Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Environmental Sciences 11 (2011) 763 – 773

Procedia
Environmental Sciences

Effect of Polyacrylamide Applications on Soil Hydraulic Characteristics and Sediment Yield of Sloping Land

Yi Li[1], Mingan Shao[2], Robert Horton[3]

[1]Northwest Agriculture and Forestry Sci-Tech University, Yangling, Shaanxi, 712100, China;
[2]Institute of Soil and Water Conservation, China Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi, 712100, China;
[3]Agronomy Department, Iowa State University, Ames, 50011, USA

Email: liyikitty@126.com

Abstract

The objective of this study is to determine how PAM applications to a fraction of the surface affect hydraulic parameters of flow, soil water infiltration and soil sediment yield during rainfall on steep sloping land. Five PAM application rates (PAMR) 0, 0.4, 0.7, 1.0 and 1.3 g kg-1 were used for 5 sloping plots in this study. As PAMR increased from 0 to 1.3 g kg-1 at the rainfall intensity (RI) of 1.58 mm min-1, the Froude numbers decreased from 34.7 to 9.1, the Reynolds numbers (Re) decreased from 568 to 305, and the Darcy–Weisbach coefficients increased from 0.0028 to 0.041. The total runoff values were 33.8, 35.9, 31.6, 25.6 and 18.1 mm when the PAMR were 0, 0.4, 0.7, 1.0 and 1.3 g kg-1, respectively. The cumulative sediment increased rapidly with the rainfall time. In conclusion, PAM applications to a fraction of soil surface can be effective at reducing the erosion of steep sloping land.

Selection and/or peer-review under responsibility of the Intelligent Information Technology Application Research Association.

Keywords: PAM application; sediment yield; roughness coefficient; infiltration.

1. Introduction

Polyacrylamide (PAM) is a long-chain macromolecule polymer. Its monomer is polypropylene acyl amine. PAM flocculates soils well and stabilizes soil well. The main advantages of PAM applied to soil are that it prevents soil surface sealing and crusting so as to prevent and reduce soil-water loss effectively. Impacts of PAM have been studied with furrow irrigation, flood irrigation, sprinkle irrigation and rainfall. The presence of a surface soil crust in a flood-irrigated control was evidenced by penetrometer resistance 10 times greater than in the PAM or sprinkle-irrigated treatments. Infiltration rates of the PAM and sprinkle-irrigated treatments were approximately twice as great as those of the flood-irrigated control at a PAM application rate of 650 kg ha^{-1} [1]. PAM was more efficient in cementing aggregates together and increasing their resistance to erosion compared to polysaccharide [2]. Treatments that had at least 0.7 kg ha^{-1} PAM reduced furrow sediment loss by 94% and increased net infiltration by 15% [3]. For the polymer-

Selection and/or peer-review under responsibility of the Intelligent Information Technology Application Research Association.
doi:10.1016/j.proenv.2011.12.118

treated soil, longer time is required for the surface to dry, and the formation of a crust with high mechanical strength is delayed[4]. Treatments with PAM increased the final infiltration rate of the loess from 2.0 to 23.5 mm h^{-1} and increased rain intake of an 80-mm rainstorm from 12.3 to 64.2 mm[5]. Surface sealing and crusting were largely controlled by the surface application of small amounts of PAM [6]. 2 kg ha^{-1} was the best rate for controlling runoff and erosion in repeated PAM application experiments, but greater rates were applicable for one-time only application in sprinkler irrigation[7]. Polyacrylamide increased infiltration rates on the soils relative to the control. Twenty and 30% charge density PAMs performed best in maintaining high infiltration rates on Heiden clay[8]. For steep slopes (up to 7.5%), PAM application rates of 6.0 kg ha^{-1} were required to enhance the final infiltration rate and to reduce the runoff and soil erosion[9]. Sediment loss from polymer-treated furrows was less than that of control furrows in the first (treated) and second (untreated) irrigations, but not in the fourth (untreated)[2]. Spreading PAM mixed with phosphogypsum was effective in maintaining final infiltration rate >12 mm h^{-1}, low runoff, and erosion levels compared with control treatment[10].

The Loess Plateau is located in the middle reaches of the Yellow River watershed in China with an area of 6.29×10^5 km^2 and an elevation of 1200 to 1600 m above sea level[11]. The average and maximum annual erosion rates are 150 Mg ha^{-1} and 390 Mg ha^{-1}, respectively[12]. The Loess Plateau is one of the four vulnerable ecology-environment regions in China, where water resources are deficit and soils are eroded by storms. Sloping land, especially steep sloping land in the Loess Plateau is the dominant physiognomy factor which causes serious soil and water loss. Measures have been taken to prevent the soil and water erosion in this area since the end of 1950s and better conditions were obtained in the past decades. The common measures are to plant trees and grass in order to establish vegetation coverage. However, large-scale vegetation restoration also aggravates water scarcity and gradually leads to soil desiccation accompanied with erosion area control and vegetation coverage increase [11]. Therefore, it is necessary to try other methods such as PAM application for soil erosion control in this region since PAM has been shown to have positive impacts on water loss and erosion control at other locations.

