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677 South Segoe Rd., Madison, WI 53711 USA

Reducing Phosphorus Losses from Surface-Irrigated Fields: Emerging Polyacrylamide Technology

R. D. Lentz,* R. E. Sojka, and C. W. Robbins

ABSTRACT

Most P losses from surface-irrigated fields occur via runoff, are associated with eroded sediment, and can be minimized by eliminating irrigation-induced erosion. A convenient new practice that eliminates furrow irrigation-induced soil losses uses a high molecular weight, anionic polyacrylamide (PAM) applied to initial irrigation inflows. We hypothesized that, compared to control furrows, PAM treatment would reduce field losses of ortho P, total P, NO_3, and lower tailwater chemical oxygen demand (COD). Two PAM treatments were tested: I_{10} applied 10 mg L^{-1} PAM only during the furrow advance (i.e., the application was halted after runoff began) and C_1 applied 1 mg L^{-1} PAM continuously throughout the irrigation. Soil was Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthid) with 1.6% slope. Initial inflows were cut back from 23 to 15 L min^{-1} after 1.5 to 6 h. Total soil loss over four irrigations was 3.06 Mg ha^{-1} for control furrows vs. 0.33 (C_1) and 0.24 (I_{10}) for PAM-treated furrows. Ortho-P and total P concentrations in control tailwaters were five to seven times that of PAM treatments, and COD levels were four times those of PAM treatments. Runoff in controls was two times that of PAM-treated furrows. PAM-I_{10} lowered furrow stream nutrient concentrations more than did PAM-C_1, but owing to disparities in runoff, the two treatments produced similar cumulative sediment and nutrient mass losses. The PAM is effective, convenient, and economical, and greatly reduces P and organic material (COD) losses from surface-irrigated fields.

Understanding and control of point-source P inputs into natural surface waters is relatively well advanced, but less is known about nonpoint inputs. Current research is identifying and developing controls for agricultural nonpoint P sources (Sharpley, 1995). Highly managed surface-irrigated farming operations, which are often considered less important nonpoint source contributors than rainfed systems, are also being examined. Brockway and Robison (1992) reported that sediment and nutrient contributions to native surface waters from irrigation return flows are substantial and problematic.

Agricultural P leaves the field via overland flow or drainage. Annual P losses in surface runoff have been reported to be as much as 1.5 to 10 times greater than in subsurface drainage (Carter et al., 1973; Alberts and Spomer, 1985). While P losses in drainage water are important, few studies have investigated how irrigation management impacts these losses. In the face of this knowledge gap, we focus primarily on surface P losses in this paper.

In runoff from irrigated or rainfed agriculture, total P and soluble, or ortho-P losses, were largely associated with concomitant sediment loss (Fitzsimmons et al., 1972; Carter et al., 1976; Andraski et al., 1985; Brown, 1985; Lenat and Crawford, 1994). Erosion and sediment losses to surface irrigated return flows must be controlled if nutrient contributions to surface waters, particularly P, are to be successfully managed (Carter and Bondurant, 1977). Koluvek et al. (1993) recently reviewed the topic of irrigation-induced erosion and sediment loss. The authors noted that subsurface and trickle irrigation produce no sediment loss because they do not produce overland flow. Sprinkler irrigation produces runoff and erosion when application rate exceeds soil infiltration capacity. Kincaid et al. (1990) reported that as much as 43% of center-pivot applied water runs off from conventionally tilled fields. In theory, most sprinkler runoff can be eliminated. The system, however, must be properly designed and managed, and include the use of reservoir tillage. Most erosion occurs with surface irrigation, and in particular furrow irrigation, where water is conveyed across fields in shallow channels, also called furrows or corrugates (Trout and Neibling, 1993). Concentrated flow in the furrows produces shear forces that detach and transport soil particles downstream.

PRACTICES FOR CONTROLLING SEDIMENT AND PHOSPHORUS LOSSES

Three approaches can be used to effectively eliminate sediment and surface P losses. These either halt runoff, curtail soil erosion, or purge sediment from runoff before it exits the field. These approaches are applied in several furrow erosion control practices reviewed by Carter (1990). Some surface flood irrigation systems, such as level-basin or level-border, produce no runoff and hence no surface P losses. Converting from furrow irrigation to one of these level flood systems, trickle, subsurface, or a properly designed and managed sprinkler system effectively stops surface P loss. However, level basin and border irrigation installations often require land grading, and the capitalization and energy costs associated with trickle, subsurface, or sprinkler systems are high (Carter and Bondurant, 1976). Total energy costs are about 10 to 20 times that of furrow irrigation systems (Carter and Bondurant, 1977). In underdeveloped nations, not only do energy costs limit use of the more expensive irrigation systems, but in many cases electrical power is not available.

