POLYACRYLAMIDE APPLICATION TO CONTROL FURROW IRRIGATION-INDUCED EROSION

R. D. Lentz and *R. E. Sojka*

U.S. Department of Agriculture, Agricultural Research Service
Soil and Water Management Research Unit
3793 N 3600 E
Kimberly, ID 83341

ABSTRACT

Furrow-irrigation induced soil erosion threatens sustainable irrigated agriculture worldwide. Small concentrations of a moderate-charge-density anionic polyacrylamide (PAM), dissolved in irrigation water has been used to nearly eliminate soil loss from irrigated furrows and has increased net infiltration (total inflow minus total outflow). This paper summarizes polymer-related field studies conducted on highly erodible Idaho silt loam soils. A range of furrow lengths (163–264 m), slopes (0.5–7%), and inflows (15–38 L min^{-1}) were used in the studies. Field trials compared various PAM application strategies. PAM was applied to irrigation water in gated irrigation pipe as dry granules, or to furrow heads as a stock solution. Treatment efficacy varied primarily with irrigation inflow-rate, PAM concentration in irrigation water, duration of furrow exposure, and total PAM applied. The most effective treatments either applied PAM at 10 g m^{-3} in irrigation inflows during the entire furrow advance period (initial-load, $I_{10,100\%}$), or applied 5 g m^{-3} during the entire furrow advance, then reapplied PAM for 5–15 min episodically at similar concentrations (initial plus episodic, $IE_{5,100\%}$). Over a range of application rates of at least 0.7 kg ha^{-1} PAM and mean of 1.3 kg ha^{-1}, treatments reduced furrow sediment loss by 94% and increased net infiltration by 15%. The full-advance $I_{10,100\%}$ and $IE_{5,100\%}$ treatments were nearly twice as effective as the continuous 0.25 g m^{-3} PAM application on these soils when slopes were 1–2%. The $I_{10,100\%}$ strategy protected furrows on slopes ranging up to 3.5%. Dry and solution applications controlled erosion about equally. The PAM applications were economical and effective methods for controlling furrow-irrigation induced erosion, under a broad range of field conditions.

INTRODUCTION

Polyacrylamides have been employed for decades as settling agents in a variety of industries, including water treating, mineral processing, and paper manufacturing (Barvenik, 1994). Agricultural-related polymer applications began in the mid-1950s, when surface and plow-layer incorporation methods were employed to stabilize soil structure, reduce erosion, and improve other soil properties (Weeks and Colter, 1952; Hedrick and Mowry, 1952). However, high cost at recommended application rates ranging from 250–500 kg

ha^{-1} discouraged agronomic use of polymers. Currently manufactured polyacrylamides are more effective than early products, and new application techniques have reduced application rate requirements (Lentz et al., 1992). Hence, the benefits of polymer-conditioned soils are within economic reach of today's farmers (Sojka and Lentz, 1994b). Specifically, polyacrylamide was demonstrated to be an effective, economical erosion deterrent in furrow-irrigated agriculture (Lentz et al., 1992; Lentz, 1996). Of the many forms of polyacrylamide available, a water soluble anionic polyacrylamide having a molecular weight of 12–15 Mg mol^{-1} and charge-density of 8–35% was most effective for furrow erosion control (Lentz et al., 1993). Subsequent use of the terms polyacrylamide, or PAM in this paper, refer to this particular type of polyacrylamide.

Environmental regulation, safety, and toxicity concerns associated with PAM and its use in irrigation were reviewed by Seybold (1994) and Barvenik (1994). Polyacrylamides have been authorized for use as potable water and food additives, and no significant hazards to aquatic or edaphic organisms, nor crops have been documented when PAM is applied at recommended concentrations and rates.

