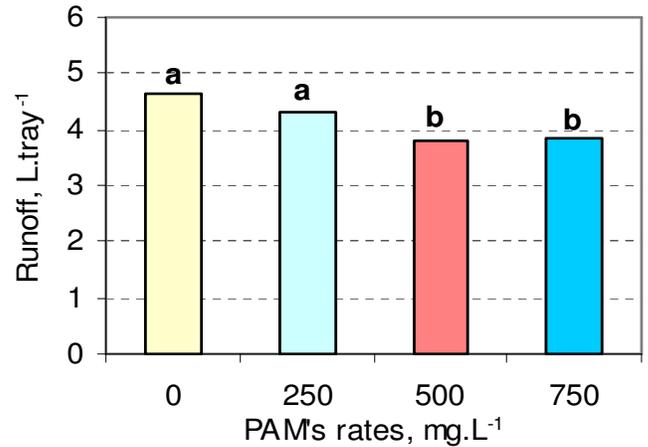


Figure 10. Runoff for different application rates of PAM. Columns labeled by the same letter do not differ significantly at the 0.05 level.

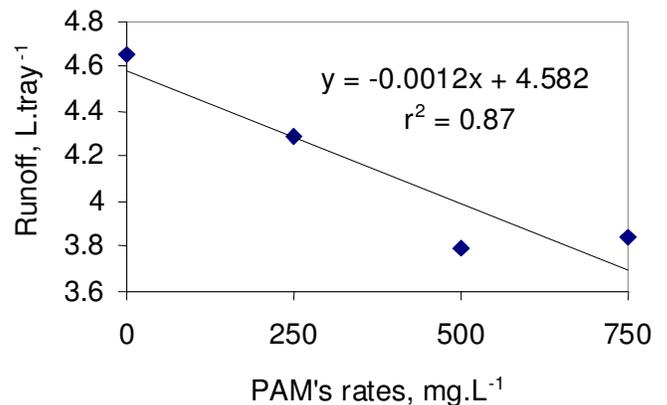


Figure 11. Relationship between runoff and PAM application rates.

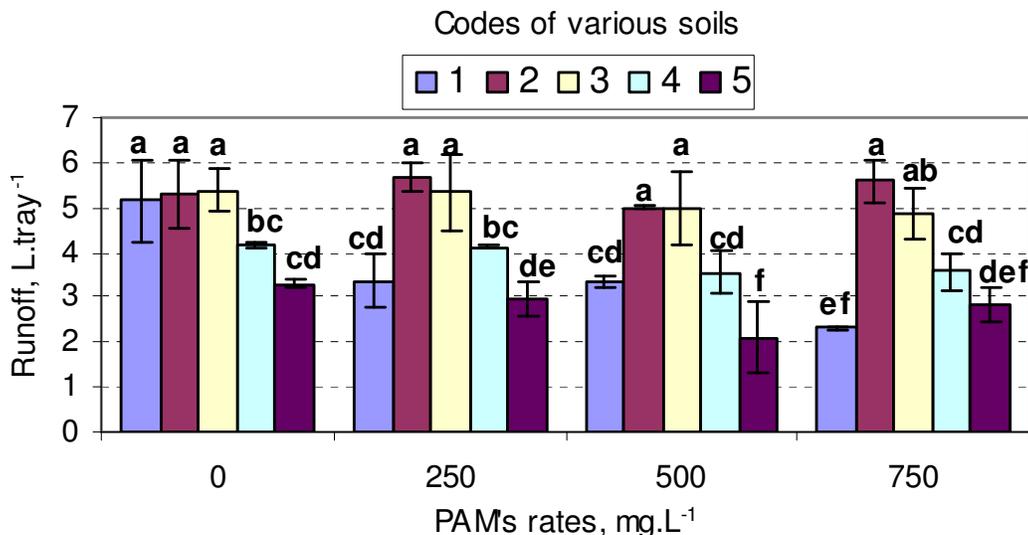


Figure 12. The interaction between the different application rates of PAM and various soil types in terms of the effects on runoff.