Several furrow irrigation-system modifications can be made to reduce erosion and sediment loss. To reduce stream size or velocity, furrow slope can be lessened, furrow length can be shortened, and/or an inflow cutback system can be employed. These improvements re-

U.S. Dep. of Agriculture, Agricultural Research Service, Northwest Irrigation and Soils Research Laboratory, 3793 N 3600 E, Kimberly, ID 83341. Received 23 Dec. 1996. *Corresponding author (lentz@kimberly.ars.pn.usbr.gov).

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Abbreviations: PAM, water soluble anionic polyacrylamide; COD, chemical oxygen demand; EC, electrical conductivity; ESP, exchangeable sodium percentage; SAR, sodium adsorption ratio.

duce stream erosivity (Carter, 1990). Sediment retention basins can be constructed to collect runoff water, slowing its velocity sufficiently to permit settling of the water's bedload and most suspended sediment (Brown et al., 1981). These basins are effective only if sediment is regularly cleared from the reservoir. Basin maintenance can cost one to several thousand dollars per year for a 40-ha field. Retention basins trap sediment more effectively than they recover P from irrigation runoff because significant portions of clay-sized soil particles do not settle in the pond, and clays contain a disproportionately large share of runoff P (Carter et al., 1974; Brown et al., 1981). The suspended clay-P also dissolves into the water until equilibrium is reached. The more clay in suspension, and the longer the clay is in suspension, the greater the fraction of adsorbed P that goes into solution. In another modification, a tailwater-reuse pumpback facility can be installed in a downstream collection basin to transport runoff and sediment back to the top of the field for reuse (Carter et al., 1993). These systems eliminate 100% of surface P losses but are relatively expensive to install and maintain.

Several tillage, cultivation, and cropping practices can also be used to reduce surface P losses. Carter and Berg (1991) reported that conservation tillage cropping sequences for furrow irrigation reduced sediment losses by 47 to 100% and increased farm profitability. Crop residue placement in furrows also can reduce sediment and P losses (Aarstad and Miller, 1981). Even on steep slopes of 1.9 to 3.9%, straw mulching reduced sediment losses by 69 to 90% (Brown and Kemper, 1987). If properly installed and managed, a vegetative filter strip of small grains planted in a 3- to 6-m band along the lower end of row-crop fields is a simple and economical way to reduce sediment losses by 40 to 60% (Carter, 1990). However, these sediment and P retention practices require farmers to alter their normal tillage operations, consequently farmer acceptance and adoption has been limited.

EMERGING TECHNOLOGIES

Recent studies demonstrated that direct conditioning of furrow soils with whey, a low-cost dairy by-product can reduce furrow irrigation sediment losses by 86% on furrows with 2.3% slopes (Brown et al., 1998). This method is economical if a whey source is located near the fields. Whey appears to have strong potential for reducing furrow runoff P losses based on its capacity to reduce sediment losses (Fitzsimmons et al., 1972).

Another emerging technology uses small applications of a soluble PAM with $\sim 13.5 \times 10^6$ Da molecular weight and 18% charge density to treat irrigation water. In the standard treatment (Spofford, 1996), 10 mg PAM L^{-1} is dissolved in irrigation water as it first entered the furrows and PAM application is stopped once the treated water begins to run off the field. Untreated water is used during the remainder of the irrigation set. The resulting PAM application of 1 to 2 kg ha^{-1} reduced furrow irrigation-induced soil losses by 94% (Lentz et al., 1992; Sojka and Lentz, 1993; Lentz and Sojka, 1994). The PAM technology is an economical, noninvasive practice that is rapidly being adopted in several regions of the irrigated West.

At rates and concentrations employed by this technology, the anionic PAM has demonstrated no known toxic effects for mammalian and aquatic organisms, or plants, though a slight and apparently soil specific shift in some soil organism population densities has been observed (Barvenik, 1994). The practice standard requires that only the purest PAM formulations be applied, eliminating potential impacts from residual or contaminating materials. The PAM is quite stable in the soil environment (10% degradation per year), but physical shearing and strong oxidizing agents such as peroxide, ozone, and UV radiation will cleave the PAM C backbone and reduce the molecular weight of the molecule (Barvenik et al., 1996). Soil microorganisms convert the amide group on the molecule to a carboxyl and use the resulting ammonia as a N source (Kay-Shoemake and Watwood, 1996). The charge density of the polymer is increased in the process. Ultimately, certain microorganisms can metabolize the hydrolized and cleaved (hexamer or smaller) polymers, producing CO_2 and H_2O (Barvenik et al., 1996).

