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Preventing Irrigation Furrow Erosion with Small Applications of Polymers

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ABSTRACT

Soil erosion is a serious problem threatening sustainability of agriculture globally and contaminating surface waters. The objective of this study was to determine whether low concentrations of anionic polymers in irrigation water would appreciably reduce irrigation furrow erosion on Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthid), a highly erodible soil. Furrow slope was 1.6%, furrow length was 175 m, and irrigation rates ranged from 15 to 23 L min^{-1}. Inflow during the first 1 to 2 h of the first 8-h irrigation was treated. Subsequent irrigations were untreated. Polyacrylamide (PAM) or starch copolymer solutions were injected into irrigation water entering furrows at concentrations of 0, 5, 10, and 20 g m^{-3}. Sediment loss from polymer-treated furrows was significantly less than that of control furrows in the first (treated) and second (untreated) irrigations, but not in the fourth (untreated). The PAM provided better erosion control than the starch copolymer. Efficacy of PAM treatments varied depending on its concentration, duration of furrow exposure, and water flow rate. In the initial (treated) irrigation and at low flow rates, 10 g m^{-3} PAM reduced mean sediment load by 97% compared with untreated furrows. Residual erosion abatement in a subsequent irrigation, without further addition of PAM, was approximately 50%. The PAM increased net infiltration and promoted greater lateral infiltration. Effective erosion control was achievable for a material cost below \$3 ha^{-1} irrigation^{-1}.

THE MAGNITUDE of soil erosion associated with irrigation in general, and with furrow erosion in particular, has been recognized in recent years (Carter, 1990; Hajek et al., 1990). In Washington, Oregon, and Idaho approximately 1.5 million ha of the most erosive soils in the USA are surface irrigated. The region's soils are derived from ash and loess, are low in organic matter and clay, and have little structure and few durable aggregates. Typically, from 5 to 50 t of soil ha^{-1} yr^{-1} can be lost from irrigated fields, and nearly three times that amount from near the furrow inlets (Berg and Carter, 1980; Kemper et al., 1985). Where soils are underlain with subsurface horizons rich in Ca carbonates, their exposure or mixing with eroded surface soil has resulted in plant nutritional problems and physical degradation. Eroded areas have reduced crop productivity and require increased inputs per unit of yield (Carter et al., 1985).

Use of known erosion control practices coupled with conservation tillage and selected cropping sequences can nearly eliminate erosion. Unfortunately, many farmers hesitate to adopt such a program in its entirety. Furrow erosion may be reduced using various approaches, including settling ponds (Brown et al., 1981), minibasins and buried pipe to control runoff (Carter, 1985), straw placed in furrows (Berg, 1984; Brown, 1985), and sodded furrows (Cary, 1986). Farmers have resisted the implementation of these effective alternatives for several reasons. In some cases, the techniques cannot be conveniently incorporated into existing farm plans; for some, the philosophical or economic inducements are not great enough to justify the additional effort. In general, erosion control practices are not uniformly implemented to the extent necessary or in the combinations needed to eliminate erosion concerns. Farmers may more readily employ a simple erosion prevention method that permits them to use familiar tillage and crop cultural practices.

Overland flow applies shear forces to the soil surface, which causes particle detachment and movement. As flow velocities increase, shear forces increase and eventually exceed the shear stress required to overcome the cohesive forces between soil particles. As the water infiltrates the soil, the sediments deposit at the furrow surface to form a thin seal, or depositional layer (Segeren and Trout, 1991). The seal conductivity values on the Portneuf silt loam reached values 0.1 to 8% of the conductivity of the soil underlying the seal (Segeren and Trout, 1991). If furrow erosion is halted, depositional seal formation is slowed down and high infiltration is maintained.

Organic polymers, mainly PAM and polysaccharides have been used in laboratory studies to maintain soil structure and permeability of soils subject to artificial rainfall (Helalia and Letey, 1988; Shainberg et al., 1990). Treatment of the soil surface with 5020 kg ha^{-1} of anionic PAM increased the final infiltration rate of soils exposed to rain by an order of magnitude and reduced runoff and interrill erosion by severalfold. Laboratory studies demonstrated that no rill erosion occurred in PAM solutions that contained 2.5, 5.0, and 10.0 g PAM m^{-3} (per unit of water). As long as there was PAM in the water, no soil detachment was evident even on steep slopes (30%) and with high flow rates with a shear stress of 10 Pa (I. Shainberg, 1991, personal communication). It was hypothesized that PAM in small quantities will increase the cohesive forces between soil particles in a thin layer at the soil surface and will prevent rill erosion. Success at completely halting rill erosion of a number of soils using laboratory erosion simulators prompted testing of materials and application methods in the field. The current understanding of the role of a thin layer at the soil surface in controlling rain infiltration or rain and furrow erosion allows for the concept of treating only the soil surface with organic polymers rather than mixing the polymers with the cultivated layer. This application technique employs smaller quantities of the polymers, thus making their use more cost effective. This promotes, also, the manufacturing of polymers

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Abbreviations: PAM, polyacrylamide; SAR, sodium adsorption ratio.

based on starch grafted with PAM, which is more effective, easier to apply in the field, less costly, and biodegradable. Starch is perhaps the most abundant and lowest cost natural polymer on the market. Such a starch copolymer was also tested here.

