Polyacrylamide effects on infiltration in irrigated agriculture

R.E. Sojka, R.D. Lentz, C.W. Ross, T.J. Trout, D.L. Bjorneberg, and J.K. Aase

Interpretive summary

Polyacrylamide (PAM) for erosion control is an effective soil conservation practice used on about a million hectares worldwide. Initial research and promotion focused primarily on furrow irrigation erosion reduction and sediment retention. PAM use increases infiltration on fine- and medium-textured soils due to differences between non-treated and PAM-treated surface seals. However, subsurface compaction and coarse texture reduce the infiltration effects of PAM use. Infiltration increases with PAM in sprinkler irrigation are initially large, but more transient than with furrow irrigation. Understanding these effects has important implications for management.

Key words: erosion, infiltration, intake, PAM, polyacrylamide, polymer, runoff, soil amendment, surface seal.

ABSTRACT: Using polyacrylamide (PAM) following the NRCS conservation practice standard increases infiltration in furrow irrigation. PAM at 10 g m⁻³ (10 ppm) during water advance nearly precludes detachment and transport of soil in furrows. If any sediment is entrained in the flow, it is readily flocculated in the presence of PAM and settles to the furrow-bottom in loose pervious structures. It was hypothesized that depositional surface seals that block pores are reduced or made more permeable with PAM. On Portneuf silt loams (coarse-silty, mixed, superactive, Durinodic Xeric Haplocalcid) furrow irrigation net infiltration increased 15%. Net increases on finer textured soils were generally higher. Furrow streams containing more than 5 g L⁻¹ (5,000 ppm) sediment reduced infiltration and infiltration rate more than fivefold compared to streams of clean water. Tension infiltrometry confirmed that PAM's maintenance of open pores to the furrow surface provides the infiltration increase mechanism. Infiltration rates at 40 and 100 mm (1.6 and 3.9 inches) tension in PAM-treated furrows were double the rates of control furrows. Recirculating infiltrometer data showed a 30% infiltration increase with PAM use and infiltration was inversely related to maximum sediment concentration in the flow. Furrow inflow of 45 L min⁻¹ (12 gal min⁻¹) with PAM treatment decreased stream advance time 13% while reducing sediment loss 76% compared to untreated 23 L min⁻¹ (6 gal min⁻¹) inflows. Use of PAM in sprinkler irrigation streams reduced runoff 70% and sediment loss 75%, but tension infiltration measurements were inconsistent, suggesting changes in surface-sealing effects with sprinkler application of PAM are transient.

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The fundamental aspects and history of polyacrylamide (PAM) use in irrigation water have been covered in several publications (Wallace and Wallace 1986a and b; Lentz et al. 1992; Barvenik 1994; Lentz and Sojka 1994; Ben-Hur 1994; Lentz 1995; Lentz and Sojka 1996; Sojka and Lentz 1996; Sojka and Lentz 1997). In agriculture, the two greatest benefits of this practice are erosion control and increased infiltration. Key observations were made as early as 1975 (Paganyas 1975). Rapid acceptance of this new technology began with the documentation that as little as 1 kg ha⁻¹ (1 lb ac⁻¹) PAM applied in dilute solution during initial water advance down an irrigation

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furrow could halt 94% of erosion and increase infiltration 15% (Lentz et al. 1992; Lentz and Sojka 1994). Industry estimates put PAM use for erosion control and infiltration augmentation in irrigation in the United States at 200,000 ha (500,000 ac) in 1996 (Lilleboe 1997) and over 240,000 ha (600,000 ac) in 1997 (Oakford Bain, personal communication).The large erosion reduction has both on-site and downstream economic and environmental benefits (Agassi et al. 1995; Bahr and Steiber 1996; Lentz et al. 1992; Lentz and Sojka 1994; Lentz 1995; Lentz and Sojka 1996; Lentz et al. 1998; McCutchan et al. 1993; Singh et al. 1996; Sojka and Lentz 1993; Sojka et al. 1995; Sojka and Lentz 1997). Infiltration effects are a substantial aspect of these benefits, but have been less thoroughly considered in reports to date.

Rapid adoption of PAM use has been related to three factors: 1) farm operational and/or economic benefits associated with reducing erosion; 2) environmental altruism regarding and/or regulation of water quality standards for sediments, pesticides, and nutrients in waters receiving irrigation return flows; or 3) need for increased water intake. These considerations often are intensified by the need to minimize water cost, maximize water availability, or avoid crop stress to safeguard crop yield and/or quality (value). On fine-textured soils, improving water intake can be more compelling than erosion or pollution prevention.Polyacrylamide affects infiltration in two ways. First, PAM influences soil water processes at the soil surface. If infiltration is governed by subsurface conditions (e.g, compacted layers), PAM in irrigation water cannot affect changes, other than to sometimes alter the timing of expression or onset of subsurface factors during an irrigation. Second, PAM stabilizes soil structure in its zone of activity near the soil surface, but PAM cannot create soil structure. A minor exception to this caveat is PAM's formation of floccules from sediments carried in irrigation water. As these floccules settle on the furrow bottom, they provide a more pervious layer than the surface seals that form when irrigating with untreated water.

