Fate and Efficacy of Polyacrylamide Applied in Furrow Irrigation: Full-Advance and Continuous Treatments

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ABSTRACT

Polyacrylamide (PAM) is applied to 400 000 irrigated hectares annually in the USA to control irrigation-induced erosion, yet the fate of dissolved PAM applied in irrigation water is not well documented. We determined the fate of PAM added to furrow streams under two treatments: *Initial-10*, 10 mg L^{-1} PAM product applied only during the initial hours of the irrigation, and *Cont-1*, 1.0 mg L^{-1} PAM product applied continuously during the entire irrigation. The study measured PAM concentrations in 167-m-long PAM-treated furrow streams and along a 530-m tail ditch that received this runoff. Soil was Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid) with 1.5% slope. Samples were taken at three times during the irrigations, both during and after PAM application. Polyacrylamide was adsorbed to soil and removed from solution as the streams traversed the soil-lined channels. The removal rate increased with stream sediment concentration. Stream sediment concentrations were higher when PAM concentrations were <2 mg L^{-1} a.i., for early irrigations, and when untreated tributary flows combined with the stream. In these cases, PAM concentration decreased to undetectable levels over the flow lengths used in this study. When inflows contained >6 mg L^{-1} PAM a.i., stream sediment concentrations were minimal and PAM concentrations did not change down the furrow, though they decreased to undetectable levels within 0.5 h after application ceased. One percent of applied PAM was lost in tail-ditch runoff. This loss could have been eliminated by treating only the furrow advance or not treating the last two irrigations.

An increased awareness and heightened state and federal scrutiny of agriculture-related nonpoint-source contributions has encouraged producers in the western USA to reduce irrigation-induced erosion and runoff losses coming from their fields. Increasingly, farm managers are adopting PAM technology as an effective, convenient, and economical means of reducing erosion and improving runoff water quality from furrow-irrigated and sprinkle-irrigated fields. One practice recommended as a Natural Resources Conservation Service (NRCS) conservation standard applies 10 mg L^{-1} PAM product to irrigation water inflows only during the initial advance of water across the field, then untreated water is used to finish the remainder of the irrigation. We term this approach as the Initial-10. The Initial-10 treatment reduces runoff sediment, P, and N losses by 85 to 99%, lowers levels of chemical and biological oxygen demand in runoff by 83% (Lentz et al., 1992, 1998; Lentz and Sojka, 1994; Bahr et al., 1996), and decreases soil-sorbed pesticide losses in furrow runoff (Agassi et al., 1995; Bahr et al., 1996). Polyacrylamide also reduced microbial biomass in furrow streams (Sojka and Entry, 2000).

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Published in J. Environ. Qual. 31:661–670 (2002).

An alternative application strategy, termed Cont-1, continuously adds 1 mg L^{-1} PAM product to irrigation inflows during the entire irrigation period. The Cont-1 approach was initially employed in California and was preferred because it applied PAM to irrigation water at low concentrations and PAM's continual presence in the furrow stream may have better prevented soil loss during the late hours of the irrigation. Lentz and Sojka (2000) reported that Initial-10 and continuous PAM applications of 1 to 2 mg L^{-1} controlled furrow erosion similarly on 1.5% sloping fields.

Polyacrylamide has low toxicity to aquatic and terrestrial organisms at concentrations used in this agricultural application (Barvenik, 1994; Deskin, 1996). Concerns about the use of PAM in irrigated agriculture persist, however, because it is not known whether applied PAM is transported via irrigation return flows to natural surface waters. Often, irrigation runoff from individual fields enters a wastewater ditch, which collects runoff and sediment from several farms. Some of the wastewater may be used by downstream irrigators. Some may enter a main irrigation return-flow channel, which ultimately conveys this water and runoff from other "sub-watersheds" in the irrigation district to a natural surface drainage.

The linear PAM molecule assumes the form of a hydrated random coil when dissolved in water. Solvated PAM molecules in the furrow stream collide with soil particles when treated water infiltrates into soil or when turbulent flow drives the molecules against entrained sediment or the wetted soil perimeter. The dissolved high molecular weight polymers are readily adsorbed to soil particles via electrostatic, hydrogen, and chemical bonding, and by displacement of inner solvation-sphere water molecules (LaMer and Healy, 1963; Mortland, 1970; Jin et al., 1987; Malik et al., 1991; Laird, 1997). As a result, incoming PAM is bound to soil in the upper 1 to 5 cm of the profile (Malik et al., 1991). Dry soil adsorbs more polymer than wet soils because sorbed water reduces the number of potential soil binding sites (Chang et al., 1991). Polyacrylamide is adsorbed to and flocculates soils suspended in water. Polymer adsorption on soil occurs rapidly during the first minutes of exposure, but may continue at a reduced rate for several hours or days (Van de Ven, 1994).

In batch tests (soil, water, and dissolved PAM mixed in a shaker), Nadler et al. (1992) reported that little or no polymer desorbed from the soil while it remained wet, and the polymer became irreversibly bonded to the soil upon drying. In flowing systems, Lee and Fuller

Abbreviations: Cont-1, 1 mg L^{-1} polyacrylamide product (0.8 mg L^{-1} a.i.) applied continuously to furrow inflows; Initial-10, 10 mg L^{-1} polyacrylamide product (8 mg L^{-1} a.i.) applied to initial irrigation inflows only; PAM, water-soluble anionic polyacrylamide.

Table 1. Irrigation parameters for study. Polyacrylamide (PAM) Initial-10 added an aqueous PAM solution to initial irrigation inflows at 10 mg L^{-1} (whole-product basis), and Cont-1 applied 1 mg L^{-1} PAM during the entire irrigation.

Irrigation	Date	Irrigation furrow type	Irrigation length	Inflow rates	Average advance	Soil water, 0–3 cm
			h	L m^{-1}	min	kg kg^{-1}
1	5 July 1995	newly formed	12	23–>15	32.3	7.0
2	17 July 1995	newly formed	12	23–>15	44.2	6.7
3†	26 July 1995	newly formed	12	15	–	–
4‡	31 July 1995	newly formed	12	23–>15	67.6	5.4
5	7 Aug. 1995	repeat	12	23–>15	44.1	13.7
6	14 Aug. 1995	repeat	12	23–>15	51.8	9.5
7†‡	23 Aug. 1995	repeat	12	15	–	–

† Nontreated nonmonitored irrigation.
‡ Irrigation switched to unused alternate furrows at this date.

(1985) found that polymer adsorption rate decreased with increasing velocity of flow. Polymer desorption did not occur under quiescent conditions, but was observed when the adsorbent material was subjected to flow shear. Desorption increased with increasing flow velocity (Lee and Fuller, 1985).

