USE OF POLYACRYLAMIDE IN SIMULATED LAND APPLICATION OF LAGOON EFFLUENT: PART II. NUTRIENT LOSS

D. C. Flanagan, N. H. Canady

ABSTRACT. *Land application of agricultural wastewater can contribute to eutrophication of water bodies by increasing the quantities of dissolved and particulate nutrients that are transported in runoff during rain storm events. Anionic polyacrylamide (PAM) is a soil amendment that has been shown to reduce soil erosion and nutrient transport during rainfall and irrigation. We hypothesized that dissolving PAM in low-concentration, land-applied lagoon effluent would reduce nutrient losses during subsequent rainfalls. Swine wastewater from a third-stage anaerobic lagoon was mixed with PAM at concentrations of 0, 10, and 20 ppm and then surface applied to soil packed in erosion boxes. A rainfall simulator was used to study PAM's effectiveness at multiple slope (4% and 8%) and cover levels (0% and 30%). Two consecutive storms with constant and varying rainfall intensities were simulated. Soluble ortho−P, combined NO_2^- and NO_3^-−N, NH_4^+−N, and particulate N and P concentrations were determined in runoff samples obtained during the storms. Under various levels of slope and cover treatment, PAM use reduced NH_4^+−N loss from 34% to 92% and reduced ortho−P loss from 31% to 71%. PAM treatment was also effective in reducing particulate nutrient losses, including reductions of 22% to 72% for total P. These results indicate that PAM can be effective for controlling surface nutrient losses in runoff in the time period immediately following land application of low-concentration agricultural wastewater.*

Keywords. *Agricultural pollution, Lagoon effluent, Nitrogen, Nutrient transport, PAM, Phosphorus, Polyacrylamide, Soil amendments, Wastewater irrigation.*

Successful agronomic production requires the addition of nutrients to cropland in the form of fertilizers or manure. Therefore, runoff from agricultural fields often contains nutrient concentrations that exceed the amounts found in runoff waters from virgin land. The introduction of excessive nutrients to water bodies has been identified as the main cause of surface water quality impairment in the U.S. (U.S. EPA, 2000; USDA-ARS, 2003). Excess nutrients are found in 22% of lakes in the U.S., and high nutrient concentrations account for 50% of all water quality problems reported in lakes (U.S. EPA, 2000). The main consequence of heavy nutrient loadings to surface waters is eutrophication.

Application of both synthetic fertilizers and animal manures in excess of the land's assimilative capacity to hold nutrients can result in nutrient movement into water bodies (Brichford et al., 1993). One source of nutrient loading to water bodies is runoff from fields that have been subjected to surface application of effluent from aerobic or anaerobic lagoons. These effluents contain considerable quantities of nutrients in both mineral and organic forms. Studies have shown increased losses of nutrients from surface-applied manures in comparison to incorporation of the manure by tillage or injection (Mueller et al., 1984; Nichols et al., 1994). Although incorporation of animal manure is the most efficient way to make nutrients available for plants, it is frequently not possible or desirable (Tarkalson and Mikkelsen, 2004).

The size of rainfall events as well as the timing between land application of manure and rainfall events significantly affects nutrient loss. The greater part of annual runoff in a watershed may occur in only one or two major storm events that can contribute over 90% of the watershed's annual P loads (Sharpley, 1995). Generally, losses of P in runoff are less than 5% of the total P applied, unless rainfall immediately follows land application (Sharpley, 1995). Storm events immediately following surface application of wastewater or manure can also increase the risk of higher than normal nutrient loadings to streams, since nutrients are in a mobile state and crop uptake and soil absorption processes have had little time to occur. Therefore, timing of manure application to avoid close proximity to rainfall events is very important to minimize P losses from land-applied soils (Sharpley, 1982; Schroeder et al., 2004). However, the realities of limited on-farm manure storage capacity and the uncertainty associated with prediction of weather events cause inevitable periods of overlap between land application of manure and rainfall. Management practices are needed to protect water

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bodies from excessive nutrient loadings in the critical period immediately following land application of wastewater nutrients.