Anionic polyacrylamide's capacity to reduce runoff sediment loss is well documented, although little research is published describing PAM's effect on runoff nutrient losses, and in particular, P. Lentz et al. (1992) reported results from a 1992 preliminary experiment that continuously applied 0.25 to 0.5 mg L^{-1} emulsified neutral polyacrylamide to furrow inflows during a single 24-h irrigation. Analysis of runoff water samples taken at 4 and 9 h into the irrigation showed that PAM had little effect on ortho P, but reduced total P concentration approximately 25%.

Our objectives were to test the following hypotheses: (i) PAM treatment substantially reduces total P, ortho P, NO_3–N, and COD concentrations and mass losses in irrigation runoff; (ii) PAM accomplishes this by reducing sediment loss; and (iii) the NRCS standard PAM application method and a continuously applied 1 mg L^{-1} PAM treatment differ in their control of surface nutrient losses.

MATERIALS AND METHODS

Field Plot

The field study was conducted in 1994 at the USDA-ARS Northwest Irrigation and Soils Research Laboratory at Kimberly, ID. Dry bean (*Phaseolus vulgaris* L .“Viva Pink”) was planted in rows spaced 0.56 m on Portneuf silt loam. The seedbed was prepared with disk and roller harrow. Surface soil texture was silt loam (10% clay, 70% silt), organic matter was 10 to 13 g kg^{-1}; cation exchange capacity was 190 $mmol_c$ kg^{-1}; saturated-paste-extract electrical conductivity (EC) was 0.7 dS m^{-1}; exchangeable sodium percentage (ESP) was 1.5; pH was 7.7; and calcium carbonate equivalent was 5%. Furrows were 175 m long, with a 1.6% slope. Furrows were formed during planting with a weighted wedge-shaped forming tool. Only alternate wheel-trafficked furrows were irrigated and monitored to avoid the confounding effects of intake variability associated with wheel-tracked and nonwheel-tracked furrows.

Irrigations, Sediment Sampling, and Runoff Monitoring

The bean field was irrigated five times during the season (Table 1). A gated pipe conveyed water to each furrow, and adjustable spigots controlled inflow rates. A cutback irrigation strategy was employed to reduce runoff, that is, initial irrigation inflows of 23 L min^{-1} pushed water down field relatively quickly, then all flows were reduced to 15 L min^{-1}. Irrigations were 8 to 24 h in duration. Snake River water was used for irrigation. Its electrical conductivity was 0.5 dS m^{-1} and SAR was 0.5 [mmol$_c$ L^{-1}]$^{0.5}$.

Furrow inflows and outflows were monitored, and runoff sediment concentrations were measured throughout each irrigation (Table 1). Measurements were made at one-half hour intervals early in the irrigation, every hour during mid-irrigation, and every 3 to 5 h later in the irrigation, when outflows and sediment loads had stabilized (at >10 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). 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).

Experimental Design, Treatments, and Nutrient Sampling

The experimental design was a complete randomized block, with three replications. The study compared three treatments: (i) control furrow streams contained no PAM; (ii) PAM was applied throughout the irrigation at 1 mg L^{-1} in a continuous PAM treatment (C_1); and (iii) was applied at 10 mg L^{-1} only during the initial hours of the irrigation in a standard PAM treatment (I_{10}). PAM injection in the I_{10} treatment was curtailed an average 110 min after the irrigation began, that is, shortly after the end of the advance phase, and untreated water was used for the remainder of the irrigation set. Stock PAM solutions, prepared 1 to 2 d prior to the irrigation (Lentz and Sojka, 1996), were metered into the head of each furrow with positive displacement pumps. Turbulence created by the incoming water stream mixed and dispersed the aqueous PAM concentrate into the flow.