When furrow inflows were treated with 10 mg L^{-1} PAM and permitted to flow down the entire furrow, polymer concentration in runoff was 6 to 10 mg L^{-1} PAM (Lentz and Sojka, 1996). To our knowledge, no published research has described dissolved PAM transport within treated irrigation furrows or determined its fate in receiving tail-water ditches where it mixes with untreated runoff. The objective of this study was to determine dissolved PAM concentrations and mass losses in treated irrigation furrows and tail waters, and relate furrow PAM concentration to associated furrow sediment loads and infiltration. We also wished to determine how PAM transport in furrows may differ when inflows were treated with an initial 10 mg L^{-1} PAM application vs. a continuous 1 mg L^{-1} PAM application. It was hypothesized that (i) PAM concentrations in treated-furrow irrigation inflows decrease with distance downstream from the application point; (ii) PAM does not desorb from treated soil, so furrow stream concentrations rapidly decline once the application ceases; and (iii) PAM effects on furrow erosion and infiltration are a function of its concentration in the furrow stream.

MATERIALS AND METHODS

The study was done on a 0.34-ha field located near Kimberly, Idaho. Soil was a Portneuf silt loam. The silt loam surface horizon had 100 g kg^{-1} clay, 700 g kg^{-1} silt, and 10 to 13 g kg^{-1} organic matter; a cation exchange capacity of 190 $mmol_c$ kg^{-1}; saturated-paste-extract electrical conductivity (EC) of 0.07 S m^{-1}; exchangeable sodium percentage (ESP) of 1.5; pH of 7.7; and calcium carbonate equivalent of 5%. Irrigation furrows were 167.2 m long with 1.5% slope. The field plot was disked twice, roller-harrowed, and planted to bean (*Phaseolus vulgaris* L.). Irrigation furrows at 0.56-m spacing were formed in wheel-trafficked lanes using a v-shaped sled. Only every other furrow was watered during a given irrigation, resulting in an irrigation furrow spacing of 1.12 m.

A commercially available granular anionic PAM with 18% charge density and molecular weight of 12 to 15 Mg mol^{-1} (Superfloc A-836; CYTEC Industries, Stamford, CT[1]) was added dry to irrigation water or used to produce aqueous stock solutions. Polyacrylamide stock solutions were added to furrow streams on a whole-product basis to attain target concentrations. Since PAM granules contained 80% active ingredient, actual furrow stream PAM concentration for the whole-product 10 mg L^{-1} target was 8 mg L^{-1}, and for the 1 mg L^{-1} target, 0.8 mg L^{-1}.

Two PAM treatments were compared: the Initial-10 and the alternative Cont-1. Note that the Initial-10 treatment applied PAM for 1.2 to 2 h longer than recommended by the NRCS standard, which curtails PAM application immediately after runoff begins. This extended application allowed time for furrow stream PAM concentration to approach equilibrium, facilitated simultaneous sampling, and ensured uniform tail-water flow conditions across all irrigations. Hence, we used nearly two times more PAM here than is typically applied in Initial-10 treated irrigations (Table 1). Of seven irrigations applied, five were treated and monitored, including sampling of furrow and wastewater streams for PAM analysis (Table 1).

The completely randomized design consisted of a control and two PAM application treatments. The experimental unit was a single irrigation furrow. Samples for PAM analysis were taken from each treated furrow at three positions, 3 m (top), 76 m (middle), and 167 m (bottom) downstream from the inflow end (Fig. 1). The samples were collected from the end of flumes placed in the furrows. Samples were taken at three times during the irrigation, at approximately 2, 3, and 7 h into the irrigation set. For the Initial-10, treatment times corresponded to −0.5, 0.5, and 5 h after the PAM application was curtailed. Therefore, for each irrigation, PAM furrow stream data comprised (2 PAM treatments) by (3 positions) by (3 times) by (6 replicates) = 108 samples. The PROC MIXED procedure (SAS Institute, 1997) was used to fit a split-split plot model separately for each irrigation; with *treatments* as main plots, *positions* as subplots, and *time* as sub-subplots. Degrees of freedom used in confidence intervals on the *treatment* by *time* by *position* means were adjusted by Huynh–Feldt ε values to account for lack of sphericity in the covariance structure across time. To stabilize variances, a square root transformation was applied to concentration and mass-loss values, after adding a small constant to avoid negative values.

During an irrigation, runoff from all six furrows (replicates) per treatment including controls passed into a collection ditch oriented perpendicular to the furrows (Fig. 1). The combined flow then entered a 530-m-long tail ditch. Occasional tail-water contributions from neighboring farms entered the tail ditch at locations >274 m down the ditch. The tail ditch was newly formed prior to the first irrigation, but left undisturbed (except for irrigation) for the remainder of the season. Runoff water was subsampled in triplicate at locations 0 (top), 93 (middle), and 154 m (bottom) down the tail ditch, at the same times as those collected from furrow streams. During each irrigation, stream water samples were taken at 2 h from the

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

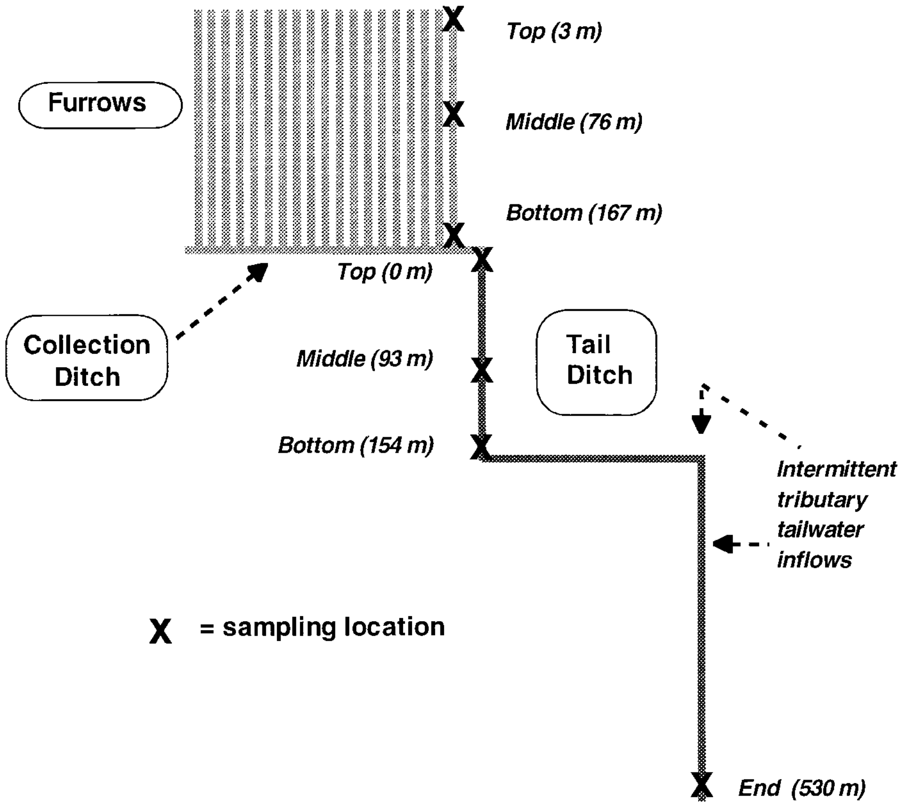

Fig. 1. Field plot showing sampling locations in furrows and tail-ditch streams.

