Polyacrylamide and straw residue effects on irrigation furrow erosion and infiltration

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ABSTRACT: Water-soluble anionic polyacrylamide (PAM) is a highly effective erosion deterrent in furrow irrigation, but little is known about the effect of plant residues on PAM efficacy. We hypothesized that increasing plant residue in irrigation furrows may alter PAM's ability to control erosion. Furrows with 10 g m^{-1} (485 kg ha^{-1}) on treated area and 30 g m^{-1} (1490 kg ha^{-1}) wheat straw applications, irrigated with PAM or untreated water, and conventionally irrigated furrows (no PAM and no straw) were used. Five irrigations were monitored on a field with 1.5% slope and silt loam soil (*Durinodic Xeric Haplocalcids*). PAM was applied as a granular patch at the furrow inflow end (33 g or 1 kg active ingredient ha^{-1}). Compared to controls, individual straw and PAM+straw treatments reduced sediment loss in all irrigations by 64% to 100%, but increased infiltration (1.3x to 2.5x) only for irrigation one, when furrows were fresh. Adding more straw to low straw (with or without PAM) treatments increased average sediment loss reduction from 86% to 94% in the first two irrigations, but provided no extra benefit in subsequent irrigations (relative to controls). Adding PAM to low and high straw treatments increased average sediment loss reduction from 80% to 100% in the first two irrigations, and from 94% to 99.8% in subsequent irrigations. Combining plant residue and PAM in furrows produced greater erosion control and larger infiltration enhancements than with straw alone. An important additional benefit of PAM is that it greatly reduced detachment, transport, and redistribution of residue in furrows, which helped prevent furrow blockage and attendant overflow problems, allowing farmers to use conservation tillage in furrow irrigated fields.

Keywords: Erosion, furrow irrigation, infiltration, sediment discharge, straw residue

Polyacrylamides have been used as settling agents in water treatment, mineral processing, and paper manufacturing industries for decades. In a more recent application, polyacrylamide-amended irrigation water was used to reduce furrow irrigation induced erosion and sediment loss (Lentz and Sojka, 1994). Of the many forms of polyacrylamide manufactured, a water-soluble anionic polyacrylamide, having a molecular weight of 12 to 15 Mg mol^{-1} (13 to 16.5 ton mol^{-1}) and charge density of 8% to 35%, has been found to be most effective for furrow erosion control (Lentz et al., 2000). In this paper, use of the terms polyacrylamide, or PAM, will refer to this specific type of polymer.

Lentz and Sojka (1994) demonstrated that applying 10 mg PAM L^{-1} water (10 ppm) during the advance phase of the irrigation, reduced sediment loss from treated furrows by an average 94% when compared to untreated furrows. The 10 mg L^{-1} (10 ppm) PAM concentration applied during the initial irrigation period was found to be optimal (Lentz et al., 2000). This PAM application method, adopted as the U.S. Department of Agriculture-Natural Resources Conservation Service practice standard, also reduced runoff losses of nitrogen (N), phosphorous (P), and chemical-oxygen-demand by 80% to 90%, and pesticide losses by at least 50% to 70%, compared to that of untreated furrows (Lentz et al., 1998). Sojka and Lentz (1997) discussed general technical and practical guidelines concerning PAM application to furrow irrigated agriculture.

During furrow irrigation, the advancing water stream inundates soil aggregates, which slake and break down, and soil particles are detached, dispersed, and transported down furrow. Some transported sediment is deposited along the wetted furrow perimeter, resulting in a smoothed surface that has less resistance to flowing water. These processes simultaneously promote surface seal formation, which decreases furrow infiltration (Segeren and Trout, 1991) and increases runoff and sediment loss. PAM-amended irrigation water affects this process in two ways: 1) it adsorbs to soil surfaces, increasing soil cohesion and aggregate stability; and 2) it flocculates fine soil particles suspended in the furrow stream, producing larger aggregates that settle out of the flow instead of exiting the field in runoff water. Together, these processes produce a well-aggregated system that better maintains roughness and permeability of the furrow surface when compared with untreated furrows (Trout et al., 1995). Hence, PAM-treated furrows generally have greater infiltration, less runoff, lower soil detachment rates, and reduced sediment transport rates compared to untreated furrows.

Crop residues occur in furrows as a result of incomplete incorporation or are placed there to control erosion (Aarstad and Miller, 1981), increase infiltration rates (Miller and Aarstad, 1971), or decrease nutrient losses in runoff (Shock et al., 1997). Crop residues decrease stream velocities (Evans et al., 1995), increase the wetted perimeter (Miller and Aarstad, 1971; Brown, 1985), and decrease runoff sediment concentrations (Aarstad and Miller, 1981) in furrows, relative to those that have no residues. When compared with PAM applications, Shock and Shock (1998) reported that straw residues more effectively increased furrow infiltration.

Sediment and unincorporated crop residue at inflow ends of furrows can be detached and transported downstream. This sediment and residue can eventually settle or be trapped at susceptible locations along the furrow, potentially filling and blocking it, and causing the stream to overtop and escape the furrow (Berg, 1984). This leads to nonuniform water application and is one reason why farmers prefer to clean-till their furrow-irrigated fields. Dissolved organic carbon (DOC) can leach from plant residues (Kalbitz et al., 2000) and increase DOC concentrations in furrow streams. Elevated DOC

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concentrations in water can reduce PAM's capacity to flocculate dispersed mineral particles (Lentz et al., 1996). A combined PAM and straw residue treatment applied for a single irrigation produced no significant increase in erosion control or infiltration relative to straw-only or PAM-only treatments (C. Shock, personal communication, August 2000).

Little published information is available that describes the combined influence of crop residue and PAM applications for furrow irrigation. Our objective was to test the hypothesis that the amount of crop residues in furrows alters PAM's capacity to increase infiltration and control erosion. We monitored infiltration and sediment loss for irrigation furrows treated with two levels of straw residue, with or without PAM application, in order to quantify the effects of PAM residue interactions on furrow processes.

