USE OF POLYACRYLAMIDE IN SIMULATED LAND APPLICATION OF LAGOON EFFLUENT: PART I. RUNOFF AND SEDIMENT LOSS

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ABSTRACT. *Agriculture contributes considerably to water quality problems in the U.S. Tillage systems and land application of wastewaters from animal production facilities can increase both sediment and nutrient loadings to surface waters. Sediment transported to surface waters can decrease biodiversity and the usefulness of water for industry, drinking, and recreation. Anionic polyacrylamide (PAM) is a soil amendment that has been shown to reduce soil erosion during rainfall and irrigation. We hypothesized that dissolving PAM in land-applied lagoon effluent would reduce runoff and sediment loss in subsequent rainfalls. Swine wastewater from a third-stage anaerobic lagoon was mixed with high molecular weight PAM at concentrations of 0, 10, and 20 ppm and then surface applied to a silt loam soil packed in erosion boxes. A rainfall simulator was used to study PAM's effectiveness at two slopes (4% and 8%) and two cover levels (0% and 30%). Two consecutive storms with constant and varying rainfall intensity were simulated. PAM treatment reduced runoff from covered soils by up to 66%. On bare soil, the 10 ppm PAM treatment reduced first storm sediment losses by about 60%, while the 20 ppm PAM treatment resulted in about a 40% reduction. Lagoon effluent irrigation was found to produce higher sediment losses than water irrigation, but PAM treatment reduced sediment losses in lagoon-irrigated soils to levels that were comparable to water-only irrigations. These results indicate that application of anionic PAM with wastewater during surface irrigation can be an effective treatment to reduce runoff and erosion during subsequent rainfall events.*

Keywords. *Erosion control, Lagoon effluent, PAM, Polyacrylamide, Soil amendments, Soil erosion, Wastewater irrigation.*

Agricultural practices contribute significantly to water pollution in the U.S., affecting 18% of streams and lakes in the country. More than 40% of stream and lake impairments are directly attributed to contaminants found in agricultural runoff. Tillage and harvesting methods, as well as the land application of manure and wastewater from confined animal production facilities, increase the risk of soil erosion and nutrient movement into surface waters (U.S. EPA, 2000). Soil erosion by water occurs as: (1) soil particles are detached by raindrop impact or the shear stress induced by water flow, and (2) transported by shallow overland flow or in concentrated water flow. The main factors affecting soil erosion (Evans, 1980) are rain and soil properties and surface characteristics (vegetation or cover; rainfall energy and runoff generation; and soil texture, aggregation, surface roughness, and slope). An important phenomenon affecting erosion is surface sealing. Rainfall impact causes the breakdown and dispersion of small soil particles that can settle into and clog pore spaces, thus forming a surface crust that significantly slows infiltration (McIntyre, 1958). The reduced infiltration and corresponding increase in runoff from sealed soils can lead to increases in sediment loss (Bradford et al., 1987). Surface vegetation or tillage systems that leave plant residues on the soil surface can significantly reduce sealing and erosion by absorbing the impact energy of rainfall and reducing detachment and dispersion (Evans, 1980; Dabney et al., 2004).

Agricultural practices, such as land application of treated wastewaters and manures as a water supply and nutrient supplement for growing crops, may inadvertently contribute to soil erosion. Application of treated wastewaters increases the risk of nutrient movement into water bodies, but it can also have detrimental effects on the erodibility of soils that receive the effluent. The presence of suspended solids in the effluent can cause blockage of soil pores (Rice, 1974; Vinten et al., 1983), and the presence of dissolved organic matter and large amounts of sodium may cause dispersion of clay particles (Durgin and Chaney, 1984; Gardiner, 1996), thus decreasing soil hydraulic conductivity and percolation, and increasing the soil susceptibility to seal formation and erosion. Mamedov et al. (2000) observed higher runoff levels and erosion in variously textured soils that were long-term irrigated with secondary treated wastewaters compared to soils irrigated with fresh water.

One management practice that has been studied recently for erosion control is the application of synthetic polymers such as polyacrylamide (Levy et al., 1992; Lentz and Sojka, 2000). Initially, the use of polymers for agricultural soil

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stabilization was cost inhibitive, but the advent of newer, more economical polymers as well as an increased awareness of the environmental consequences of agriculture has resulted in renewed interest in the use of chemical soil conditioners, particularly polyacrylamide (Seybold, 1994; Sojka and Lentz, 1994). Polyacrylamide (PAM) is a high-molecular weight, water-soluble organic polymer that has been found to be highly effective for improving soil structure, increasing water infiltration, and reducing erosion.

PAM interacts with the clay fraction of soils, reducing erosion by bonding clay particles together, thus increasing the strength of existing soil aggregates and flocculating fine clays out of suspension, initiating deposition (Seybold, 1994; Chamberlain and Cole, 1996). Anionic PAM with approximately 20% charge density has been found to be the most effective formulation for control of soil erosion (Shainberg et al., 1990; Malik and Letey, 1991). Lentz and Sojka (2000) reported reductions in sediment losses of as much as 93% when irrigation water with 10 ppm of PAM was applied in an initial full advance application to furrows.

Peterson et al. (2003) investigated the use of PAM (80 kg ha^{-1}) for stabilization of unprotected earthen waterways and ephemeral gullies. Reductions in sediment yield ranging from 93% to 98% were observed for PAM-treated channels in comparison to control treatments. Flanagan et al. (2002a, 2002b) studied the effect of PAM (80 kg ha^{-1}) in combination with granular gypsum (5 Mg ha^{-1}) to control erosion on very steep slopes (>30%) under both simulated and natural rainfall. After a series of simulated rainfall events, total runoff and soil loss were reduced by 40% and 83% with PAM alone and by 52% and 91% with PAM plus gypsum, respectively, in comparison to the control (Flanagan et al., 2002a). Application of the same soil amendment treatments to earthen embankments of 35% and 45% slope resulted in reductions in sediment loss over all storm events in the range of 40% to 54% compared to the control (Flanagan et al., 2002b). The authors also noted that grass establishment and growth on PAM-treated slopes was superior to that of untreated slopes.

