0038-075X/94/1584-274$03.00/0
SOIL SCIENCE
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October 1994
Vol. 158, No. 4
Printed in U.S.A.

FIELD RESULTS USING POLYACRYLAMIDE TO MANAGE FURROW EROSION AND INFILTRATION[1]

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Furrow irrigation-induced soil erosion is a serious threat to sustainable irrigated agriculture globally. Recent field studies have demonstrated that small concentrations of polymers dissolved in irrigation water appreciably reduce soil loss from irrigated furrows and increase net infiltration (total inflow - total outflow). This paper summarizes polymer-related field studies conducted in Idaho on highly erodible silt loam soils (Durixerollic Calciorthids, Xerollic Haplargids, Haploxerollic Durargids). A range of furrow lengths (163–264 m), slopes (0.5–7%), and inflows (15–38 L min^{-1}) were included in the studies. A moderate-charge-density anionic polyacrylamide (PAM), highly effective for controlling furrow sediment losses, was employed in the field trials. Treatment efficacy depended primarily on application rate, PAM concentration in irrigation water, duration of furrow exposure, and inflow rate. Nontreated furrow soil loss in 75% of the irrigations exceeded soil loss tolerance (T) for these soils, whereas only 13% of the PAM-treated irrigations exceeded T. Those treatments that applied at least 0.7 kg ha^{-1} PAM (mean, 1.3 kg ha^{-1}) reduced furrow sediment loss by 94% (range: 80–99%) and increased net infiltration by 15% (range: −8–57%). One of the most effective treatments applied PAM at 10 g m^{-3} in irrigation inflows during the furrow advance period. This initial high-load treatment was nearly twice as effective as a continuous 0.25 g m^{-3} PAM application on these soils when slopes were 1–2%. The initial high-load treatment protected furrows with slopes ranging from 0.5 to 3.5%. PAM reduced total phosphorus (84% of control value), nitrate (83%), biochemical oxygen demand (72%), and sediment (57%) in treated runoff water.

Research applying polyelectrolytes to improve soil physical properties began in the early 1950s, but use of more advanced polyacrylamide (PAM) polymers was not initiated until the last decade. PAM formulations with a wider range of molecular weights, charge types, and densities are now available for agricultural uses. They are more effective, less expensive, and more convenient to use than early polymers (Wallace A. and Wallace 1986). Thus, they have a greater potential for use in soil management.

PAM can be applied to soils as dry granules, broadcast with or without mixing (Terry and Nelson 1986), and in solution, by spraying (Levy et al. 1991) or diluted in irrigation water (Mitchell 1986). Application of solutions is most efficient and effective (Cook and Nelson 1986; Shaviv et al. 1987). A subsequent 'curing' or drying period often enhances its soil activity (Shainberg et al. 1990; El-Morsy et al. 1991). When applied to the soil surface as a solution, PAM is readily and irreversibly adsorbed to soil particles (Malik et al. 1991b); hence, main effect occurs within 1–5 cm depth (Mitchell 1986) and perhaps even closer. Most of the applied PAM is apparently bound to external surfaces of soil aggregates (Malik and Letey 1991).

Physical properties of PAM-treated soils differ from their untreated counterparts. PAM increases soil wettability (Janczuk et al. 1991) and liquid limit (Bryan 1992). PAM treatments increase water-stable aggregation in soils (Terry and Nelson 1986; Helalia and Letey 1989; Nadler and Letey 1989; Bryan 1992) and stabilize shrinkage cracks in clayey soils against imbibitional swelling forces (Malik et al. 1991a). After additions of PAM, soil aggregates are more resistant to slaking during rapid wet up (Mitchell 1986) and are better able to withstand the impact of falling water drops (Shainberg et al. 1992).

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Received June 3, 1994; accepted June 9, 1994.