end of the tail ditch, located 530 m downstream from the top. Tail-ditch-end samples were collected at 3 and 7 h times during Irrigations 4 and 5. Tail-ditch-end data were not included in the statistical model because the sample set was not complete, but were used to estimate mean cumulative PAM loss per irrigation at the tail-ditch-end position. A repeated measures analysis using means of triplicate subsamples produced Huynh–Feldt ε values >1, so a split plot analysis was employed to evaluate the three tail-ditch positions (top, middle, and bottom), with *time* as the main plot, *positions* as the subplots, and *irrigations* as the random effect. Confidence intervals ($P = 0.05$) were constructed on the *position* means. Early-season irrigation responses varied considerably from those late-season Irrigations 4, 5, and 6. Thus, a separate analysis for late-season irrigations employed orthogonal contrasts to test for tail-ditch position effects at the first sampling. For this analysis irrigations were considered a random effect. Finally, trends in tail-ditch responses from Irrigation 2 were examined by plotting means and confidence limits using variances from triplicate subsamples.

Irrigations and Monitoring

A gated pipe conveyed water to each furrow, and adjustable spigots controlled inflow rates. Initial irrigation inflows were set high to speed irrigation advance (Table 1). When water in all furrows had traversed the field, inflows for all treatments were simultaneously decreased to reduce runoff and sediment losses. Irrigation sets were 12 h long. Newly formed furrows were irrigated early in the season. If furrows were undisturbed by cultivation since the previous irrigation, these were termed repeat furrows. Repeat furrows were used mainly during late-season irrigations. Irrigation water supplied by the Twin Falls Irrigation District had an electrical conductivity of 0.05 S m^{-1} and sodium adsorption ratio (SAR) of 0.5 $[mmol_c\ L^{-1}]^{0.5}$. Polyacrylamide was added to irrigation water at a rate that produced the desired furrow stream target concentration, either by injecting a 300 mg L^{-1} (Cont-1) or 2400 mg L^{-1} (Initial-10) stock solution into the turbulent flow pouring from the gated pipe spigots. Furrow inflows, and stream flow rate and sediment concentrations were measured throughout each monitored irrigation at furrow top, middle, and bottom positions. Measurements were made at 30-min 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 >7 h 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). Runoff sediment was measured using the Imhoff cone technique (Sojka et al., 1992). Details of the flow and sediment monitoring procedure were given by Lentz et al. (1992). The computer program, WASHOUT (Lentz and Sojka, 1995), calculated runoff and PAM loads using measured flow rates and sediment and polymer concentrations. Runoff PAM loads were computed under the assumption that runoff component concentrations were constant between sampling intervals.

Sample Handling and Analysis

Sediment was removed from PAM furrow stream samples within 90 min of field sampling by centrifugation (10.2 RCF, 10 min, 10 to 15°C). We added small amounts of boric acid and 2-propanol to inhibit biologic activity and stabilize polymer present in the samples (Lentz et al., 1996). Polyacrylamide polymer concentrations were determined using a flocculation method (Lentz et al., 1996, protocol with Option 2). We employed the high-precision option, which required preparation of additional calibration standards for waters with varying sediment concentrations. The procedure could detect as little as 0.1 mg PAM L^{-1}. Precision was ±3% for solutions with <2.5 mg PAM L^{-1} and ±6% for solutions with >2.5 mg PAM L^{-1}.

RESULTS AND DISCUSSION

Erosion and Infiltration Effects

The Initial-10 treatment applied an average 1.8 kg ha^{-1} PAM (whole product) per irrigation, compared with 0.7 kg ha^{-1} for Cont-1 (Table 2). The PAM concentration in water entering Cont-1 furrows in Irrigation 1 was about one-fifth the target value, so those results from that treatment are not comparable. A total of 227 g PAM a.i. was applied to treated furrows at each irrigation (Irrigations 2, 4, 5, and 6), 27 g to each of the six Initial-10 furrows and 10.8 g to each of the six Cont-1 furrows.

In the first two irrigations, runoff sediment losses from untreated furrows were some of the highest observed for such fields (Lentz and Sojka, 1994, 2000). Initial-10 reduced furrow sediment loss by 74% in Irrigations 1 and 2, significantly more than the 25% reduction attained with Cont-1 in Irrigation 2 (Table 2). In this experiment, Initial-10 did not control sediment losses in the first two irrigations as successfully as the 92% previously observed by Lentz and Sojka (2000), even though their PAM applications continued for only 0.5 h after advance. Relative to that in the first two irrigations, erosion in subsequent irrigations was less and both Initial-10 and Cont-1 treatments were more effective in controlling sediment losses. In Irrigations 4, 5, and 6, Initial-10 reduced furrow sediment loss by 92% and Cont-1, 70%.

In early irrigations, PAM treatment had no effect on furrow infiltration (Table 2). However, an analysis combining data from Irrigations 2, 4, 5, and 6 showed that cumulative infiltration, as a percent of the total water applied, differed among treatments ($P = 0.0001$). The average cumulative infiltration for the treatments in decreasing order was: Cont-1(59%) > Initial-10 (51%) > Controls (47%). These results confirmed that the low-concentration continuous PAM treatment produced a larger net furrow infiltration increase than Initial-10, relative to untreated furrows (Lentz and Sojka, 2000). Santos and Serralheiro (2000) reported that the cumulative infiltration of their Cont-1 treatment trended higher than that of Initial-10, but could not establish a statistical separation.

Polyacrylamide Concentration in Furrow and Tail-Ditch Streams

Data from monitored Irrigations 2, 4, 5, and 6 were included in the statistical analysis because both PAM treatments in these irrigations met the concentration targets. For these irrigations, furrow stream PAM concentration differed significantly depending on main effects, that is, PAM treatments, furrow field positions, and time. The main-effect interaction terms were also significant for all irrigations, except *position* by *time* for Irrigations 5 and 6, and *treatment* by *position* by *time* for Irrigation 5 (Table 3).

While polymer was still being applied to Initial-10 furrows at 2 h, stream PAM concentration was 6 to 8 mg L^{-1} at each top, middle, and bottom furrow position. Initial-10 effectively controlled erosion and maintained low mean furrow stream sediment concentrations, averaging 0.2 mg L^{-1} (Table 4). Thus, little sediment was available to adsorb the polymer, and furrow stream PAM concentrations remained unchanged as the flow crossed the field. Thirty minutes after Initial-10 application ceased, the furrow stream PAM concentration had decreased to undetectable levels, with the exception of Irrigation 6 (Fig. 2). It is not clear why PAM concentrations in Irrigation 6 at 3 h and 7 h did not decline to near zero, as occurred for previous irrigations. The response was not restricted to one or two furrows. It was consistent across all replicates.

Table 2. Hydraulic, sediment, and polyacrylamide (PAM) application parameters.