Methods and Materials

The 0.4 hectare field plot was located on Portneuf silt loam—coarse silty, mixed superactive, mesic Durinodic Xeric Haplocalcids—at the U.S. Department of Agriculture-Agricultural Research Service, Northwest Irrigation and Soils Research Laboratory in Kimberly, Idaho. Surface soil included 14% clay and 68% silt. Soil organic matter was 14 g kg^{-1} (1.4%), cation exchange capacity was 18 cmol$_c$ kg^{-1}, electrical conductivity (EC, saturated paste extract) was 0.07 S m^{-1} (.7 mmho cm^{-1}), exchangeable sodium percentage was 1.5, pH was 7.8, and calcium carbonate equivalent varied from 2% to 8%. The slope was 1.5%.

Portneuf soils are highly erodible. The dry soil aggregates slake quickly during a rapid wetting event, such as that occurring at the front of an advancing furrow stream. The plot was disked twice in the fall after silage corn was harvested and roller harrowed in late March. On May 17, 1999, we incorporated a pre-emergence herbicide application into plot soils with a roller harrow, formed 173 m (567 ft) long, furrows at 0.75 m (30 in) spacing, with a weighted furrow-forming tool, and planted to corn (*Zea mays L.*). An initial nonmonitored irrigation was applied to plots. The field was cultivated and furrows reformed on July 2, 1999. Straw residue treatments were applied to these freshly formed furrows.

Furrow treatments consisted of low residue (10 g m^{-1} [0.10 oz ft^{-1}] of furrow, 485 kg ha^{-1} [433 lb ac^{-1}] on a treated area basis; or 64 kg ha^{-1} [57 lb ac^{-1}] on a whole field basis), and high residue (30 g m^{-1} [0.32 oz ft^{-1}], 1490 kg ha^{-1} [1330 lb ac^{-1}] on a treated area basis; or 196 kg ha^{-1} [175 lb ac^{-1}] on a whole field basis), with or without PAM treatment, and an untreated control. Wheat straw was applied by hand along the entire length of the furrow by simply dropping it into the channel. No effort was made to press the straw into furrow soils. We applied 33 g (1.2 oz) of granular PAM in a 0.1 m^2 (1.1 ft^2) patch at the head of each PAM-treated furrow (equivalent to 1 kg PAM ai ha^{-1} or 0.9 lb PAM ai ac^{-1}). The PAM was manufactured and marketed under the trade name Superfloc® A110 (= Magnifloc® 836A) by CYTEC Industries Inc., Stamford, Connecticut[1]. The white granular crystals were 80% PAM (ai). The patch was positioned so that impinging turbulence from incoming water would promote PAM hydration and solution. Five irrigations were made after furrow treatments were applied, beginning on July 13, 1999 (Table 1), and all were monitored. The first irrigation was made to the fresh furrows and the four repeat irrigations followed on these same furrows, which were not subsequently disturbed by tillage. We refer only to monitored irrigations (Table 1), numbering them from one to five, with Irrigation 1 being the first irrigation applied after straw was placed in the furrows. Irrigations were two weeks apart, except for one and two, which were one week apart. Irrigations began at 8:00 am and were curtailed twenty-four hours later. Inflow rate during furrow advance was 23 L min^{-1} (6 gpm). In later irrigations, this initial inflow rate was reduced to 19 L min^{-1} (4 gpm) after furrow advance in order to reduce runoff and soil losses. Irrigation water was applied to wheel-trafficked furrows (i.e., every other furrow 1.52 m [60 in] apart, from a gated pipe via adjustable spigots). The irrigation water was diverted from the Snake River and had an electrical conductivity equal to 0.05 S m^{-1} (0.5 mmho cm^{-1}) and sodium adsorption ratio of 0.5 [mmol$_c$ L^{-1}]$^{0.5}$.

We measured irrigation furrow inflow and outflow rates, and collected runoff samples to determine sediment concentration. Measurements were made at one-half hour intervals early in the irrigation, every hour during mid-irrigation, and every three hours later in the irrigation when outflows and sediment loads had stabilized at more than seven hours into the set. Inflows were measured by timing the filling rate of a known volume, and outflows were measured with long throated v-notch flumes (Trout and Mackey, 1988). We determined runoff sediment concentrations by measuring settled sediment volumes in 1 L Imhoff cones and relating this volume

Table 1. Description of irrigations applied during the study, including soil water content in furrow surface soils before starting inflows.

Irrigation Number	Irrigation Date	Irrigation Furrow Type	Irrigation Length (hr)	Inflow Rates (L m^{-1})	Average Furrow Advance (min)	Soil Water 0-3 cm Control (kg kg^{-1})	Soil Water 0-3 cm All Straw treatment (kg kg^{-1})
0†	7-5-99	Fresh (newly formed)	24	23	—	—	—
1	7-13-99	Fresh (newly formed)	24	23	175	0.039	0.032
2	7-21-99	Repeat	24	23 then 19‡	65	0.081	0.12
3	8-3-99	Repeat	24	23 then 19‡	129	0.043	0.047
4	8-18-99	Repeat	24	23 then 19‡	117	0.046	0.052
5	9-1-99	Repeat	24	23 then 19‡	115	0.055	0.058

† Initial irrigation was applied prior to treatment applications and was not monitored.

‡ Inflows were reduced to the lower value after furrow advance, except where high infiltration rates prevented the cut back.

¶ Irrigation of previously irrigated but otherwise undisturbed furrow channel.

Table 2. Irrigation parameters for Irrigations 1 and 2, and 3, 4, and 5 combined for monitored irrigations.