Three runoff samples per irrigation were collected for nutrient analysis. Samples were taken from outflow monitoring flumes on each furrow. Runoff nutrient concentrations were monitored in all but the fifth (last) irrigation. Brown (1985) reported that P losses in the last of five irrigations contributed only 1% of the total seasonal P losses. We assumed other nutrient losses produced by the final irrigation would also be negligible. Three runoff samples per furrow were collected at 1 to 2 h, 5 to 6 h, and 8 to 10 h into the irrigation. Samples were analyzed for total P (Greenberg et al., 1992), ortho P (Watanabe and Olsen, 1965), chemical oxygen demand, COD (American Public Health Assoc. et al., 1971), and NO_3–N (2.0 m*M* potassium benzoate eluent and liquid ion chromatography). Runoff samples were stored at 2°C for <8 d before being analyzed. Ortho-P analysis was done on unfiltered samples. Inflows were sampled during irrigations and analyzed to determine nutrient background concentrations.

Analysis

Furrow infiltration and sediment/nutrient field loss calculations were estimated with the computer program, WASHOUT (Lentz and Sojka, 1995). The program integrated runoff and pollutant losses over the duration of the irrigation. Net furrow infiltration was calculated as the difference between total inflow and total outflow. Cumulative total P, ortho-P, NO_3–N, and COD mass losses were computed with the assumption that runoff constituent concentrations remained constant between sampling intervals. Treatment means for all analyses were averaged across all irrigations and compared using the Duncan multiple range test at the 95% probability level (Snedecor and Cochran, 1980). We examined the linear relationship between pairs of runoff sediment and nutrient concentration variables using Pearson Correlation (Snedecor and Cochran, 1980). In the correlation analysis, stream concentration values were normalized across irrigations by representing values as a fraction of the maximum stream concentration observed for each component in each irrigation.

RESULTS AND DISCUSSION

Cumulative soil loss for all five irrigations was 3140 kg ha^{-1} for control furrows, 345 kg ha^{-1} for PAM-C_1, and 250 kg ha^{-1} for PAM-I_{10} treatments. Sediment losses contributed by untreated furrows in the fifth irrigation were 2.6% of the total seasonal cumulative loss, suggesting that associated nutrient losses from the last irrigation were also a small component of the cumulative seasonal mass losses. An implied nutrient mass loss of a few percent in the fifth irrigation agrees with that reported by Brown (1985). In view of their dominating contributions, only data from the first four irrigations are presented. Phosphorus, COD, and NO_3–N concentrations in irrigation inflows were relatively constant throughout the irrigation season. Mean concentrations were 0.10 mg L^{-1} for total P; 0.03 mg L^{-1} for ortho P; 11.8 mg L^{-1} for COD, and <0.02 mg L^{-1} for NO_3–N.

Infiltration, Runoff, and Material Concentrations

The C_1 and I_{10} PAM treatments altered hydraulic characteristics of furrow streams and their nutrient concentrations relative to control furrows. Net sediment and nutrient field-losses were influenced by both hy-

Table 1. Timing, sampling, and characteristics of each irrigation.

Irrigation no.	Date (1994)	Furrow condition†	Irrigation length, h	Inflow rates, L min^{-1}	Time inflows cut back, h into irr.	Sampling for nutrients	Stream flow monitored, sediment sampled
1	15 June	Newly formed	8	23 → 19	6	Yes	Yes
2	29 June	Repeat	12	23 → 15	1.5	Yes	Yes
3	13 July	Newly formed	24	23 → 15	5	Yes	Yes
4	27 July	Repeat	24	23 → 15	1.5	Yes	Yes
5	10 August	Repeat	12	23 → 15	2	No	Yes

† Furrows were formed on 2 June and cultivated and reformed on 5 July. Repeat furrows were undisturbed since the last irrigation.

Table 2. Furrow flow, infiltration, and anionic polyacrylamide (PAM) application parameters for four fully monitored irrigations.

Parameter Treatment	Irrigation no. 1	2	3	4	Mean	Total
Inflow, mm						
Control	56	59	141	116	93a	372a
C_1†	56	59	140	116	93a	371a
I_{10}†	56	59	140	116	93a	372a
Runoff, mm						
Control	26	22	73	54	44a	175a
C_1	17	17	22	34	22c	90c
I_{10}	8	21	43	47	30b	119b
Mean runoff rate, L min^{-1}						
Control	11.5	6.1	10.4	7.5	8.9a	–
C_1	8.4	4.9	3.6	4.7	5.4b	–
I_{10}	4.5	6.0	6.5	6.5	5.9b	–
Net infiltration, mm						
Control	30	37	68	61	49a (54%b)*	196c
C_1	39	42	119	82	71a (74%a)	281a
I_{10}	48	38	97	69	63a (70%a)	253b
Advance time, min						
Control	77	47	96	46	66a	–
C_1	115	56	324	61	139a	–
I_{10}	172	65	172	63	118a	–
PAM applied, kg ha^{-1}‡						
Control	0.00	0.00	0.00	0.00	0.0c	0.0c
C_1	0.5	0.6	0.8‡	0.8	0.6b	2.7b
I_{10}	2.5	1.0	2.8	1.0	1.8a	7.2a