Application of a PAM solution via sprinklers might also provide effective erosion control and increased water use efficiency, and has been examined by a few researchers (Aase et al., 1998; Bjorneberg and Aase, 2000). Aase et al. (1998) tested this hypothesis by applying PAM to soil with an oscillating nozzle rainfall simulator. PAM applied in the first irrigation significantly increased the wet aggregate stability of the receiving soil. Runoff was reduced by 70% and soil loss by 75% in comparison to the control when PAM was applied at a rate of 2 kg ha^{-1} in an initial irrigation of 20 mm.

PAM has also been shown to help alleviate crust formation and increase infiltration associated with wastewater irrigation (Gardiner, 1996). Gardiner (1996) found that field saturated infiltration rates for PAM-treated plots were twice as high as control treatments, and that PAM was more effective than gypsum. The beneficial effects of PAM were found to persist for several weeks after the last application.

Because of PAM's demonstrated efficacy for the control of sediment and nutrient loss from agricultural fields under numerous conditions, it was hypothesized that PAM would also be useful for controlling erosion and nutrient movement from fields irrigated with agricultural lagoon wastewater. The purpose of this study was to investigate the effectiveness of potential management practices in which PAM is dissolved in treated lagoon effluent before land application. Runoff and sediment results are presented here, and the results for soluble and total nutrient losses are presented in a companion article (Flanagan and Canady, 2006).

Materials and Methods

This study was conducted in the hydraulics laboratory of the USDA-ARS National Soil Erosion Research Laboratory in West Lafayette, Indiana. The effect of three main treatment factors on runoff, sediment yield, and nutrient losses were examined. The three treatment factors used were surface residue cover (0% and 30%), slope (4% and 8%), and PAM concentration in the lagoon effluent applied to the soil (0, 10, and 20 ppm). The main experiment was performed in a complete randomized design with three replicates. Besides the primary treatments, an additional test was conducted using only de-ionized water application at 4% slope, with no cover or PAM, in order to clarify the effect of lagoon effluent on runoff and erosion.

Selected properties of the soil and the applied lagoon effluent are presented in table 1. Topsoil (0-20 cm) was excavated from the Purdue Animal Science Research and Education Center (ASREC) for use in the study. The soil was an alfisol from an area containing Crosby and Miami series soils, and was under pasture management. The soil was found to have a silt loam texture determined by the pipette method (Franzmeier et al., 1977). All soil was passed through an 8 mm wire mesh screen to remove debris and to homogenize the aggregate size distribution. After being sieved, the soil was allowed to air dry to an average moisture content of 2.7%. The lagoon effluent used for the study was obtained from the experimental swine production facility at the Purdue ASREC. Subsamples of the lagoon water were taken for evaluation of solids and nutrient content (table 1).

Soil was packed into aluminum boxes measuring 31 cm wide, 45 cm long, and 30 cm deep that were designed for interrill erosion experiments (Canady, 2005). Holes drilled into the bottom of the boxes allowed for free drainage during rainfall events. The first 14 cm depth of the boxes was filled with pea gravel to allow infiltrated water to drain freely from the openings. Soil was packed into the boxes to achieve a uniform bulk density of approximately 1.3 g cm^{-3} by pouring a known mass of soil (3600 g per layer) into a marked volume (2 cm layer thickness in the box) and then compressing to the mark with a wooden board. The boxes were set on portable

Table 1. Selected properties of soil and lagoon effluent wastewater.

Soil Properties[a]

Clay (%)	Silt (%)	Sand (%)	OM (%)	CEC (meq kg^{-1})	EC (dS m^{-1})	pH	Bray-P (mg L^{-1})
20	66	14	2	120	2.1	7.2	24

Lagoon Effluent Properties[b]

Suspended Solids (%)	TON (mg L^{-1})	OPO_4-P (mg L^{-1})	NH_4-N (mg L^{-1})	EC (dS m^{-1})	pH
0.13	3.5	33	65	2.9	8.2

[a] OM = organic matter, CEC = cation exchange capacity, and EC = electrical conductivity.

[b] TON = total oxidized nitrogen, OPO_4-P = orthophosphate phosphorus, and NH_4-N = ammonium nitrogen.

stands of about 0.3 m height that had hinged tops to allow variation of the slope.

Wheat straw was used to simulate field residue cover. The mass of the straw needed to provide 30% cover to the boxes was determined using residue mass and cover relationships specified by Gregory (1982). A mass of 9.8 g of straw was distributed evenly on each box receiving the cover treatment. The polyacrylamide used for this study was of anionic charge with 30% charge density and with a molecular weight of about 18 Mg mol^{-1} (Magnafloc 156, Ciba Specialty Chemicals, Suffolk, Va.). Recent prices of PAM products are in the range of \$4.50 to \$5.50 kg^{-1} (W. C. Broadway, Ciba Specialty Chemicals Corp., personal communication, March 2005). Using a median PAM price of \$5.00 kg^{-1}, surface application of lagoon effluent would cost \$5.00 and \$10.00 cm^{-1} ha^{-1} for PAM concentrations of 10 and 20 ppm, respectively. PAM was mixed at the appropriate concentrations with lagoon water in buckets using a magnetic stirrer for 1 h before application to the soil boxes. Lagoon effluent was sprayed onto the soil boxes using a handheld garden spray bottle over the course of about 10 min.