Lentz and Sojka (1994a) and Lentz (1996) reviewed the literature pertaining to PAM field-application methods and soil-PAM interactions. Early methods applied polymer as a solid or solution to the entire soil surface, then mixed it into the entire topsoil volume, with the aim of stabilizing plow layer soil structure. Applying polymer solutions was the most effective and efficient method for treating surface soils. Well-aggregated soils treated with PAM had a lower bulk density, lower penetrometer resistance, greater hydraulic conductivity, less dispersion, and were less susceptible to surface seal formation than untreated soils. In furrow irrigation, PAM was dissolved in the source-water supplying the furrow stream, and therefore was applied only to the wetted perimeter of furrows (Lentz et al., 1992). Polyacrylamide was immediately adsorbed to soil particle and aggregate surfaces during wetting with treated water, and was irreversibly bound to soil particles (Letey, 1994). As the treated water infiltrated the soil profile, PAM adsorption continued on the outer surfaces of aggregates in the upper 1–5 cm of soil (Mitchell, 1986; Malik and Letey, 1991).

Lentz et al. (1992) demonstrated that an initial small application of PAM to irrigation water nearly eliminated furrow irrigation-induced sediment loss on Portneuf silt loam. Applying 10 g PAM per m^3 water, i.e., 10 ppm, during the first 2 hr of the irrigation reduced sediment loss from treated furrows by 97 percent when compared to untreated furrows. PAM treatments also increased net infiltration and reduced phosphorus and biochemical-oxygen-demand levels in runoff, when compared with their untreated counterparts (Lentz and Sojka, 1994a). General technical and practical guidelines concerning PAM application to furrow-irrigated agriculture were discussed by Sojka and Lentz (1994a); Lentz et al. (1995); and Lentz (1996).

Trout and Neibling (1993) concluded that furrow erosion is largely controlled by two factors, furrow stream hydraulics and soil characteristics. Flow velocity determines the amount of shear or drag force available to detach soil particles. Velocity also determines the stream's sediment transport capacity, which, along with sediment/aggregate size and density characteristics, determines the amount of detached soil that can be transported along the furrow. Soil characteristics, aggregate stability and soil cohesion, determine soil susceptibility to flow shear force, and they also control sediment and aggregate size distribution characteristics, which in turn influence stream transport capacity.

Portneuf and other similar Southern Idaho soils erode easily because their aggregates are unstable. Typically, surface soils in a newly cultivated furrow are cloddy and rough, and are usually very dry before irrigation, containing only 6–10% (w/w) water. During furrow irrigation, rapidly advancing water is quickly absorbed by the dry soil. Aggregates slake and break down, and soil particles tend to disperse. Flow shear easily dislodges and moves the dispersed soil particles, and the transported sediment is deposited in surface cavities along the wetted furrow perimeter, or leaves the field with runoff. The resulting smoothed surface has little resistance to flowing water, which maximizes the velocity and erosiveness of the furrow stream. The initial high furrow-infiltration rate is quickly reduced when suspended sediment, invading the soil with infiltrating water, blocks soil pores and initiates formation of a slowly permeable depositional layer, or surface seal (Segeren and Trout, 1991). Consequently, runoff and soil losses increase.

Introducing even low PAM concentrations into irrigation water had several impacts on furrow conditions. During initial wetting, PAM contacted and was bound to aggregate surfaces, making them more resistant to slaking, dispersion, and stream shear forces than their untreated counterparts. PAM caused fine soil particles in the furrow stream to flocculate and settle as aggregates. Together these processes produced a well aggregated system that better maintained roughness and permeability of the furrow surface, compared with untreated furrows (Trout et al., 1995). Hence, infiltration rates remained higher, runoff rates lower, and soil detachment rates were more limited in the PAM-treated furrows. Compared to untreated furrows, sediment transport capacity of the stream was reduced because stream velocity was lower and the average aggregate size in the system was larger, and therefore less easily transported (Lentz, 1996). PAM also may have increased viscosity of flowing water, resulting in lower turbulence and smaller shear forces, compared to untreated water.

In this paper, we summarize results from several studies conducted over a 3-yr period in Southern Idaho. The objectives of these experiments were to evaluate effectiveness of different PAM application strategies for controlling furrow-irrigation induced erosion, and determine whether furrow slope influenced PAM's erosion control efficacy.