To date, most interest has been in PAM use for furrow irrigation. Prior to Lentz et al. (1992), little PAM research for furrow irrigation had been published. The earliest report found described reduced furrow irrigation and induced erosion in cotton using furrow pretreatment with water-soluble polymers (Paganyas 1975). Unfortunately, their report identified the polymers only as "K" compounds. The description was vague but suggested a polyacrylamide copolymer of some kind. Few papers have dealt with the effects of PAM on infiltration in detail, especially infiltration from furrow irrigation measured in the field (Mitchell 1986; Lentz et al. 1992; Lentz and Sojka 1994; McCutchan et al. 1993). These papers do not agree on all aspects of their interpretation of PAM effects on infiltration. This paper summarizes both published findings and new (sometimes preliminary) data from recent laboratory and field studies. The objective in bringing these results together in a single paper is to facilitate a better understanding of PAM effects on infiltration and how those effects can be used for improved irrigation management.

Methods and materials

Unless stated otherwise, the results discussed were largely from a series of studies conducted from 1991 through 1997 at or near the USDA Agricultural Research Service's Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho. Soils included Xerollic Haplargids and Haploxerollic Durargids, but most studies were on Portneuf silt loam (coarse-silty, mixed, superactive, Durinodic Xeric Haplocalcid). Surface horizons and physical and chemical characteristics of all soils were similar. Textures were silt loams (10 to 21% clay, 60 to 75% silt). Organic matter ranged from 10 to 13 g kg^{-1} (1.0 to 1.3%). Saturated paste extract electrical conductivity (EC) was 0.7 to 1.3 dS m^{-1} (0.7 to 1.3 mmho cm^{-1}); exchangeable sodium percentage (ESP) was 1.4 to 1.7; pH was 7.6 to 8.0 with $CaCO_3$ equivalent of 2 to 8%. Slopes varied from 0.5 to 3.5%, but unless noted otherwise, data were from slopes of 1 to 1.5%.

Furrow irrigation (via spigoted plastic pipe or siphon tubes) was applied to conventionally tilled fields, usually disked in autumn and spring, then roller harrowed following incorporation of fertilizer and herbicides prior to planting. Furrows, typically 0.1 m (4 in) deep, ranged from 175 to 264 m (575 to 866 ft) long and were prepared with weighted 75° shaping tools. Furrow spacing varied with crops, which included edible dry beans (*Phaseolus vulgaris*) @ 56 cm (22 in), corn (*Zea mays*) @ 76 cm (30 in) and potato (*Solanum tuberosum*) @ 91.5 cm (36 in). Irrigation was on every other furrow only (hence, 112, 152, and 183 cm (44, 60, and 72 in) between irrigated furrows, respectively), usually in wheel-track furrows. Per unit area sediment loss and infiltration were calculated based on the spacing between irrigated furrows. Irrigation water came from the Twin Falls Canal Company system and had an EC of 0.5 dS m^{-1} (0.5 mmho cm^{-1}) and a sodium adsorption ratio (SAR) of 0.4 to 0.7. Net infiltration, runoff, and sediment-loss measurements were accomplished via periodic flow monitoring and sampling using automated data analysis (Sojka et al. 1992 and 1994; Lentz and Sojka 1995). All furrow irrigation studies involved randomized split-plot designs with a minimum of three replications.

Polyacrylamide copolymer, unless noted otherwise, was a dry granular material with a molecular weight of 12 to 15 Mg mole^{-1} (33,039.6 lb mole^{-1}) with an 18% negative charge density, manufactured by Cytec Industries, Wayne, New Jersey. It is marketed in the United States by American Cyanamid Company under the trade name Superfloc A836. Numerous similar granular, compressed cake materials and high-concentrate liquids or inverse emulsions are available worldwide. The most frequent means of application in this study involved preparing liquid stock solutions of 1,200 to 2,400 g m^{-3} (1,200 to 2,400 ppm), which were metered into furrow-stream flows to achieve a 10 g m^{-3} (10 ppm) concentration in the advancing water flow before runoff began. Typical flow rates ranged from 13 to 38 L min^{-1} (3.5 to 10 gal min^{-1}) during advance, reduced to 13 to 23 L min^{-1} (3.5 to 6 gal min^{-1}) at initiation of runoff.