Flow velocity is important in describing the water flow over the land surface. The most widely used equations for calculating flow velocity are the Darcy-Weisbach and Manning equations[13,14]. Manning's coefficient n varies with the type of vegetation and, for a particular plant type, it also varies with flow depth, slope and shape of the channel [14]. To date vegetation coverage effects on the hydraulic and erosion characteristics have been researched [13,16~18], but limited research has been done on the impacts of PAM applications on the hydraulic and erosion characteristics of steep sloping land. Research of PAM application has been focused on full coverage to the soil surface or on PAM applications to the irrigation water. Few research studies have been performed to investigate how the PAM application to a fraction of the surface impacts water infiltration, erosion and sediment transport. Treating only a fraction of the surface is a strategy for reducing application costs. The objective of this study is to investigate the effects of PAM applications to a fraction of soil surface in a steep sloping land on the hydraulic flow parameters, the soil water infiltration, and the erosion characteristics.

2. Materials and Methods

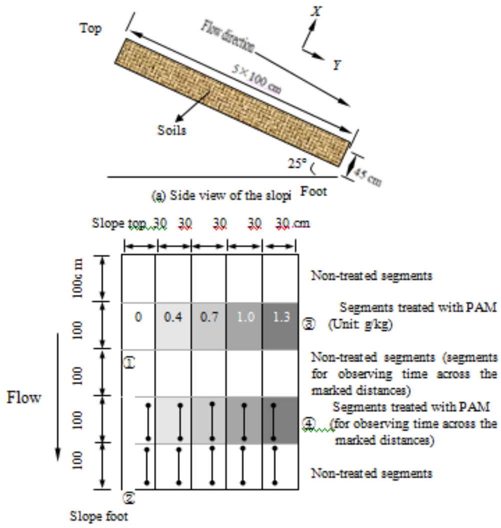
Huangmian soil was collected from a 10-cm thick surface layer of a field in the Liudaogou valley located in the typical water-wind erosion belt in Shenmu county of Shannxi province, China. There is a typical continental climate in this area. The geographic coordinate is 38°13′ to 39°27′ north latitude and 109°40′ to 110°54′ east longitude with elevation of 738 to 1448 m.

Soil samples were air dried, crushed and sieved through a 5-mm sieve. Five plots were packed with Huangmian Soil (silty loam) at a bulk density of 1.3 g cm^{-3} and a water content of 0.04 cm^3 cm^{-3}. The area of each plot was 500 cm × 30 cm, and the depth of the packed soil was 45 cm (Figure 1a). After the soils were packed, the soil surface was scratched in order to have a relatively rough surface. 2 kg of fine moist soil (moisture: 0.20 cm^3 cm^{-3}; < 1 mm in diameter) mixed long enough with PAM were put uniformly on two 100-cm long separate segments for each plot. The same masses of non-PAM-treated wet soils were put uniformly on the surfaces of the other three 100-cm long segments in order to get similar surface soil for all of the segments. Five different PAM rates (*PAMR*) were applied to the soils. The rates were 0, 0.4, 0.7, 1.0 and 1.3 g kg^{-1}, corresponding to 0, 1.3, 2.3, 3.3, 4.3 kg hm^{-2}, respectively (Figure 1b). The PAM cover ratio on the soil surface was 40% for each plot. The slopes of all 5 plots were 25°.

The artificial rainfall experiments were performed inside a precipitation hall in the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau at the Institute of Soil and Water Conservation of Chinese Academy of Sciences. Wind influence was negligible. The precipitation equipment consisted an array of fixtures including penstock, pressure-adjustment machine, pressure gauge and downward spray nozzles. The nozzles were 16 m high and the raindrop uniformity coefficient was 95%.

Two simulated rainfall intensities, 1.0 and 1.58 mm min^{-1}, were used. The raindrop height was 16 m and the terminal velocity was reached as the raindrops impacted the soil surface. After the rainfall intensity was calibrated for 5 minutes with 12 water boxes with volume of 20 cm × 20 cm × 20 cm, the rainfall experiments started. The total rainfall time for each experiment was 60 min.

The rainfall-runoff time and the time for flow across the marked distances on the land surface were recorded. Small plastic buckets were put under the outlet of the plots to take runoff and sediment samples.