MATERIALS AND METHODS

Field studies were conducted at the USDA-ARS Northwest Irrigation and Soils Research Laboratory at Kimberly, Idaho, and on fields of cooperating farmers near Filer, Hansen, and Emmett, Idaho. Soils included Durixerollic Calciorthids, Xerollic Haplargids, and Haploxerollic Durargids. Surface soils in these studies were similar, though subsoils varied among sites. Surface soil textures were silt loams (10–21% clay, 60–75% silt), organic matter was 10–13 g kg^{-1}, cation exchange capacity was 18–20 $cmol_c$ kg^{-1}, electrical conductivity (EC, saturated paste extract) was 0.7–1.3 dS m^{-1}, ESP was 1.4–1.7, pH was 7.6–8.0, and calcium carbonate equivalent varied from 2–8%. Slopes were 0.5–7.0%. Seedbeds were disked or moldboard plowed, then roller-harrowed, and planted to corn or field beans. Electrical conductivity of irrigation water was 0.1 at Emmett and 0.5 dS m^{-1} at Kimberly, Filer, and Hansen, and SAR was 0.4–0.7.

Furrows were shaped with a weighted furrow-forming tool. Only wheel-trafficked furrows were monitored in each study. Irrigation water was applied from adjustable spigots on gated pipe or syphon tubes set in concrete head ditches. Furrow lengths were 175–264 m. Irrigation duration was 8–12 h. Inflow rates were 13–38 L min^{-1} during furrow advance, with highest rates on gentle slopes; subsequent inflows were reduced to 13–23 L min^{-1} when feasible.

Furrow infiltration and soil-loss studies were all randomized and replicated. All studies employed a high molecular weight anionic PAM with moderate charge density, manufactured and marketed under the trade name Superfloc 836A by CYTEC Industries, Wayne, N.J. The material was composed of white granular crystals with a grain size slightly larger than ordinary table salt. The granular PAM was used to prepare a 1200 or 2400 g m^{-3} aqueous stock solution that was pumped into the head of each furrow, at the position where turbulence from incoming water produced rapid mixing. Stock solutions were mixed using tap water having an EC = 0.9 dS m^{-1}, and a SAR = 1.5. PAM application procedures and furrow monitoring procedures were identical to those of Lentz et al. (1992). Furrow soil loss and infiltration were computed from field data with FUROFIGR, an analytical computer program (Lentz and Sojka, 1994b). Soil Loss reduction was computed as percent difference between the control and PAM-treated relative to control values. Error bars displayed in graphs represent standard deviations between treatment replicates.

Different PAM application strategies were tested during experimentation (Figure 1). PAM was applied continuously, or for a specified period, starting when inflow began. Continuous low applications employed 0.25 ($C_{0.25}$) or 0.5 g m^{-3} ($C_{0.5}$) PAM concentrations. Non-continuous strategies employed an initial PAM application (I) and some treatments included additional episodic/intermittent short-term applications made subsequent to the initial dose (I.E.). Both I and I.E. strategies applied PAM during the period when water first traversed the dry furrow (advance phase), and in some cases for 30–90 min after runoff began. PAM concentrations used in I applications ranged from 5–20 g m^{-3}, and in the I.E., 5–10 g m^{-3}. The additional intermittent treatments used in the I.E. method were 5–15 min in duration at 5–10 g m^{-3} PAM, applied every 1–4 hr.

One study compared PAM stock-solution application with a dry-application method. The latter added PAM granules directly to the furrow water supply in the gated distribution pipe. Irrigation water was supplied to the plot via two pipe lines. Water in one was conveyed to control and PAM-solution treated furrows. Water in the other was treated with dry PAM and conveyed to those furrows receiving that treatment. An Aqua Control Inc. Aqua II dry PAM applicator was installed above a Krause-K head-control box on the dry-PAM pipe line. Polyacrylamide dropped from the Aqua II's metering gandy into the inflow-side of the K-box's open top, where turbulence created by the subsequent overfall helped dissolve and disperse the PAM granules. The dry-PAM treated water was allowed to flow 30 m through the pipe before it was distributed into furrows.