The objectives of this study were to test the effect of two polymer compounds on the furrow erosion of a recognized erosive soil. In the first experiment, two polymers at two concentrations were applied to soils during furrow advance. We hypothesized that the polymer would increase resistance of the soil surface to tractive forces of flowing water and prevent formation of a depositional seal. Net infiltration would increase and runoff and erosion would decline. The second and third experiments tested the concept that an increase in the time of polymer–soil contact would increase the cohesive forces between soil particles and provide added soil stability. If true, this would allow application of smaller polymer concentrations while retaining similar erosion protection. In these studies the period of polymer application was increased from 1 to 2 h. A surge, or interrupted irrigation, was included in the second study. This technique was employed to (i) increase soil cohesion by PAM during condensation and orientation of soil particles in the brief drying time, (ii) stabilize zones of weakness in the furrow (these areas crack during flow interruption and were treated with a subsequent PAM application), and (iii) improve uniformity of polymer application. We hypothesized that use of this technique would increase the effectiveness of the PAM treatment for several irrigations. An intermittent treatment was included in the third study. This treatment tested the hypothesis that intermittent, brief applications of PAM throughout an irrigation would refresh initially treated surfaces, engage surfaces newly exposed during erosive episodes, and increase effective erosion control.

METHODS AND MATERIALS

The study area, near Kimberly, ID, was on a Portneuf silt loam on a field having a 1.6 % slope. Three studies were conducted in June 1991 on a conventionally prepared and planted field of dry edible beans ('Viva Pink' *Phaseolus vulgaris* L.). The field had not been tilled after the previous season's bean harvest, but little crop residue remained on the surface. In spring, the seedbed was prepared with disk and roller-harrow; beans were conventionally planted at 175 000 seeds ha^{-1} in 56-cm rows. Snake River water was used for irrigation; average electrical conductivity is 0.05 S m^{-1}, and mean SAR is 0.06 (Carter et al., 1973).

Furrows were formed as an integral part of the planting operation using weighted furrow-forming tools on a rear tool bar. Furrows were formed into 75°, 20-cm-deep (approximately) V shapes. For this study the field was trafficked in all monitored furrows to eliminate infiltration variation from wheel compaction. Furrow spacing was 1.12 m. Irrigation was by individually regulated siphon tubes from a cement-lined head ditch. Furrows were 175 m from inlet to outflow. Exact furrow lengths were employed in related calculations. Water application to each treated furrow was predetermined and periodically monitored.

Three experiments (described below) evaluated combinations of polymer material and application methods, as well as their residual effectiveness in subsequent irrigations. All three studies employed randomized block designs with three replicates. Two polymers were used in the first study. One was a starch copolymer supplied by G. F. Fanta, USDA-ARS National Center for Agricultural Utilization Research, Peoria, IL. This material was prepared by polymerization of acrylamide–acrylic acid mixtures onto starch. The starch copolymer had a high molecular weight and was negatively charged with medium charge density. The other material was Magnifloc 836A[1] (Cyanamide Corp., Wayne, NJ), a commercially available PAM formulation. It is a low-charge (20% hydrolysis) anionic PAM with a high molecular weight (MW = 10^7). The second and third studies used only PAM. Desired treatment concentrations were achieved by metering an appropriate quantity of polymer stock solution (1.2 g L^{-1}) into irrigation water at each furrow head. Rates of irrigation inflow and polymer injection were monitored during the experiment to ensure constancy. Furrows in the three studies were given five irrigations during the growing season, at approximately 2-wk intervals. Inflow, outflow, and sediment concentration measurements were collected for the first, second, and fourth irrigations. Polymer treatments were employed only in the beginning of the first irrigation and successive irrigations were untreated. Duration of the first irrigation was 8 h and the inflow rate varied for each study. For successive irrigations (monitored), duration was 12 h and inflow rates were the same for all treatments. Individual experiments and treatments are described in detail below.

Experiment 1

On 19 June 1991, polymers were injected into irrigation water only during furrow advance. Thus, treatment time varied for each furrow; the average time is given in parentheses. Inflow rate was continuous at 22.7 L min^{-1}. Treatments consisted of a control (untreated water), PAM at 10 g m^{-3} (PAM-10, 37 min), PAM at 20 g m^{-3} (PAM-20, 42 min), starch copolymer at 10 g m^{-3} (Starch-10, 62 min), and starch copolymer at 20 g m^{-3} (Starch-20, 61 min).