PAM's forte is structure maintenance. For example, simple PAM applications onto compacted soils will not improve their physical condition, just stabilize the original degraded structure (Cook and Nelson 1986; Shaviv et al. 1987). Thus, PAM applications are typically made to well aggregated soils. Treated surface soils have a lower bulk density (Terry and Nelson 1986) and decreased penetrometer resistance (Cook and Nelson 1986; Helalia and Letey 1989), although granular PAM produces more erratic penetrometer results than does an aqueous PAM solution (Cook and Nelson 1986; Steinberger and West 1991). Hydraulic conductivity of PAM-treated soil is greater than for nontreated soils (El-Morsy et al. 1991; Malik et al. 1991a; Bryan 1992) and may be attributed to PAM's capacity to maintain soil structure (El-Morsy et al. 1991), reduce soil dispersion (Helalia and Letey 1988), and prevent the formation of a slowly permeable surface seal (Shainberg et al. 1990; Lentz et al. 1992).

Several researchers have applied PAM to irrigated soils. Most employed rainfall simulators in the laboratory or on small field plots to simulate drop-impact conditions present under either sprinkler irrigation or natural rainfall. Few studies have examined PAM applications under flood or furrow irrigation, which differ significantly from sprinkler or rainfall conditions. Soil detachment under flood/furrow results from rapid wetting and flow shear forces (no drop impact). Other differences relate to soil conditions during initial stream advance and downstream flow rate changes (Lentz et al. 1993a).

In rainfall/sprinkler field studies PAM (20–67 kg ha^{-1}) was applied on different soils, producing a 10–100% increase in infiltration (compared to control) and soil-loss reduction of 6–100%, though most reduction values were between 30 and 85% (Wallace G. A. and Wallace 1986; Levy et al. 1991; Agassi and Ben-Hur 1992; Flanagan et al. 1992; Fox and Bryan 1992; Norton 1992). In a flood-irrigation study, 400 kg ha^{-1} dry PAM was tilled into the upper 10 cm of soil and irrigated with 250 kg ha^{-1} aqueous PAM (1000 g m^{-3}). Infiltration rates of treated plots were 200% of the controls (Terry and Nelson 1986).

By wetting furrows with 15–40 kg ha^{-1} polymer solution before irrigation, Russian scientists were the first to demonstrate that water-soluble polymers could reduce soil loss (by 80–98%) and increase infiltration in furrows, although polymer properties were not specified (Paganyas 1975). Mitchell (1986) applied 6.6–32.2 kg ha^{-1} anionic PAM diluted (150 g m^{-3}) in furrow irrigation water. PAM stabilized the surface soil against dispersion and slaking, and promoted formation of a more porous depositional seal. Thus, initial infiltration rates for PAM-treated furrows were significantly higher than controls. Final rates, however, were similar because deep percolation was ultimately limited by the low permeability of high shrink-swell subsoils. Had Mitchell applied PAM to soils when in a dry and cracked state, the polymer would have penetrated deeper and may have had a greater impact on infiltration (Malik et al. 1991a).

Furrow irrigation subjects smaller surface areas to erosive forces of water than does rainfall or sprinkler irrigation. Therefore, much lower PAM application rates are effective. Laboratory studies using mini-flumes first substantiated this concept (Shainberg et al. 1994). In a furrow-irrigated field study, Lentz et al. (1992) applied minute quantities of PAM to a highly erodible soil. Five to twenty g m^{-3} anionic PAM (0.5–1.2 kg ha^{-1}) was added to irrigation water during the first 40–120 min of inflow. PAM treatments increased net infiltration 10–40% and reduced soil loss 44–99%. PAM increased surface lateral wetting extent by us much as 25%. Residual PAM protection in a second untreated irrigation was half that of the treated run.

The soil-PAM response differs with charge type and density of applied PAM and quality of the water solvent or soil solution. Polymer type and water quality (EC, SAR) influenced PAM adsorption on soil (Lakatos et al. 1981; Malik and Letey 1991), soil dispersion (Helalia and Letey 1988), and PAM's aggregate stabilizing capacity (Nadler and Letey 1989; Shainberg et al. 1990). PAM impacts on infiltration and hydraulic conductivity were also influenced by the water quality of the soil water or infiltrating polymer solution (Shainberg et al. 1990; El-Morsy et al. 1991).