Polyacrylamide (PAM) is a synthetic, organic polymer that can be dissolved in water and applied to soil surfaces as an amendment to improve soil structure and aggregate strength. Anionic PAM is commonly used to stabilize soils that lack natural cover because of tillage or construction. PAM functions by interacting with soil clays. As the long PAM molecules attach to clays, they increase the strength of existing aggregates and cause flocculation of soil particles from suspension (Seybold, 1994; Chamberlain and Cole, 1996). PAM has been shown to effectively reduce erosion in concentrated flow regimes such as with furrow irrigation (Lentz and Sojka, 2000) and man-made earthen waterways (Peterson et al., 2003), as well as in overland flow under both simulated and natural rainfall (Flanagan et al., 2002a, 2002b) or sprinkler irrigation (Aase et al., 1998; Bjorneberg and Aase, 2000; Bjorneberg et al., 2000).

In addition to its demonstrated benefits for erosion and runoff reduction, anionic PAM application has also been found to reduce the loss of both dissolved and particulate-associated nutrients in runoff. PAM is thought to reduce the nutrient content of soil water by hindering dissolution and desorption from soil particles and by sorbing ions in solution to itself (Entry and Sojka, 2003; Orts et al., 2000). Lentz et al. (1998) measured ortho−P and total P losses from furrows treated either with 1 ppm continuously or with 10 ppm of anionic PAM during the furrow advance. They found that ortho−P and total P concentrations in untreated control furrows were five to seven times greater than from furrows receiving PAM treatments. The initial high concentration of PAM was found to be more effective at reducing P concentrations than continuous application of the low-concentration PAM treatment; however, the two treatments had similar sediment and nutrient mass losses because of differences in total runoff.

Entry and Sojka (2003), who examined PAM's usefulness in reducing furrow irrigation-induced losses of sediment, water, and nutrients, stressed that PAM treatments reduced tailwater nitrate concentration by 85% and total P concentration by 90% in comparison to control treatments. Moreover in this experiment, depending on the irrigation rate, the export of nutrients by sediment was two to five times higher for the control than for the PAM-treated furrows.

Bjorneberg et al. (2000) simulated application of PAM through a sprinkler irrigation system onto a residue-covered soil by using a rainfall simulator. Anionic PAM was applied to a loam soil by the simulator at rates of 0, 2 and 4 kg ha^{-1} at 80 mm h^{-1} for 1 h, and then followed by two more PAM-free irrigations. Soil boxes were covered with wheat straw at levels of 30% and 70% surface cover. They found that straw surface cover levels of 70% were more effective than the 2 and 4 kg ha^{-1} PAM applications at controlling runoff, erosion, and P losses. PAM application and 30% straw cover were equally effective. However, application of PAM in combination with straw surface cover was more effective than either treatment used separately, diminishing irrigation-induced runoff by as much as 80% and thus also reducing sediment and phosphorus loss considerably.

Since PAM has been found to be effective for reducing sediment and nutrient losses in surface runoff during rainfall and irrigation, we hypothesized that dissolving PAM in lagoon effluent before surface application would help to protect soil and nearby surface waters by reducing sediment and nutrient transport during rainfall events that occur after land application of the effluent. The objective of this study was to examine the usefulness of various PAM applications under a range of conditions in reducing runoff, soil erosion, and nutrient losses. This article discusses the results found for dissolved and particulate forms of N and P.

Materials and Methods

This experiment was performed at the USDA-ARS National Soil Erosion Research Laboratory in West Lafayette, Indiana. The study was conducted by applying simulated rainfall to interrill soil erosion boxes that had received an application of lagoon effluent containing PAM, and collecting runoff samples for analysis of sediment and nutrient concentration. Three treatment factors were studied in a complete randomized design with three replicates: surface residue cover at levels of 0% and 30%, slopes of 4% and 8%, and PAM concentrations of 0, 10, and 20 ppm. Additionally, a treatment using de-ionized water instead of lagoon effluent was completed in order to compare the effects of lagoon effluent irrigation to water irrigation. This treatment did not have surface cover or PAM application, and was done only at 4% slope.