Irrigation (date)	Treatment	Water applied	Infiltration	Runoff	Advance time	Sediment loss	PAM application†
		mm			min	Mg ha^{-1}	kg ha^{-1}
1 (5 July 1995)	control	66.9	26.8a‡	40.2	30.7a	5.61a	0.00
	PAM-$C_{0.2}$§	65.8	28.3a	37.5	32.0a	4.25a	0.14
	PAM-I_{10}	67.7	30.2a	37.6	26.3a	0.75b	1.73
2 (17 July 1995)	control	65.7	30.0a	35.8	43.7a	4.94a	0.00
	PAM-C1	65.7	31.4a	31.4	45.3a	3.72a	0.66
	PAM-I_{10}	66.4	31.7a	34.8	43.7a	2.00b	1.71
4 (31 July 1995)	control	75.5	33.9c	41.5	54.8b	3.75a	0.00
	PAM-C1	75.2	48.8a	26.4	84.5a	1.01b	0.79
	PAM-I_{10}	75.2	41.0b	34.1	63.5b	0.37b	1.79
5 (7 Aug. 1995)	control	66.5	32.4b	34.1	37.5b	2.43a	0.00
	PAM-C1	65.0	37.7a	27.4	45.0a	0.99b	0.79
	PAM-I_{10}	66.3	33.4ab	33.0	49.7a	0.25b	2.04
6 (14 Aug. 1995)	control	64.9	31.9b	33.0	42.8b	1.92a	0.00
	PAM-C1	66.6	40.3a	26.3	46.7b	0.46b	0.66
	PAM-I_{10}	68.5	34.0b	34.5	66.2a	0.04b	1.68
Mean (5 irrigations)	control	67.9	31.0	36.9	41.9	3.73	0.00
Mean (4 irrigations)‡	PAM-C1	68.1	40.3	27.9	55.4	1.54	0.73
Mean (5 irrigations)	PAM-I_{10}	68.8	34.1	34.8	51.9	0.68	1.79

† Whole-product basis.
‡ Similar lower-case letters indicate nonsignificant differences between treatments in each irrigation ($P = 0.05$).
§ Furrow stream PAM concentration did not attain 1 mg L^{-1} target value, instead was 0.2. This irrigation was not used to calculate irrigation mean values.

Table 3. The influence of polyacrylamide (PAM) treatment, field position (POS: upper, middle, and bottom locations in furrows), and sampling time during irrigation (TIME: 2, 3, and 7 h into the irrigation) on PAM concentration and mass-loss rates in furrow streams. Table gives *P* values for main effect and interaction terms that were derived from an analysis of variance.

	Dependent variable							
	PAM concentration				PAM mass loss			
Source of variation	Irrigation 2	Irrigation 4	Irrigation 5	Irrigation 6	Irrigation 2	Irrigation 4	Irrigation 5	Irrigation 6
TRT	***	***	***	***	***	***	***	***
POS	***	***	***	***	***	***	***	***
TIME	***	***	***	*	***	***	***	***
TRT × POS	***	***	***	***	***	***	***	NS
TRT × TIME	***	***	***	***	***	***	***	***
POS × TIME	**	**	NS	NS	***	***	***	***
TRT × POS × TIME	***	***	NS	**	***	**	**	NS

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.

Compared with the Initial-10, PAM concentration in the Cont-1 treatments changed less abruptly between sampling times during irrigation, but changed more with sampling position. At 2 h, inflow PAM concentration for Cont-1 furrows was 0.9 mg L^{-1} a.i. (Fig. 3) and mean stream sediment concentrations were nearly 40 times greater (Table 4) than for Initial-10 furrows. The greater sediment availability increased PAM adsorption onto entrained soil and decreased PAM concentration in the stream as it flowed across the field. Thus, 2-h Cont-1 furrow-stream PAM concentrations had declined to undetectable levels by the time the flow had traveled to the mid-furrow position.

The rate of decrease in PAM concentration with distance downstream was greatest during the first 2 to 3 h of an irrigation relative to Hours 7 through 12, and greatest during Irrigations 2 and 4 than for Irrigations 5 and 6 (Fig. 3). Thus, by the 7-h sampling time in Irrigation 6, we observed no change in the PAM concentration as the stream traversed the furrow. This pattern of changing PAM concentration paralleled that of furrow stream sediment. On average, sediment concentrations in Cont-1 furrow streams progressively decreased with time; from 7.7 g L^{-1} during the initial hours of the irrigations to 4.2 g L^{-1} at irrigations' end, and from 12.6 g L^{-1} in Irrigation 2 to 0.9 g L^{-1} in Irrigation 6 (Table 4). Less PAM would be adsorbed to soil solids and be removed from furrow stream flows as stream sediment concentration decreased. Therefore, we hypothesized that the flattening of PAM concentration versus flow-distance relationship was generally due to the decreased availability of adsorbent (sediment) in the furrow stream. Evidence in Irrigation 6 suggests that a second process may also have influenced the decline rate of furrow-stream PAM concentration over time. Furrow-runoff PAM concentration in Cont-1 furrow streams decreased significantly between middle and bottom sampling positions at 3 h, but not at 7 h (Fig. 3). Yet, stream sediment concentrations were the same at the two times, so the PAM concentration differences observed at 3 and 7 h were apparently not caused by a difference in the availability of entrained sediment adsorbent. Polyacrylamide absorbance may have declined in response to a number of time-related factors: (i) A number of physical and chemical characteristics of the stream flow probably changed with time as a

Table 4. Runoff and sediment for polyacrylamide (PAM)-treated furrow and the tail-water streams (mean of three sampling positions).

		PAM-I_{10} furrow stream			PAM-C_1 furrow stream			Tail-water stream		
			Sediment			Sediment			Sediment	
Irrigation (date)	Sample time	Flow	Concentration	Load	Flow	Concentration	Load	Flow	Concentration	Load
		L min^{-1}	g L^{-1}	g min^{-1}	L min^{-1}	g L^{-1}	g min^{-1}	L min^{-1}	g L^{-1}	g min^{-1}
2 (17 July 1995)	early	17.3	0.2	3.5	24.0	15.9	382	219	21.6	4730
	mid	11.2	3.0	33.6	25.4	10.7	272	117	15.4	1802
	late	11.8	5.0	59.0	18.7	11.3	211	138	7.9	1090
4 (31 July 1995)	early	15.1	0.2	3.0	13.0	8.1	105	150	9.4	1410
	mid	12.5	0.8	10.0	11.6	7.1	82	132	17.1	2257
	late	13.5	0.7	9.5	12.3	2.7	33	156	7.3	1139
5 (7 Aug. 1995)	early	17.4	0.2	3.5	15.8	5.5	87	195	8.8	1716
	mid	11.6	0.3	3.5	10.4	3.1	32	111	11.2	1243
	late	10.2	1.7	17.3	9.7	2.3	22	105	6.0	630
6 (14 Aug. 1995)	early	18.2	0.1	1.8	15.5	1.3	20	195	4.8	936
	mid	11.6	0.2	2.3	9.7	0.7	7	117	10.5	1229
	late	10.8	0.2	2.2	10.0	0.6	6	126	6.0	756
2	mean	13.4	2.7	32.0	22.7	12.6	288	158	15.0	2541
4	mean	13.7	0.6	7.5	12.3	6.0	74	146	11.3	1602
5	mean	13.1	0.7	8.1	12.0	3.6	47	137	8.7	1196
6	mean	13.5	0.2	2.1	11.7	0.9	11	146	7.1	1192
All irrigations	early	17.0	0.2	2.9	17.1	7.7	148	190	11.2	2198
All irrigations	mid	11.7	1.1	12.4	14.3	5.4	98	119	13.6	1633
All irrigations	late	11.6	1.9	22.0	12.7	4.2	68	131	6.8	1067