This study was designed to simulate a situation in which lagoon effluent is surface applied (7 mm depth) to a field for two consecutive days, and then followed on the third day by a rainfall event. One liter of the PAM-effluent solution was sprayed evenly on the boxes twice, 24 h apart. Twenty-four hours after the final effluent application, the simulated rainfall events and sampling were initiated.

Simulated precipitation was applied to the boxes using two programmable rainfall simulator troughs (Foster et al., 1979) suspended 3 m above the soil surface. The simulator troughs contained two oscillating VeeJet 80100 nozzles spaced 1.1 m apart, and the two troughs were spaced 1.3 m apart. Two consecutive separate storms with a 30 min break were simulated. The first storm consisted of a 1 h duration with a constant intensity, designed to be 64 mm h^{-1}. The second storm had varying intensities of 64, 94, and 25 mm h^{-1} in sequential 20 min increments.

For the first storm, sediment sampling began immediately after runoff initiation, and ponding time was recorded. The sampling interval was divided into 6 min increments; for the first 4 min of each increment, a sediment/runoff sample was collected in a tared 1 L bottle. During the second storm, three sampling intervals were completed during each 20 min increment of the same rainfall intensity. Sediment samples were immediately weighed and then oven-dried at 105°C. Runoff volume and sediment concentrations were determined gravimetrically. Total runoff was determined by calculating the runoff rate using the 4 min samples, multiplying the rate by an appropriate time period, and summing the runoff increments. Total sediment losses were determined by multiplying the sediment concentration by the runoff volume for each increment and summing all of the increments.

Analysis of variance (SAS, 1995) was used to determine treatment factor effects on ponding time, total runoff, average sediment concentration, and total sediment yield. In order to examine differences caused by PAM treatment, Tukey-Kramer honestly significant difference (HSD) tests were conducted at a significance level of $\alpha = 0.10$ for each combination of slope and cover treatment (SAS, 1995).

Results and Discussion

Storm 1 Results

All three of the main treatments (slope, cover, and PAM) significantly affected ponding time during the first constant intensity storm (table 2). Both cover and 20 ppm PAM treatments increased factor-level mean ponding time from 14 min to about 25 min (table 3). Within a given level of slope and cover treatment, PAM significantly increased ponding time at 4% slope and 30% cover (table 4).

Runoff

Total runoff was significantly affected by cover ($P < 0.0001$) and PAM ($P = 0.0001$) treatment factors during the first storm (table 2). Slope did not have an effect on total

Table 2. ANOVA significance of treatment main effects and interactions of slope, cover, and PAM on runoff and sediment loss for storm 1.

Source	Ponding Time	Total Runoff	Sediment Conc.	Sediment Loss
Model R^2	0.85	0.98	0.91	0.98
Slope	**	ns	***	***
Cover	***	***	***	***
Slope × Cover	ns	ns	***	***
PAM	***	***	***	***
Slope × PAM	ns	ns	**	*
Cover × PAM	ns	ns	***	***
Slope × Cover × PAM	ns	ns	ns	**

* = P < 0.10, ** = P < 0.05, *** = P < 0.01, and ns = not significant.

Table 3. Overall runoff and sediment factor-level means for storm 1.[a]

Treatment		Ponding Time (min)	Total Runoff (mm)	Average Sediment Conc. (g L^{-1})	Total Sediment Loss (Mg ha^{-1})
Slope	4%	22 a	24.2	8.2 b	2.3 b
	8%	18 a	25.0	13.4 a	4.4 a
Cover	0%	14 b	34.6 a	15.1 a	5.6 a
	30%	26 a	14.6 b	6.5 b	1.0 b
PAM	0 ppm	14 b	32.6 a	13.7 a	5.2 a
	10 ppm	21 ab	19.7 b	8.7 a	2.0 b
	20 ppm	25 a	21.5 ab	9.9 a	2.8 ab

[a] Factor-level means followed by the same letter are not significantly different at $\alpha = 0.10$ using the Tukey-Kramer HSD test.

Table 4. Ponding time, runoff, and sediment losses for storm 1.[a]

Slope (%)	Surface Cover (%)	PAM Treatment (ppm)	Ponding Time (min)	Total Runoff (mm)	Sediment Conc. (g L^{-1})	Sediment Loss (Mg ha^{-1})
4	0	0	11.8 a	39.8 a	14.1 a	5.62 a
4	0	10	16.7 a	28.8 a	8.31 b	2.34 b
4	0	20	17.7 a	34.5 a	9.68 b	3.35 b
8	0	0	8.30 a	41.4 a	28.7 a	11.7 a
8	0	10	10.3 a	31.9 a	13.4 b	4.30 b
8	0	20	12.0 a	37.9 a	16.8 ab	7.39 b
4	30	0	22.0 b	19.6 a	4.60 a	0.92 a
4	30	10	31.0 ab	8.15 b	6.47 a	0.49 a
4	30	20	36.0 a	10.2 ab	5.78 a	0.59 a
8	30	0	17.0 a	22.9 a	6.78 a	1.80 a
8	30	10	24.7 a	11.5 b	6.90 a	0.84 ab
8	30	20	31.3 a	7.77 b	7.57 a	0.60 b

[a] Quantities for a given combination of slope and surface cover level followed by the same letter are not significantly different at $\alpha = 0.10$ using the Tukey-Kramer HSD test.

runoff volume, whereas cover reduced runoff amounts by 58% (table 3). Dissolution of PAM in the applied effluent at a concentration of 10 ppm reduced overall runoff from 32.6 to 19.7 mm (a 40% reduction), while the 20 ppm PAM treatment did not reduce runoff volumes significantly relative to the control (table 3).