One study involved use of a recirculating infiltrometer in which water was applied to test furrow sections 6 m (20 ft) in length with a recirculating blocked-furrow infiltrometer (Blair and Trout 1989; Trout et al. 1995). The system continually recycled all sediment that ran off the furrow section, so that sediment concentration eventually equilibrated at a level equivalent to the nearly steady-state condition at the end of a long furrow. Flow rates were 18 to 23 L min^{-1} (5 to 6 gal min^{-1}). Study durations were generally eight hours, with a control furrow and a PAM-treated furrow running simultaneously.

Another study involved measuring steady-state infiltration rates near mid-field 12 hr after irrigation under soil water tensions of 40 and 100 mm (1.6 and 3.9 in). The study used disc permeameters 10 cm (4 in) in diameter described by Cook et al (1993) and similar to the design of Perroux and White (1988). Each instrument was placed on a bed of fine [0.1 to 0.3 mm (4 to 12 × 10^{-3} in)] wet quartz sand contained in 2 cm (0.78 in) deep metal rings of 115 mm (0.45 in) diameter, pushed 1 to 2 mm (4 to 8 × 10-3 in) into the furrow bottom. Six to 12 replicate observations were made in each monitored treatment. Infiltration at 40 mm-(1.6 in) tension includes flow through pores less than 0.7 mm (0.03 in) in diameter; at 100 mm (3.9 in) tension, flow is through pores smaller than 0.30 mm (0.01 in). The same technique also was used to evaluate tension infiltration in sprinkler-irrigated fields, and in soil boxes in which untreated irrigation water or PAM-treated irrigation water was applied.

Sprinkler irrigation comparisons involved field observations under center pivot and linear move systems and an indoor simulator. The indoor simulator sprinkled water onto 1.2 × 1.5 × 0.2 m (4′ × 5′ × 8″) soil boxes on 2.4% slopes. Irrigation water was either untreated or PAM-treated with various 1 to 6 kg ha^{-1} (1 to 6 lb ac^{-1}) equivalent PAM application rates applied in 20 mm (0.79 in) of water, i.e., at concentrations of 5 to 30 g m^{-3} (5 to 30 ppm). Runoff and sediment losses were collected from soil boxes. In center pivot and linear move field comparisons, PAM was applied as inverse emulsion liquids using the American Cyanamid product Pristine, or the Allied Colloid product Soilfix-LDP. These products have PAM-properties similar to those described above, but the PAM is encapsulated in a coating of mineral spirits and surfactant, allowing a high concentration of polyacrylamide in liquid form at relatively low viscosity. The inverse emulsion PAMs were injected in the initial irrigation of the center pivots or linear moves at approximately 2 kg ha^{-1} (2 lb ac^{-1}) with 10 mm (0.4 in) of irrigation water at 20 g m^{-3} (20 ppm) concentration.

Results and discussion

Lentz et al. (1992) reported the effects of PAM-treated water on furrow irrigation advance, net-infiltration amount and rate, runoff and sediment loss and rates, and sediment concentration changes for PAM rates ranging from 5 to 20 g m^{-3} (5 to 20 ppm). PAM was applied in several application strategies, including the current NRCS standard of treating the water advance (only) with 10 g m^{-3} (10 ppm) PAM. These treatments virtually halt furrow irrigation-induced erosion, using about 1 kg ha^{-1} (1 lb ac^{-1}) per treated irrigation.

Net furrow infiltration in Idaho field-scale tests generally increased about 15% when treating furrow advance water with up to 20 g m^{-3} (20 ppm) PAM (Lentz et al. 1992; Lentz and Sojka 1994). Using recirculating infiltrometers, Trout et al. (1995) saw infiltration increase 30% on the same soils. McElhiney and Osterli (1996) and Valiant (1996) reported doubling of infiltration on finer textured soils with PAM treatments.

Initial field-scale furrow irrigation, recirculating infiltrometer, and soil column studies conducted recently on a Hanford sandy loam soil from the east side of California's Central Valley have failed to show any increased infiltration with PAM applications from 5 to 20 g m^{-3} (5 to 20 ppm). Column studies of a Wasco fine sandy loam also showed no PAM-effect. These soils are coarser in texture than those of previous studies and their sediment transport tends to be low because of low erodibility and shallow slopes. However, some smoothing of the furrow perimeter during irrigation was visible, suggesting seal formation, and surface sealing has been blamed for low infiltration rates.