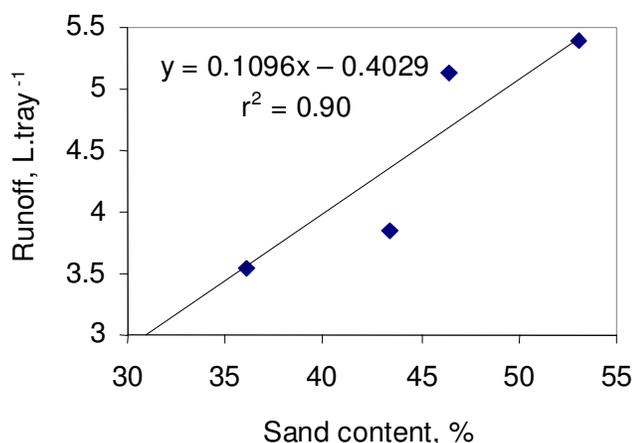


Figure 13. Relationship between runoff and soil sand content.

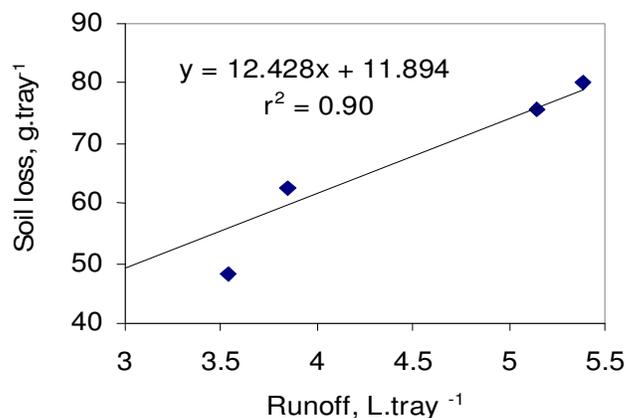


Figure 14. Relationship between soil loss and runoff.

sandy clay loam (SC:2 and 3) or clay loam-textured soils (SC:4).

Sand content of soil was the most important soil characteristic causing variations in runoff losses. A significant linear relationship was found between soil-sand content and runoff (Figure 13). Runoff increased as sand content of soil samples increased. Although, general acceptance of the higher sand content of soil leads the lower runoff, rainfall on sandy soil at sloping fields may cause easy dispersion of soil aggregates, reduce infiltration rate and hydraulic conductivity and depending on all these causes it may increase runoff. Among different soil types used in our research, aggregate stabilities and hydraulic conductivity of three soil types of sandy clay loam (SC:2 and 3) and clay loam (SC:4) with higher sand content were lower than the other two clay (SC:1 and 5) soil types (Table 1). Increased runoff

depending on increased sand content of soil in our study could be explained by considering the slope of 9% for PAM applied experimental trays and heavy rainfall (61 mm.h⁻¹) application to these trays.

A significant positive relationship ($r^2:0.9$) was obtained between runoff and soil losses (Figure 14). Although this is generally scatter around the linear best-fit line, a definite relationship is observed. This result is somewhat different from those reported by Kemper et al. (1985) and Aase et al. (1998). They observed a curvilinear relationship between soil loss and runoff. But, This result is in accordance with findings reported by Sepaskhah and Bazrafshan-Jahromi (2006).

Infiltration rate

Infiltration rates of the experimental soils showed great

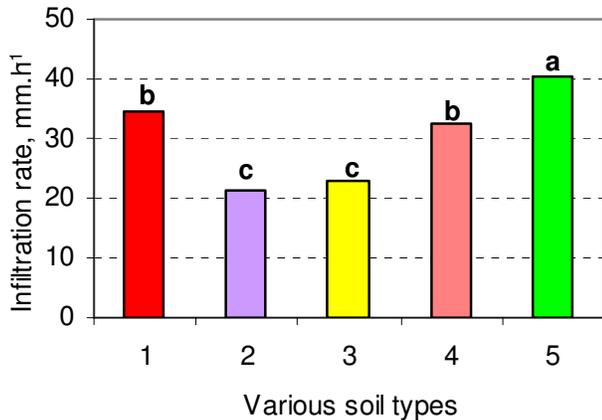


Figure 15. Infiltration rate from various soil types as a function of PAM's applications. Columns labeled by the same letter do not differ significantly at the 0.05 probability level.