Total runoff results from the 10 and 20 ppm PAM treatments were not significantly different from each other (table 4). Other researchers have observed decreases in runoff with higher PAM rates (Al-Abed et al., 2003) or increases in runoff with higher PAM rates (Soupir et al., 2004), with the differences most likely an effect of specific soil and polymer properties in the individual studies. Here, PAM treatment significantly reduced total runoff on straw-covered soils, but not on bare soils. For instance, treatment with 10 ppm of PAM on 4% sloped, straw-covered soils reduced total runoff by 58%, while the 20 ppm PAM treatment reduced runoff by 66% on covered soils at 8% slopes (table 4). PAM and cover treatments seemed to work synergistically to reduce runoff. The low effect of the PAM-only treatment may be explained by: (1) breakdown and disintegration of the soil surface aggregates under rain intensity (64 mm h^{-1} wetting rate) or rain energy, and (2) because of the low electrolyte concentration of the lagoon effluent, PAM treatment was not able to hold aggregates together long enough to prevent clogging of soil pores except when surface cover was available to absorb the impact energy of the rainfall. With protection from direct rainfall impact, PAM-treated aggregates were more stable as they were wetted by surface water, and therefore infiltration was higher than on PAM-free control treatments.

Sediment Concentration and Total Soil Loss

Slope (P = 0.0002), straw cover (P < 0.0001), and PAM (P = 0.0124) treatment factors all had significant effects on average sediment concentration in runoff and total sediment loss during the first storm (table 2). Increasing the slope from 4% to 8% increased factor-level mean sediment concentration by about 60%, while the presence of 30% cover decreased factor-level mean sediment concentrations by about 60% (table 3). PAM treatment resulted in significantly lower final sediment concentrations, as seen in figures 1 and 2, which present the average sediment concentration of three replicates as a function of time for the bare soil treatments. PAM was found to be useful for reducing sediment concentration on soils with no straw cover. Bare soils receiving 10 ppm PAM treatment had 41% and 53% lower sediment concentrations than control treatments on 4% and 8% slopes, respectively (table 4). The 20 ppm PAM treatment also significantly reduced average sediment concentrations, but no differences were found in the results between the two PAM treatment levels (table 4). On the 8% slope treatment, the PAM-free control treatment exhibited a rapid increase in sediment concentration, followed by a decrease, due to seal formation and transport of easily erodible sediment on the steep slope (fig. 2). Treatment with both levels of PAM protected the soil from this effect on 8% slopes, smoothing and attenuating the rate at which sediment concentration increased during the storm.

When increasing the slope from 4% to 8%, greater slopes tended to have higher sediment concentrations, and slope effects on total sediment losses were significant (table 2). Cover treatment was very effective for controlling runoff and sediment loss. In combination with runoff reductions,

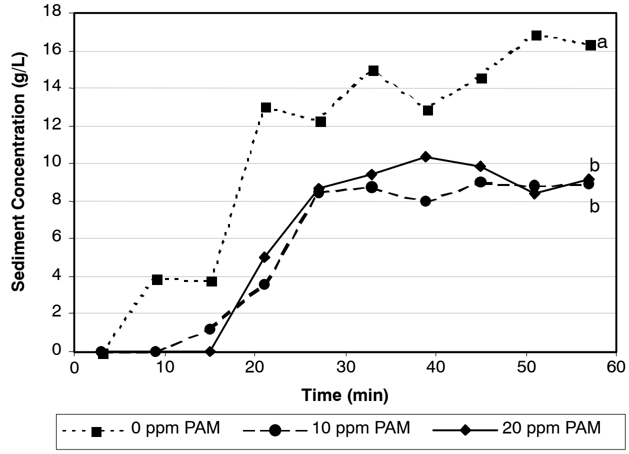

Figure 1. Sediment concentration with time for boxes with 4% slope and no straw residue cover during storm 1. Concentration lines with the same letter do not have significantly different final sediment concentrations (Tukey-Kramer HSD, α = 0.10).

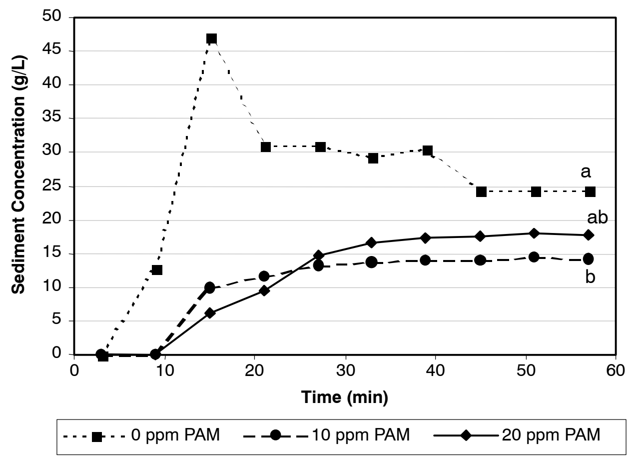

Figure 2. Sediment concentration with time for boxes with 8% slope and no straw residue cover during storm 1. Concentration lines with the same letter do not have significantly different final sediment concentrations (Tukey-Kramer HSD, α = 0.10).