Mitchell (1986) used PAM-treated furrow irrigation water to investigate infiltration on Holtville silty clay (clayey over loamy, montmorillonitic, calcareous, hyperthermic Typic Torrifluvents), a shrink-swell clay soil. PAM was applied in the advance water only at 2.5, 5, and 15 times the current NRCS standard (Anonymous, 1995) of 10 g m^{-3} (10 ppm), using a PAM formulation similar to ones currently used. At first inspection, Mitchell reported what appear to be contradictory data for PAM use, namely increased infiltration and more rapid stream advance (implying lower infiltration) compared to controls. He reported a 30 to 57% increase in initial infiltration rate, measured immediately after completion of advance. At irrigation's end, however, infiltration rates of treated and untreated plots were similar. There was no effect of treatments on final profile water contents, and this was interpreted as no effect on net infiltration.

The initial infiltration rate increase and faster advance might be reconciled by considering viscosity effects and timing of infiltration rate measurements relative to onset of seal-formation in the system. At Mitchell's high PAM rates, the briefer advance times were attributed to increased viscosity of the PAM-treated water reducing hydraulic conductivity and, thus, infiltration during the advance. High PAM rates have been linked to reductions of infiltration rate, with one explanation being increased effective viscosity of water moving in soil pores (Malik and Letey 1992).

Using lower PAM concentrations, Lentz and Sojka (1994) consistently observed greater net infiltration in PAM-treated furrows compared to controls. At low concentrations, like the 10 g m^{-3} (10 ppm) of the NRCS practice standard, PAM does not raise viscosity enough to overcome advance-phase infiltration rate increases that result from surface seal prevention. Surface seal prevention preserves pore continuity to the soil surface (prevents surface pore blockage) and maintains greater surface roughness, which decreases surface velocity. Seal formation in untreated furrows is a rapid process. In Mitchell's studies, PAM viscosity effects may have lowered infiltration enough during advance to raise runoff rate (greater effective stream size along the furrow) compared to controls. Thus, during the advance, water infiltration into controls was at a high rate. However, as the advance proceeded in control furrows, surface sealing would have occurred rapidly in the wake of the advancing stream of water. By the time runoff began from control furrows, seal formation was more restrictive to water entry than the viscosity effects in the PAM-treated furrows without surface seals. Thus, infiltration rate rankings at the time of measurement were likely the inverse of the rankings that determined the advance rates. Mitchell (1986) did not measure soil erosion but noted clear runoff and elimination of dispersion and slaking with PAM.

In California, McCutchan et al. (1993) reported that 2.5 g m^{-3} (2.5 ppm) PAM, continuously applied in furrow streams, did not alter advance time but reduced outflow 10%; they did not report net infiltration amounts. Sojka et al. (1998) found that the relative infiltration effects of 10 g m^{-3} (10 ppm) PAM-treatment (in advance water only) depended on furrow type and number of irrigations compared. Infiltration of PAM-treated wheel-track furrows increased for the first one or two irrigations of the season compared to untreated wheel-track furrows. For the remaining 20 to 24 irrigations of each season, however, advance time and infiltration of wheel-track furrows were unaffected by PAM treatment. In the same study, PAM treatment of nonwheel-track furrows showed a consistent infiltration advantage and slower water advance along furrows throughout the season.

Lentz et al. (1992) and Lentz and Sojka (1994) reported work from Idaho with irrigations of 8- to 12-hr durations on wheel-track furrows. The Lentz et al.

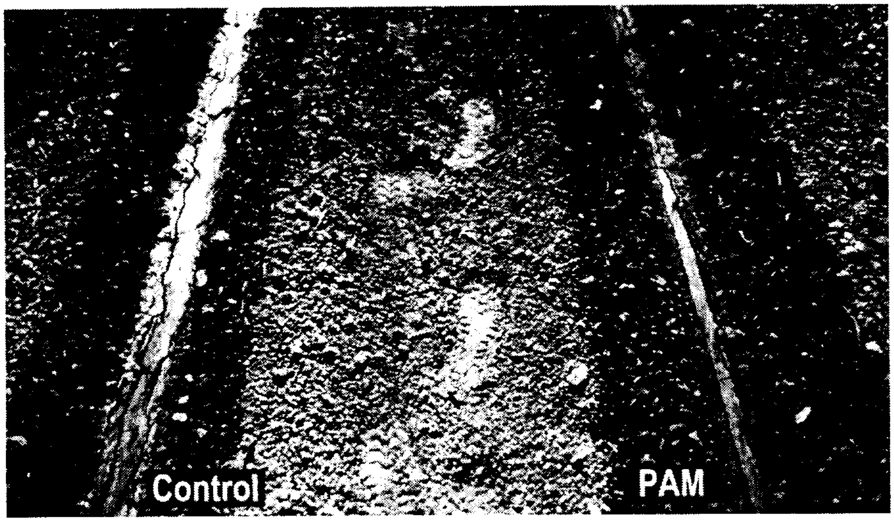

Figure 1. Photograph showing degraded channel and surface seal of untreated control furrow (left) on Portneuf silt loam 24 hr after an irrigation compared to PAM-treated furrow (right) with 25% wider lateral wetting extent