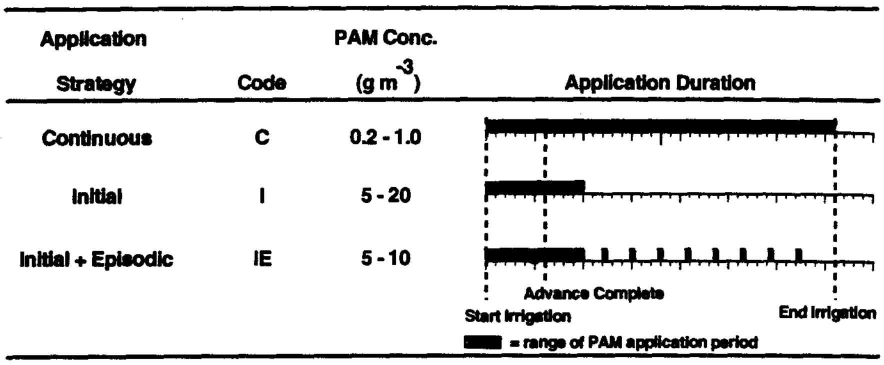

Figure 1. PAM application strategies employed in various studies.

RESULTS AND DISCUSSION

Data from like-treatments of 3–6 furrows were averaged and paired with their corresponding control furrow values (Lentz and Sojka, 1994a). Thus, data groups were similar, in that all PAM treatments employed Superfloc 836A, but data groups differed with respect to one or more specific treatment characteristics such as irrigation period, furrow slope, or inflow rate. Total sediment loss from PAM-treated furrows was significantly less than that of the corresponding untreated furrows (Table 1).

Treatment-induced soil-loss reductions for each data group are reported in Table 2. On average, sediment losses from furrows treated with less than 0.7 kg ha^{-1} PAM were 30% of the controls. Sediment losses for furrows treated at rates greater than 0.7 kg ha^{-1}, and averaging 1.3 kg ha^{-1}, were only 6% of control values. The standard deviations (SD) and coefficients of variation (CV) of the group means were notably larger for application rates < 0.7 kg ha^{-1} (Table 2). This indicated that larger PAM application rates produced consistently small furrow soil losses while treatment rates below 0.7 kg ha^{-1} produced more erratic results. Polyacrylamide effects on furrow infiltration have been presented elsewhere (Lentz and Sojka, 1994a). When PAM application was less than 0.7 kg ha^{-1}, net infiltration for PAM-treated furrows was 11% greater than controls. PAM applications applying more than 0.7 kg

Table 1. Sediment Loss (Mg/ha) per Field Application-rate Range.

Parameter	PAM field application rate					
	0–0.3 kg ha^{-1}		0.3–0.7 kg ha^{-1}		≥ 0.7 kg ha^{-1}	
	Control	PAM	Control	PAM	Control	PAM
Mean	0.57	0.17	1.14	0.44	.97	0.08
SD†	0.12	0.13	0.17	0.05	0.10	0.04
# Data	12	12	17	17	12	12

† SD = standard deviation, computed as the mean of all data-group SDs in each application-rate range.

Table 2. Sediment Loss Reduction (%[†]) per Field Application-rate Range.

	PAM Field Application Rate (kg ha^{-1})		
Parameter	0–0.3	0.3–0.7	> 0.7
Mean	70	70	94
SD[‡] (Data Group Means)	23	25	6
CV[‡] (Data Group Means)	3.05	2.80	0.93

[†] [100*(Control SL - PAM SL)]/Control SL; where SL = net sediment loss per furrow.
[‡] SD = standard deviation; CV = coefficient of variation (mean/SC)

ha^{-1} produced 15% greater net infiltration compared to untreated furrows. Treatment effects on net infiltration varied widely, even when PAM application rates exceeded 0.7 kg ha^{-1}. Such variation was expected, since even untreated furrows show large inter-furrow variation in net infiltration (Trout and Mackey, 1988).

Data groups within each application strategy category in Figure 2 are arranged in order of increasing mean outflow in PAM furrows. The I_{10} and IE_5 application strategies were most effective; both reduced furrow soil loss by 80%, while the C strategy reduced soil losses by an average 63%, compared to controls. Seasonal erosion losses are considered unacceptable when they exceed the soil loss tolerance (T), beyond which soil productivity will decline. Since T represents a seasonal soil loss value, it was converted to an equivalent value corresponding to furrow soil-loss from an initial single irrigation (Lentz and Sojka, 1994a). Seventy-five percent of untreated furrow groups exceeded soil-loss tolerance for these soils, while only 13% of PAM-treated groups exceeded the tolerance level (Figure 2). Recall that not all PAM treatments in each application-strategy category were optimal in terms of total PAM applied.