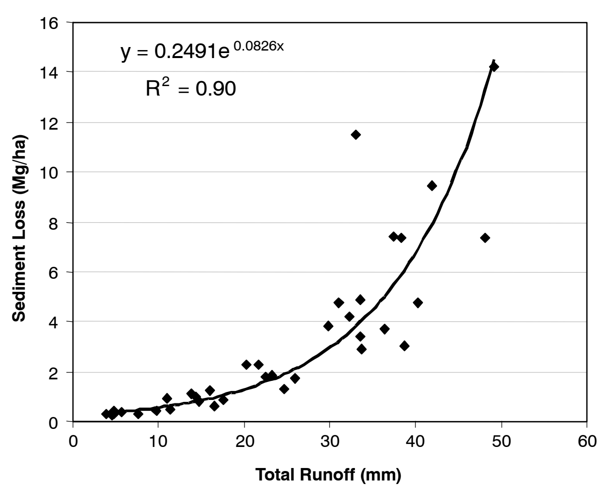

Figure 3. Sediment loss as a function of total runoff for all treatments during storm 1.

declines in sediment concentration due to cover treatment caused an overall reduction in sediment loss of about 80% during the first storm (table 3). Similar to sediment concentration, PAM treatment was most important for controlling sediment loss on bare soils (tables 3 and 4). Dissolving PAM in the lagoon effluent at a concentration of 10 ppm caused comparable reductions in sediment loss (58% and 63%) on the 4% and 8% slope treatments (table 4) on bare soil. The results from the 20 ppm PAM treatment were not significantly different from those from the 10 ppm PAM treatment (table 4). Cover treatment alone was very effective for reducing sediment loss, and although there is probably a benefit in adding PAM to moderately covered soils, fewer differences in sediment loss due to PAM treatment on 30% straw-covered soils were observed here. It is interesting to note that while runoff was significantly reduced with combinations of PAM and cover, compared to cover alone, this was not usually the case for the sediment loss. More research is needed to determine better how PAM and cover interact to affect runoff and soil loss. Sediment loss was highly correlated with total runoff. The data were well fit by an exponential relationship with a coefficient of determination (R^2) of 0.90 (fig. 3).

Storm 2 Results

Runoff

During the second simulated rain storm, total runoff was only significantly affected by cover, and not by slope or PAM (table 5). This is likely because the soil was pre-wetted under rain from the first storm, and steady-state runoff and sediment loss rates were already established. PAM seemed to lose its effectiveness during the high-intensity rainfall periods, for which only the cover appeared to provide sufficient protection to affect total runoff. After the change to a higher rainfall rate, the differences in runoff rates quickly diminished. This may indicate the degradation of PAM's effectiveness in preventing soil sealing because of: (1) the length of time that the rain had occurred, (2) the increase in rainfall rate or raindrop disintegration impact, (3) infiltration rates had reached a steady state given the soil's level of aggregation with PAM treatment, and (4) the effect of PAM decreased with an increase in the breakdown, failure, and disintegration in surface aggregates.

Sediment

Figures 4 and 5 show sediment concentration as a function of time during the second storm. The 10 ppm PAM treatments were initially effective at reducing sediment concentration, but lost effectiveness after the rainfall intensity increased

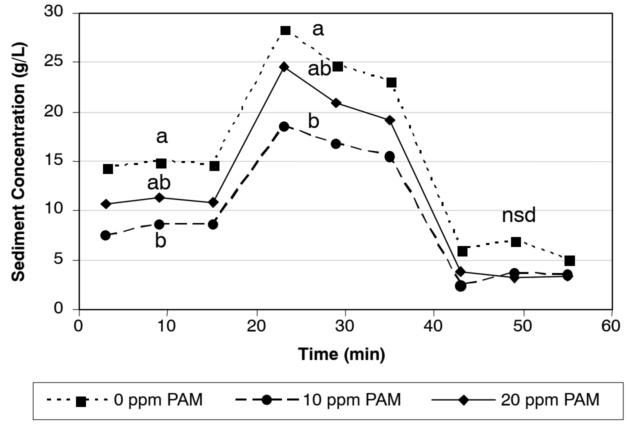

Figure 4. Sediment concentration with time for boxes with 4% slope and no straw residue cover during storm 2. Concentration lines with the same letter do not have significantly different final sediment concentrations (Tukey-Kramer HSD, α = 0.10, nsd = no significant difference).

then decreased. Sediment concentration results for the second storm were similar to the results for the first storm, although the treatment differences were of decreased magnitude. The three main factors being studied each had significant effects on sediment concentration during the second storm (table 5). The factor-level mean sediment concentration for 8% slope was about 38% higher than that of the 4% slope, while 30% cover lowered the factor-level mean sediment concentration by 56% (table 6). PAM treatment only significantly decreased sediment concentration (by 37%) on 4% slopes with bare soil (table 7). As with the first storm, treatment with either concentration of PAM did not significantly change average sediment concentration on straw-covered boxes during the second storm (table 7).

Cumulative sediment loss during the second storm was significantly affected by slope, cover, and PAM treatments (table 5). Differences in factor-level means were only evident for the 30% cover treatment, having 61% less sediment loss than bare soils (table 6). On bare soil at 4% slope, the lesser 10 ppm concentration of PAM decreased sediment loss by 44% in comparison to the control (table 7). Neither PAM treatment was significantly different from the control on bare soils at 8% slope (table 7). For the second storm, sediment

Table 5. ANOVA significance of treatment main effects and interactions of slope, cover, and PAM on runoff and sediment loss for storm 2.

Source	Total Runoff	Sediment Conc.	Sediment Loss
Model R^2	0.61	0.87	0.91
Slope	ns	***	***
Cover	*	***	***
Slope × Cover	ns	**	*
PAM	ns	**	***
Slope × PAM	ns	ns	ns
Cover × PAM	ns	***	***
Slope × Cover × PAM	ns	ns	ns

* = P < 0.10, ** = P < 0.05, *** = P < 0.01, and ns = not significant.