Experiment 2

On 20 June 1991, polymer was injected into inflowing water during the initial 2 h of the irrigation (excluding periods of flow interruption). Inflow rate was 22.7 L min^{-1} during furrow advance and 15.1 L min^{-1} during the remaining irrigation. The surge option included a 25-min flow interuption after furrow advance. For treated, surge furrows, polymer application was resumed after flow interruption for the balance of the 2-h period (120 min minus minutes of furrow advance). Treatments consisted of a Control, Control–Surge (untreated water, surge mode), PAM at 10 g m^{-3} with surge (PAM-10–Surge) PAM at 10 g m^{-3} (PAM-10), PAM at 5 g m^{-3} (PAM-5).

Experiment 3

On 25 June 1991, two types of polymer injections were employed. Inflow rates were the same as in Exp. 2, but a surge mode was not included. Treatments consisted of a control, PAM at 10 g m^{-3} for 2 h (PAM-10), and PAM at 5 g m^{-3} during furrow advance, with intermittent injections of PAM at 5 g m^{-3} for 5 min each hour (PAM-5 × 5).

Irrigation and runoff initiation times were noted in all monitored studies. Runoff volumes were periodically monitored using calibrated V-notch flumes (Honkers Supreme, Twin Falls, ID), which were manually read at hourly or shorter intervals throughout the course of each irrigation set. The V-notch flumes, originally developed and calibrated by Robinson and Chamberlain (1960), satisfy the

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[1] Mention of trademarks, proprietary products, or vendors does not constitute a guarantee or warranty of the product by the USDA-ARS and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

hydraulic requirements for long-throated flumes (Bos et al., 1984) up to a flow depth of 90 mm (a gauge reading of 100 mm, or 100 L min^{-1} flow rate). Net furrow infiltration was determined from the difference between inflow and runoff volumes. The extent of the lateral wetting front was measured at 10 random locations along each furrow in each treatment of each experiment.

One-liter runoff samples were collected from free-flowing flume discharge at each flume reading. Samples were collected every 30 min during the first 2 to 3 h of the irrigation and every 60 min thereafter. In surge treatments, samples were collected every 5 min, starting after the flow was interrupted and continuing until the resumed flow had stabilized. The weight of sediment per liter of runoff was determined from the settled volume of sediment in Imhoff cones (Sojka et al., 1992), by calibrating the volume of settled sediment and sediment weight per unit volume of runoff (R^2 = 0.99 for >0.5 g L^{-1}).

Sediment reduction was computed as the ratio of sediment loss difference (treated minus control) to sediment loss of the control. Cumulative sediment reduction as a function of polymer applied was calculated by dividing the difference in sediment loss (kg ha^{-1}) between treated and control furrows by polymer applied (kg ha^{-1}). Analysis of variance was employed to test for significance of treatment effects in each study. The Waller–Duncan multiple comparison procedure examined sediment-loss mean separations for (i) treatments within each study and (ii) identical treatments among all studies.

RESULTS

Erosion

Sediment loss data are presented in Table 1. In the first irrigation, mean sediment losses for untreated, or PAM-10 furrows of Exp. 1 (19 June) were significantly greater than those of Exp. 2 (20 June) or Exp. 3 (25 June). This reduction in erosion resulted primarily from lower inflow rates employed in Exp. 2 and 3. For a given treatment, it is known that variation in sediment loss between irrigations can result from (i) differing inflow rates, (ii) varying lengths of irrigations, (iii) seasonal changes in field conditions, e.g., as the season progressed, growth of crop roots and weeds in furrow soils reduced water velocity and stabilized soil against flow shear. In this study, we propose an additional factor, the temporal changes in soil–polymer linkages that effect soil erodibility.

Soil loss varied dramatically among treatments of each experiment in the first and second irrigations (Table 1). Application of starch copolymer (Exp. 1, Starch-10 and Starch-20) in the initial irrigation produced no significant reduction in sediment loss when compared with the control; however, in the second irrigation, starch-copolymer-treated furrows had significantly smaller (30– 34%) sediment loss than nontreated furrows. This suggests that aging or drying of treated furrows strengthened cohesive bonding between soil and starch copolymer. The injection of PAM into irrigation water significantly reduced total soil loss by 68 to 99% in the initial irrigation, and by 38 to 58% in the second irrigation. Although no measurements were made during the third irrigation, many of the PAM-treated furrows appeared to have lower sediment loads than their respective controls. No significant sediment reduction was observed for any treatments in the fourth irrigation. These data suggest that the residual effect of PAM declines with each subsequent irrigation after application. In the fourth irrigation, increased variability in sediment loss for PAM-treated furrows may be associated with erratic failure rates of residual PAM protection. The negative sediment reduction values observed for PAM-treated furrows imply that, when protection of the furrow surfaces was exhausted, subsequent erosion exceeded that of the control. This may be a consequence of the previous erosion regimes in treated relative to control furrows.