PAM's soil-loss control generally decreased with increasing PAM-furrow outflow (Figure 2). This suggested that PAM's erosion-control effectiveness could have declined as stream flow rate increased. However, the response may have actually been caused by a correlated factor such as furrow infiltration, since stream flow rate is inversely related to infiltration. If inflows were constant, flow rate would increase with increasing furrow slope, implying that PAM efficacy would respond inversely with furrow slope. The effect of furrow slope on total soil-loss from I_{10} PAM-treated irrigations is illustrated in Figure 3. Compared to controls, PAM treatments reduced soil loss from treated furrows by 83–99% on slopes ranging up to 3.5%. These results suggest that factors other than furrow slope and stream-flow rate influence PAM efficacy, e.g., infiltration rate or antecedent surface-water content.

Field responses to specific PAM treatments also varied among irrigations, especially at application rates less than 0.7 kg ha^{-1}. A number of factors potentially influence PAM efficacy in a given field or furrow. In each irrigation studied, factors related to polymer, PAM-application, field, irrigation, and irrigation water-quality characteristics were held reasonably constant. However, soil properties were more difficult to control or quantify because they vary spatially within and between fields and cannot be controlled or easily quantified. Antecedent soil-water content, slope-length, and inflow water-quality factors influence PAM efficacy in irrigated furrows also, and very little has been done to quantify these effects.

Comparing Application Strategies

We tested several specific application strategies: *i)* $I_{10,100\%}$, 10 g m^{-3} PAM applied for at least 100% of the furrow advance period; *ii)* $C_{0.25}$, 0.25 g m^{-3} applied continuously; *iii)* $IE_{5,100\%}$, 5 g m^{-3} PAM applied during 100% of the advance period, followed by intermittent hourly injections, and *iiii)* $IE_{5,40\%}$, 5 g m^{-3} PAM applied during the first 40% of the furrow advance period, followed by intermittent hourly injections. Experimental plot slope was 1.7%. Total PAM applied per irrigation was computed on an entire-field basis. It varied for each application strategy depending on inflow, furrow stream advance rate, and furrow length and spacing. PAM applied averaged 0.95 kg ha^{-1} for $I_{10,100\%}$, 0.50 kg ha^{-1} for $IE_{5,100\%}$, and 0.2 kg ha^{-1} for $C_{0.25}$ strategies.