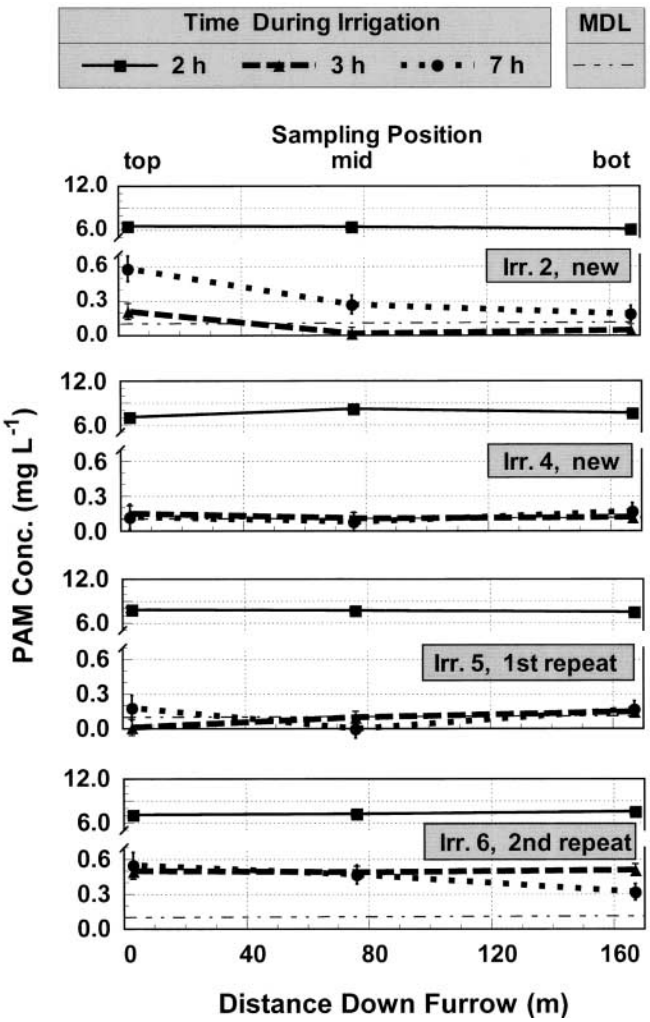

Fig. 2. Polyacrylamide (PAM) concentrations in Initial-10 furrow streams, by sampling position and time. Polyacrylamide was being applied at 2 h into the irrigation, but was stopped approximately 30 min prior to the 3-h sample time. Note break and change in *y* axis scale. MDL, method detection limit.

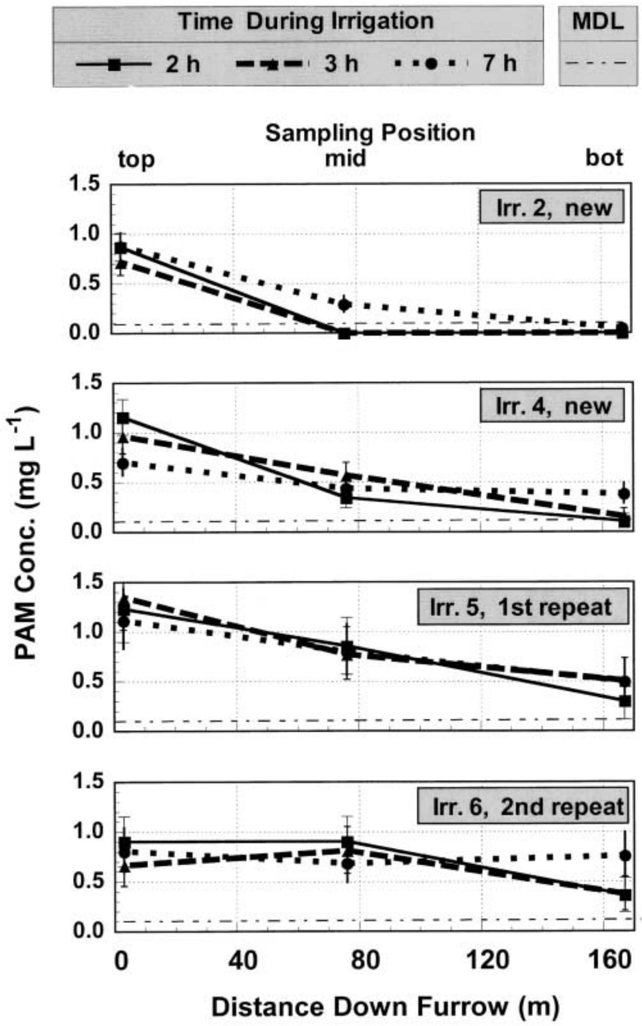

Fig. 3. Polyacrylamide (PAM) concentrations in Cont-1 furrow streams by sampling position and time for similar monitored irrigations. MDL, method detection limit.

result of changing flow rates, which may have decreased adsorption of dissolved PAM onto soil surfaces; and (ii) soil-lined channels may have a finite capacity for nonequilibrium adsorption of PAM at the time scale imposed here (<12 h), and this adsorption capacity was progressively filled over the period of PAM application. Thus, fewer PAM molecules were absorbed to the soil-wetted perimeter as time progressed, and more incoming dissolved PAM moved downstream.

Recall that runoff collected from treated and nontreated furrows flowed into the 530-m-long tail-water ditch, where it was sampled at the top, middle, and bottom positions at 2, 3, and 7 h, and at the end position at 2 h during each irrigation. The tail-ditch end was sampled at 3 and 7 h during only two irrigations. When Irrigations 2, 4, 5, and 6 were analyzed together, only time ($P = 0.0001$), and not field position ($P = 0.14$), or the *time* by *position* interaction term ($P = 0.39$) significantly affected PAM concentration in tail-ditch flows. Mean tail-ditch PAM concentration at 2 h was 0.9 mg L^{-1}, when polymer was being applied to both Initial-10 and Cont-1 furrows, but was one-tenth of this 2-h value at the 3-h (<0.1 mg L^{-1}) and 7-h (0.1 mg L^{-1}) sampling times, when PAM was being applied only to Cont-1 furrows. A large portion of variability among irrigation responses was contributed from Irrigation 2, which exhibited a response pattern quite different than those for Irrigations 4, 5, or 6 (Fig. 4). A separate analysis for the late-season irrigations showed that tail-ditch position influenced PAM concentration at the 2-h sampling time. The 2-h tail-ditch PAM concentrations averaged 1.6 mg L^{-1} at top, middle, and bottom positions but had decreased to 0.28 mg L^{-1} at the tail-ditch end (Fig. 4).