* Values in parentheses give infiltration as a percent of water applied, and letters indicate treatment differences at $P < 0.05$.
† Treatment I_{10} applied 10 mg L^{-1} PAM only during the furrow advance phase (until runoff began), and C_1, applied 1 mg L^{-1} PAM throughout the irrigation (except in irrigation three, C1 furrows were irrigated for 24 h, but PAM was applied only for the first 12 h).
‡ Mean PAM amounts applied per treatment were computed from actual stock solution metering rates, and may differ slightly from the target application amounts.

draulics and stream-loading factors. Net infiltration for PAM-treated furrows was 1.45 times (C_1) and 1.28 times (I_{10}) that of control values (Table 2). Accordingly, the average runoff rate for PAM-treated furrows was 40% less than that for control furrows (Table 2). Commonly, differences in treatment runoff were observed throughout the irrigation (Fig. 1). Clearly, PAM applications could decrease field soil and nutrient losses strictly by reducing runoff rates. But if this were the sole mechanism, it would be an unsatisfactory field solution because irrigators may decide to increase inflow rates to shorten furrow advance times, which might, in turn, increase runoff and surface sediment and nutrient mass losses.

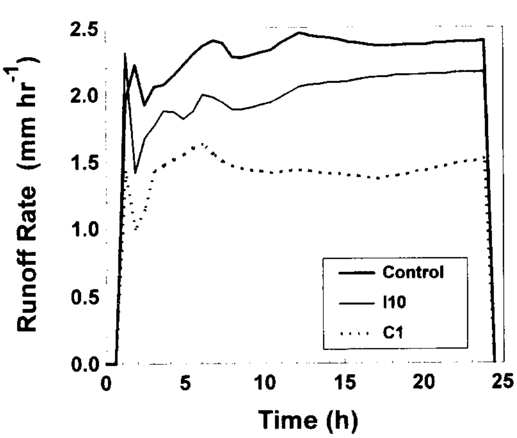

Fig. 1. Runoff rates from control and PAM treatments from irrigation four. Treatment I_{10} applied 10 mg L^{-1} PAM only during the furrow advance phase (until runoff began), and C1 applied 1 mg L^{-1} PAM throughout the irrigation.

Fortunately, PAM applications also reduced runoff concentrations of sediment and nutrients, including total P, ortho P, and COD (Table 3). Mean NO_3–N concentrations in furrow runoff did not differ among treatments (Table 3). Runoff from control furrow streams contained five to seven times greater total P and ortho-

Table 3. Measured furrow stream concentrations.

Parameter Treatment	Irrigation no. 1	2	3	4	Treatment avg.†
Sediment, g L^{-1}					
Control	2.16	2.22	1.99	0.95	1.83a*
C_1‡	0.88	0.75	0.10	0.09	0.45b
I_{10}‡	0.45	0.22	0.29	0.05	0.25b
Total P, mg L^{-1}					
Control	0.50	1.06	0.91	0.97	0.86a
C_1	0.27	0.43	0.07	0.26	0.26b
I_{10}	0.14	0.13	0.17	0.06	0.12b
Ortho P, mg L^{-1}					
Control	0.36	0.40	0.18	0.74	0.42a
C_1	0.14	0.37	0.06	0.20	0.19a
I_{10}	0.10	0.11	0.14	0.03	0.09b
NO_3–N, mg L^{-1}					
Control	0.03	0.02	0.12	0.09	0.06a
C_1	0.05	0.03	0.59	0.09	0.19a
I_{10}	0.07	0.06	0.09	0.06	0.07a
COD, mg L^{-1}§					
Control	70	163	134	143	128a
C_1	51	131	54	94	83b
I_{10}	38	34	37	26	34c

* Similar lower case letters indicate no difference between treatment means ($P < 0.05$).
† Mean separations used replications averaged across irrigations.
‡ Treatment I_{10} applied 10 mg L^{-1} PAM only during the furrow advance phase (until runoff began), and C_1 applied 1 mg L^{-1} PAM throughout the irrigation (except in irrigation three, C1 furrows were irrigated for 24 h, but PAM was applied only for the first 12 h).
§ COD, chemical oxygen demand.