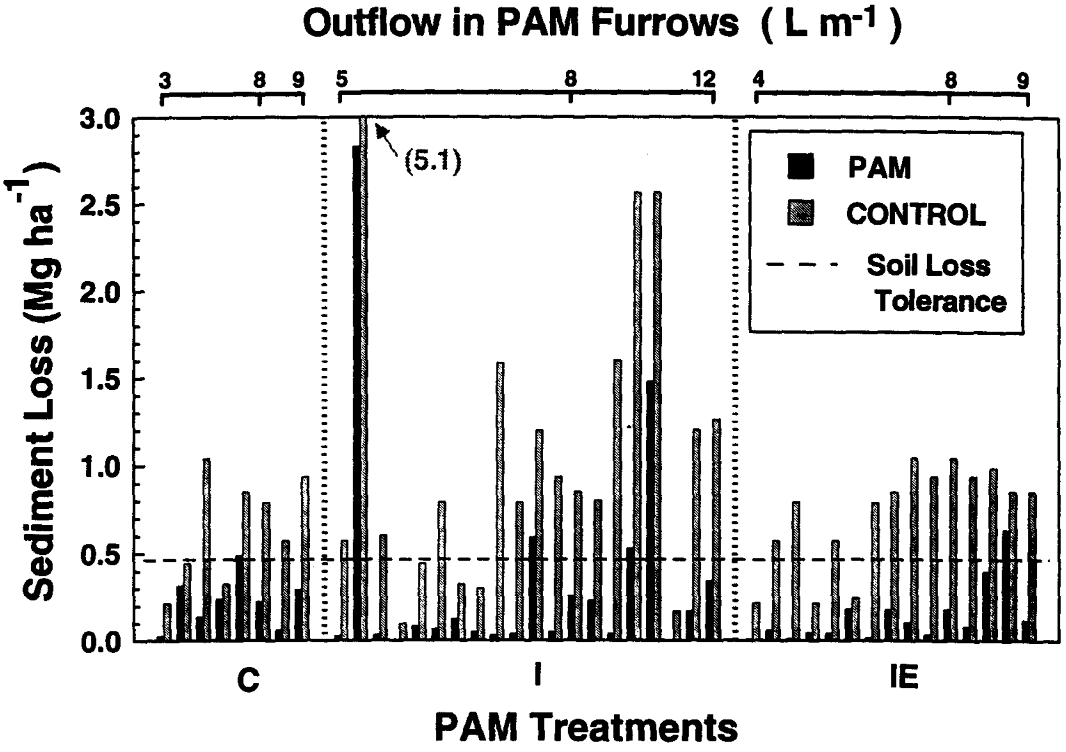

Figure 2. Total sediment loss from data groups (including control and PAM-treated furrows) representing different PAM-application strategies. Pairs result from treated irrigations on freshly cultivated furrows, within pairs, parameters were identical, but PAM application strategy, irrigation duration, inflow rates, and furrow slope varied between pairs.

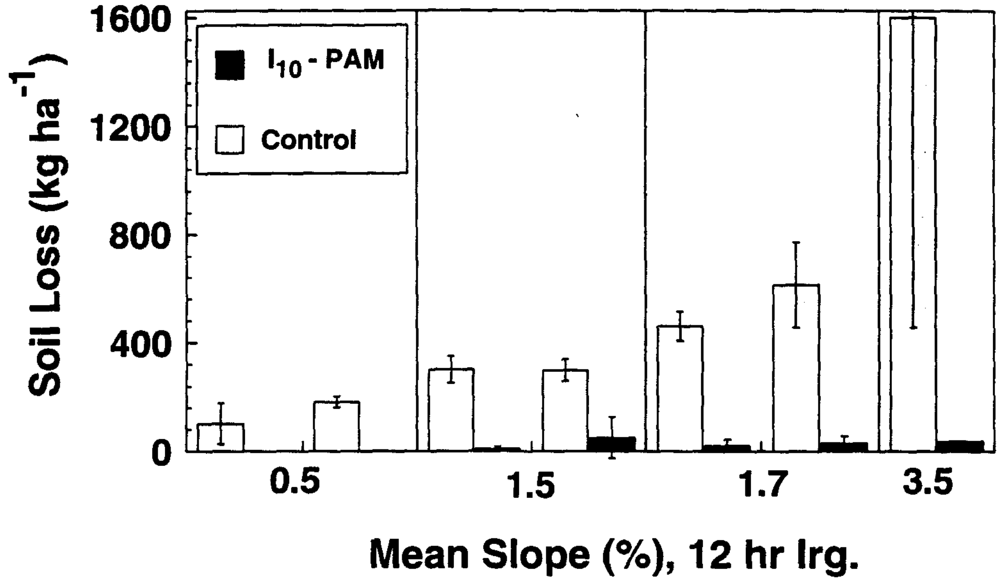

Figure 3. Mean sediment loss for newly cultured furrows from selected irrigations. PAM was applied (avg. 1.4 kg ha^{-1}) at 10 g m^{-3} during furrow advance ($I_{10,100\%}$ strategy).