(1992) data were from the initial irrigation on each furrow. Lentz and Sojka (1994) reported data from throughout several seasons but on freshly prepared furrows. Trout et al. (1995) reported data from 8-hr irrigations on freshly prepared wheel-track furrows of the same soils (silt loams with a silica and calcium cemented restrictive layer at about 45 cm [18 in] in depth). In California, Mitchell (1986) performed 12 hr or slightly longer irrigations on a deep shrink-swell clay soil of the Imperial Valley, where roots could extract water to a 1.2-m (4-ft) depth. The Vernalis loam soil of the California study by McCutchan et al. (1993) was a deep, structured, well aggregated loam, and data were collected for less than 7 hr. Antecedent profile water contents were not reported for any of the studies.Infiltration rates and amounts are affected by soil pore status (texture, structure, pore size distribution, pore continuity and profile water content, and distribution), especially at the soil surface. Early in an irrigation, the infiltration rate is most influenced by conditions in the upper profile. Late in an irrigation, infiltration may be more influenced by conditions deep in the profile. Soils like Idaho's Portneuf silt loam sustain moderate percolation rates even when the profile is saturated, but infiltration is limited by surface-seal formation (Segeren and Trout 1991). In other soils, the presence of subsurface drainage barriers slow water entry, reducing the vertical soil water potential gradient, which can greatly limit infiltration late in an irrigation.

All studies cited above had some improvement of water intake with PAM, especially early in an irrigation. Antecedent profile water content determines the water absorption rate and capacity. If irrigation duration is short, or if the soil profile is dry, infiltration rates will remain high for a large proportion of the irrigation set, and PAM-treatment of the inflows may show relatively large effects. Thus, where surface seals affect infiltration rate and amount, the relative PAM-treatment effect is larger in short than in long irrigation durations.

The studies already discussed also showed that PAM can improve irrigation efficiencies (the ratio of water volume stored for crop use to the water delivery volume needed to achieve that storage). This is particularly important if short irrigation durations are desirable. Brief irrigation durations can facilitate irrigating multiple fields from a single water source while still avoiding crop stress. PAM's furrow-erosion abatement affects infiltration dynamics. Because PAM-treated furrows do not erode a deeper channel, the water level relative to planted rows is higher, compared to untreated furrows. This, coupled with seal prevention along the wetted perimeter, promotes greater lateral flow out and away from the furrow. Lentz et al. (1992) measured a 25% increase in the extent of lateral wetting (Figure 1) from shallow furrows between flat beds of a field bean crop. However, PAM effects did not improve lateral wetting in deep furrows and 0.3 m (1 ft) high beds in furrow-irrigated potatoes (Sojka et al. 1998).

Trout et al. (1995) confirmed that the infiltration benefit of PAM was related to a decrease in transported sediment (Figure 2). As sediment concentration of flowing water declined, infiltration increased. This was true whether relating cumulative infiltration for the entire 8 hr to mean sediment concentration of the initial hour (Figure 2a), or relating final infiltration rate with initial sediment concentration (Figure 2b). The curve shapes show that for Portneuf soil, irrigated with Snake River water, furrow stream sediment concentrations must be below 3 to 5 g L^{-1} (0.3 to 0.5%) to prevent infiltration rate reduction from surface sealing. The average seasonal runoff sediment concentrations of Pacific Northwest furrow-irrigated land are about 15 g L^{-1} (1.5%).

Furrow surface seals form when infiltration-reduced carrying capacity of the furrow stream causes deposition of transported sediments. Segeren and Trout (1991) showed that seals as thin as 0.2 mm (8×10^{-3} in) lower hydraulic conductivity two orders of magnitude below the conductivity of the parent soil, and reduce infiltration by 50%. Sojka and Lentz (1994) noted that PAM-treated furrows also form noticeable surface seals, but postulated that these seals had a higher permeability than the seals in control furrows. They concluded this because net infiltration after 8 to 12 hr of irrigation was significantly higher in PAM-treated furrows.

Ross et al. (1996) tested this hypothesis by comparing steady-state infiltration of PAM-treated and control furrows under slightly unsaturated conditions. Unlike the net infiltration and transient state infiltration rate data of the previously cited studies, the tension infiltrometer measures steady-state values unaffected by changing water potential gradients within soil profiles. Using water under slight tension also allowed an evaluation of water transmission through pores of specific equivalent diameters, excluding flow from large pores and fissures. Because all furrows presumably had similar surface pore geometry prior to irrigation, this measurement assessed the degree of seal formation that resulted from irrigation with untreated water vs. PAM-treated water.