In 1992 and 1993 we conducted a number of studies to broaden understanding of PAM as a furrow irrigation erosion control agent. One study, detailed in a separate paper, assessed the impact of intrinsic PAM factors (charge type and density) on its erosion control efficacy. Preliminary results (Lentz et al. 1993b) indicated that anionic PAM of moderate to high charge-density (18–30% hydrolysis) reduced sediment loss more effectively than other types. This form of PAM was employed in subsequent field studies that we have summarize in this paper. Objectives of this work were to (i) assess field response variability, (ii) determine how slope effects PAM erosion protection potential, (iii) examine the effect of PAM concentration and application strategy on its efficacy, and (iv) ascertain how PAM influences tailwater quality.

METHODS AND MATERIALS

Field studies were conducted at the USDA-ARS facility at Kimberly, ID, and on fields of cooperating farmers near Filer, Hansen, and Emmett, ID. Surface soils treated with PAM were similar, though subsoils varied among sites. Surface soil textures were silt loams (10–21% clay, 60–75% silt); organic matter ranged from 1.0–1.3%, electrical conductivity (EC) was 0.7–1.3 dS m^{-1}, ESP was 1.4-1.7, pH range was 7.6–8.0, and calcium carbonate equivalent varied from 2 to 8%. Slopes ranged from 0.5 to 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 forming tool. Only trafficked furrows were monitored in each study. Irrigation water was applied from adjustable valves on gated pipe or syphon tubes set in concrete head ditches. Furrow length ranged from 175 to 264 m. Irrigation duration was 8–12 h. Inflow rate ranged from 13 to 38 L min^{-1} during furrow advance (highest rates on gentle slopes and vice versa); subsequent inflows were reduced to 13–23 L min^{-1} when feasible.

PAM application strategies were varied during experimentation. PAM was applied continuously, or for a specific period, starting when inflow began. Continuous applications always employed low PAM concentrations (CL). Noncontinuous strategies employed initial high PAM loads (IH), and some applications included additional episodic (intermittent) short-term applications made subsequent to the initial dose (IE). The IH strategies were further distinguished by altering the duration of initial application. The length of this application was described as a multiple of the furrow advance period (time required for water to advance to the end of the furrow). PAM concentrations ranged from 0.25 to 0.5 g m^{-3} for CL applications, from 5 to 20 g m^{-3} for IH applications, and from 5 to 10 g m^{-3} for IE applications.

Furrow infiltration and soil-loss studies employed randomized block designs with three replications. All studies employed a high molecular weight (15 Mg mol^{-1}) anionic PAM with moderate charge density, manufactured and marketed under the trade name Magnifloc 836A[2] by CyTec Industries (Wayne, NJ). In all but one of the reported studies, a granular PAM was used to prepare a 1200 g m^{-3} aqueous stock solution that was metered into furrow heads. Stock solutions were mixed using tap water (EC = 0.9 dS m^{-1}, 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 1994).

Tailwater-quality study

The field study assessing tailwater quality impacts was located near Filer, ID. Furrows were treated with a high molecular weight, nonionic PAM applied in the form of a water/mineral-oil emulsion. This material has a syrup-like consistency, contains 30% PAM, and adequately disperses in a turbulent water stream. Aqueous solutions prepared from PAM crystals require vigorous mixing to dissolve and disperse the solids. When polymer concentration exceeds 1%, these solutions become highly viscous, are difficult to handle, and disperse slowly in flowing water. Inflows were 15 L min^{-1}. PAM furrows were treated continuously at a concentration of 0.5 g m^{-3} for the entire 24-h irrigation (0.5 kg ha^{-1}). Tailwater samples were taken at furrow outfall 4 and 9 hours after irrigation onset. Samples were analyzed for nitrate (cadmium reduction on Flow Injection Analyzer), ortho-phosphate (ascorbic acid method, Murphy and Riley 1962), total phosphate using persulfate digestion (Franson 1985) and the ascorbic

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

acid method (Murphy and Riley 1962), and biochemical oxygen demand (#507, Franson 1985). Treatment differences were determined from nine treated/nontreated furrow pairs with a Student's t-test.