Cumulative furrow soil-loss patterns produced by the four application schemes were distinctly different (Figure 4). Both $I_{10,100\%}$ and $IE_{5,100\%}$ applications were highly successful, reducing soil loss by 93–96%, providing the entire furrow advance period was treated. The $IE_{5,40\%}$ approach that inadequately treated the advance reduced soil loss by just 63%, while $C_{0.25}$ produced only a 51% reduction. Note in Figure 4 that the initial slope of the cumulative soil-loss curve for $C_{0.25}$ was identical to that of the control furrows. The $C_{0.25}$ treatment could not protect the furrow from the high soil loss that typically occurs early in an irrigation, i.e., the loss of loose and easily detached soil particles. Once these had been eroded from the furrow, the more stable soils remaining were protected by the PAM-amended irrigation water. This is indicated in Figure 3 at time = 2 h, when the cumulative-loss curve for $C_{0.25}$ declined below that of the control. These results corroborate those of Lentz et al. (1992). The I_{10} application may not be optimal for all field conditions. For example, a continuous (> 3 g m^{-3}) or initial plus episodic strategy may be more effective than an I_{10} under circumstances in which flow shear is relatively high, i.e., steeper slopes or higher florets. But total PAM applied may exceed I_{10}.

Erosion-control efficacy of solution- and dry-PAM application treatments was similar (Table 3). The average seasonal soil loss reduction was 84.3% for the dry-PAM application and 91.5% for the PAM solution treatment, although, differences were not significant ($p = 0.27$). An emerging trend among individual irrigations, indicated the solution approach produced greater or equal soil-loss reduction than the dry method. In addition, dry PAM granules applied to the gated-pipe water stream did not completely hydrate and disperse. At season's end, partially hydrated slimy masses of PAM were discovered in the gated supply pipe, indicating arr incomplete and inefficient use of the applied PAM.

Management Considerations for PAM Use

Users should adjust their irrigation management to fully utilize PAM technology benefits related to irrigation efficiency and crop management. Curtailing soil

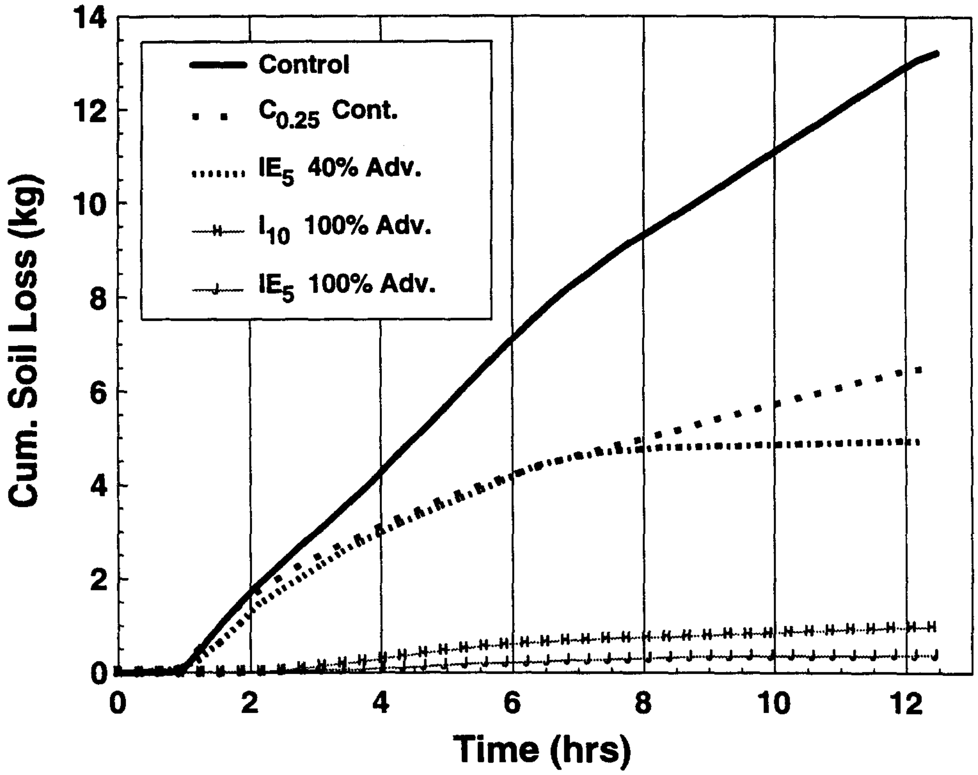

Figure 4. Furrow soil loss as a function of irrigation time. Plots for each treatment are means of replicate furrows from one or more irrigations. PAM was applied with the given concentrations.