Figure 3 shows the steady-state infiltration under 40 and 100 mm (1.6 and 3.9 in) tension in furrow bottoms 12 hr after each of five irrigations in 1995. Each point is the mean of six determinations. Infiltration at 40 mm (1.6 in) tension varied among irrigations over a range of 12.9 to 31.8 mm hr^{-1} (0.51 to 1.25 in hr^{-1}) for controls and 26.7 to 52.2 mm hr^{-1} (1.05 to 2.06 in hr^{-1}) for PAM-treated furrows. Similarly, infiltration at 100 mm (3.9 in) tension varied from 12.3 to 29.1 mm hr^{-1} (0.48 to 1.15 in hr^{-1}) for controls and

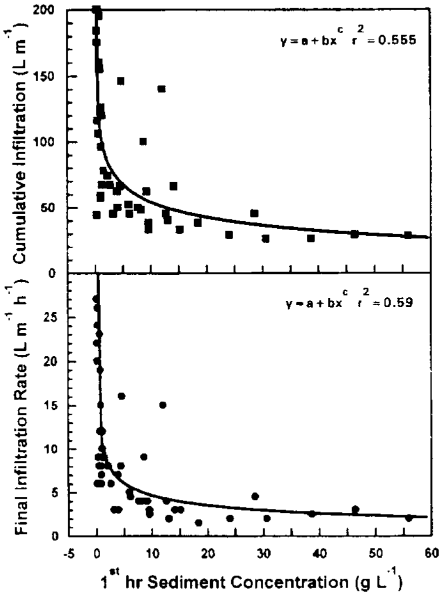

Figure 2A. Effect of sediment concentration in furrow water on cumulative infiltration into a Portneuf silt loam as measured for 8 hr using a recirculating infiltrometer; B) Effect of the first hour's sediment concentration on final (8 hr) infiltration rate into a Portneuf silt loam, measured using a recirculating infiltrometer

Data presented for both A and B combine several treatment regimes. Figures are adapted from data originally presented by Trout et al. (1995)

22.3 to 42.4 mm hr^{-1} (0.88 to 1.67 in hr^{-1}) for PAM-treated furrows.

The lower infiltration of controls was attributed to the deposition of fines (especially clay) in the furrow with each irrigation. Seals formed in PAM-treated furrows as well, however, they were consistently about twice as permeable under slight tension as the seals formed in controls. Thus, PAM-treated furrows had more unblocked pores with equivalent mean spherical diameters of less than 0.75 mm (0.03 in) at 40 mm (1.6 in) tension or less than 0.30 mm (0.01 in) at 100 mm (3.9 in) tension throughout the irrigation season. Thus, the physical nature of the seal formed is important. The influence of particle or aggregate size or amendments on seal properties are more important to seal conductivity than the concentration of carried sediment alone.

Similar data were obtained in several studies monitored in 1995. In one study, 1120 kg ha^{-1} (1000 lb ac^{-1}) PAM was broadcast dry and rototilled 0.10 to 0.15 m (4 to 6 in) deep in plots and was then furrow-irrigated with PAM-treated water. Mean conductivities for two observation dates were 28.3 mm hr^{-1} (1.11 in hr^{-1}) at 40 mm (1.6 in) tension, and 24.4 mm hr^{-1} (0.96 in hr^{-1}) at 100 mm (3.9 in) tension, when irrigated with untreated water in control plots, compared to 69.2 and 55.9 mm hr^{-1} (2.72 and 2.20 in hr^{-1}) when irrigated with PAM-treated water in PAM-treated plots.

The combined observations of researchers suggest that the infiltration effect of PAM treatment is probably a balance of viscosity and free pore-size effects. On soil with stable large open pores, viscosity effects on hydraulic conductivity dominate. A reduced infiltration rate is likely, regardless of pore geometry, if PAM concentration in infiltrating water is high enough [perhaps more than 25 g m^{-3} (25 ppm)]. Where pore size is large, no observable infiltration effect will occur if PAM concentration is low. Where pore size is small, PAM's ability to prevent pore blockage (surface sealing) during deposition of transported clay material tends to result in higher infiltration rate (compared to untreated water) if PAM concentration is low enough to avoid the viscosity effect on hydraulic conductivity. This is because the conductivity reduction of sealing is greater than the viscosity effect of low PAM concentrations.

The furrow irrigation net infiltration also is affected by the size of the wetted perimeter (Izadi and Wallender 1985). With PAM treatment, the furrow geometry is relatively stable throughout the season, whereas without PAM treatment, gradual slaking of furrow sides and/or deposition of eroded soil in lower reaches of the field increase the wetted perimeter. If furrows are not mechanically reshaped during the season, these differences can result in a gradual equalization of net infiltration between treated and untreated furrows, or even an increase in net infiltration of controls late in the season (Sojka et al. 1998). These furrow "widenings" occur at the expense of erosion and soil transport in the field. Widening may be localized, e.g., at the outflow ends of furrows or where furrow slope abruptly decreases. Farmers using PAM need to be aware of these potential effects and, if need be, compensate for them with changed water management or cultivation practices, bearing in mind that furrow reshaping typically costs \$20 ha^{-1} (\$8 ac^{-1}).