(b) Soil surface of the plots treated with PAM. The plots were isolated with PVC board. The marked distances were all 50 cm in the middle of the segments. There were 4 plexiglass walls on the sides for observing the depths of wetting front in the labeled numbers from ① to ④.
Figure 1 Sloping flume and the soil plots treated with PAM

When runoff initiated, the time interval for the runoff and sediment samplings was 1 minute for the first 10 minutes before changing the sampling interval to 3 minutes. The wetting front depths of soil water infiltration were observed by viewing plexiglas-walls supporting the non-treated plot and the plot with *PAMR* of 1.3 g kg^{-1}. Dye tracers ($KMnO_4$ solution) were used to determine the flow time required for the tracer to travel across a marked 50-cm long distance according to the color-front propagation. The marked distances were all in the middle of the selected PAM and non-treated segments of the plots.

The volumes of the runoff samples were measured with a graduated cylinder. The runoff samples were allowed to clarify for 2 days. After the supernatant was removed, the wet sediments were oven-dried to determine their dry mass and volume. Net runoff was the difference of volume of sediment-water mixture minus volume of the sediment.

Immediately following a simulated rainfall, the soil was sampled every 25 cm along the sloping land to the depth of wetting front. Soil samples were oven-dried to determine soil moisture content.

3. Theory

The hydraulic parameters include runoff flow depth, flow velocity, Reynolds number, Froude number, Darcy-Weisbach friction coefficient and Manning roughness coefficient. The mathematical relationships are written as follows:

$$h = \frac{Q}{UBt} = \frac{q}{U} \tag{1}$$

$$R_e = \frac{Uh}{\nu} \tag{2}$$

$$F_r = \frac{U}{\sqrt{gh}} \tag{3}$$

$$f = \frac{8ghS}{U^2} \tag{4}$$

$$n = \frac{h^{\frac{2}{3}} S^{\frac{1}{2}}}{U} \tag{5}$$

where h – surface runoff flow depth, mm; q – unit flux, cm s^{-1}; Q - runoff volume during time t, ml; U - flow velocity, cm s^{-1}; B - width of water-crossing segment, cm; g - acceleration of gravity, cm s^{-2}; ν - kinematical viscosity, cm^2 s^{-1}; S - hydraulic slope and is the sine function of slope gradient; R_e - Reynolds number; F_r - Froude number; f - Darcy-Weisbach friction coefficient; n - Manning roughness coefficient. These hydraulic parameters are useful in characterizing retardation of flow (Rudi, et al., 2003; Pan and Shangguan, 2006). In this work, Q values of the PAM treated segments and non-treated segments were assumed to be the same. Mean flow velocity values for the observed segments were used. In this sense, the other related hydraulic parameters such as h, R_e, F_r, f and n were also mean values for the studied segments.

Soil water infiltration rates (f_i) were as follows:

$$f_i = (I\cos\alpha - 10R_i)/At \tag{6}$$

Where f_i – infiltration rate, mm min^{-1}; I - rainfall amount, mm; α – slope gradient, degree; t - interval time, min; R_i - the ith runoff volume collected, ml; A - area of the plot, cm^2. The cumulative infiltration was:

$$F = \int_0^t f_i dt \tag{7}$$

Where F - cumulative infiltration, mm. A power function was fitted to the cumulative infiltration:

$$F = At^B \tag{8}$$

Where *A* and *B* are fitting parameters.

4. Results and discussions

4.1 Influences of PAM application on the hydraulic characteristics for overland flow

Table 1 presents the mean soil hydraulic characteristics of different PAM application rates (*PAMR*) at the rainfall intensities (*RIs*) of 1.0 and 1.58 mm min^{-1}. The unit flux (q) decreased from 2.04 to 0.73 cm s^{-1} at the *RI* of 1.0 mm min^{-1} and from 5.73 to 3.08 cm s^{-1} at the *RI* of 1.58 mm min^{-1} as *PAMR* increased from 0 to 1.3 g kg^{-1}. The mean flow velocities (U) decreased almost monotonically from 13.2 to 5.5 cm s^{-1} at the *RI* of 1.0 mm min^{-1} and from 40.7 to 13.6 cm s^{-1} at the *RI* of 1.58 mm min^{-1} as *PAMR* increased from 0 to 1.3 g kg^{-1}. The decrease of mean U with the increase of *PAMR* occurred for both the PAM treated segments and the non-PAM-treated segments within each plot. U values of the PAM-treated segments were slightly smaller than the non-PAM-treated segments for the same plot at the same *RI*.

The mean flow depth (h) ranged from 1.22 to 1.69 mm with an average of 1.53 mm at the *RI* of 1.0 mm min^{-1} as *PAMR* increased. h-values increased from 1.41 to 2.26 mm at the *RI* of 1.58 mm min^{-1}as *PAMR* increased from 0 to 1.3 g kg^{-1}. Values h of the PAM-treated segments were slightly larger than the non-treated segments for the same plot at the same *RI*.