RESULTS AND DISCUSSION

Sediment loss data representing treatment means from treated irrigations on newly cultivated fields are presented in Fig. 1. While all PAM treatments employed Magnifloc 836A, specific treatment characteristics, irrigation period, furrow slope, and inflow rates varied among the graphed pairs. On average, sediment losses from furrows treated with less than 0.7 kg ha^{-1} PAM were 30% (2–76%) of the controls. Sediment losses for furrows treated at rates greater than 0.7 kg ha^{-1} (avg., 1.3 kg ha^{-1}) were only 6% (1–20%) of control values. Larger PAM application rates produced consistently small furrow soil losses, while treatment rates below 0.7 kg ha^{-1} produced more erratic results. Factors that influence PAM field activity are discussed below. Net infiltration for PAM-treated furrows was 11% greater than for controls, when PAM application was less than 0.7 kg ha^{-1}, and 15% greater for heavier applications (Fig. 2). Treatment effects on net infiltration varied widely (−8 to 48% increase over controls), even when PAM application rates surpassed 0.7 kg ha^{-1}. Results of this study corroborate those of Lentz et al. (1992), with respect to both furrow soil losses and infiltration, when equivalent treatments are compared.

Seasonal erosion losses

To determine the potential impact of furrow soil losses on field soils, furrow-loss values must be related to seasonal soil erosion loss. A rough estimate of seasonal erosion may be obtained by multiplying sediment loss values (Fig. 1) by a conversion factor. This factor is a product of three components that account for the fact that (i) most soil erosion occurs in the upper third of a uniformly sloping furrow (Brown 1985), (ii) significant amounts of eroded upper-furrow sediment are deposited in lower reaches and are not measured at the outfall, and (iii) under corn, an initial irrigation on newly formed furrows typically accounts for 20–30% of the seasonal soil loss. Estimated multipliers were 3× for component (i), 2× for component (ii), and 4× for component (iii). The product of component multipliers gives a conversion factor of 24, a value we considered conservative. This factor converts between initial irrigation sediment yield from the tail-end of the field and seasonal soil loss from the upper end of the field. Erosion is unacceptable when seasonal soil loss exceeds Portneuf's soil-loss tolerance or T value, 11 Mg ha^{-1}. In a single initial irrigation (Fig. 1), the furrow soil loss representing the tolerance limit is 460 kg ha^{-1} (i.e., 11×10^3 kg $ha^{-1}/24$). Results in Fig. 1 show that nontreated furrows in 75% of the irrigations exceeded T, and 37% exceeded 2T, in the upper end of the furrows. Erosion from only 13% of PAM-treated furrows exceeded T, and most of these occurred when

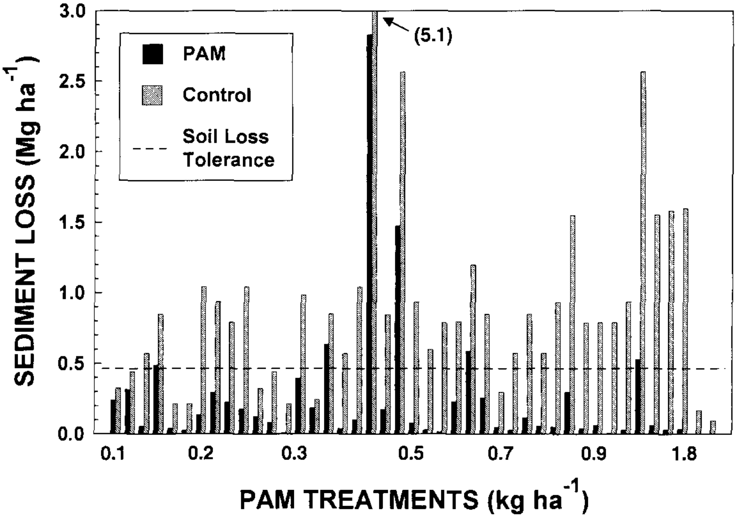

FIG. 1. Average Sediment loss from control and 836A PAM treated furrows. Pairs result from treated irrigations on freshly cultivated furrows, but PAM application strategy, irrigation duration, inflow rates, and furrow slope may differ.