Polyacrylamide concentration patterns in the tail ditch were similar to those for furrows: (i) Tail-ditch PAM concentration declined rapidly following the reduction in furrow inflow PAM concentration; and (ii) PAM concentration did not decrease as rapidly with distance downstream as the season progressed. This result supported the hypothesis that the rate of PAM concentration diminution with flow distance declined as stream sediment concentration decreased over the irrigation season (Table 4). However, it was noted that

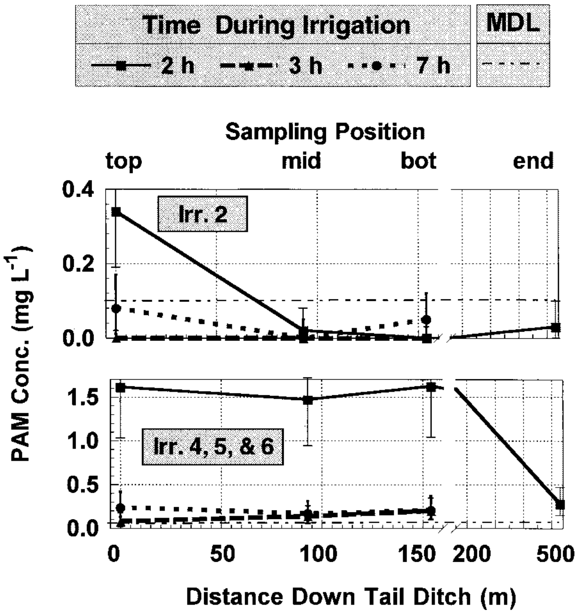

Fig. 4. Polyacrylamide (PAM) concentrations in tail-ditch streams by sampling position and time for Irrigation 2 and Irrigations 4, 5, and 6. Note break and change in *x* axis scale. MDL, method detection limit.

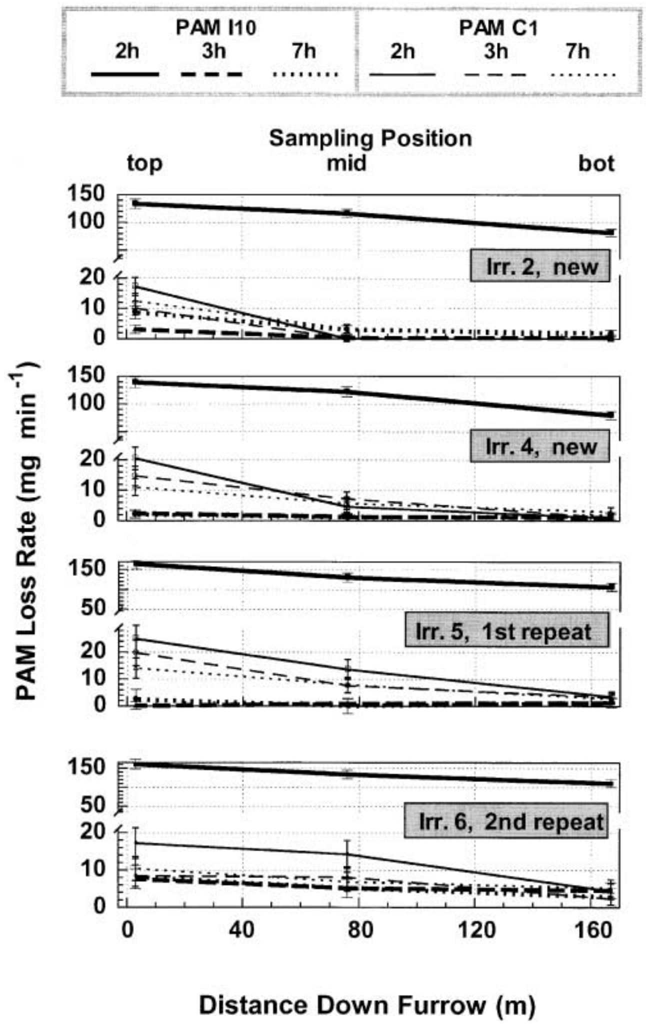

Fig. 5. Mean polyacrylamide (PAM) mass-loss rate for treated furrow streams by sampling position and time. Note *y* axis break and scale change for Initial-10 2 h.

the PAM concentration did not decline along the upper 90 m of Cont-1 furrows during Irrigation 6 at 2 h (Fig. 3), nor along the upper 90 m of the tail-water stream during Irrigations 4, 5, and 6 at 2 h (Fig. 4). These responses were similar despite the fact that mean sediment concentrations in the tail ditch were 10 times that for Cont-1 furrows (Table 4). This suggested that other factors influenced the rapidity of PAM removal or adsorption from the furrow stream as it flowed downfield. Physical and chemical characteristics of the stream flow can change with distance downstream as a result of infiltration and a declining flow rate, and these may have influenced polymer dynamics. Or, it may simply be that the adsorption capacity of sediment entering the tail ditch was already nearly saturated and thus had little effect on the dissolved PAM it encountered in the stream.

Polyacrylamide Loss Rate in Furrow and Wastewater Streams

Statistics for PAM mass-loss rate paralleled those for concentration. Main effects, treatment, furrow field position, and time significantly influenced PAM mass-loss rates (Table 3). Main effect interaction terms were also significant for all irrigations, except interactions *treatment* by *position* and *treatment* by *position* by *time* for Irrigation 6. For any given irrigation and sampling time, mass-loss rates decreased with distance downfield. As furrow streams traversed the field, increasing infiltration opportunity produced flow-rate reductions. The flow-rate decrease with distance downfield caused moderate declines in PAM mass-loss rates of Initial-10 furrows (Fig. 5). Polyacrylamide mass-loss rates for Cont-1 furrows decreased more rapidly with distance down furrow than for Initial-10. The reason was that PAM concentration in continuously treated furrows decreased down furrow (Fig. 3), while downstream concentrations in Initial-10 furrow streams were constant (Fig. 2).