Both the soil and the lagoon effluent used in this study were obtained from the Animal Science Research and Education Center at Purdue University in West Lafayette, Indiana. The soil was a Crosby-Miami complex alfisol with a silt loam texture. Topsoil (0-20 cm) was excavated from a field under pasture management and then passed through an 8 mm wire mesh screen before being allowed to air dry. Properties of the soil and lagoon effluent are presented in table 1. The moisture content of the soil used for the experiment was 2.7%. The lagoon effluent used in the study was taken from a third-stage lagoon used to treat swine manure and wastewater.

Aluminum boxes measuring 31 cm wide, 45 cm long, and 30 cm deep were used for this study. The boxes were set on 0.3 m high stands with adjustable tops for modification of slope. Pea gravel was added to the first 14 cm depth of the boxes to allow infiltration water to drain freely from holes drilled into the bottom of the boxes. Soil was then packed above the gravel to a bulk density of about 1.3 g cm^{-3}. Cover treatment of 30% was achieved by spreading 9.8 g of wheat

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.

straw on the soil surface as specified in relationships developed by Gregory (1982). Anionic polyacrylamide (Magnafloc 156, Ciba Specialty Chemicals, Suffolk, Va.) with 30% charge density and a molecular weight of about 18 Mg mol^{-1} was mixed with lagoon effluent in buckets using a magnetic stirrer for 1 h before application to the soil. Lagoon effluent was applied to the soil using a handheld garden sprayer to a total depth of 7 mm per application. Therefore, 7 mm of the lagoon effluent was applied to the soil twice, 24 h apart, to simulate field irrigation with lagoon effluent.

One day after the last application of lagoon effluent, simulated rainfall events were initiated. Two separate storms were simulated during the experiment using two programmable rainfall simulator troughs (Foster et al., 1979) spaced 1.3 m apart. The troughs contained oscillating VeeJet 80100 nozzles with 1.1 m spacing. The initial storm was 1 h long with a constant intensity of 64 mm h^{-1}. Thirty minutes after the completion of the first storm, a second storm was simulated that had varying intensities of 64, 94, and 25 mm h^{-1} in sequential 20 min increments.

Sediment and nutrient sampling began as soon as ponding and runoff initiation occurred during the first storm. Sampling occurred in 6 min increments, with 4 min allotted for acquisition of sediment samples. During the next 2 min of the interval, runoff samples were acquired in separate bottles for analysis of dissolved and total nutrients. Three sampling intervals were completed during each 20 min rainfall intensity increment during the second storm.

Processing of nutrient samples was begun immediately after completion of the simulated storm events. A volume of 30 mL of each of the soluble nutrient samples was filtered using 0.45 μm nitrocellulose syringe filters. A drop of concentrated sulfuric acid was added to each sample to lower pH and aid in preservation (Clesceri et al., 1998). Both soluble nutrient and total nutrient samples were frozen until chemical analysis could take place (Clesceri et al., 1998). A Konelab 20 water chemistry auto-analyzer was used to determine soluble nutrient concentrations in the runoff samples. The three tests performed were total oxidized nitrogen (TON), which determines combined nitrogen content due to nitrates and nitrites, ammonium-nitrogen (NH_4^+−N), and orthophosphates (ortho−P). The test methods for TON, ammonium−N, and ortho−P were based on EPA methods 353.1, 350.1, and 365.2, respectively (U.S. EPA, 1979).