		Low Straw		High Straw	
	Control	No PAM	PAM	No PAM	PAM
Irrigation 1 (fresh furrows)					
Mean Outflow (L min^{-1})	13.8 c†	12.2 c	6.8 a	9.6 b	5.7 a
Sediment Loss (Kg ha^{-1})	3000 d	636 c	3 a	212 b	0.5 a
Net Infiltration (mm)	54 a	63 b	92 d	77 c	96 d
Mean Sediment Conc. (g L^{-1})	4.3 d	1.0 c	0.02 a	0.45 b	0.00 a
Furrow Advance (min)	102 a	129 a	228 b	168 ab	250 b
Irrigation 2 (repeat-1 irrigation furrows)					
Mean Outflow (L min^{-1})	10.8 a	11.3 a	9.8 a	10.1 a	9.2 a
Sediment Loss (Kg ha^{-1})	2633 d	941 c	0.7 a	444 b	1.2 a
Net Infiltration (mm)	47 a	47 a	56 a	53 a	58 a
Mean Sediment Conc. (g L^{-1})	4.5 d	1.5 c	0.00 a	0.8 b	0.00 a
Furrow Advance (min)	51 a	59 a	65 a	67 a	83 b
Irrigation 3, 4, 5 (repeat irrigation furrows)					
Mean Outflow (L min^{-1})	10.4 a	9.3 a	9.4 a	9.1 a	9.3 a
Sediment Loss (Kg ha^{-1})	1078 c	80 b	3 a	41 ab	1 a
Net Infiltration (mm)	56 a	60 a	63 a	61 a	62 a
Mean Sediment Conc. mg L^{-1})	1.9 b	0.2 a	0.00 a	0.1 a	0.01 a
Furrow Advance (min)	85 a	99 ab	138 c	112 bc	164 c

† Values within a row with the same letter are not significantly different.

to sediment mass (R^2 >95%). Details of the flow and sediment monitoring procedure were given by Lentz and Sojka (1994). The computer program, WASHOUT (Lentz and Sojka, 1995), calculated runoff and PAM loads using measured flow rates, and sediment and polymer concentrations and infiltration, as the net difference between furrow inflow and runoff at each monitoring time. Soil loss reduction was computed as the percentage difference between the control and treated furrow values. The means and 95% confidence limits of four replicate values for each treatment and irrigation were calculated. Mean values were plotted as a function of time in duration graphs. The study employed a split plot design with residue application rates as the main plot and PAM application rate as the subplot, with four replicates. Residue and PAM treatments were analyzed in a split block analysis to maximize precision for comparing: 1) overall PAM treatment effects, and 2) PAM effects within each main plot residue treatment (in the case of factor interactions). Additional conventionally irrigated control furrows were included in each block. A randomized complete block analysis included the control furrows and compared them with the residue and PAM treatments. Hypotheses and mean separations were determined with a probability of P = 0.05. Response values for given treatments in Irrigations 3, 5, and 6 were more similar to one another, than to those of Irrigations 1 and 2. Hence, furrow responses from Irrigations 3, 5, and 6 were averaged together and analyzed as a group.

Table 3. Irrigation parameter comparisons between levels of straw or PAM treatments, and significance of the straw-PAM interaction.

	Low Straw	High Straw	Straw Alone	Straw + PAM	Signif. Straw X PAM Interaction
Irrigation 1 (fresh furrows)					
Mean Outflow (L min^{-1})	9.5 b†	7.6 a	10.9 b	6.3 a	NS‡
Sediment Loss (Kg ha^{-1})	319 b	106 a	424 b	1.7 a	***
Net Infiltration (mm)	78 a	86 b	70 a	94 b	NS
Mean Sediment Conc. (g L^{-1})	0.5 b	0.2 a	0.8 b	0.1 a	***
Furrow Advance (min)	178 a	209 a	148 a	239 b	NS
Irrigation 2 (repeat-1 irrigation furrows)					
Mean Outflow (L min^{-1})	10.6 a	9.6 a	10.7 a	9.6 a	NS
Sediment Loss (Kg ha^{-1})	471 b	223 a	693 b	1 a	***
Net Infiltration (mm)	51 a	56 a	50 a	57 a	NS
Mean Sediment Conc. (g L^{-1})	0.8 b	0.4 a	1.2 b	0.0 a	***
Furrow Advance (min)	62 b	75 a	63 a	74 a	NS
Irrigation 3, 4, 5 (repeat irrigation furrows)					
Mean Outflow (L min^{-1})	9.4 a	9.2 a	9.3 a	9.4 a	NS
Sediment Loss (Kg ha^{-1})	42 a	21 a	61 b	1.9 a	NS
Net Infiltration (mm)	61 a	61 a	60 a	62 a	NS
Mean Sediment Conc. (g L^{-1})	0.1 a	0.0 a	0.1 b	0.0 a	NS
Furrow Advance (min)	119 a	138 b	106 a	151 b	NS

† For a given straw-level or PAM-level comparison, values within a row with the same letter are not significantly different.