P concentrations than runoff from PAM-I_{10} furrows. Similarly, the COD concentrations in untreated furrow runoff were four times higher than in PAM-I_{10} treated furrows (Table 3). Sediment, P, and COD concentrations in PAM-C_1 furrows were equal to or larger than those in PAM-I_{10} furrow streams, but PAM-C_1 material concentrations were still significantly lower than those of control streams. Thus, both PAM treatments decreased furrow runoff volume and, with the exception of NO_3–N and ortho P for C_1, reduced furrow-stream pollutant concentrations. The combined effect decidedly reduced surface P, sediment, and COD losses.

Overall Surface Losses of Sediment, Phosphorus, and Other Nutrients

The PAM-I_{10} treatment reduced cumulative sediment loss from the first four irrigations by 92% and PAM-C_1 reduced cumulative sediment loss by 89% relative to control furrows (Table 4). Across these four irrigations, the PAM-I_{10} application reduced total P mass losses by 91% while PAM-C_1 reduced total P losses 86% over control values (Table 4). The PAM-I_{10} treatment reduced cumulative mass losses of ortho P by 86% while PAM-C_1 reduced ortho-P mass losses by 77% relative to those contributed by control furrows (Table 4). Following a similar pattern, cumulative COD losses were reduced 83% by PAM-I_{10} and 60% by PAM-C_1 in comparison to control values (Table 4). Cumulative NO_3–N losses from all furrows were uniformly low (Table 4). Although cumulative NO_3–N losses from PAM treatments were half that of controls, the differences were not statistically significant (P = 0.24). Anionic polyacrylamide reduced NO–N_3 losses primarily by decreasing runoff, since stream NO_3–N concentrations did not differ between treatments.

Comparing Anionic Polyacrylamide Treatments

The PAM-I_{10} treatment produced smaller ortho-P and COD concentrations in furrow streams than PAM-C_1 (Table 3). Yet no PAM-treatment differences for cumulative material losses were observed (Table 4). The reason for this is that, though material concentrations were greater in PAM-C_1 furrows, they also had less runoff than PAM-I_{10} furrows (Table 2). Thus, PAM-treatment differences in material concentration were countered by treatment runoff effects, effectively nullifying any potential disparities in cumulative material mass losses. A large increase in furrow advance time is not always desired because it leads to decreased water application uniformity. Suppose PAM-C_1 irrigation inflows were increased to generate furrow advance times equivalent to those of PAM-I_{10} furrows. Assuming PAM-treatment runoff material concentrations remain equal, the resulting rise in PAM-C_1 runoff would increase PAM-C_1 cumulative mass losses above those of PAM-I_{10}. One advantage of the PAM-C_1 treatment is that it applied about half as much PAM as the PAM-I_{10} (Table 2).

Relationships between Sediment, Phosphorus, and Other Nutrients

In general, nutrient concentrations in runoff were positively correlated with sediment concentration. Changes in treatment sediment concentrations during the irrigations were generally mirrored by total P, ortho-P, and COD components, for example, large decreases in sediment concentration for a given treatment were usually associated with relatively large decreases in other component concentrations (Table 5). The pattern of runoff sediment concentrations produced during irrigation four was representative of other irrigations as well (Fig. 2). Runoff sediment concentrations in control

Table 4. Mass losses of sediment, P, and other nutrients during four monitored irrigations.

Parameter Treatment	Irrigation no. 1	2	3	4	Average	Cumulative losses
Sediment, kg ha^{-1}						
Control	584	480	1479	518	765a*	3061a
C_1†	152	128	22	32	84b	334b
I_{10}†	37	50	130	24	60b	242b
Total P, kg ha^{-1}						
Control	0.14	0.30	0.57	0.44	0.36a	1.45a
C_1	0.02	0.12	0.01	0.05	0.05b	0.20b
I_{10}	0.01	0.03	0.06	0.03	0.03b	0.13b
Ortho P, kg ha^{-1}						
Control	0.11	0.09	0.16	0.35	0.18a	0.71a
C_1	0.01	0.10	0.01	0.04	0.04b	0.16b
I_{10}	0.01	0.02	0.05	0.02	0.03b	0.10b
NO_3–N, kg ha^{-1}						
Control	0.01	0.00	0.09	0.02	0.03a	0.12a
C_1	0.02	0.01	0.01	0.02	0.01a	0.05a
I_{10}	0.01	0.02	0.03	0.01	0.02a	0.07a
COD, kg ha^{-1}‡						
Control	19.9	40.1	82.2	57.2	49.8a	199a
C_1	8.8	26.2	8.7	35.5	19.8b	79b
I_{10}	3.3	7.0	14.8	9.1	8.5b	34b