Samples acquired for testing of total nutrients were digested using the "total Kjeldahl digestion in waters" method (Wendt, 1997; Liao, 1998). After digestion, all samples were filtered with 0.45 μm nitrocellulose syringe filters to remove residual silica precipitates. The samples were analyzed using a Lachat QuikChem 8000 auto-analyzer. The methods and principles of detection of total Kjeldahl nitrogen (TKN) and total phosphorus (TP) concentrations are identical to those used to determine ammonia and orthophosphate concentrations in water. Standards were prepared using an identical chemical matrix as the digested samples.

This article presents net surface loss of soluble and total N and P. For each storm, net transport of soluble and total nutrients losses were calculated by multiplying the measured nutrient concentrations by the runoff volume for each time increment and summing the total nutrient losses found for each increment. Analysis of variance (SAS, 1995) was used to determine the significance of treatment factor effects on average concentrations and total transport of TON, NH_4^+−N, ortho−P, TKN, and TP. Means comparisons were conducted using a Tukey-Kramer honestly significant difference (HSD) test at α = 0.10 (SAS, 1995).

Results and Discussion

Storm 1 Results

Table 2 shows the results of analysis of variance (ANOVA) of the data for the average concentration and total surface losses of soluble nutrients. Unlike slope, PAM and cover treatments did not have significant main effects on TON concentration (table 2). The factor-level TON concentration mean for 8% slopes was more than 70% higher than for 4% slopes (table 3). PAM treatments caused no significant decrease in TON concentrations for any combination of slope and cover (table 4).

Total loss of TON during the first storm was greatly affected ($P < 0.001$) by slope and cover treatments (table 2). The factor-level mean TON loss went from 41.7 g ha^{-1} on 4% slopes to 113 g ha^{-1} on 8% slopes, an increase of over 170% (table 3). The 30% cover treatment reduced TON loss by about 66% (table 3). PAM factor-level mean treatment levels were not significantly different (table 3). PAM treatment was effective at reducing TON losses during the first storm only on covered soils at 4% slope (table 4).

Slope may have had the observed effect of increasing TON concentration for several reasons. An increase in slope

Table 2. ANOVA significance of treatment main effects and interactions of slope, cover, and PAM on soluble nutrient concentrations and losses from storm 1.

	TON		NH_4^+−N		Ortho−P	
Source	Conc.	Loss	Conc.	Loss	Conc.	Loss
Model R^2	0.73	0.85	0.70	0.76	0.84	0.93
Slope	***	***	ns	ns	ns	ns
Cover	ns	***	**	**	***	***
Slope × Cover	***	***	ns	ns	ns	ns
PAM	ns	*	***	***	***	***
Slope × PAM	ns	ns	**	ns	*	ns
Cover × PAM	ns	ns	ns	ns	ns	ns
Slope × Cover × PAM	*	*	ns	ns	*	*

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

Table 3. Overall soluble nutrient concentration and loss factor-level means for storm 1.[a]

	TON		NH_4^+−N		Ortho−P	
Treatment	Conc. (mg L^{-1})	Loss (g ha^{-1})	Conc. (mg L^{-1})	Loss (g ha^{-1})	Conc. (mg L^{-1})	Loss (g ha^{-1})
Slope						
4%	0.26 b	41.7 b	0.42	95.1	0.56	125
8%	0.45 a	113 a	0.36	94.1	0.54	124
Cover						
0%	0.32	110 a	0.33 a	115 a	0.44 b	152 a
30%	0.39	44.1 b	0.45 a	73.8 b	0.66 a	96.4 b
PAM						
0 ppm	0.34	93.2 a	0.60 a	184 a	0.66 a	199 a
10 ppm	0.40	79.8 a	0.37 b	59.3 b	0.50 b	83.5 b
20 ppm	0.33	57.8 a	0.21 c	40.7 b	0.49 b	90.4 b

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

Table 4. Soluble nutrient average concentrations and total losses from storm 1.[a]