The Froude numbers (F_r) decreased from 10.7 to 4.8 at the *RI* of 1.0 mm min^{-1} and from 34.7 to 9.1 at the *RI* of 1.58 mm min^{-1}as *PAMR* increased from 0 to 1.3 g kg^{-1}. For each plot, F_r of the PAM-treated segment was smaller than the non treated. According to the criterion of open channel flow, all the flow regimes were turbulent since F_r >1.

Table 1 Calculated mean hydraulic characteristics of overland flow at various PAMR

RI(mm min^{-1})	*PAMR*(g kg^{-1})	Segment	q(cm s^{-1})	U (cm s^{-1})	h (mm)	F_r	R_e	F $\times10^{-2}$	N $\times10^{-2}$
1.0	0	1	2.04	13.2	1.55	10.7	202	3.0	1.42
1.0	0	1	2.04	13.1	1.56	10.6	202	3.0	1.44
1.0	0.4	No PAM	1.87	11.3	1.66	8.83	185	4.34	1.74
1.0	0.4	PAM segment	1.87	11.1	1.69	8.60	185	4.6	1.80
1.0	0.7	No PAM	1.76	10.5	1.68	8.19	174	5.05	1.88
1.0	0.7	PAM segment	1.76	10.4	1.69	8.07	174	5.19	1.91
1.0	1.0	No PAM	1.20	8.6	1.40	7.3	119	6.27	2.04
1.0	1.0	PAM segment	1.20	7.9	1.53	6.4	119	8.18	2.36
1.0	1.3	No PAM	0.73	6.0	1.22	5.5	72.2	11.2	2.66
1.0	1.3	PAM segment	0.73	5.5	1.33	4.8	72.2	14.5	3.07
1.58	0	1	5.73	40.7	1.41	34.7	568	0.28	0.43
1.58	0	2	5.73	40.0	1.43	33.7	568	0.30	0.45
1.58	0.4	No PAM	5.69	38.1	1.49	31.5	564	0.34	0.48
1.58	0.4	PAM segment	5.69	34.9	1.63	27.6	564	0.44	0.56
1.58	0.7	No PAM	4.96	30.1	1.65	23.7	491	0.60	0.65
1.58	0.7	PAM segment	4.96	28.2	1.76	21.5	491	0.73	0.72
1.58	1.0	No PAM	4.18	24.1	1.74	18.5	414	0.99	0.84
1.58	1.0	PAM segment	4.18	22.7	1.84	16.9	414	1.19	0.93
1.58	1.3	No PAM	3.08	16.0	1.93	11.6	305	2.49	1.35
1.58	1.3	PAM segment	3.08	13.6	2.26	9.14	305	4.05	1.77

Notes: RI-rainfall intensity; PAMR-PAM application rate; segment ‘1’ for PAMR of 0 g kg-1 was the lower segment relative to ‘2’. U -flow velocity; q - unit flux; h – surface runoff flow depth; Re - Reynolds number; Fr - Froude number; f - Darcy-Weisbach friction coefficient; n - Manning roughness coefficient.

The Reynolds numbers (R_e) decreased from 202 to 72 at the *RI* of 1.0 mm min^{-1} and from 568 to 305 at the *RI* of 1.58 mm min^{-1}as *PAMR* increased from 0 to 1.3 g kg^{-1}. Both the Darcy–Weisbach coefficient (*f*) and Manning roughness coefficients (*n*) increased as *PAMR* increased from 0 to 1.3 g kg^{-1}. Values of *f* increased from 0.03 to 0.145 at the *RI* of 1.0 mm min^{-1}and from 0.0028 to 0.041 at the *RI* of 1.58 mm min^{-1} as PAMR increased. Values of *n* ranged from 0.014 to 0.031 at the *RI* of 1.0 mm min^{-1}and from 0.004 to 0.018 at the *RI* of 1.58 mm min^{-1}. For the same plot at the same *RI*, the differences of *f* between the PAM treated segments and the non-treated segments became larger as *PAMR* increased.

Generally, there were differences in the soil hydraulic characteristics between various *PAMR*. For the same plot, the soil hydraulic characteristics were different between PAM-treated segments and non-treated segments. PAM applications to the soil surface decreased the unit fluxes, Reynolds numbers, Froude numbers and flow velocities but increased the friction and roughness of the sloping surface compared to the non-PAM-treated plot. Large *PAMR* had large impacts on improving the soil hydraulic characteristics in this study.

4.2 Influences of PAM application on soil water movement

4.2.1 Wetting fronts and soil water distributions

There are many external factors influencing soil water infiltration on sloping land. Surface factors include roughness, mulching and slope. Rainfall factors include rainfall duration and rainfall intensity. As to soil aspects, infiltration is affected by soil texture, soil structure, initial soil water content and organic matter content. Applying PAM to land impacts infiltration by affecting surface and soil conditions. When PAM is applied to a soil surface, the roughness of the soil surface may change and the soil particles may aggregate. Figure 2 shows the influence of PAM on depths of infiltration wetting front at different positions of slope and 2 *RI* for *PAMR* of 0 and 1.3 g kg^{-1}.