Polyacrylamide mass-loss rate also changed with time. After furrow runoff began and before PAM application ceased (2 h), the PAM mass-loss rate at Initial-10 furrow-bottom positions averaged 95 mg min^{-1} over the four irrigations (Fig. 5). This level of loss rate was permitted for 0.5 to 1.0 h in our experimental furrows because PAM application was extended in order to reduce inter-irrigation variability of tail-water measurements. During typical farm use, this stage of PAM treatment would be very brief since further application after advance is unnecessary and would decrease PAM-use efficiency. Thirty minutes after PAM application ceased (3 h), mean PAM mass-loss rate at Initial-10 furrow bottoms had decreased to 1.8 mg min^{-1}, and the 7-h Initial-10 mass-loss rate was similar, 1.9 mg min^{-1}. Polyacrylamide mass-loss rates in Cont-1 furrows were generally slightly less at 3 and 7 h than at 2 h. The smaller PAM mass-loss rate at later sampling times was caused primarily by a decrease in furrow-stream flow rates (Table 4). The irrigation cutback approach used here reduced furrow

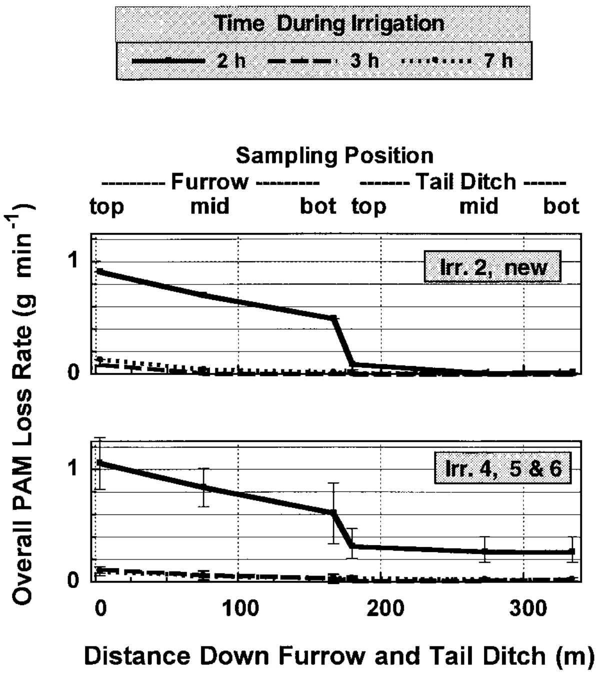

Fig. 6. Rates of overall polyacrylamide (PAM) mass loss at each furrow and tail-ditch sampling position for Irrigation 2 and Irrigations 4, 5, and 6, where furrow loss rates represent the total PAM loss rate from all furrows from each PAM treatment (12 total).

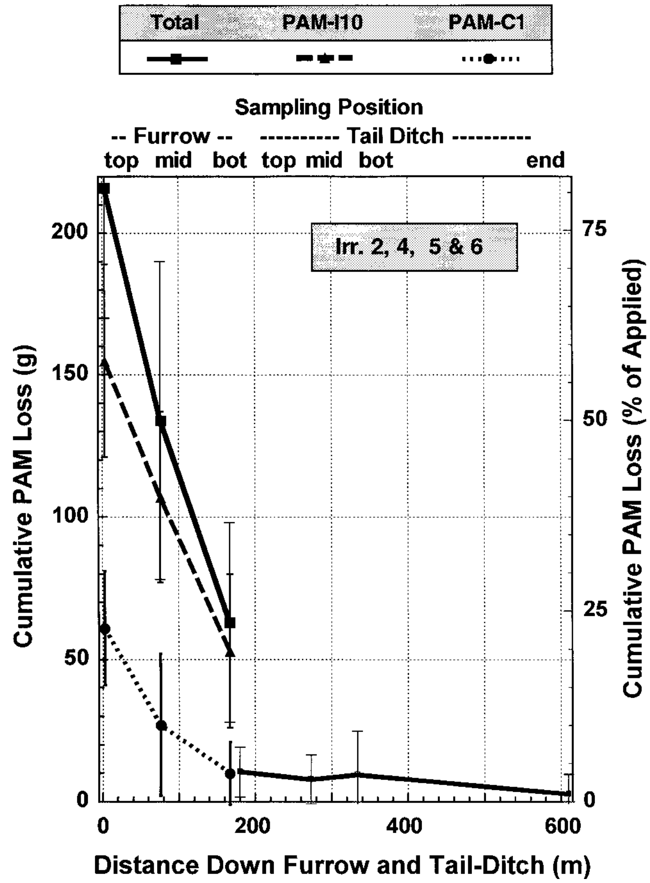

Fig. 7. Cumulative polyacrylamide (PAM) mass losses from all treated furrow streams at each furrow sampling position, and at tail-ditch positions (mean values for Irrigations 2, 4, 5, and 6.)

inflows after furrow advance, resulting in smaller furrow-stream flow rates at 3 and 7 h than at 2 h.

The 2-h PAM mass-loss rate declined dramatically at the collection ditch where dissolved PAM from treated furrows mixed with suspended sediment largely contributed from untreated furrows. Polyacrylamide flocculated and adsorbed to the sediment, which resulted in an 80% reduction in dissolved PAM loss rate in Irrigation 2 and an average 50% reduction in Irrigations 4, 5, and 6 (Fig. 6). Some of the resulting flocculated and aggregated sediment continued to move downstream as bedload and, at 2 h, was clearly evident in the top tail-ditch flow.

Overall PAM mass-loss rates from all furrows as irrigation water flowed across the field and down the tail ditch are plotted in Fig. 6. In Irrigation 2 at 2 h, the overall PAM loss rate at the bottom of the tail ditch was 0.01 g min^{-1}, nearly two orders of magnitude smaller than that at the top (inflow end) of the furrow, 0.9 g min^{-1}. The pattern differed for Irrigations 4, 5, and 6, where the average 2-h overall PAM loss rate at the tail-ditch bottom was 0.26 g min^{-1}, about one-fifth that at the top of the furrow, 1.05 g min^{-1}. The increase in PAM loss rate at the tail-ditch bottom from early to late season (Fig. 6) was caused by an increase in stream PAM concentration (Fig. 4), since tail-ditch flow changed little between early- and late-season irrigations (Table 4).

For all irrigations, overall PAM loss declined greatly after PAM application in Initial-10 furrows had ceased, and PAM was being applied to Cont-1 furrows only (3 and 7 h sampling times). This emphasizes the importance of stopping PAM application in Initial-10 furrows once runoff begins, in order to minimize PAM runoff losses and maintain high PAM-use efficiencies.

At any given sampling time, overall PAM mass-loss rate in the furrow and tail-ditch flows decreased with distance downstream. The rate of decline was greater at 2 h, when dissolved PAM concentrations were greatest. Furrow infiltration rates were highest in the early hours of the irrigation. Hence, furrow flow rate declined more steeply with distance downstream at the 2 h sampling time than at 3 or 7 h. Since PAM mass-loss rate is a function of flow rate, loss rates declined more steeply with distance at the 2-h sampling time than at later times (data not shown).

Cumulative Polyacrylamide Mass Losses

Runoff at the tail-ditch end transported a total of 2.6 g PAM off the farm during each of Irrigations 2, 4, 5, and 6 (Fig. 7). Thus, only 1% of the total PAM a.i. applied per irrigation exited the area as irrigation return flow. Had the Initial-10 PAM application been curtailed when furrow runoff commenced, PAM contributions from those furrows to the tail ditch would have been considerably reduced (see discussion below), and cumulative PAM mass losses at the tail-ditch end would have been about one-fifth of the 2.6 g measured in this study, or about 0.2% or less of the total PAM a.i. applied.