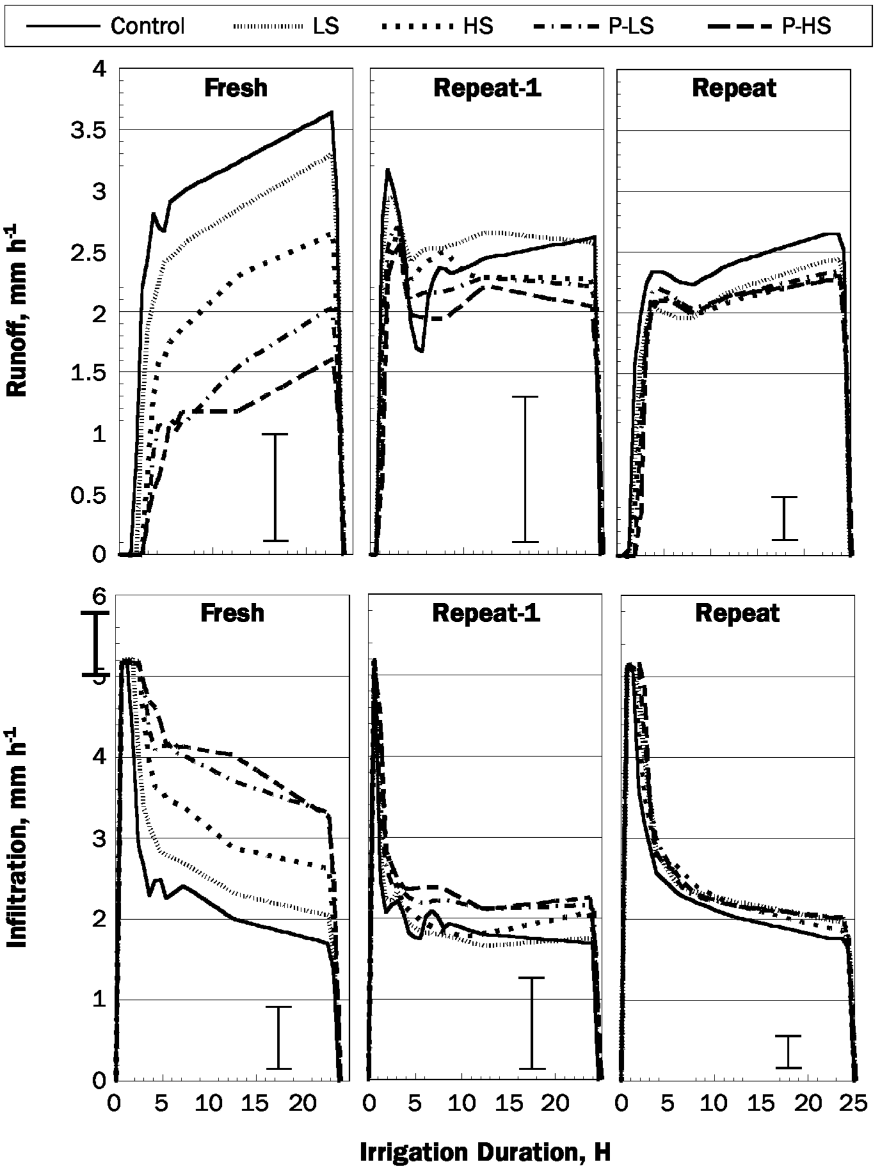
‡ NS, nonsignificant; ***, P □ 0.001

Results and Discussion

Relative to untreated control furrows, the addition of straw or straw+PAM increased net infiltration and advance time for freshly formed furrows in Irrigation 1, and greatly reduced erosion and sediment loss for all irrigations (Table 2). Analysis of variance showed that main effects, straw or PAM application rate, significantly influenced mean outflow rate, net infiltration, furrow advance, mean runoff sediment concentration, and sediment loss during Irrigation 1 on fresh furrows (Tables 2 and 3). In subsequent irrigations, however, straw rate or PAM application had less effect on furrow processes. In the last three irrigations (Irrigations 3, 4, and 5), straw rate affected only furrow advance time, while PAM rate influenced sediment loss, mean sediment concentration, and advance time (Table 3). We found significant straw × PAM interactions only for sediment loss and mean runoff sediment concentration, and only for irrigation on fresh (Irrigation 1) and first repeat furrows (Irrigation 2).

Comparison with untreated controls. Duration plots for fresh furrows demonstrate that mean outflow rate decreased and infiltration rate increased progressively with increasing amounts of straw applied, and again when

Figure 1
Treatment runoff and infiltration rates during Irrigation 1 on fresh furrows (fresh); Irrigation 2, on previously irrigated but undisturbed furrows (repeat-1); and Irrigations 3, 4, and 5, the last three repeat irrigations (repeat). Bars indicate upper and lower mean 95% confidence limits for duration values. (Treatments: LS = low straw; HS = high straw; P-LS = PAM-low straw; P-HS = PAM-high straw.)



PAM was applied (Figure 1). During the last three irrigations, however, differences among the straw and PAM+straw treated furrows disappeared and the group differed only slightly from control furrows. Similarly, during the last three irrigations when soil erosion in control furrows was at a minimum, we observed few differences in runoff sediment concentrations and cumulative soil losses among straw and PAM+straw treatments (Figure 2). Note that the sharp decline and rebound in runoff for controls in the Repeat-1 irrigation (Figure 1) resulted when a plugged valve temporarily decreased inflow into one of the control furrows.

On fresh furrows (Irrigation 1), straw application on average reduced sediment loss by 86%, reduced mean sediment concentration by 81%, and increased infiltration 1.3×, and increased furrow advance time 1.5×, compared to untreated control furrows (Tables 2 and 3). On first repeat furrows (Irrigation 2) on average, straw alone reduced sediment loss by 74% and sediment concentration by 73% relative to controls. For the last three repeat irrigations (Irrigations 3, 4, and 5), the straw-induced reduction in sediment loss and concentration was nearly 94%, compared to controls.