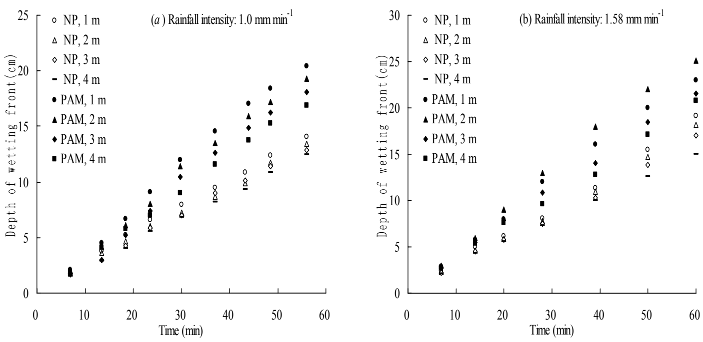


Figure 2 Wetting front variations at 4 positions on the sloping land under 2 rainfall intensities. NP-no PAM application; the distance from slope foot was 1 m. PAM application rate was 1.3 g kg^{-1}

For the same *RI*, the wetting front curve versus time increased slightly near the slope foot for no PAM and *PAMR* of 1.3 g kg^{-1}. The depths of wetting front for the plot that was partially treated with *PAMR* of 1.3 g kg^{-1} were generally larger than those of the non-treated plot. At the *RI* of 1.0 mm min^{-1}, the final depths of the wetting front for the non-treated plot were 14.1, 13.4, 12.9 and 12.5 cm at distances of 1, 2, 3, 4 m from the slope foot. For the plot with *PAMR* of 1.3 g kg^{-1}, the wetting fronts were 20.4, 19.3, 18.1 and 16.9 cm at distances of 1, 2, 3, 4 m from the slope foot. At the *RI* of 1.58 mm min^{-1}, the final depths of the wetting fronts for non-PAM-treated plot were 19.1, 18.2, 17 and 15 cm at distances of 1, 2, 3, 4 m from the slope foot. For the plot with *PAMR* of 1.3 g kg^{-1}, they were 25.1, 23.0, 21.5 and 20.8 cm at distances of 1, 2, 3, 4 m from the slope foot. When *RI* increased from 1 to 1.58 mm min^{-1}, the wetting front depths increased. The infiltration wetting fronts increased as *PAMR* increased. Generally, applying PAM to the soil had influences on the depths of the wetting fronts. The depths of the wetting fronts for the PAM-treated plots were larger than for the non-treated plot.

The soil moisture distributions along the sloping land at different *PAMR* for *RI* of 1.58 mm min^{-1} are illustrated in Figure 3. The soil moisture along the Y-direction was smaller at the slope top than at the slope foot for all of the 5 plots. The mean surface soil moisture of the plots (0~2 cm depth) was 0.28 cm^3 cm^{-3}. The surface soil moisture increased slightly when *PAMR* increased. The decrease of soil moisture from the slope foot to the top in the Y-direction along the sloping land was more obvious when the depths increased. There was a deeper wet-dry interface of soil moisture for the plots with larger *PAMR*. In general, soil moisture was larger at the same depth for the PAM-treated plots than for the non-treated plot.

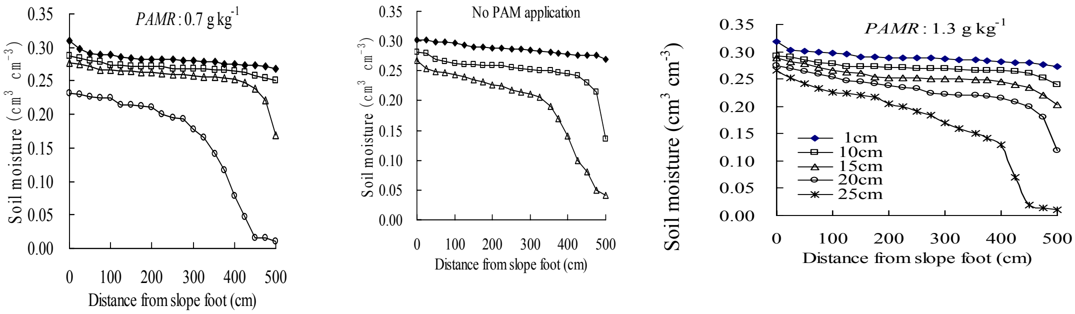


Figure 3 Soil moisture distributions along the sloping land at different PAMR (PAM application rate)

4.2.2 Infiltration rates and cumulative infiltrations

Based on the observations at the *RI* of 1.58 mm min^{-1}, the infiltration rate and the cumulative infiltration are illustrated in Figure 4. At the beginning of the rainfall before the runoff started, the infiltration rate was equal to the net RI (1.41 mm min^{-1}) on the sloping land and the cumulative infiltration was equal to the net rainfall amount. After the land surface was ponded and runoff initiated, the infiltration rate decreased with time for various *PAMR*. Both final infiltration rate and cumulative infiltration increased as *PAMR* increased. The final infiltration rates were 0.18, 0.27, 0.33, 0.40 and 0.53 mm min^{-1} for *PAMR* of 0, 0.4, 0.7, 1.0 and 1.3 g kg^{-1}, respectively. Steady infiltration was not observed for any of the plots. In general, PAM applications to a fraction of soil surface improved soil infiltration capacity.