Table 1. Inflow rates†, sediment loss, and sediment reduction in polyacrylamide (PAM)-treated (first) and successive untreated (second, fourth) irrigations.

	First irrigation				Second irrigation		Fourth irrigation	
Treatment	Polymer added	Mean inflow	Sediment loss	Sediment reduction	Sediment loss	Sediment reduction	Sediment loss	Sediment reduction
	kg ha^{-1}	L min^{-1}	kg ha^{-1}	% of control	kg ha^{-1}	% of control	kg ha^{-1}	% of control
Experiment 1								
Control	0.0	22.7	2635$^{\mathrm{A}}$‡	0	3067$^{\mathrm{A}}$	0	747.6$^{\mathrm{a}}$‡	0
10 g m^{-3} PAM	0.49	22.8	1460$^{\mathrm{AB}}$	44.6	1896$^{\mathrm{BC}}$	38.1	367.8$^{\mathrm{a}}$	50.8
20 g m^{-3} PAM	1.11	22.7	505$^{\mathrm{B}}$	80.8	1598$^{\mathrm{C}}$	47.9	582.5$^{\mathrm{a}}$	22.1
10 g m^{-3} starch	0.82	22.6	2097$^{\mathrm{A}}$	20.4	2038$^{\mathrm{B}}$	33.6	347.4$^{\mathrm{a}}$	53.5
20 g m^{-3} starch	1.63	22.7	2212$^{\mathrm{A}}$	16.0	2155$^{\mathrm{B}}$	29.7	549.6$^{\mathrm{a}}$	26.5
Experiment 2								
Control	0.0	16.2	1654$^{\mathrm{A}}$§	0	4236$^{\mathrm{A}}$	0	622.6$^{\mathrm{a}}$	0
Control–Surge	0.0	15.5	1677$^{\mathrm{A}}$	0	4069$^{\mathrm{a}}$	0	558.4$^{\mathrm{a}}$	0
10 g m^{-3} PAM Surge	1.20	15.8	20$^{\mathrm{B}}$	98.8	2017$^{\mathrm{b}}$	50.4	657.0$^{\mathrm{a}}$	−17.7
10 g m^{-3} PAM	1.23	16.0	54$^{\mathrm{B}}$§	96.7	2237$^{\mathrm{b}}$	47.2	712.2$^{\mathrm{a}}$	−14.4
5 g m^{-3} PAM	0.60	16.0	295$^{\mathrm{B}}$	82.2	4197$^{\mathrm{a}}$	1.0	787.4$^{\mathrm{a}}$	−26.5
Experiment 3¶								
Control	0.0	15.8	843$^{\mathrm{A}}$	0	4567$^{\mathrm{A}}$	0	537.5$^{\mathrm{a}}$	0
10 g m^{-3} PAM	1.23	16.0	267$^{\mathrm{B}}$§	68.3	2526$^{\mathrm{B}}$	44.7	655.0$^{\mathrm{a}}$	−21.9
5 g m^{-3} PAM, intermittent	0.55	16.2	181$^{\mathrm{B}}$	78.5	1902$^{\mathrm{B}}$	58.3	538.4$^{\mathrm{a}}$	−0.2

† Inflow rates varied between experiments in the first irrigation, but were the same across all experiments in the second (19.2 L min^{-1}) and fourth (17.5 L min^{-1}) irrigations.

‡ Similar uppercase letters (P = 0.05) or lowercase letters (P = 0.10) indicate significance between treatments in each study.

§ Treatment is significantly different (P = 0.05) from the identically named treatment in Exp. 1.

¶ Rain showers occurred between 20 and 25 June disturbing the surface condition of the furrows prior to the first irrigation of Exp. 3 (25 June). A brief heavy rain shower also occurred in the late afternoon during the irrigation.

Table 2. Cumulative values for polymer applied, sediment loss, and sediment reduction of polymer treatments for three irrigations.

Treatment	Polymer added	Sediment loss	Sediment reduction	Sediment reduction per unit of polymer applied
	— kg ha^{-1} —		% of control	kg kg^{-1}
Experiment 1				
Control	0.0	6450^{A}†	0	–
10 g m^{-3} PAM	0.49	3724^{B}	42.3	5563
20 g m^{-3} PAM	1.11	2686^{B}	58.4	3391
10 g m^{-3} starch	0.82	4482^{AB}	30.5	2399
20 g m^{-3} starch	1.63	4917^{AB}	23.8	941
Experiment 2				
Control	0.0	6513^{A}	0	–
Control–Surge	0.0	6304^{A}	0	–
10 g m^{-3} PAM, Surge	1.20	2693^{B}	57.9	3154
10 g m^{-3} PAM	1.23	3004^{B}	56.3	2978
5 g m^{-3} PAM	0.60	5280^{AB}	21.0	2274
Experiment 3				
Control	0.0	5948^{a}‡	0	–
10 g m^{-3} PAM	1.23	3448^{b}	42.0	2032
5 g m^{-3} PAM, intermittent	0.55	2622^{b}	55.9	6047

† Similar uppercase letters indicate nonsignificnat differences ($P = 0.05$) between treatments in each study.