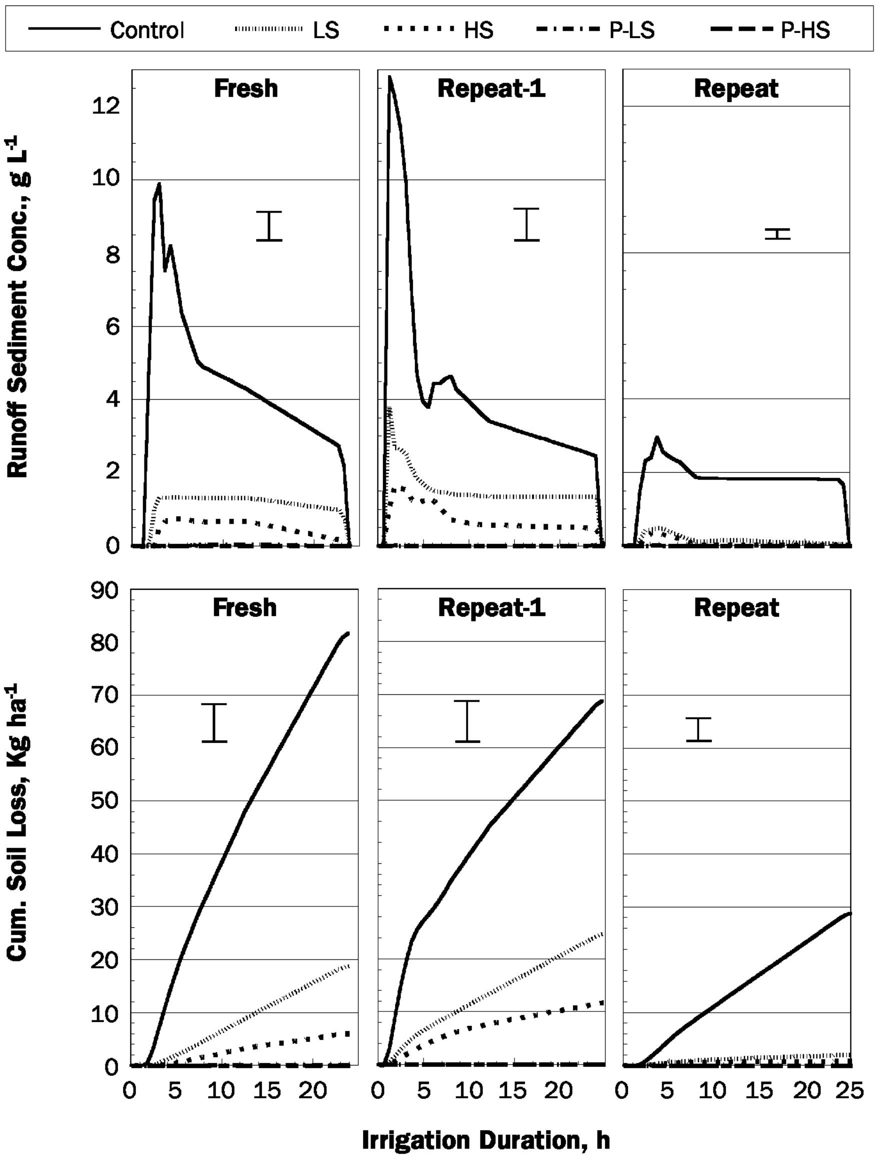
The PAM+straw treatment had a greater impact than straw alone. On fresh furrows (Irrigation 1), PAM+straw reduced sediment loss and mean sediment concentration by nearly 100%, reduced mean outflow rate by 54%, and increased infiltration 1.7× and furrow advance time 2.3×, compared to untreated control furrows. A similar near 100% reduction for sediment loss and concentration was observed in Irrigations 2, 3, 4, and 5 (Table 2).

Straw effects. This main effect examined the influence of the high straw treatment relative to that of the low straw. When averaged over both PAM rates on fresh furrows (Irrigation 1), tripling the straw application rate increased net infiltration 1.1×, decreased mean outflow by 20%, decreased sediment loss by 70%, and mean sediment concentration by 60% (Table 3). For later, repeat irrigations, increasing straw rate affected only the furrow advance period, increasing it by 1.2×.

PAM effects. This main effect examined the influence of the PAM+straw treatment relative to that of the straw only. When averaged over both straw rates on fresh furrows (Irrigation 1), PAM+straw increased net infiltration 1.3×, decreased mean outflow by 42%, and increased the furrow advance time 1.6×. PAM+straw also decreased sediment loss by more than 99%, and mean runoff sediment concentration by 88%, compared to straw-only treatments (Table 3). For repeat furrows (Irrigations 3, 4, and 5), PAM application to furrows containing straw significantly decreased sediment loss (97%) and mean runoff sediment concentration (~100%), but because furrow erosion rates were generally lower in repeat irrigations, the numerical differences between treatments (straw alone vs straw+PAM) were small. In these later repeat irrigations, PAM increased furrow advance time (1.4×) relative to straw-only furrows.

PAM notably influenced sediment and straw residue transport in furrows. Compared to control and straw-only treatments, the cross-section of PAM-straw furrows near the outflow ends showed little evidence of sediment transport and deposition (Figure 4). PAM also helped to prevent

Figure 2
Treatment runoff sediment concentrations and cumulative sediment loss in runoff during Irrigation 1 on fresh furrows (fresh); Irrigation 2, on previously irrigated but undisturbed furrows (repeat-1); and Irrigations 3, 4, and 5, the last three repeat irrigations (repeat). Note: Cumulative soil losses for P-LS and P-HS treatments were 0.09 kg ha^{-1} on fresh furrows and 0.03 kg ha^{-1} for repeat-1 and repeat furrows. Bars indicate upper and lower mean 95% confidence limits for duration values. (Treatments: LS = low straw; HS = high straw; P-LS = PAM-low straw; P-HS = PAM-high straw.)



movement of the straw, which we emphasize was not pressed or incorporated into furrow soils. In straw-only furrows, the straw tended to move downstream where it accumulated with sediment to form dams. The turbulence created when the furrow stream bypassed or overtopped the blockage caused additional erosion. The reaches stripped of straw were also more susceptible to erosion. Water that backed up behind the restrictions increased furrow-wetted perimeters and caused maximum local infiltration, which decreased irrigation uniformity.

Straw X PAM interaction. The ANOVA showed a significant interaction between straw and PAM main effects only in Irrigations 1 and 2 for runoff sediment loss and concentration parameters (Table 3). PAM had a greater relative impact on runoff sediment losses and concentrations in low straw furrows than in high straw furrows (Table 2).

The 30 g m^{-1} (0.32 oz ft^{-1}) straw-only treatment on fresh furrows produced slightly smaller infiltration increases (1.4× vs. 1.6×) and greater soil loss reductions (93% vs. 87%) than a 45 g m^{-1} (0.48 oz ft^{-1}) pressed-in straw mulch application reported by Shock et al. (1997). The two treatments produced similar soil loss reductions in repeat irrigations, however, the Shock et al. (1997) straw treatment continued to enhance infiltration during repeat irrigations, while our straw-only application had little effect (Table 2). This difference in efficacy does not appear to be related to straw anchoring; PAM applied in our straw+PAM treatment prevented straw movement in the furrows, yet it did not enhance furrow infiltration during repeat irrigations (Figure 1).