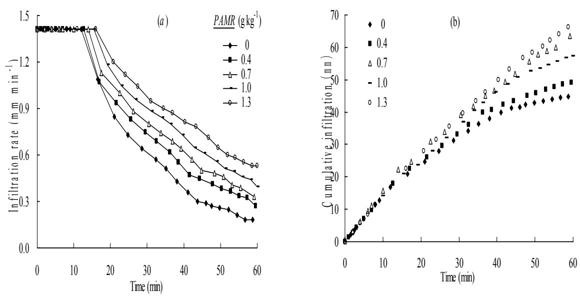


Figure 4 The infiltration rate and the cumulative infiltration variations with time for different PAMR. PAMR - PAM application rate.

The infiltration parameters at the *RI* of 1.58 mm min^{-1} are given in Table 2. When *PAMR* increased from 0, 0.4, 0.7, 1.0 to 1.3 g kg^{-1}, the initial runoff start times were 11.7, 14.0, 15.7, 16 and 17 min, respectively. The time to ponding increased slightly as the *PAMR* increased. The maximal depths of the wetting fronts increased from 18.2 to 25.1 cm, the average infiltration rate increased from 0.68 to 0.98 mm min^{-1} and the cumulative infiltration increased from 40.9 to 59.0 mm when *PAMR* increased from 0 to 1.3 g kg^{-1}. The increasing percentage of the infiltration depth and the cumulative infiltration compared to non-treated plots were 37.9% and 44.3% for *PAMR* of 1.3 g kg^{-1}. These results indicated that PAM application to a fraction of the surface of sloping land improved soil infiltration.

Table 2 Influence of PAM application rates (PAMR) on infiltration characteristics at RI of 1.58 mm min^{-1}

PAMR (g kg^{-1})	0	0.4	0.7	1.0	1.3	average
T_{runoff} (min)	11.7	14.0	15.7	16	17	14.9
D_{inf} (cm)	18.2	20.1	23.0	23.3	25.1	21.9
A_{inf} (mm min^{-1})	0.68	0.76	0.81	0.90	0.98	0.75
F (mm)	40.9	45.4	48.6	54.0	59.0	49.6
A	1.11	1.12	1.17	1.19	1.29	1.17
B	0.97	0.97	0.98	0.96	0.99	0.96

Notes: Trunoff - time when the runoff started; Dinf – maximum wetting front depth; Ainf - average infiltration rate; F-total infiltration; A, B – fitted parameters for equation 7. Both the infiltration depth increase percentage and the total infiltration increase percentage were calculated based on no PAM application, and the fitted points for the cumulative infiltration was 18, R2 is the coefficient of determination.

4.3 Influences of PAMR on the runoff and the sediments

The total runoff values were 3.25, 3.06, 2.80, 2.31 and 1.22 mm at the *RI* of 1.0 mm min^{-1} and 33.8, 35.9, 31.6, 25.6 and 18.1 mm at the *RI* of 1.58 mm min^{-1} when the corresponding *PAMR* were 0, 0.4, 0.7, 1.0 and 1.3 g kg^{-1}, respectively. When *PAMR* increased, the runoff decreased, which was in correspondence with the increases of the cumulative infiltration.

There was very little sediment yield at the *RI* of 1.0 mm min^{-1}. The cumulative sediment during rainfall at various *PAMR* is illustrated in Figure 5 at the *RI* of 1.58 mm min^{-1}. The longer the rainfall time, the larger the cumulative sediment for each *PAMR*. For each *PAMR*, the cumulative sediment values increased with increasing rainfall time. When *PAMR* was smaller than 0.7 g kg^{-1}, the cumulative sediment increased rapidly with the rainfall time especially when the time was longer than 40 minutes. Generally, PAM application to the soil reduced the total sediment on sloping land. The exponential functions were fitted for sediment mass versus *PAMR*. The coefficients of determination were all relatively large (>0.91) for the *PAMR* treatments.

The total sediment mass decreased with increasing *PAMR*. A parabolic function was fitted to the total sediment vs. *PAMR*:

$$W = 421.7\,P^2 - 1838\,P + 1738 \quad R^2 = 0.99$$

Where *W*-the total sediment mass, *g*; *P*- *PAMR*, g kg^{-1}.