‡ Similar lowercase letters indicate nonsignificant differences ($P = 0.10$) between treatments in each study.

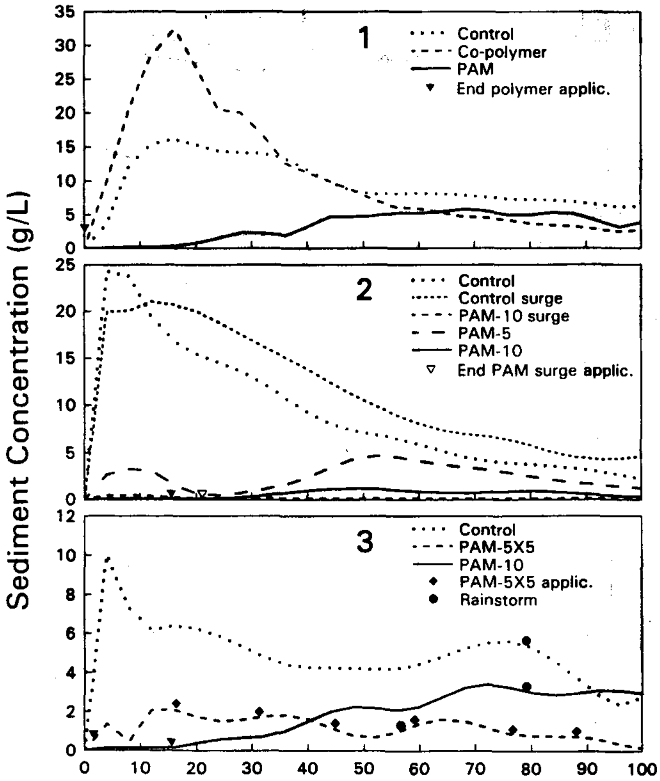

Fig. 1. Sediment concentration in runoff during the first irrigation. Values are means of all furrows in each treatment group for Exp. 1, 2, and 3. (Note changing scale of y axis.)

Most of the erodible soil aggregates in control furrows had been stripped away in preceding irrigations; this same material remained intact in treated furrows, protected by the PAM. Therefore, when residual protection of the PAM failed, a greater proportion of soil became susceptible to flow erosion in treated, relative to control, furrows.

Overall, the erosion results are similar to those of a laboratory investigation in which PAM was initially applied to water in rills (I. Shainberg, 1991, personal communication). These researchers eliminated erosion in artificial rills for slopes up to 30% with application of 5 g m^{-3} PAM. In our field experiment, 10 g m^{-3} PAM was required to consistently obtain similar results. Cumulative soil losses during three monitored irrigations, and the relative effectiveness of PAM applications, appear in Table 2. Overall sediment reduction was greatest for PAM-20 (58%) in Exp. 1, PAM-10–Surge (58%) and PAM-10 (56%) in Exp. 2, and PAM-5 × 5 (56%) in Exp. 3. The greatest reduction in cumulative sediment loss per unit of applied PAM was obtained using 5 g m^{-3} PAM applied during furrow advance, with intermittent 5-min injections in each subsequent hour of the irrigation.

Sediment concentration and cumulative sediment loss in runoff of the first irrigation are presented in Fig. 1 and 2. To permit comparisons between treatments, data were plotted as a function of time after runoff began. Time is given as a percentage of the remaining irrigation period (e.g., runoff begins at time = 0%, irrigation ends at time = 100%); where each 10% interval represents ≈40 min. In the following discussion, references to irrigation length refer to this post-advance stage. Graphed values are averages of all included furrows. Note that, in Fig. 1.1 and 2.1, polymer curves include both 10 and 20 g m^{-3} treatment levels. Typically, sediment concentration for untreated furrows varied most in the first one-half of irrigation, and gradually decreased during the remaining period. For untreated and copolymer-treated furrows, peak concentration occurred during the first 2 h (Fig. 1.1). Peak concentration of sediment for copolymer treatments was higher than untreated furrows during the first 2 h of the irrigation, but this had small impact on total sediment loss (Fig. 2.1) because flow rates of copolymer-treated furrows were less than those of controls during this period. Data presented in Fig. 1.1 and 2.1 show that the copolymer did not act immediately to combat erosion, suggesting that this soil–polymer interaction was time dependent, requiring about 4 h aging before becoming effective. In contrast, PAM was immediately potent in controlling soil loss. Sediment concentration for PAM-treated furrows remained very low during the initial 1 to 3 h of irrigation (1–3 h after curtailing PAM injection), peaked at about the midpoint, then gradually declined (Fig. 1.1 and 1.2). During the initial interval, when PAM was mixed with irrigation water, the effectiveness of all PAM treatments was virtually 100%. This observation was, in fact, what prompted the inclusion of the PAM 5 × 5 treatment in Exp. 3. In Exp. 3, sediment concentrations appeared to oscillate more widely than in other studies (Fig. 1.3). Such fluctuations were not unusual for treated or untreated furrows, and may be related to variable distribution of soil properties across the plot. We hypothesize that these periods may result from accelerated erosion associated with advancing channel head cuts. For example, Fig. 1.3 shows a PAM-10 peak occurring at time = 72% that results