* Similar letters indicate no difference between treatment means ($P < 0.05$).
† Treatment I_{10} applied 10 mg L^{-1} PAM only during the furrow advance phase (until runoff began), and C_1 applied 1 mg L^{-1} PAM throughout the irrigation (except in irrigation three, C1 furrows were irrigated for 24 h, but PAM was applied only for the first 12 h).
‡ COD, chemical oxygen demand.

Table 5. Furrow nutrient stream concentrations at three sampling times (mean of all irrigations).

Parameter / Treatment	Sequence and time (hours into irrigation) of sampling — First 1.8 h	Second 5.8 h	Third 9.0 h
Sediment, g L^{-1}			
Control	3.77a*	2.06a	1.55a
C_1†	2.19b	0.36b	0.41b
I_{10}†	0.12c	0.27b	0.38b
Total P, mg L^{-1}			
Control	1.20a	0.73a	0.54a
C_1	0.86a	0.10b	0.06b
I_{10}	0.10b	0.13b	0.13b
Ortho P, mg L^{-1}			
Control	0.46a	0.37a	0.33a
C_1	0.64a	0.08b	0.04b
I_{10}	0.07b	0.11b	0.12b
NO_3–N, mg L^{-1}			
Control	0.12a	0.04a	0.02a
C_1	0.11a	0.21a	0.08a
I_{10}	0.13a	0.04a	0.03a
COD, mg L^{-1}‡			
Control	188a	100a	78a
C_1	160a	93a	28b
I_{10}	37b	34a	30b

* Similar lower case letters indicate no difference between treatment means for each component ($P < 0.05$).
† Treatment I_{10} applied 10 mg L^{-1} PAM only during the furrow advance phase (until runoff began), and C_1 applied 1 mg L^{-1} PAM throughout the irrigation (except in irrigation three, C1 furrows were irrigated for 24 h, but PAM was applied only for the first 12 h).
‡ COD, chemical oxygen demand.

and PAM-C_1 furrow streams were highest during the first 2 to 4 h, then decreased to a more moderate level of 25 to 50% peak value. Total P, ortho-P, and COD runoff concentrations followed a similar pattern for these treatments (Table 5). Sediment concentrations in PAM-I_{10} furrow streams were initially very low, then increased slightly as the irrigation progressed. Again, PAM-I_{10} total P and ortho-P runoff concentrations paralleled that of PAM-I_{10} sediment concentration. The NO_3–N concentrations, however, did not correspond to runoff sediment in any of the treatments. For example, while sediment concentration was greater in control furrows than in PAM-C_1 furrows, NO_3–N concentration in PAM-C_1 was equal to or greater than that of controls (Table 5).

Pearson's correlations between sediment concentration and total P, ortho P, and COD were highly significant ($P < 0.01$) and ranged from 0.5 to 0.66, while the sediment/NO_3–N relationship was not significant (Table 6). Total P was most strongly related to sediment content. When PAM treatment reduced runoff sediment concentrations to <0.1 mg L^{-1}, nearly the entire P concentration was attributed to the ortho-P component (Table 5). The analysis also revealed a very strong correlation (0.88, $P < 0.01$) between total P and COD content in runoff water (Table 6). One may consider using total P concentration as a qualitative indicator of water COD levels, although this relationship may not hold for soils or waters with different organic P or organic matter contents.

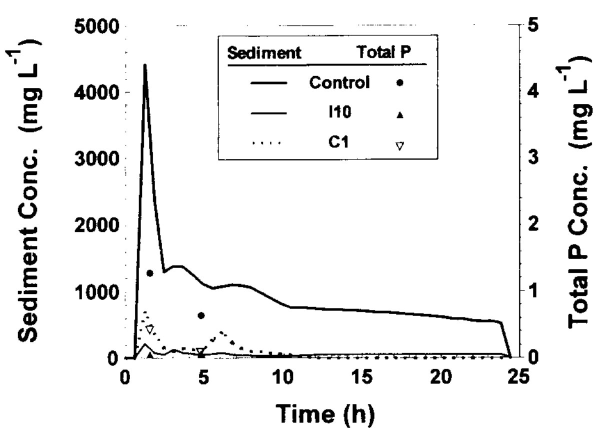

Fig. 2. Runoff sediment and total P concentration during irrigation four. Treatment I_{10} applied 10 mg L^{-1} PAM only during the furrow advance phase (until runoff began), and C_1 applied 1 mg L^{-1} PAM throughout the irrigation.