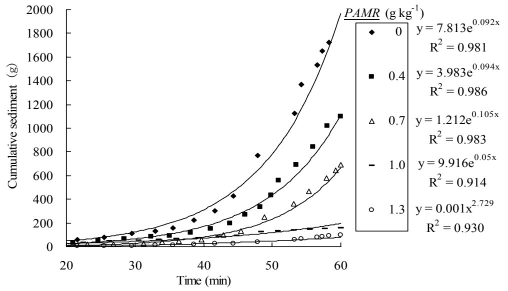


Figure 5 The cumulative sediment variations with time at different PAMR

The sediment concentration in runoff was calculated as the ratio of sediment mass to runoff volume at various time. Figure 6 indicates the sediment concentration in runoff (SCIR) with time at various *PAMR* at the RI of 1.58 mm min^{-1}. SCIR increased slowly with rainfall time, when the time was less than 40 minutes. It increased rapidly to the peak value when the time was generally 40 to 55 minute and then decreased till the rainfall finished for *PAMR* < 0.7 g kg^{-1}. The peak values decreased and ranged from 0.215 to 0.049 g ml^{-1} when *PAMR* increased from 0 to 0.7 g kg^{-1}. The time when the peak values occurred delayed slightly and ranged from 52 to 53.6 min when *PAMR* increased from 0 to 0.7 g kg^{-1}. When *PAMR* was larger than 0.7 g kg^{-1}, SCIR increased slowly with time during the whole rainfall. For the plots with *PAMR* > 0.7 g kg^{-1}, SCIR were much smaller than for the plots with *PAMR* < 0.7 g kg^{-1}.

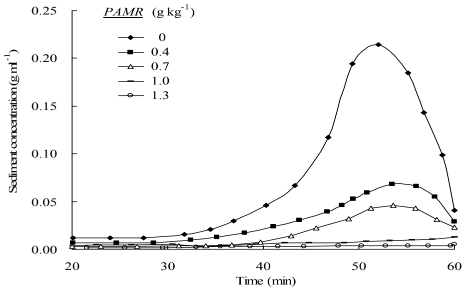


Figure 6 Variations of sediment concentration in runoff with time at different PAMR

Table 3 Characteristics of runoff and sediment production for different PAMR

PAMR (g kg^{-1})	0	0.4	0.7	1.0	1.3
TR (10^3 ml)	33.8	35.9	31.6	25.6	18.1
TS (g)	1721	1100	689	240	96
SI_{max} (g min^{-1})	146	82.2	47.8	6.9	4.7
SC_{max} (g ml^{-1})	0.215	0.066	0.049	0.012	0.004
S_{max}(g)	365	173	133	51	12
R_s (%)	0	36	56	86	94
SC_{mean} (g ml^{-1})	0.051	0.031	0.021	0.009	0.005

Notes: TR- total runoff; TS - total sediment; SImax-Maximal sediment intensity; SCmax - Maximal sediment concentration in runoff; Smax-Total sediment mass; Rs-Sediment reduction percentage; SCmean - mean sediment concentration in runoff.

The sediment intensity was the sediment mass per minute. The curves of the sediment intensity with time were similar in curve shape to the sediment concentration in runoff at different *PAMR* for the *RI* of 1.58 mm min^{-1}. The statistical characteristics of sediment yield are presented in Table 3. The sediment intensity increased slightly when the rainfall time was shorter than 40 min but increased rapidly later and then decreased. Similar to the variations of sediment concentrations, there were also peak values of sediment intensity for the plots with *PAMR* < 0.7 g kg^{-1}. The peak values decreased and ranged from 147 to 47.1 g min^{-1} when the *PAMR* increased from 0 to 0.7 g kg^{-1}. The larger the *PAMR*, the smaller the peak values in the sediment intensity curves.

The total sediment mass decreased as *PAMR* increased. The sediment reduction ratio (R_s) was calculated as follows:

$$R_s\,(\%) = 100\,(TS_{\mathrm{PAMR}} - TS_0) / TS_0$$

Where TS_{PAMR} was the total sediment mass at a selected *PAMR* and TS_0 was the total sediment mass for the non-PAM treatment. R_s increased when *PAMR* increased and was 94.4% at *PAMR* of 1.3 g kg^{-1}.

Generally, when *PAMR* increased, the total runoff, the total sediment mass, the maximal sediment concentration in runoff and the maximal sediment intensity all decreased. This implied that PAM applications to a fraction of the soil surface could reduce erosion from sloping land. The larger the *PAMR*, the smaller the runoff and the sediment yield.