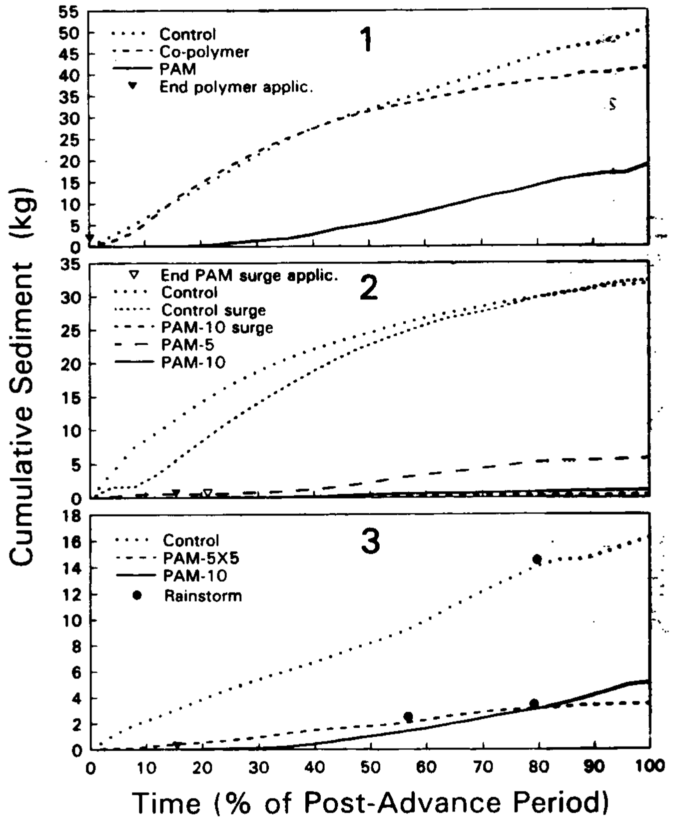

Fig. 2. Cumulative sediment loss during the first irrigation. Values are means of all furrows included in each treatment group for Exp. 1, 2, and 3. (Note changing scale of *y* axis.)

almost entirely from high soil losses associated with one of the three treated furrows. Some fluctuations in PAM-5 × 5 sediment concentration may be related to increased vulnerability of soils as the potency of a single polymer application declined with time. In addition, a brief intense rain shower coincident with Exp. 3 contributed to small sediment load peaks that occurred late in the irrigation (Fig. 1.3).

Infiltration and Runoff

Runoff values reflect differences in infiltration between treatments. Infiltration of all monitored furrows was typical of values seen for this soil with first (8-h) irrigation grand means of 28.5 mm for all studies, and a second (12-h) irrigation mean of 46.1 mm (Table 3). Variances on net furrow infiltration are known to be high and generally exceed 10% of the measured infiltration rate on these soils (Trout and Mackey, 1988a,b). In spite of large variability, a significant flow rate effect was measured. The infiltration in Exp. 1 (flow rate of 22.7 L min^{-1}) was higher than that in Exp. 2 and 3 where the flow rate for most of the irrigation period was 15.1 L min^{-1}. In the experiments with high flow rate, the shearing force was high and a depositional seal did not form. Thus, the infiltration was maintained at 31.1 mm, compared with 22.4 to 22.7 mm from the low flow rate. Similarly, in spite of large variability, significant differences were observed between polymer treatments in Exp. 2 and 3. Mean infiltration rates were greater for PAM treatments than for controls, but only PAM-10 furrows (Exp. 2 and 3) were statistically distinct. Net infiltration for these PAM-10 treatments were 30 to 40% greater than control furrows. Segeren and Trout (1991) reported that furrows in which surface seal formation was precluded had 85% greater net infiltration than sealed furrows. Allowing for effects of wetted perimeter differences, the infiltration increase may have been about 60%. This suggests that PAM treatments reduced erosion and hindered formation of a depositional seal on the furrow perimeter, and thereby mitigated the drop in intake rate experienced during furrow irrigation on Portneuf soils (Segeren and Trout, 1991).