Table 6. Pearson's Correlations describing relationships between furrow stream sediment and other nutrients.

	Sediment	Ortho P	Total P	NO_3–N	COD†
Sediment	1.0	0.50**	0.66**	0.08	0.62**
Ortho P	–	1.0	0.68**	−0.05	0.64**
Total P	–	–	1.0	−0.07	0.88**
NO_3–N	–	–	–	1.0	−0.02
COD	–	–	–	–	1.0

** Correlations are significant at $P < 0.01$.
† COD, chemical oxygen demand.

Runoff sediment was only moderately positively correlated with total P and ortho-P concentrations (Table 6). Thus sediment concentration alone failed to explain observed variability in nutrient concentration. Carter et al. (1974) reported that finer sediments produced proportionately greater P than sand- or silt-sized particles. The sediment-nutrient relationship could be affected if some treatments were capable of enriching clay concentrations in transported sediment. Some evidence of clay enrichment and dilution may be seen in P/sediment concentration ratios derived from data reported for each sampling time in Table 5. The P/sediment ratio was 0.00012 and 0.00032 initially, and remained constant or slightly increased for total P and ortho P in control furrows. The ratios for PAM C_1 and I_{10} treatments initially were greater than control furrow values at the first sampling (0.00029–0.00083), but decreased as the irrigation proceeded. This suggests that PAM treatment increased sediment-load clay concentrations early in the irrigation, but the magnitude of this enrichment effect declined with time. It is not clear how PAM may have altered sediment-size distributions in treated furrow streams, but the phenomenon may partially explain the moderate correlation values obtained for sediment-nutrient relationships.

CONCLUSIONS

The PAM additions to furrow inflows substantially reduced furrow-irrigation field-losses of sediment, total P, ortho P, and COD (organic matter), compared to untreated furrows. The PAM treatment did not significantly decrease NO_3–N losses.

The PAM treatment reduced field losses by decreasing material concentrations in runoff and by reducing runoff volume. Anionic polyacrylamide accomplished the latter by maintaining higher net infiltration rates in treated furrows than in nontreated furrows. The highly significant correlation between furrow stream sediment and total-P, ortho-P, and COD concentrations suggested that PAM decreased these nutrient concentrations by controlling erosion and reducing runoff sediment concentrations.

The PAM-I_{10} treatment, where 10 mg L^{-1} PAM was metered into furrow irrigation inflows during at least the furrow advance (during water's initial advance down furrow), produced the smallest total nutrient losses, although these loss values were not significantly smaller than those of PAM-C_I. PAM-I_{10} reduced total field losses of sediment by 92%, total P by 91%, ortho P by 86%, and COD (organic matter) by 83%, compared to untreated furrows. While ortho-P and COD concentrations in PAM-I_{10} treated furrow streams were significantly smaller than those in PAM-C_I, cumulative nutrient mass losses produced by the PAM treatments were similar. The effect of the treatment concentration differences was partially offset by concomitant differences in runoff volumes, with PAM-C_I furrows producing less runoff than PAM-I_{10}.

The emerging PAM technology is rapidly being accepted as a means of reducing furrow irrigation-induced erosion and sediment loss. This study shows that PAM can also be used to greatly reduce P loading and chemical oxygen demand of runoff and hence, improve the quality of irrigation tailwater and return flows. Since PAM controls nutrient discharge largely by managing erosion, this emerging technology should effectively avert P losses under a wide range of soil conditions (where PAM is already used to control furrow erosion). The PAM technology has several advantages that make it an especially attractive practice for controlling agricultural nonpoint P contributions: (i) initial and maintenance costs of PAM application are relatively low; (ii) it requires no alteration of a farmers current cultivation and tillage regimen or cropping sequences; and (iii) it reduces erosion and down cutting of furrows and can eliminate the need for one or more tillage passes each season to reform furrows. Anionic polyacrylamide also increases water intake and lateral wetting (Lentz et al., 1992), and hence crop quality and/or yield, especially on steeper furrows.

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