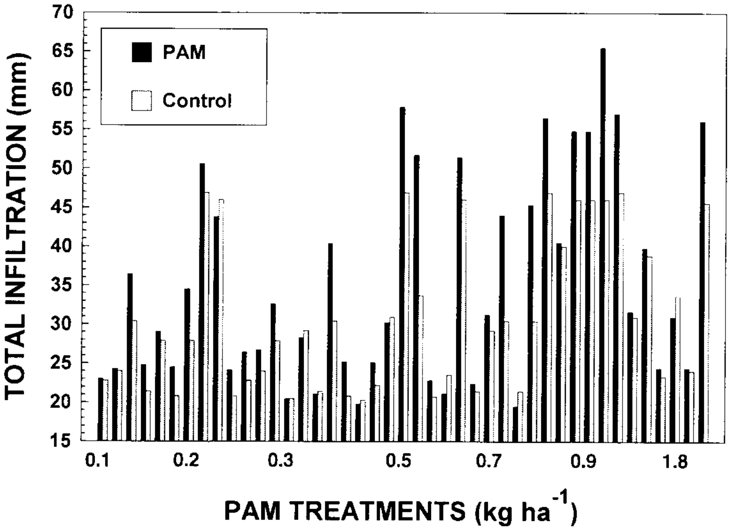

FIG. 2. Average net infiltration of control and 836A PAM treated furrows. Pairs result from treated irrigations on freshly cultivated furrows, but PAM application strategy, irrigation duration, inflow rates, and furrow slope may differ.

furrows were treated with less than 0.7 kg ha^{-1} PAM.

Influence of slope

A change in furrow slope has a greater impact on furrow-stream erosiveness than varying furrow flow-rates (Trout and Neibling 1993). A pertinent question, therefore, is whether PAM's erosion control potential declines with an increase in field slope. Results from fields with slopes of 0.5–3.5% indicate that 10 g m^{-3} PAM treatments, applied during furrow advance, suppressed sediment losses to 1–17% of control furrow losses (Table 1). While soil loss in untreated furrows greatly increased with increasing furrow slope, PAM's protective capacity as represented by the PAM/control ratio did not vary consistently with slope. No effect of slope on net infiltration of control or PAM-treated furrows was evident. Net infiltration in PAM-treated furrows exceeded those of controls in almost every case, but the effect was not conclusive because induced infiltration differences were relatively small compared to measured variability observed among replicates. Measured infiltration can vary substantially among irrigated furrow replicates (Trout and Mackey 1988a,b).

Response uniformity

Furrow processes across a field are inherently variable. For these soils, coefficients of variation (CV) for furrow sediment loss ranged from 10 to 150% (e. g., Table 2). Sediment loss values within replicates are often consistent except for the occurrence of one or two anomalous ex-

TABLE 1

Mean sediment loss and net infiltration for newly cultured furrows from selected irrigations. PAM was applied (Avg. 1.4 kg ha^{-1}) at 10 g m^{-3} during furrow advance

Furrow slope (%)	Initial inflow rate (L/min)	Sediment Loss (Kg ha^{-1})			Infiltration (mm)	
		Control	PAM	PAM/control	Control	PAM
0.5	38	95a[a]	1b	.01	46a	56a
0.5	38	169a	2b	.01	24a	24a
1.5	23	300a	10b	.03	22a	32a
1.5	23	299a	50b	.16	29a	31a
1.7	23	461a	21b	.05	29a	35a
1.7	23	613a	30b	.05	29b	42a
3.5	23	1600a	37b	.02	34a	31a

[a] Dissimilar letters indicate significant differences between paired columns ($P < 0.05$).

tremes. The anomalies are either very susceptible to erosive flow shear or somewhat invulnerable. Consequently, detection of relatively small treatment differences can sometimes require 5–10 replicates.