Table 3. Water and polymer application, runoff, net infiltration, and lateral wetting extent at the soil surface.

Treatment	First irrigation						Second irrigation			
	Flow on	Run off	Polymer added	Net infiltration		Wetting extent	Flow on	Run off	Net infiltration	
	mm	mm	kg ha^{-1}	mm	%	cm	mm	mm	mm	%
Experiment 1										
Control	56.6^{A}†	25.4^{A}	0.0	31.1^{A}	54.9	15.0^{A}	71.7	25.6^{A}	46.1^{A}	64.3
10 g m^{-3} PAM	56.9^{A}	25.9^{A}	0.49	30.9^{A}	54.3	20.6^{CD}	71.7	23.1^{A}	48.6^{A}	67.8
20 g m^{-3} PAM	56.6^{A}	24.5^{A}	1.11	32.0^{A}	56.5	21.2^{D}	71.7	24.1^{A}	47.6^{A}	66.4
10 g m^{-3} Starch	56.4^{A}	21.1^{A}	0.82	35.3^{A}	62.6	19.1^{B}	71.7	24.1^{A}	47.7^{A}	66.5
20 g m^{-3} Starch	56.6^{A}	22.6^{A}	1.63	34.0^{A}	60.1	20.0^{C}	71.7	24.1^{A}	47.6^{A}	66.4
Experiment 2										
Control	40.4^{A}	17.8^{A}	0.0	22.7^{A}	56.2	18.2^{A}	72.0	30.4^{A}	41.6^{A}	57.8
Control–Surge	38.7^{B}	15.1^{AB}	0.0	23.6^{A}	61.0	17.0^{A}	72.0	28.4^{A}	43.7^{A}	60.7
10 g m^{-3} PAM Surge	39.4^{B}	14.6^{AB}	1.20	24.8^{A}	62.9	23.0^{B}	72.0	22.7^{A}	49.3^{A}	68.5
10 g m^{-3} PAM	39.8^{A}	7.7^{C}	1.23	32.0^{B}	80.4	22.0^{B}	72.0	23.0^{A}	49.0^{A}	68.1
5 g m^{-3} PAM	39.9^{A}	12.1^{BC}	0.60	27.8^{AB}	69.7	21.5^{B}	72.0	27.5^{A}	44.5^{A}	61.8
Experiment 3§										
Control	39.5^{A}	17.1^{a}‡	0.0	22.4^{a}	56.7	25.9^{A}	71.7	29.8^{A}	41.8^{A}	58.3
10 g m^{-3} PAM	40.0^{A}	11.3^{b}	1.23	28.6^{b}	71.7	28.4^{B}	71.7	28.4^{A}	43.3^{A}	60.4
5 g m^{-3} PAM, intermittent	40.3^{A}	14.8^{ab}	0.55	25.5^{ab}	63.3	24.5^{A}	71.7	25.4^{A}	46.3^{A}	64.6

† Similar uppercase letters indicate nonsignificant differences ($P = 0.05$) between treatments in each study.

‡ Similar lowercase letters indicate nonsignificant differences ($P = 0.10$) between treatments.

§ Rain showers occurred between 20 and 25 June, disturbing the surface condition of the furrows prior to the first irrigation of Exp. 3 (25 June). A brief heavy rain shower also occurred in the late afternoon during the irrigation.

There was a significant difference in the lateral extent of wetting seen at the soil surface (Table 3). The wetting front at the soil surface was wider for furrows treated with either the starch copolymer or with PAM. Differences in infiltration rates contributed to these wetting patterns, but other processes may also be involved. This pattern was probably also the result of erosion in the control furrows lowering the furrow bottoms, and hence the surface of furrow water relative to the bed elevation. Although this phenomenon was not studied in great detail, the effect could have practical implications for directing water and nutrients to row crops. The increased lateral wetting effect of the polymers did not occur in the subsequent irrigations. This was probably because of the eventual erosion of the treated furrows and the partial formation of depositional crusts in the second irrigation.

DISCUSSION

Optimal application strategies are likely to vary with factors of soil, irrigation flow rate, and quality of irrigation water. Soils respond to polymer applications differently, depending on (i) soil characteristics, i.e., clay type and content, pH, salinity, and sodicity; (ii) polymer characteristics, i.e., polymer type, charge, and concentration; and (iii) irrigation water quality (Wallace et al., 1986; Aly and Letey, 1988; Shainberg et al., 1990). It is feasible that a different polymer type, or one of different charge, will be more effective in controlling erosion on this soil. If so, we may be able to reduce application amounts below those used in this initial set of field trials.