The effect likely resulted from the greater mass of straw, lower inflow rates, and more frequent irrigations applied to the Shock et al. (1997) 45 g m^{-1} (0.48 oz ft^{-1}) straw-treated furrows, relative to our straw-only treatment. Furrow inflow rates for the 45 g m^{-1} (0.48 oz ft^{-1}) straw treatment were one third of that applied to our 30 g m^{-1} (0.32 oz ft^{-1}) straw-only furrows. Brown (1985) reported that decreasing stream size in furrows containing straw produced greater infiltration gains, particularly during later irrigations. Furthermore, weekly irrigations in the Shock et al. (1997) study maintained furrow soil moisture levels at relatively high levels. Relative to bare furrows, the 45 g m^{-1} (0.48 oz ft^{-1}) straw-mulched soils experienced less evaporation and stayed wetter, which better stabilized them during the next irrigation, and its attendant rapid rewetting event (Kemper et al., 1985). Greater soil stability, as evident by low sediment loss, tended to increase furrow infiltration.

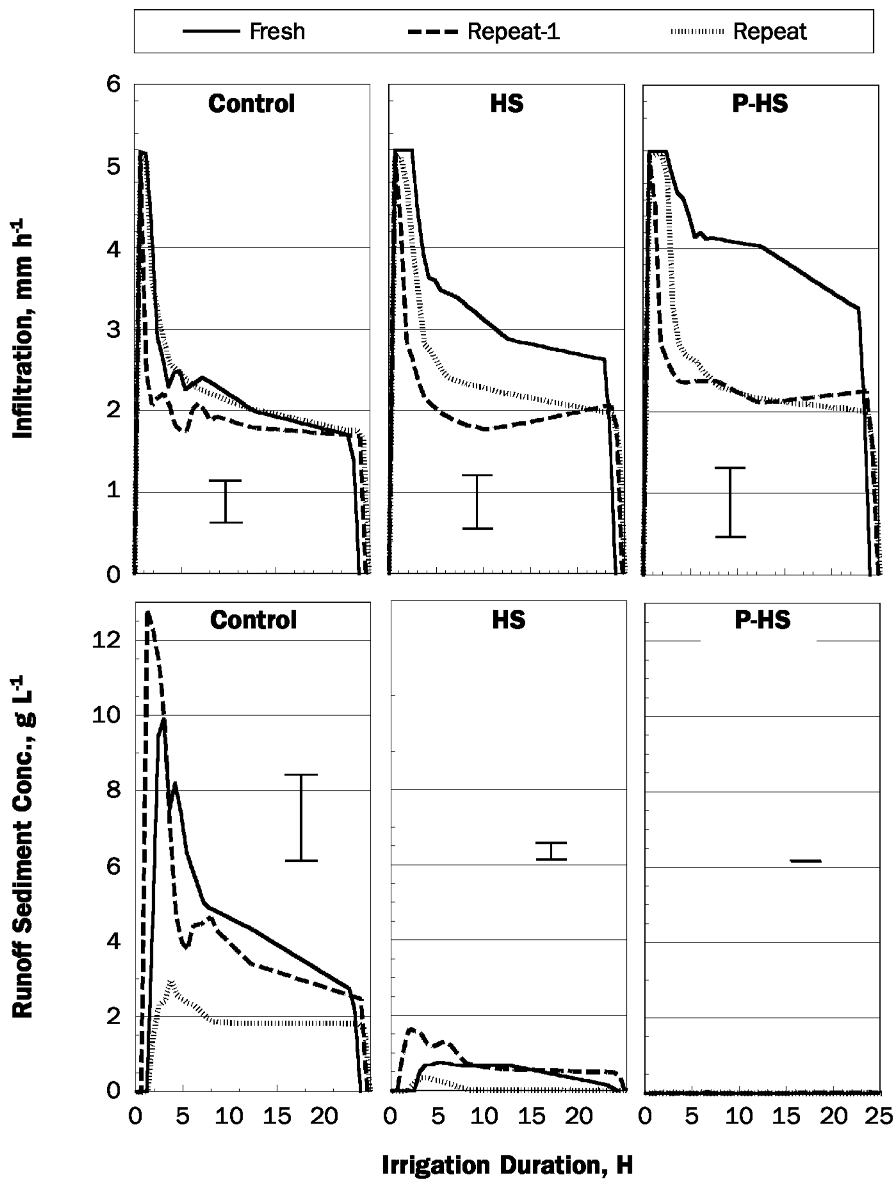
The addition of both PAM and straw to furrows dramatically decreased erosion and stream sediment concentrations in all irrigations (Figure 3). The treatment increased infiltration rates during irrigations on fresh furrows (Irrigation 1) compared to controls, but had relatively little effect on infiltration in repeat irrigations (Figure 3). Three important processes affect surface sealing and infiltration in freshly cultivated furrows: 1) rapid wetting breaks down surface soil aggregates and sediment is deposited on the wetted perimeter (Eisenhauer, 1984); 2) dispersed sediment and microaggregates are suspended in the furrow stream, move into soil with infiltrating water, and clog soil pores (Brown et al., 1988); and 3) soil consolidation upon drying reduces soil porosity and permeability in subsequent irrigation events (Saleh and Hanks, 1989).

During irrigation of fresh, untreated furrows, aggregate breakdown, deposition, and pore clogging, as evidenced by high stream sediment concentrations (Kemper et al., 1985; Segeren and Trout, 1991), caused a steep decline in infiltration within four to five hours after irrigation began (Figure 3). Straw reduced furrow stream velocity, sediment concentration, and sediment transport; hence infiltration remained higher in straw-treated furrows than in controls. Adding PAM to the straw treatment provided extra protection against seal formation by preventing aggregate break down, flocculating dispersed sediment, and virtually eliminating stream sediment load. Thus, infiltration was greatest in PAM+straw treated fresh furrows (Figure 3). Subsequent consolidation of soils, upon drying, reduced porosity and permanently reduced the infiltration potential in both untreated and treated furrows. Treatment effects on soil sealing and infiltration patterns in repeat-irrigated furrows were more similar, and mean outflow rates in treated furrows during repeat irrigations were higher than in Irrigation 1, suggesting that stream velocities were greater in repeat irrigations. Hence, infiltration rates in treated repeat irrigated furrows may have been lower in response to increased stream velocities (Trout, 1992).