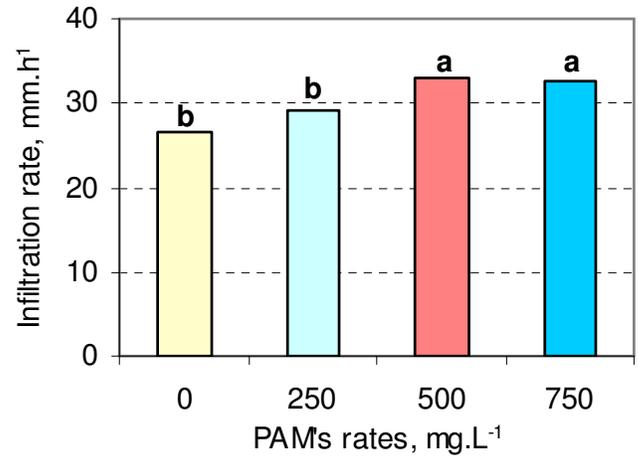


Figure 17. Infiltration rate for different application rates of PAM. Columns labeled by the same letter do not differ significantly at the 0.05 probability level.

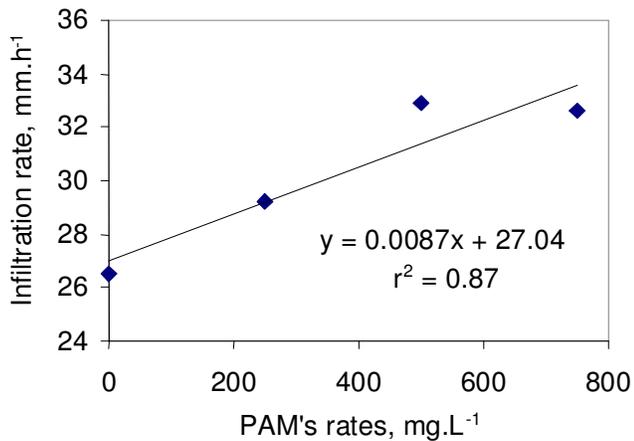


Figure 16. Relationship between infiltration rate and PAM's application rates.

variabilities (Figure 15). In clay textured-soil (SC:5) a great amount of rainfall infiltrated into the soil. However, infiltration rate was the lowest in sandy clay loam-textured soil samples (SC:2 and 3). Infiltration level of the precipitation water into the soil and its continuity are especially depended on the hydraulic conductivity of soil. As hydraulic conductivity of soil decreases its infiltration rate decreases as well. Infiltration rate was the highest in soils with clay textured (SC:5) among various soil types (Table 1).

Infiltration rate of soils varied in a significant level according to the different application rates of polyacrylamide (PAM). A significant positive relationship ($r^2:0.87$) between infiltration rate and PAM doses was obtained (Figure 16). It was found that increasing PAM application rates increased the infiltration rate of soils (Figure 17). Similar relationships were observed by Shainberg et al. (1990) and Al-Abed et al. (2003) as well.

Polyacrylamide does not stimulate aggregate formation, but improves aggregate stability in soils. It prevents ready slaking of aggregates and dispersion of mineral particles against to the raindrops impact. Therefore, it leads to high infiltration and maintains soil hydraulic conductivity. Shanmuganathan and Oades (1982) reported that, synthetic polymers are effective in increasing hydraulic conductivity. Soil infiltration increases with PAM application, because hydraulic conductivity of soil treated by PAM is greater than that of non-treated soil (Al-Abed et al., 2003). High aggregate stability helps maintain adequate pore space for infiltration. Polyacrylamide's ability to maintain soil structure, reduce soil dispersion and prevent the formation of slowly permeable surface seal was reported by Lentz and Sojka (1994) and this will explain the increased infiltration rate of PAM applied soil.