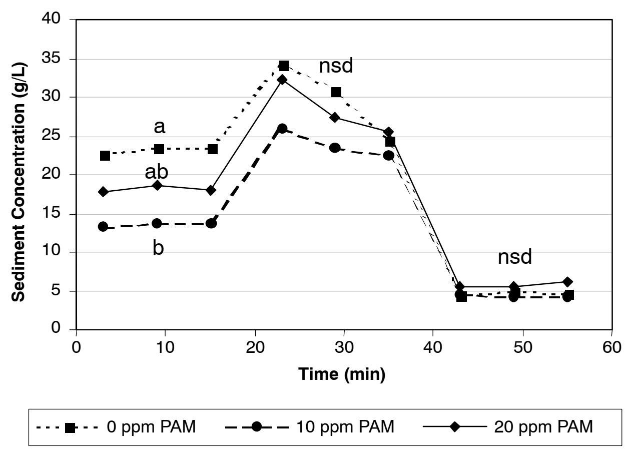

Figure 5. Sediment concentration with time for boxes with 8% slope and no straw residue cover during storm 2. Concentration lines with the same letter do not have significantly different final sediment concentrations (Tukey-Kramer HSD, α = 0.10, nsd = no significant difference).

Table 6. Overall runoff and sediment factor-level means for storm 2.[a]

Treatment		Total Runoff (mm)	Average Sediment Conc. (g L^{-1})	Total Sediment Loss (Mg ha^{-1})
Slope	4%	52.0	11.6 b	6.24 a
	8%	51.5	16.0 a	8.78 a
Cover	0%	54.2 a	19.2 a	10.8 a
	30%	49.4 b	8.5 b	4.26 b
PAM	0 ppm	54.0	15.7 a	8.38 a
	10 ppm	49.6	12.1 a	6.14 a
	20 ppm	51.8	13.7 a	8.01 a

[a] Factor-level means followed by the same letter are not significantly different at α = 0.10 using the Tukey-Kramer HSD test.

Table 7. Runoff and sediment losses for storm 2.[a]

Slope (%)	Surface Cover (%)	PAM Treatment (ppm)	Total Runoff (mm)	Sediment Conc. (g L^{-1})	Sediment Loss (Mg ha^{-1})
4	0	0	58.2 a	19.5 a	11.3 a
4	0	10	51.6 a	12.3 b	6.36 b
4	0	20	61.4 a	15.7 ab	9.55 ab
8	0	0	48.5 a	27.0 a	12.9 ab
8	0	10	51.8 a	18.4 a	9.56 b
8	0	20	59.8 a	22.2 a	14.9 a
4	30	0	49.6 a	6.90 a	3.53 a
4	30	10	43.4 a	7.83 a	3.36 a
4	30	20	44.6 a	7.37 a	3.32 a
8	30	0	54.0 a	9.28 a	5.82 a
8	30	10	52.9 a	9.88 a	5.27 a
8	30	20	45.5 a	9.44 a	4.25 a

[a] Quantities for a given combination of slope and surface cover level followed by the same letter are not significantly different at α = 0.10 using the Tukey-Kramer HSD test.

loss was much less correlated with total runoff than in the first storm (fig. 6), as would be expected since runoff differences were insignificant while significant differences in total sediment loss were observed.

Reductions in sediment loss from this study as a result of PAM treatment were less dramatic than from some other studies using PAM. One reason is that this study was performed on an interrill scale, while PAM may be more effective at controlling rill erosion. For example, Flanagan et al. (1997) observed sediment concentrations and discharge rates that were significantly higher than, or the same as, control treatments on small, 0.8 × 0.6 m interrill plots that were treated with 10 ppm of PAM. However, Flanagan et al. (1997) also observed beneficial effects with PAM treatment on 10.7 m long rill plots. Thus, PAM treatment seems to be of primary benefit under the concentrated flow conditions that can occur only on slopes of relatively great length. Another important factor is the use of lagoon effluent as the solvent for applying PAM. Lagoon effluent contains suspended organic matter that can interfere with PAM's ability to flocculate soil clays. Suspended solids in lagoon effluent may also seal soil pores. In addition, certain cations, such as sodium and ammonium, dissolved in the lagoon effluent may act to destroy aggregates and disperse clays. Smaller aggregates and clays reduce soil porosity and are more easily transported in surface runoff, adding to the overall sediment load in runoff.

Rainfall Rate Effects

In addition to considering the cumulative results over all of the rainfall intensities during the second storm, rainfall rate effects were also analyzed. With all treatments combined, average sediment concentrations were found to be significantly different at different rainfall intensity levels (fig. 7). Soil loss increased with increases in rainfall intensity; at the highest (94 mm h^{-1}) rainfall intensity, average sediment concentration was 63% higher than for the 64 mm h^{-1} rainfall intensity, while sediment concentration during the lowest (25 mm h^{-1}) rainfall intensity was 71% lower than during the 64 mm h^{-1} intensity (fig. 7). There was a continuing cover treatment effect on sediment concentration throughout all of the different rainfall intensity periods, and slope had a significant treatment effect during the medium and high rainfall intensities (table 8). PAM treatment was only found to be effective during the first 20 min of the storm, at the 64 mm h^{-1} rainfall intensity.

Comparison of De-Ionized Water and Lagoon Effluent Irrigations

In order to clarify the net effect of lagoon treatment on runoff and soil loss, de-ionized water was used instead of

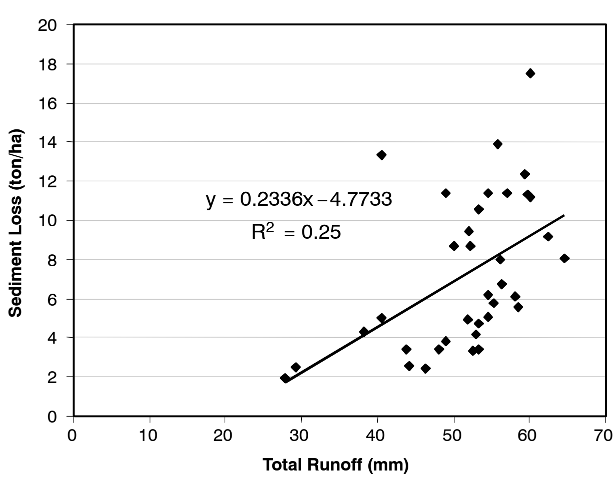

Figure 6. Sediment loss as a function of total runoff for all treatments during storm 2.