PAM's capacity for holding straw residue in place is a potential benefit to irrigators because applied straw stays where protection is required, furrow conformation is better maintained, and the tendency for furrow stream blockage and escape is reduced. Accordingly, farmers whose irrigation furrows contain significant quantities of crop residues could benefit from using PAM, regardless of whether straw was intentionally applied or the result of other practices such as minimum tillage. The low straw rate was approximately equivalent to 30% surface cover (conservation tillage) and the high straw rate provided about 50% surface cover, which would be similar to direct seeding. Farmers may wish to forego the time and expense of plowing their furrow-irrigated fields, and instead, implement reduced tillage practices followed by PAM-treated irrigations.

Figure 3

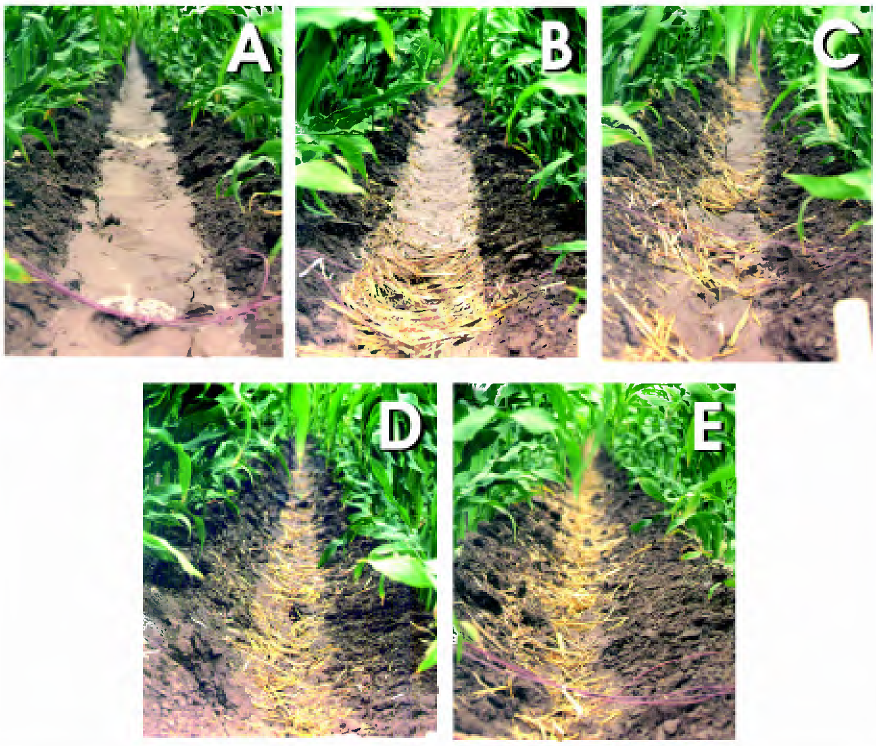
Comparing infiltration rates and runoff sediment concentrations during fresh, repeat-1, and repeat irrigations for three treatments, control, high-straw (HS), and PAM/high straw (P-HS). Note: Runoff sediment concentrations for the P-HS treatments were _0.02 g L⁻¹. Bars indicate upper and lower mean 95% confidence limits for duration values.



PAM may have stabilized straw residues in furrows via several mechanisms. The polyacrylamide decreased furrow stream velocity more than did straw alone (indicated by increased furrow advance times). This decreased the tractive force of the flows and likely contributed to reduced detachment and transport of both sediment and straw in PAM-straw relative to straw-only furrows. PAM treatment potentially decreased drag forces in the turbulent furrow streams (Toms, 1977; Khalil et al., 2002), a phenomenon which could lead to reduced straw movement in furrows. Finally, because PAM binds both plant (Sojka et al., 2003) and soil materials, it may have stabilized straw residues in furrows by increasing their adhesion to soil surfaces. Because the PAM-straw treatment notably reduced furrow advance rates, it also increased the range of infiltration opportunity times experienced by different furrow reaches. While advance times for straw-PAM furrows

Figure 4

View upstream from the outflow end of furrows showing characteristic amounts of sediment and straw residue transported from upstream reaches and deposited there for control (A), low straw (B), high straw (C), PAM/low straw (D), and PAM/high straw (E) treatments. Photos were taken after Irrigation 1.



in this study were acceptable (<25% of the irrigation period), if the treatment is applied to flatter fields and longer furrows, one may need to increase inflows in order to avoid deleterious effects on irrigation application uniformity. With PAM, inflows can be increased without increasing furrow erosion.

Under field and irrigation conditions used in this study, increased straw applications did not hinder the erosion and infiltration-enhancing capabilities of PAM. Straw positively influenced PAM efficacy via changes to furrow hydraulics, reducing furrow stream velocity and expanding the wetted perimeter. These physical effects overcame any negative impacts that straw-induced water chemistry changes may have produced. While not seen under conditions of this study, water-chemistry effects of straw applications on PAM efficacy may occur in irrigations with more severe furrow erosion potential (e.g., in irrigation furrows with steeper slopes or higher inflow rates).

Summary and Conclusion

In this study, we applied straw to furrows at two rates, 64 and 196 kg ha^{-1} (57 and 175 lb ac^{-1}) whole field basis, both alone and in combination with a 1 kg ha^{-1} (0.9 lb ac^{-1}) PAM treatment. These were compared to untreated furrows.

Results from this and other studies (Shock et al., 1997; Brown, 1985) indicate that the straw application rates needed to obtain season-long furrow infiltration increases (1.4× or greater) in both fresh and repeat irrigated furrows may be three to four times greater than straw rates needed to achieve season-long (>93%) reductions in runoff soil losses. Thus, if season-long infiltration enhancements are desired in addition to erosion control, farmers should try applying a higher straw rate or reducing furrow inflow rates. If control of furrow erosion is desired, with minimal effects on infiltration and furrow advance rate, one should apply a lower straw rate.