Soil infiltration rate was affected by different doses of PAM (Figure 17). Soil infiltration rates were low in the control and soil treated with 250 mg L⁻¹ PAM. There was no statistically significant difference in infiltration rates of soil samples treated with higher doses of PAM (500 and 750 mg L⁻¹). When compared with the control, it was determined that soil infiltration rate increased with the application of PAM at 250, 500 and 750 mg L⁻¹ (1.667, 3.333, 5.000 kg ha⁻¹ PAM) with the rates of 10.09, 23.96 and 22.76%, respectively. Abu-Zreig (2006a) reported that, PAM spraying resulted in an increase in soil infiltration characteristics. Shainberg et al. (1990) found that 20 kg ha⁻¹ PAM was most beneficial in maintaining high infiltration rate. When applied on dry soil in a small tray prior to sprinkling with a rainfall simulator in the laboratory, Smith et al. (1990) and Levin et al. (1991) in similar studies found that, 20 kg ha⁻¹ of polyacrylamide increased infiltration.

Interaction between PAM application and various soil types showed that, different PAM application rates changed the infiltration rate (Figure 18). Infiltration rate of clay-

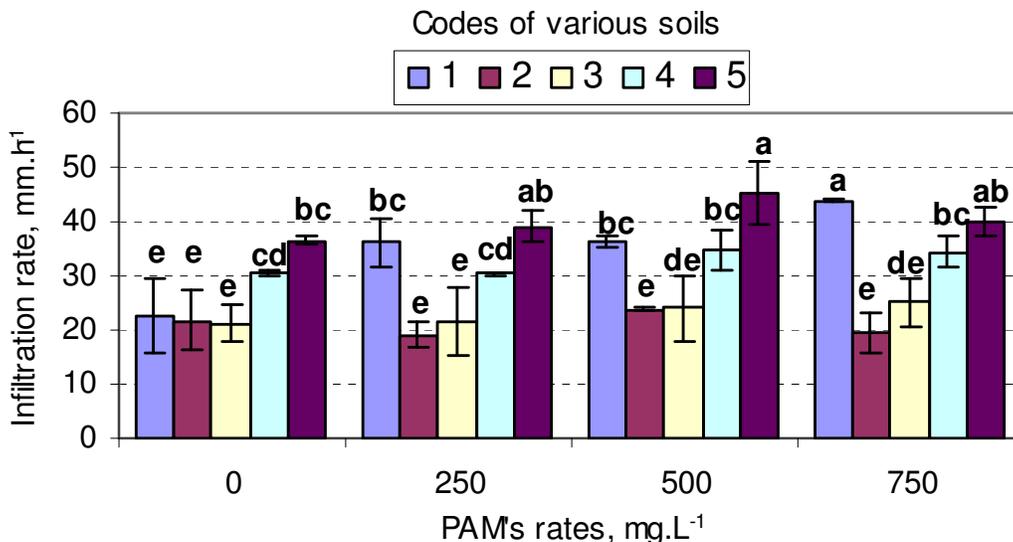


Figure 18. The interaction between the different application rates of PAM and various soil types in terms of the effects on infiltration rate.

textured soil (SC:1) increased gradually with increasing application doses. The lowest infiltration rate was obtained in soil with sandy clay loam texture (SC:2 and 3) and it stayed almost constant for polyacrylamide application doses. Effectiveness of PAM doses on soil infiltration rate varied among soils. For instance, in clay-textured soil (SC:1), the infiltration rate of soil with 750 mg L⁻¹ PAM was 91.6% higher than that of the control. This infiltration rate was the highest among all the soils tested. On the other hand, 500 mg L⁻¹ PAM application in SC:5 numbered soil sample also increased the infiltration rate as 24.4%.

Conclusions

Polyacrylamide sprayed on soil surface reduced soil and runoff losses, but increased infiltration rate of soil. PAM limits disrupting of aggregate integrity caused by water drop impact and provides keeping the amount of pore space on soil surface. The influence of PAM applications at rates of 500 and 750 mg L⁻¹ on soil loss, runoff and infiltration rate were found to be greater than the lower rates of PAM applications. By considering the price and application cost of polyacrylamide, it is concluded that, PAM application of 500 mg L⁻¹ (3.333 kg ha⁻¹) is the most appropriate for reducing soil and runoff losses and increasing the infiltration rate of soils. However, further researches are still needed to explore the application number of PAM to soil and its longevity effected the effectiveness and total cost of PAM application under various soil, slope and rainfall conditions. Effectiveness of polyacrylamide applications showed differences according to various soil types. Effectiveness of PAM applications on reducing soil and runoff losses and increasing

infiltration rate was the lowest in sandy clay loam-textured soils.

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