Field responses to particular PAM treatments also varied between 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 (Table 3). For irrigations listed in Table 2, 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. More study is needed to determine how soil property, slope length, and inflow water quality factors influence PAM efficacy in irrigated furrows.

Application strategy

Three major application strategies were tested: (i) IH, 10 g m^{-3} PAM applied for a time equivalent to 1–2 advance periods; (ii) IE, 5 g m^{-3} PAM applied during the furrow stream advance period, followed by intermittent hourly injections; and (iii) CL, 0.25 g m^{-3} applied continuously. Total PAM applied during an irrigation varied for each application strategy, depending on inflow, rate of furrow stream advance, and furrow length and spacing. Average PAM supplied by IH was 0.95 kg ha^{-1}, whereas IE provided 0.50 kg ha^{-1}, and CL furnished 0.2 kg ha^{-1}. Lentz et al. (1992) found that the IH and IE applications were equally effective for controlling furrow soil loss. Figure 3 compares the effectiveness of IH vs. CL strategies. Note that the CL treatment did 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. As the irrigation proceeded, the more stable soils remaining in the furrow were more successfully protected. In contrast, the IH treatment protected both loose and cohesive soil, and was clearly the more effective treatment for the given conditions. Compared with control furrows, it reduced soil loss by 93%, in contrast to a 51% reduction for the CL application. A continuous or intermittent application strategy may be more effective than an initial high loading under circumstances in which flow shear is relatively high (e.g., steeper slopes or high flowrates).

Tailwater quality

PAM treatment generally improved water quality of the furrow discharge, or tailwater (Table 4). Furrow sediment loss was greatest early in the irrigation, at the 4-h sampling time. At that time, PAM-treated furrow tailwater exhibited significantly lower levels of total phosphorus, nitrates, biochemical oxygen demand (BOD), and sediment, compared with nontreated furrows. It is not clear why ortho-phosphate was higher in treated furrow runoff, but ortho-P levels in runoff from all furrows were high because of a previous broadcast fertilizer application, and the difference may be an artifact. Five hours later, total-P and sediment levels in PAM-treated furrow runoff were still significantly lower than that of control furrows.

An estimate of total component loss over the 24-h irrigation period was calculated by assuming that runoff concentrations and rates at 4 h were representative of the first 6 h of the irrigation, and data from the 9-h sampling were representative of the last 18 h. Total estimated component losses for PAM-treated furrows were lower than for nontreated furrows because PAM

TABLE 2

Furrow sediment loss from four irrigations. The 12-h irrigations employed 23 L min^{-1} initial inflows on replicated, newly cultivated furrows. PAM was applied at 10 g m^{-3} (0.5 kg ha^{-1}) during furrow advance

Date (1993)	Sediment Loss (Kg ha^{-1}) From 179 m long Furrows With 1.5% Slope							
	Control				PAM			
	Mean	Min	Max	SD	Mean	Min	Max	SD
5-26	300	214	348	50	10	3	26	8
6-28	1200	633	1557	359	547	250	1073	330
7-07	798	475	1212	295	231	34	678	279
7-21	299	244	331	40	50	4	164	76

TABLE 3

Factors potentially influencing PAM's field efficacy

Polymer	PAM application	Field	Irrigation	Irrigation water	Soil chemical	Soil physical
Molecular weight	Quality of stock solution water	Furrow slope	Inflow rate	Electrical conductivity	Organic matter content	Texture
Charge type	PAM concentration in furrow	Slope profile	Irrigation timing	Ionic Species	pH	Aggregate stability
Charge density	Timing of PAM application	Furrow length	Irrigation duration	Suspended sediment load	Electrical conductivity	Antecedent water content
		Consolidation and disturbance		Temperature	Exchangeable sodium %	Cover, residue and root growth
					Mineralogy	