Relative to the total Initial-10 PAM applied, cumula-

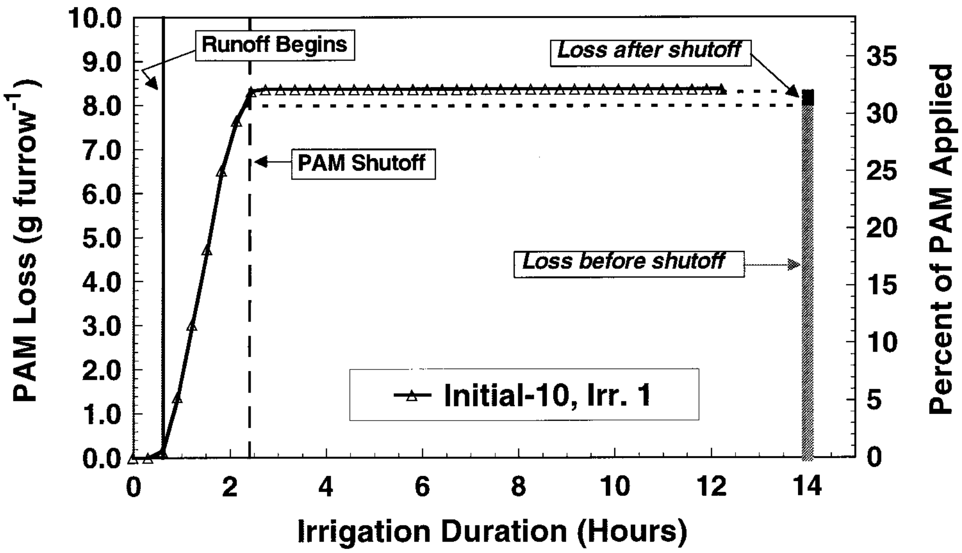

Fig. 8. Cumulative polyacrylamide (PAM) loss from the end of Initial-10 furrows, Irrigation 1, including cumulative PAM loss prior to and after PAM shutoff (vertical columns).

tive PAM losses from Initial-10 furrows would have been 1 to 2% (Irr. 1) or 5% (Irr. 2, 4, 5, 6) had PAM application been shut off at furrow advance (Fig. 8). However, because PAM application in Initial-10 furrows was permitted to continue for 75 to 120 min after advance, cumulative PAM mass losses in runoff from Initial-10 furrows were 32% (Irr. 1) and 33% (Irr. 2, 4, 5, 6) of the total applied (data not shown). By comparison, cumulative PAM losses from the ends of Cont-1 furrows averaged 15% (10 g) of the total PAM a.i. applied to Cont-1 furrows.

Cumulative PAM a.i. losses increased as the irrigation season progressed. Zero PAM losses from the bottom and end positions of the tail ditch occurred in Irrigations 1 and 2. In Irrigation 4, 4.2 g PAM was lost from the bottom, and 0.2 g was lost from the end of the tail ditch. By Irrigation 6, a total of 22 g PAM was lost at the tail-ditch bottom and 9 g at the tail-ditch end. Thus, season-long cumulative PAM losses at the tail-ditch end could have been nearly eliminated if we had not treated the last two irrigations.

Polyacrylamide Sinks

The total PAM applied per irrigation averaged 61 g a.i. for Cont-1 furrows and 155 g a.i. for Initial-10 furrows, where polymer application was allowed to continue for 75 to 120 min after runoff began. Of the total 216 g PAM a.i. applied, 51 g adhered to soil in Cont-1 furrows and 102 g adsorbed to soil in Initial-10 furrows. Thus, cumulative PAM losses from the end of all treated furrows averaged 63 g a.i. per irrigation (28% of the total PAM a.i. applied). Of this, 53 g was adsorbed to sediment present in the collection- and tail-ditch stream and removed from solution. Hence, an average 10 g dissolved PAM a.i. passed into the tail ditch in each irrigation. Of this 10-g amount, 2.6 g PAM a.i. (1% of the total applied) passed down the tail-water ditch and exited the farm.

CONCLUSIONS

This study compared effects of two PAM applications, Initial-10 vs. Cont-1, on furrow irrigation-induced erosion and infiltration, and determined the fate of applied PAM in furrow streams and downstream surface drains. Initial-10 more effectively controlled furrow erosion overall, although Cont-1 did equally well during late-season irrigations when erosion measured in untreated furrows was lower. Cont-1 increased net infiltration above that for control or Initial-10 furrows during the late-season irrigations.

When the >6 mg L^{-1} PAM a.i. application ceased, PAM concentration in furrow runoff declined rapidly. However, while dissolved PAM was being added to furrow irrigation streams, its downstream persistence in the flow was a function of its initial concentration and irrigation sequence. Results were consistent with the concept that furrow sediment concentration is an important factor controlling the downstream dissolved PAM concentrations in furrow and tail-ditch streams. When furrow inflows contained >6 mg L^{-1} PAM a.i., the polymer persisted in downstream flows because at these application rates, PAM greatly minimized entrained sediment concentrations and hence PAM adsorption. Increasing sediment concentrations in treated furrow or tail-ditch flows, either by decreasing PAM a.i. application rate to concentrations below 0.9 mg L^{-1} or by adding sediment via tributary inflows, promoted the removal of dissolved PAM in downstream flows. Other less-understood factors also appear to influence dissolved PAM concentrations in treated flows. While some results were unexplained, we found no consistent evidence that PAM desorbed from treated furrow soils. However, further study is needed to fully understand the importance of all processes that influence furrow stream PAM concentrations.

To maximize PAM-use efficacy and minimize its transport off-site, irrigators need to keep applied polymer in the field. This is best achieved by ceasing >6 mg L^{-1} PAM a.i. applications before or immediately after furrow advance occurs, and refraining from treating late-season irrigations. However, even if PAM applications were continued after advance, our results indicate that dissolved PAM concentrations decline quickly after PAM-treated flows join untreated streams. While Initial-10 PAM treatment continued for 1.2 to 2 h after advance in this study, only 1% of the applied PAM was transported to the end of the 530-m tail ditch. Tail-water ditches used on many farms in the area are two to three times longer than that used in this study. Under these conditions, and even if the PAM application were continued after advance, it appears unlikely that significant quantities of dissolved PAM could persist in tail ditch and irrigation return flows long enough to enter natural waterways.

ACKNOWLEDGMENTS

This work was supported in part by a grant from CYTEC Industries, through a Cooperative Research and Development Agreement (contract 58-3K95-4-216). We thank Dr. Craig Ross, Mr. Ron Peckenpaugh, Mr. Jim Foerster, and Ms. Barbara Prater for their valuable technical assistance, and Ms. M. Emily Aston, Ms. Elizabeth Whitchurch, and Mr. Paul Miller for their help in the lab and field.

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