Farmers often comment that PAM use improves infiltration on "steep shoulders" or "breaking slopes." These terms refer to the convex increases of slope that occur in portions of fields where untreated water can erode deep channels. Infiltration is limited by the hastened flow and the small wetted perimeter of the deep channels. Following deep erosion, the low elevation relative to the crop root structure limits such a furrow's ability to adequately supply water to the planted row. Furthermore, in these steep-eroding field portions, wetted soil (and the water it holds) are eroded nearly as rapidly as the infiltration itself. Thus, at irrigation's end, little water is stored in such areas. In this instance, PAM treatment preserves adequate wetted perimeter, maintains a favorable free water elevation (head) for transmission of water to the interrow, and prevents erosion of

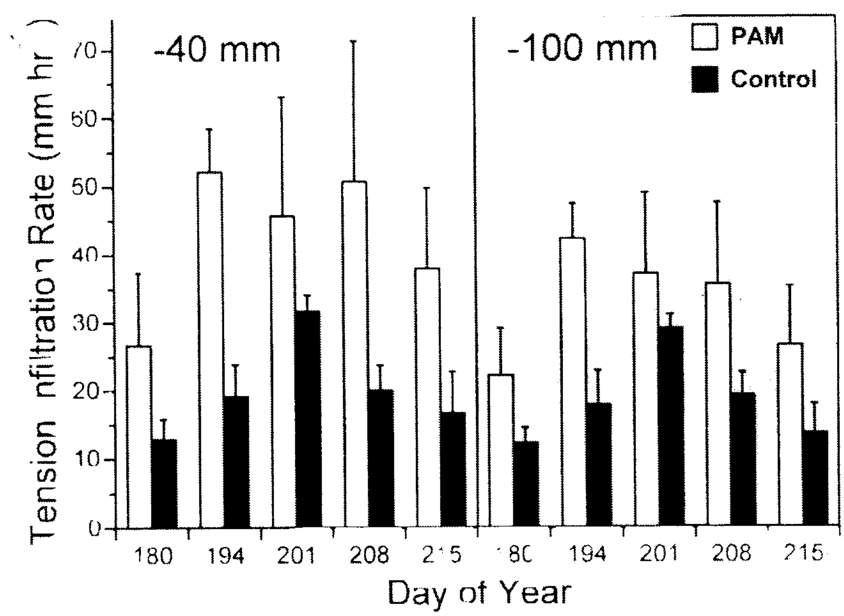

Figure 3. Steady-state infiltration rate under 40 mm and 100 mm tension measured in furrows 12 hr after irrigation of a Portneuf silt loam on five dates in 1995

At 40 and 100 mm tension, flow is only through pores smaller than 0.75 or 0.30 mm effective diameter, respectively

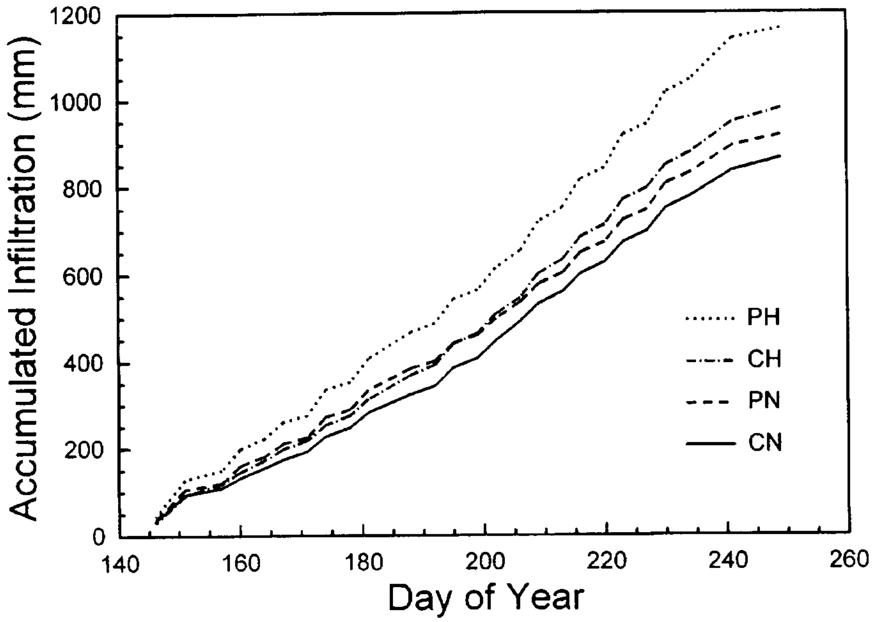

Figure 4. Cumulative seasonal infiltration as affected by control (C) or PAM (P) treatments under two inflow management regimes: normal flow rate of 23 L min^{-1} (N), or high flow rate of 45 L min^{-1} (H)

stored water from the steep sections of the furrow. These effects are in addition to the seal effects noted earlier.