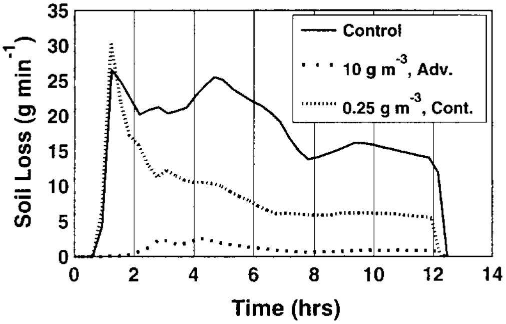

FIG. 3. Furrow soil loss as a function of irrigation time. Plots for each treatment are means of replicate furrows from one or more irrigations. PAM was applied either continuously at a very low concentration or only during the furrow advance stage at moderate concentration.

reduced component concentrations in outflow and decreased mean furrow outflow rates (5.5 vs. 7.6 L min^{-1}). Compared with controls, the PAM treatment reduced component losses over the entire irrigation by 30% for ortho-phosphate, nitrates, and BOD, 47% for total-phosphate, and 58% for sediment.

Potential impacts of PAM use

PAM applications can influence irrigation efficiency and crop management. Increased net infiltration permits shorter irrigations, especially on steeply sloping fields. Productivity of fields containing sections of steeply sloping ground may be increased because these steeper breaks are watered more effectively. Combined with greatly reduced channel downcutting, increased infiltration appears to enhance lateral wetting. This improves interfurrow irrigation coverage which is especially important when watering germinating or seedling crops and for maintaining high quality of water-sensitive crops (e. g., potatoes). Near elimination of soil loss ensures retention of valuable fertilizer and pesticide amendments, maintains field productivity, and reduces the need for costly remediation efforts on eroded fields. 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. This would reduce high leaching potentials that now occur at furrow heads and also improve in-field crop quality.

PAM applications could also have deleterious

TABLE 4

Water-quality components of furrow runoff

Sampling time (h into irr.)	Treatment	Ortho-P[a] (g m^{-3})	Total-P[a] (g m^{-3})	Nitrate[a] (g m^{-3})	BOD[a] (g m^{-3})	Sediment (kg m^{-3})
4	Control	3.1b[b]	8.9a	0.32a	9.1a	16.8a
4	PAM	3.6a	7.1b	0.23b	5.5b	10.3b
9	Control	4.0a	8.4a	0.93a	3.1a	15.7a
9	PAM	3.7a	5.7b	0.97a	3.3a	8.2b

[a] P = phosphate; NH_4-N concentration was <1% of total-N; BOD = Biochemical oxygen demand.

[b] Dissimilar letters indicate significant differences between treatments at a given sampling time ($P < 0.05$).

effects on irrigation efficiency and nutrient management. A farmer may be required to reduce the length of a treated irrigation to account for the PAM-induced increase in infiltration. If no adjustment is made, the resulting increased percolation wastes water and leaches nutrients from the root zone.

CONCLUSIONS

Results of studies carried out under varying field conditions corroborate those of Lentz et al. (1992). The PAM employed was a moderate-charge-density (18% hydrolysis) anionic form with a molecular weight of 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}. At these application rates, soil-loss reductions ranged from 24–98% and averaged 70%. PAM reduced soil erosion losses well below tolerance limits on slopes ranging from 0.5 to 3.5%. A very effective treatment consisted of an initial high load (10 g m^{-3}) applied during or slightly beyond furrow advance PAM treatments also improved tailwater quality by reducing concentrations of total phosphate, nitrate, biochemical oxygen demand, and sediment.

ACKNOWLEDGMENTS

The authors wish to thank Mr. Jim Foerster and Mr. Ronald Peckenpaugh for their invaluable field and laboratory assistance, Dr. Dave Brose and Mr. Sherm Brewster for their help in the tailwater-quality study, and three anonymous reviewers for their critical comments on the manuscript.

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