Table 3. Seasonal Sediment Loss Reduction (% of Control) for Solution Application Strategies.

Parameter	PAM Treatment			
	Solution		Dry	
	Mean	SD†	Mean	SD†
Mean	91.5	3.0	84.3	9.7

† SD = standard deviation

loss ensures that valuable fertilizer and pesticide amendments remain in the field, that field productivity is sustained, and the need for costly remediation efforts on eroded fields is eliminated. Increased net infiltration permits shorter irrigations, especially on steeply sloping fields. Productivity of steeply sloping fields may be increased because steeper sections are watered more effectively. Reduced channel down-cutting and enhanced net infiltration improve lateral wetting (Lentz et al., 1992), moving water more rapidly from the furrow to the seed row. This is especially beneficial when watering germinating or seedling crops, and for maintaining high production quality of stress-sensitive crops, i.e., potatoes. On gently sloping fields, PAM's capacity to stabilize soil under high inflows could potentially shorten furrow advance times and improve infiltration uniformity down-furrow. Infiltration-opportunity times at the furrow heads always exceed those at the tail. Since fields are generally irrigated until the lower ends have been adequately watered, this produces excessive net infiltration and leaching in the upper field. Increasing irrigation inflows with PAM can be used to improve the spatial distribution of water, reducing leaching at furrow heads and improving overall crop quality across the field with less net application of water.

If not managed properly, PAM applications could have negative effects on irrigation efficiency and nutrient management. Treated irrigations may have to be shortened or inflows increased to account for the PAM-induced increase in infiltration and resulting increase in furrow advance times. If no adjustment is made, PAM prolongs furrow advance and increases infiltration-opportunity time disparity compared to untreated furrows. The resulting excess percolation would waste water and leach nutrients from the root zone, potentially contaminating groundwater.

If PAM is used to its fullest potential, water application can be more uniform. Potentially less water is needed to adequately irrigate the same field, and irrigation set-times may be reduced enough to reduce irrigation labor costs. Crop yield and quality can be improved, while conserving inputs and reducing nutrient loss to groundwater.

PAM Costs

Farmers can purchase 25 kg (55 lb) bags of granular PAM for $7.70–12.13 per kg ($3.50–5.50 per lb). Suppose farm managers employ the simplest optimal PAM treatment strategy, $I_{10,100\%}$, and apply 1.12 kg ha^{-1} irr^{-1} (1 lb ac^{-1} irr^{-1}). Between 3 and 16 irrigations are required each season on Idaho farms, depending on the crop grown. However, an estimated 70–90% of the total seasonal irrigation-induced soil-loss occurs during the first half of the growing season, and the greatest losses occur when newly-formed or disturbed furrows are irrigated, i.e., irrigation after tillage or cultivation. In many cases, farmers could treat 2–5 of the most susceptible irrigations and reduce soil loss by 50–90%, while incurring a PAM cost of $23.10–60.65 ha^{-1} ($10.50–27.50 ac^{-1}). These costs could be halved if the slightly more sophisticated $IE_{5,100\%}$ application strategy was adopted. Furthermore, some or all of these costs can be recovered through savings resulting from reduced soil and applied-input losses, less frequent tillage operations, elimination or reduced maintenance of sediment retaining ponds, improved crop production, and diminished labor requirements.

CONCLUSIONS

PAM is an excellent soil erosion deterrent. It is a cost effective and safe technology, when used at the rates employed in this study, and greatly reduces both sediment and chemical loading in agricultural runoff. The PAM employed was a moderate-charge-density (18% hydrolysis) anionic form with a molecular weight of 12–15 Mg mol^{-1}. When applied at a rates greater than 0.7 kg ha^{-1}, PAM-treated irrigation water reduced furrow soil loss by an average 94% (80–99%) and increased infiltration by an average 15%. Response was more variable when application rates fell below 0.7 kg ha^{-1}, with soil-loss reduction averaging 70%. PAM reduced soil erosion losses well below soil-loss-tolerance limits on slopes ranging from 0.5–3.5%. A very effective approach added 10 g m^{-3} PAM to the irrigation water at the start of the set, continuing during or slightly beyond the furrow advance period.

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DISCLAIMER

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