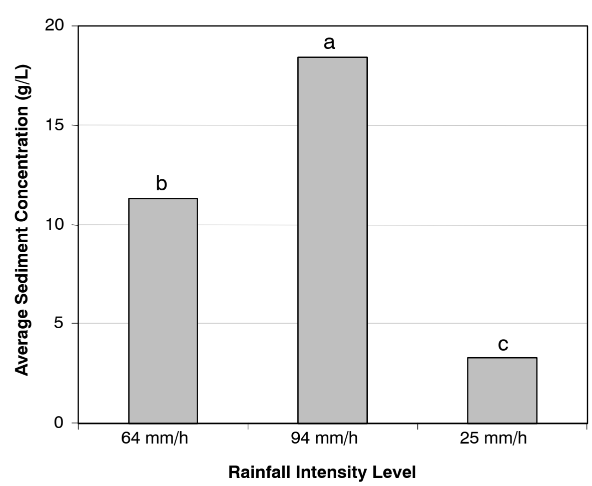

Figure 7. Average sediment concentration for three rainfall intensities. Bars labeled with the same letter are not significantly different (Tukey-Kramer HSD, α = 0.10).

Table 8. ANOVA significance of treatment main effects and interactions of slope, cover, and PAM on sediment concentration at varying rainfall intensities.

Source	Medium Intensity	High Intensity	Low Intensity
Model R^2	0.87	0.87	0.71
Slope	***	***	ns
Cover	***	***	***
Slope × Cover	**	ns	ns
PAM	**	ns	ns
Slope × PAM	ns	ns	ns
Cover × PAM	***	*	ns
Slope × Cover × PAM	ns	ns	ns

* = P < 0.10, ** = P < 0.05, *** = P < 0.01, and ns = not significant.

lagoon effluent as an irrigation treatment on a subset of replicates. This treatment was done on a 4% slope and received no PAM or surface cover additions. Total runoff and sediment results for this treatment are presented in table 9, along with lagoon-irrigated treatments with and without PAM. Total runoff was not significantly different between lagoon irrigation and water irrigation treatments for any of the storms. However, differences in average sediment concentration and total sediment loss were observed. During the first storm, both sediment concentration and sediment loss from the de-ionized water irrigation treatment were 49% less than that of the lagoon effluent-irrigated boxes (table 9). The use of either concentration of PAM in the first storm produced sediment concentrations and total sediment losses that were not significantly different from the boxes irrigated with water only (table 9). Similar results were seen during the second storm: water-irrigated boxes had essentially the same runoff as lagoon-irrigated boxes, but significantly lower average sediment concentrations. For combined storms, the de-ionized water treatment had 38% lesser average sediment concentration and total sediment loss than the lagoon effluent-irrigated treatment (table 9). PAM-treated boxes (10 ppm) had about the same sediment concentrations and loss as the water-irrigated boxes (table 9).

Figures 8 and 9 show sediment concentration with time, comparing de-ionized water irrigation and lagoon effluent irrigation treatments for both storms. Boxes receiving water irrigation had significantly lower mean final sediment

Table 9. Comparison of runoff and sediment loss for lagoon effluent and water-only simulated irrigations.[a]

Storm	Treatment[b]	Total Runoff (mm)	Sediment Conc. ($g\ L^{-1}$)	Sediment Loss ($Mg\ ha^{-1}$)
Storm 1	L	39.8 a	14.1 a	5.62 a
	LPAM10	28.8 a	8.31 b	2.34 b
	LPAM20	34.5 a	9.68 b	3.35 b
	W	37.9 a	7.22 b	2.85 b
Storm 2	L	58.2 a	19.5 a	11.3 a
	LPAM10	51.6 a	12.3 b	6.36 b
	LPAM20	61.4 a	15.7 ab	9.55 ab
	W	57.3 a	13.0 b	7.58 ab
Combined	L	98.0 a	17.3 a	16.9 a
	LPAM10	80.4 a	10.9 b	8.70 b
	LPAM20	95.9 a	13.5 ab	12.9 ab
	W	95.2 a	10.7 b	10.4 b

[a] Quantities within a given storm followed by the same letter are not significantly different at α = 0.10 using the Tukey-Kramer HSD test.

[b] L = lagoon effluent, LPAM10 = lagoon with 10 ppm PAM, LPAM20 = lagoon with 20 ppm PAM, and W = de-ionized water irrigation.

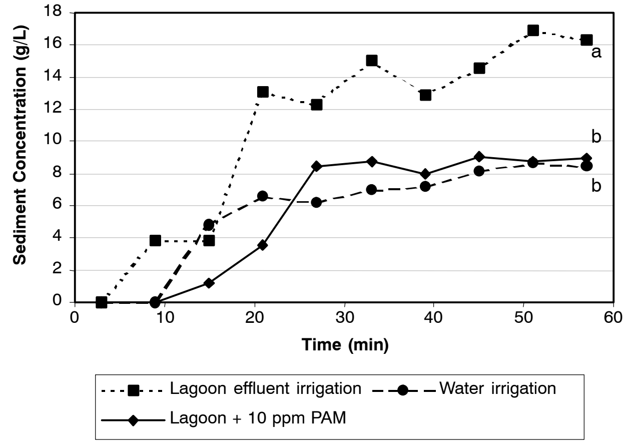

Figure 8. Storm 1 sediment concentrations with time, comparing water irrigation with lagoon effluent irrigation with and without 10 ppm PAM treatment. Concentration lines with the same letter do not have significantly different final sediment concentrations (Tukey-Kramer HSD, α = 0.10).

concentrations during the first storm, and significantly lower sediment concentrations during each period of the different rainfall intensities during the second storm, than the boxes subjected to lagoon effluent irrigation. When the boxes were irrigated with lagoon effluent containing 10 ppm PAM, the runoff had sediment concentration results that were very similar to those of de-ionized water-irrigated boxes. PAM-treated boxes had sediment concentrations that were significantly lower than lagoon-irrigated control boxes in all cases except for the final, lowest rainfall intensity period during the second, multiple-intensity storm.