Under conditions of this study, the application of PAM+straw treatments produced greater net infiltration and/or soil loss reductions than straw-only treatments, but only during the first two irrigations after straw was applied. Thus, farmers can reduce cost of PAM-straw treatment regimes without reducing erosion control efficacy by halting PAM applications after the first few irrigations. Increasing straw residues in irrigation furrows did not decrease PAM's erosion control effectiveness under irrigation conditions present in this study. When both PAM and straw were applied, straw rates exceeding 10 g m^{-1} (0.10 oz ft^{-1}) of furrow (64 kg ha^{-1} [57 lb ac^{-1}] whole field basis) produced no additional erosion control benefit.

Combining PAM applications in irrigation furrows with crop residues provided several benefits. The addition of PAM to straw-mulch applications virtually eliminated runoff soil losses. The amount of straw needed in PAM+straw applications was less than one-third that needed for straw-only applications to achieve similar erosion control. Whether crop residues are intentionally placed, or present as a result of other management practices, PAM can be used to prevent the movement of both sediment and straw, which preserves furrow shape and prevents blockage, overtopping, and crossover in furrows.

Endnote

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

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References Cited

Aarstad, J.S. and D.E. Miller. 1981. Effects of small amounts of residue on furrow erosion. Soil Science Society of America Journal 45(1):116-118.

Berg, R. 1984. Straw residue to control furrow erosion on sloping irrigated cropland. Journal of Soil and Water Conservation 39(1):58-60.

Brown, M.J. 1985. Effect of grain straw and furrow irrigation stream size on soil erosion and infiltration. Journal of Soil and Water Conservation 40(4):389-391.

Brown, M.J., W.D. Kemper, J.J. Trout, and A.S. Humpherys. 1988. Sediment, erosion and water intake in furrows. Irrigation Science 9(1):45-55.

Eisenhauer, D.E. 1984. Surface sealing and infiltration with surface irrigation. Ph.D. dissertation. Colorado State University, Fort Collins (Dissertation abstract 84-17087).

Evans, R.G., B.N. Girgin, J.F. Chenoweth, and M.W. Kroeger. 1995. Surge irrigation with residues to reduce soil erosion. Agricultural Water Management 27:283-297.

Kalbitz, K., S. Solinger, J.H. Park, B. Michalzik, and E. Matzner. 2000. Controls on the dynamics of dissolved organic matter in soils: A review. Soil Science 165(4):277-304.

Kemper, W.D., T.J. Trout, M.J. Brown, and R.C. Rosenau. 1985. Furrow erosion and water and soil management. Transactions of the American Society of Agricultural Engineers 28(5):1564-1572.

Khalil, M.F., S.Z. Kasseb, A.A. Elmiligui, and F.A. Naoum. 2002. Applications of drag reducing polymers in sprinkler irrigation systems: Sprinkler head performance. Journal of Irrigation and Drainage Engineering 128(3):147-152.

Lentz, R.D. and R.E. Sojka. 1994. Field results using polyacrylamide to manage furrow erosion and infiltration. Soil Science 158(4):274-282.

Lentz, R.D. and R.E. Sojka. 1995. Monitoring software for pollutant components in furrow irrigation runoff. Pp. 123-127. *In:* L. Ahuja, et al.(ed.). Computer Applications in Water Management, workshop proceedings, May 23-25, 1995. Colorado State University Water Resources Research Institute Information Series No. 79. Colorado State University, Fort Collins, Colorado.

Lentz, R.D., R.E. Sojka, and J.A. Foerster. 1996. Estimating polyacrylamide concentration in irrigation water. Journal of Environmental Quality 25(5):1015-1024.

Lentz, R.D., R.E. Sojka, and C.W. Robbins. 1998. Reducing phosphorus losses from surface-irrigated fields: Emerging polyacrylamide technology. Journal of Environmental Quality 27(2):305-312.

Lentz, R.D., R.E. Sojka, and C.W. Ross. 2000. Polyacrylamide charge and molecular weight effects on sediment loss and infiltration in treated irrigation furrows. International Journal of Sediment Research 15(1):17-30.

Miller, D.E. and J.S. Aarstad. 1971. Furrow infiltration rates as affected by incorporation of straw or furrow cultivation. Soil Science Society of America proceedings 35(3):492-495.

Saleh, A. and R.J. Hanks. 1989. Field evaluation of soil hydraulic property changes caused by surge water application. Soil Science Society of America Journal 53(5):1526-1530.

Segeren, A.G. and T.J. Trout. 1991. Hydraulic resistance of soil surface seals in irrigated furrows. Soil Science Society of America Journal 55(3):640-646.

Shock, C.E., J.H. Hobson, M. Seddigh, B.M. Shock, T.D. Stieber, and L.D. Saunders. 1997. Mechanical straw mulching of irrigation furrows: soil erosion and nutrient losses. Agronomy Journal 89(6):887-893.

Shock, C.E. and B.M. Shock. 1998. Comparative effectiveness of polyacrylamide and straw mulch to control erosion and enhance water infiltration. Pp. 429-444 In: A. Wallace and R.E. Terry (eds.). Handbook of Soil Conditioners, Marcel Dekker, Inc. New York, New York.

Sojka, R.E. and R.D. Lentz, R.D. 1997. Reducing furrow irrigation erosion with polyacrylamide (PAM). Journal of Production Agriculture 10(1/2):47-52.

Sojka, R.E., D.W. Morishita, J.A. Foerster, and M.J. Willie. 2003. Weed seed transport and weed establishment as affected by PAM in furrow-irrigated corn. Journal of Soil and Water Conservation 58(5):307-314.

Toms, B.A. 1977. On the early experiments on drag reduction by polymers. Physics of Fluids 20:S3-S5.

Trout, T.J. 1992. Flow velocity and wetted perimeter effects on furrow infiltration. Transactions of the American Society of Agricultural Engineers 35(3):855-863.

Trout, T.J. and B.E. Mackey. 1988. Inflow-outflow infiltration measurement accuracy. American Society of Civil Engineers Journal of Irrigation and Drainage Engineering 114(2):256-265.

Trout, T.J., R.E. Sojka, and R.D. Lentz. 1995. Polyacrylamide effect on furrow erosion and infiltration. Transactions of the American Society of Agricultural Engineers 38(3):761-765.