5. Conclusions

Applying PAM to a fraction of a soil surface impacts hydraulic characteristics of flow, water infiltration and sediment yields. When *PAMR* increased, the unit flow fluxes, the mean flow velocities, the Froude numbers and the Reynolds numbers all decreased. The Darcy-Weisbach coefficients and Manning's roughness coefficients increased as *PAMR* increased. Both the mean infiltration rates and the total infiltration increased when *PAMR* increased. A deeper infiltration wetting front was observed with a larger *PAMR*. The runoff start time increased when *PAMR* were larger. The runoff and the sediment were reduced at different *PAMR*. *PAMR of* 1.3 g kg^{-1} exhibited the best effects on increasing infiltration and reducing erosion. PAM applications to a fraction of a soil surface can be effective at increasing the roughness and infiltration as well as reducing the erosion of steep sloping land.

Acknowledgment

This work was funded by Basic Foundation for Science Operation of of Northwest Agriculture and Forestry Sci-Tech University in China(No. QN2009087).

References

[1]R. E. Terry, and S. D. Nelson. "Effects of Polyacrylamide and irrigation method on soil physical properties". Soil Sci. 1986. vol. 141, No. 5, pp: 317-320

[2]G. J. Levy, J. Levin, M. Gal, M. Ben-Hur, and I. Shainberg. "Polymer's effects on infiltration an soil erosion during consecutive simulated sprinkler irrigations". Soil Sci. Soc. Am. J., 1992. vol. 56, pp: 902-907

[3]R. D. Lentz, and R. E. Sojka. "Field results using polyacrylamide to manage furrow erosion and infiltration". Soil Sci. 1994. vol. 158, pp: 274-282

[4]G. J. Levy, and I. Rapp. Polymer effects on surface mechanical strength of a crusting loessial soil". Aust. J. Soil Res., 1999. vol. 37, pp: 91-101

[5]I. Shainberg, D. N. Warrington, and P. Rengasamy. “Water quality and PAM interactions in reducing surface sealing”. Soil Sci. 1990. vol. 149, pp: 301-307

[6]X. C. Zhang, and M. P. Miller. “Polyacrylamide effect on infiltration and erosion in furrows”. Soil Sci. Soc. Am. J, 1996. vol. 60, pp: 866-872

[7]J. K. Aase, D. L. Bjorneberg, and R. E. Sojka. “Sprinkler irrigation runoff and erosion contrall with polyacrylamide – laboratory tests”. Soil Sci. Soc. Am. J, 1998. vol. 62, pp: 1681-1687

[8]V. S. Green, D. E. Stott, and L. D. Norton. “Polyacrylamide molecular weight and charge effects on infiltration under simulated rainfall”. Soil Sci. Soc. Am. J, 2002. 66:19-25

[9]A. R. Sepaskhah, and A. R Basrafshan-Jahromi. “Controlling runoff and erosion in sloping land with polyacrylamide under a rainfall simulator”. Biosystems Engineering, 2006.vol. 93, No. 4, pp: 469-474

[10] Z. Tang., T. Lei.,J. Yu, I. Shainberg, A. I. Mamedow, M. Ben-Hur, and G. J. Levy. “Runoff and interrill erosion in sodic soils treated with dry PAM and phosphogypsum”. Soil Sci. Soc. Am. J., 2006. vol. 70, pp: 679-690

[11] H. Chen, M. Shao, and Y. Li, “The characteristics of soil water cycle and water balance on steep grassland under natural and simulated rainfall conditions in the Loess Plateau of China”. J Hydrol, 2008. vol. 360, pp: 242-251

[12] T. X. Zhu, Q. G. Cai, and B. Q. Zeng. “Runoff generation on a semi-arid agricultural catchment: field and experimental studies”. J. Hydrol, 1997. vol. 196, pp: 99-118

[13] C. W. Rose, W. L. Hogarth, H. Ghadiri, J. Y. Parlange, and A. Okom. “Overland flow to and through a segment of uniform resistance”. J. Hydrol., 2002. vol. 255, pp: 134-150

[14] H. Rudi, J. Victor, and G. Zhang. “Estimating Manning’s n for steep slopes”. Catena, 2003. 54: 77-91

[15] A. O. Ogunlela, and M. B. Makanjuola. “Hydraulic roughness of some African grasses”. J. Agric. Engng Res., 2000. vol. 75, pp: 221-224

[16] C. Z. Pan, and Z. P. Shangguan. “Runoff hydraulic characteristics and sediment generation in sloped grass-plots under simulated rainfall conditions”. J. Hydrol., 2006. vol. 331, pp: 178-185

[17] R. D. Lentz, I. Shainberg, R. E. Sojka, and D. L. Carter. “Preventing irrigation furrow erosion with small applications of polymers”. Soil Sci. Soc. Am. J, 1992. 56: 1926-1932

[18] K. Chaudhari, and D. C. Flanagan. 1998. “Polyacrylamide effect on sediment yield, runoff, and seedling emergence on a steep slope”. Annu. Meet. ASAE, Orlando, Fl, pp:12-16