Mitchell (1986) reported that PAM applied to furrows in irrigation water increased aggregate stability and hydraulic conductivity of the soil surface, but did not increase net infiltration on a swelling soil. Infiltration through the profile was controlled by a slowly permeable subsurface soil. The soil was unaffected by PAM because the polymer penetrated only to shallow depths. In our study (Table 1), net infiltration was significantly increased with PAM-10 treatments. Formation of a surface seal during irrigation is the major factor limiting water infiltration in these soils and PAM applications impeded seal development. The infiltration-stabilizing ability of the PAM treatments is a substantial benefit in and of itself. These soils typically see infiltration rate reductions of 50% from the beginning to the end of a season. The stabilizing effectiveness of the PAM treatments would be enough to reduce the duration of irrigation sets late in the season, and may be enough to ameliorate problems in local furrow-irrigated crops such as 'Russet Burbank' potato (*Solanum tuberosum* L.), which suffer quality reductions because of poor water intake in beds as the crop develops. The importance of this effect could be much more significant in areas such as the central valley of California, where intake rates decrease by 70% (Meek et al., 1992) or more during a season. This often produces a heavy negative economic impact as irrigation becomes unable to meet crop water requirement, causing both yield and quality reductions of numerous high-value crops.

The significant benefit derived from polymer application to furrow irrigation is a 5- to 20-fold reduction in PAM required to achieve significant levels of soil protection relative to rain-fed (Wallace and Wallace, 1986) or sprinkler irrigation systems (Levy et al., 1991). The high efficiency of PAM in furrow irrigation is due to two reasons: (i) only a portion of the soil surface requires treatment, and (ii) the tractive forces of flowing water are small compared with the impact forces of rain or sprinkler drops striking the soil surface. As a result, the cost/benefit ratio of PAM applied in furrow irrigation systems is favorable. The cost of the commercially available PAM formulation used in these studies varies with quantity, but is approximately \$2.50 kg^{-1}. Direct treatment cost was between \$3 for treatment of one irrigation at 1.2 kg ha^{-1} to \$15 ha^{-1} for treatment of five consecutive irrigations. Further work on application strategies may reduce this seasonal estimate.

Simplicity of application makes water treatment feasible for a wide range of field situations. Minimal equipment required by a farmer would include a container of mixed PAM stock solution, an injection pump with timer, and an agitator. With this equipment positioned in the field at the head of the feeder ditch, water could be treated for all or part of an irrigation set. Many farmers already own most of this equipment for injection of fertilizers or other chemicals. A more convenient system, already used in the food-processing industry, includes a component that simultaneously mixes solid PAM into stock solution, ready for injection. About 120 kg PAM could provide all the water treatment for a 100-ha farm during a growing season, causing little, if any, logistical inconvenience.

The potential benefits of erosion reduction of this magnitude are extensive. At the farm level, soil held in place would not deplete fertilizers and pesticides from the targeted application areas. Prevention of soil loss would eliminate maintenance of clogged drains, field ditches, and settling ponds. Elimination of soil-borne nutrients and pesticides in irrigation return flows would improve riparian and aquatic environments for wildlife and public health. Reduction of sediment in rivers and reservoirs would significantly slow impoundment filling and reduce abrasion damage to hydroelectrical generating facilities.

CONCLUSIONS

In the past, use of polymer applications to improve soil response has not proven economical at the farm scale. The scope of this preliminary investigation is limited to Portneuf soils irrigated with Snake River water, but it has demonstrated a potential economic use of polymers, i.e., the application of polymer in irrigation water for reducing furrow erosion. We emphasize the need for additional research on these and other soils, and under other conditions, to determine whether this method is generally applicable.

Our results indicate that anionic PAM was more effective than anionic starch copolymer for controlling furrow erosion under our experimental conditions. The PAM treatments (5–20 g m^{-3}) of 1- to 2-h duration reduced sediment loss by 45 to 98% in the initial (treated) irrigation. Cumulative sediment reduction during the initial and two subsequent, untreated irrigations was 42 to 58%. Similar levels of protection could be achieved at lower PAM concentrations by increasing the treatment period, or by dividing this period into a series of intermittent applications distributed over the entire irrigation. The use of surge irrigation to expose and treat zones of soil weakness in the furrow, and promote uniform PAM adsorption, did not significantly increase sediment reduction compared with nonsurge treatments.

Further research is warranted to investigate (i) alternative formulations of PAM for control at the most efficient application rates and cost, (ii) the duration of PAM efficacy, (iii) PAM's effect on soil–plant water and nutrient relationships, and (iv) decomposition products. While starch copolymer treatments were not as effective as PAM, the delayed impact of starch polyelectrolyte on furrow erosion is a property that potentially may be exploited to extend the duration of polymer-induced erosion control. To facilitate this, research is needed that will better define how starch copolymer or PAM interacts with soil to increase resistance of the soil surface to flow shear.

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