Summary and Conclusions

The effectiveness of anionic polyacrylamide dissolved in swine lagoon effluent at concentrations of 10 and 20 ppm for reducing runoff and erosion from a silt loam soil during subsequent rainfall events was evaluated. PAM's effectiveness was tested under different slope (4% and 8%) and cover (0% and 30%) conditions. Additionally, tests were conducted

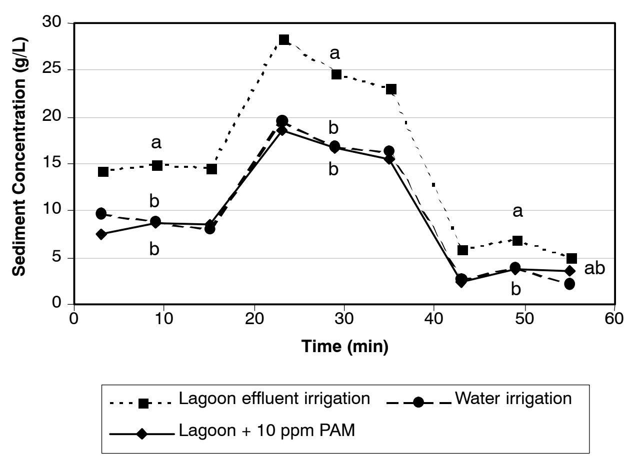

Figure 9. Storm 2 sediment concentrations with time, comparing water irrigation with lagoon effluent irrigation with and without 10 ppm PAM treatment. Concentration lines with the same letter do not have significantly different final sediment concentrations (Tukey-Kramer HSD, α = 0.10).

to compare erosion between soils receiving lagoon effluent irrigations and fresh water. Results from two different 1 h storms, the first having constant rainfall intensity and the second having varying rainfall intensities, were analyzed.

PAM treatments were found to significantly ($\alpha = 0.10$) reduce (up to 66%) total runoff during the first storm when 30% straw cover was present at both slope levels, but PAM was not effective for runoff reduction under bare soil conditions. During the second storm, only cover treatment significantly affected runoff, and only resulted in a minimal reduction of 9% in factor-level means. Neither concentration level of PAM was found to be significantly more effective than the other for reducing runoff.

Although significant PAM-induced reductions in runoff were found only on covered soils, the opposite effect was observed with regards to sediment movement during the storm events. Sediment concentrations from PAM-treated soils for the first storm, with constant rainfall intensity, were significantly lower than control treatments when there was no surface cover. The effect of this was that total sediment losses were significantly lower even though runoff was not. For bare soils, the 10 ppm PAM treatment reduced sediment loss by ~60% on both slopes. During the second storm, PAM treatments were effective less often, as the 10 ppm PAM treatment significantly reduced sediment loss only on bare soils at 4% slope. Although in most cases the two levels of PAM treatment did not differ from each other with regards to runoff and sediment loss, the 20 ppm PAM treatment resulted in significantly higher sediment loss on bare soils at 8% slope during the second storm.

Tests comparing simulated lagoon effluent irrigation with water-only irrigation on bare soils at 4% slope showed that lagoon effluent irrigation could result in up to twice as much sediment loss as water irrigation during subsequent rainfall. Dissolution of 10 ppm PAM in the lagoon effluent proved to be an effective practice for controlling excessive erosion from the lagoon-irrigated soils, bringing mean sediment loss to levels that were significantly lower than those of the lagoon-irrigated control treatments, but not different from the water-irrigated soils. This experiment only examined interrill erosion, so control of rill erosion using PAM in lagoon effluent may be different.

Results from this study suggest that PAM may have reduced effectiveness after prolonged rainfall or after high-intensity storms, and that additional PAM application would be required after such storm events. However, it is possible that these results are not due to degradation of PAM on soil aggregates, but simply due to the soil having reached maximum infiltration capacity even with PAM treatment. Thus, PAM could offer additional benefit in subsequent storms after the soil has dried. In this case, PAM application may not be necessary for every irrigation during a season. Further research is needed to test this speculation by subjecting lagoon effluent-irrigated soils treated with PAM to several rainfalls after the soil has been allowed to dry, and comparing the results with those from soils with and without a typical PAM (with no effluent used) application. Similar research at a field scale would help to confirm the results presented here and reveal practical concerns for the use of a management practice based on this research. In addition, research on different application strategies, such as applying PAM to the soil and allowing it to dry prior to lagoon effluent land application, may reveal methods that are more effective for controlling erosion and nutrient loss.

This study demonstrates that PAM, which has been shown in previous fresh water irrigation studies to effectively increase infiltration and reduce loss of sediment and nutrients in runoff, is similarly effective when used with low-concentration agricultural wastewater. Management practices that include adding a small amount of anionic PAM to lagoon effluent should be considered for control of runoff and erosion under wastewater irrigation systems. PAM use is especially recommended for land with steep slope, or on soils that lack adequate surface cover, such as those that might occur with conventional tillage practices.

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