Where steep furrow reaches often are unable to support adequate crop growth, farmers have credited PAM treatment with sustaining nearly normal growth and yield. This phenomenon is difficult to study in replicated plots that usually are established in uniform, nearly optimal fields. Yet, it provides strong economic incentive for PAM use in furrow irrigation on variable sloping topography.

With PAM use farmers need to increase furrow inflow rates. If PAM-treated inflows are not raised, increased infiltration will delay stream advance, worsening the infiltration opportunity time variation along the furrow. Because farmers usually irrigate to avoid stress at the lower field reach, this nonuniformity results in over-irrigation of upper reaches.

Increases of PAM-treated inflow rates should be substantial, for example, double or triple the normal rate. Sojka et al. (1998) showed that when doubling PAM-treated inflows from 23 L min^{-1} to 45 L min^{-1} (4 gpm to 8 gpm), average advance rates across a 175 m (570 ft) field with a 1.5% slope were 95 min for normal controls and 83 min for the higher PAM-inflow rates, yet sediment lost from the high PAM inflows was only 24% of the untreated, smaller inflows. All inflows in the study were cut back to 19 L min^{-1} (5 gal min^{-1}) once runoff began. The increased uniformity of the high-flow PAM-treated irrigation also improved potato grade (market value). Studies currently are underway to quantify leaching loss differences with PAM use, which are expected to be reduced if PAM use is coupled with higher inflows to improve field infiltration uniformity.

The infiltration effects of PAM applied through overhead sprinkler systems have been less studied than for furrow-irrigation. In several laboratory simulation studies using small trays and PAM concentrations of 20 kg ha^{-1}, (18 lb acre^{-1}), PAM reduced erosion and increased infiltration (Shainberg et al. 1990; Smith et al. 1990; Levin et al. 1991). There also have been a few field-plot studies with similar rates of PAM sprayed on the soil surface prior to sprinkling, showing similar results (Levy et al. 1991; Ben-Hur 1994; Zhang and Miller 1996).

In large-box laboratory studies in Kimberly, Idaho, 92 % of sprinkler-applied water infiltrated during the first irrigation when PAM was applied in the irrigation water at rates as low as 2 kg ha^{-1} (2 lb ac^{-1}). This compared to 70% infiltrated on the check treatment. During a subsequent water-only irrigation, infiltration on the PAM treatment was 86% versus 73% on the check treatment. On the next water-only irrigation, infiltration on the PAM treatment was not significantly different (P = 0.05) from the check treatment (Aase et al. 1998). PAM applied in 20 mm (0.78 in) of irrigation water in the first irrigation increased net infiltration, but did not affect tension infiltration measured following the third irrigation. The same amount of PAM applied in 8 mm (0.3 in) of water in the first irrigation resulted in a doubling of tension-infiltrated water following the third irrigation. There was an effect of PAM treatment on the total infiltration amount even when applied at a lower concentration with a larger volume of irrigation water, but it was apparent that the initial effect of PAM on tension infiltration diminished. However, where PAM was applied at higher concentration in smaller amounts of water, the PAM effects on soil surface structure persisted for three subsequent irrigations and still had a measurable effect on tension infiltration.

On-farm experiences from PAM application through center pivot and linear-move systems in the Pacific Northwest have been inconsistent. Controlled experiments and commercial-scale tests of new PAM application strategies for various soils, slopes, tillages, and crop management systems continue.

Conclusions

When used according to the NRCS standard, polyacrylamide (PAM) increases infiltration in addition to nearly eliminating furrow irrigation-induced erosion. The increase varies with several soil attributes, especially texture. Silt loam soils have shown about a 15% increase in net infiltration and a 25% increase in lateral wetting from shallow furrows between low flat beds. Fewer data are available for other textures, although limited reports suggest that the relative increase in net infiltration is larger for finer textured soils. The infiltration increase is enabled primarily by PAM's preservation of a more pervious pore structure during the formation of surface seals in furrows. If furrow inflows are not changed, PAM use will prolong stream advance and exacerbate furrow infiltration nonuniformity from upper to lower field reaches. However, PAM's erosion-preventing properties can be relied on to reduce erosion while greatly increasing inflow rates in order to significantly reduce stream advance rates and improve infiltration uniformity along the furrow.

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