Slope (%)	Surface Cover (%)	PAM Conc. (ppm)	TON Conc. (mg L^{-1})	TON Loss (g ha^{-1})	NH_4^+–N Conc. (mg L^{-1})	NH_4^+–N Loss (g ha^{-1})	Ortho–P Conc. (mg L^{-1})	Ortho–P Loss (g ha^{-1})
4	0	0	0.12 a	46.1 a	0.49 a	191 a	0.49 a	196 a
4	0	10	0.07 a	17.7 a	0.41 ab	126 ab	0.47 ab	133 a
4	0	20	0.10 a	33.8 a	0.19 b	64.7 b	0.39 b	136 a
8	0	0	0.49 ab	194 a	0.51 a	220 a	0.61 a	253 a
8	0	10	0.75 a	240 a	0.15 b	48.3 b	0.28 b	91.0 b
8	0	20	0.38 b	127 a	0.25 b	79.6 ab	0.42 b	138 b
4	30	0	0.45 a	82.6 a	0.65 a	128 a	0.78 a	152 a
4	30	10	0.51 a	34.6 b	0.59 a	45.8 b	0.62 b	50.2 b
4	30	20	0.35 a	32.2 b	0.20 b	18.7 b	0.58 b	62.3 b
8	30	0	0.29 a	49.7 a	0.75 a	155 a	0.77 a	163 a
8	30	10	0.28 a	29.9 a	0.53 ab	45.1 ab	0.61 ab	67.4 ab
8	30	20	0.49 a	38.3 a	0.19 b	13.1 b	0.57 b	47.5 b

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

gradient has been observed to increase downslope splash detachment (Van Dijk et al., 2003; Fox and Bryan, 1999). Since runoff interacts chemically with only a thin layer of surface soil, increasing the slope may act to increase soluble TON concentrations in runoff by reducing the onset of crusting and allowing surface water to interact with a deeper layer of soil. Moreover, the increase of fine sediment surface transport allows runoff to interact more with sediment particles that have a high surface area, so that nutrient salts precipitated on clay surfaces are exposed to runoff water. Finally, since the high-slope treatments had higher sediment loss in general (Flanagan and Canady, 2006), it is possible that the removal of surface sediment continually exposed underlying soil that still contained a supply of nitrate and nitrite salts, so that a higher concentration of TON in runoff could be maintained throughout the storm.

Ammonium nitrogen concentration in runoff was significantly affected by the cover and PAM treatments (table 2). Slope did not affect NH_4^+–N concentration. The factor-level mean NH_4^+–N concentration was reduced from 0.60 mg L^{-1} for the control treatments to 0.37 mg L^{-1} with the 10 ppm PAM treatment, and further to 0.21 mg L^{-1} with the 20 ppm PAM treatment. The greater PAM treatment significantly reduced NH_4^+–N concentration under all four combinations of slope and cover levels (table 4). This weakly aggregated silt loam soil was easily disintegrated under high rainfall energy (Flanagan and Canady, 2006). Thus, decreasing aggregate slaking and dispersion under raindrop impact with PAM treatment may considerably affect NH_4^+–N concentration (table 4).

Cover and PAM treatments also had significant effects on total NH_4^+–N loss (table 2). The NH_4^+–N loss for the 30% cover treatments was about 36% less than for treatments having no cover, whereas the PAM applications had about twice the impact of cover, lowering this nutrient loss by 66% to 78% (table 3). Moreover, on the straw-covered soils, the PAM treatment reduced NH_4^+–N loss by 64% to 92% (table 4).

Similar to ammonium loss, cover and PAM treatments significantly affected soluble orthophosphate P concentrations during the first storm (table 2). The factor-level mean ortho–P concentration was 58% higher for the 30% cover treatment than for the bare soil treatment (table 3). Both PAM treatments reduced ortho–P concentrations by about 24% to 0.5 mg L^{-1}. PAM treatments significantly reduced first storm ortho–P concentration in all four combinations of slope and cover treatment, but results from each PAM rate were not different from each other in any case (table 4).

Total ortho–P transport was also affected by the straw cover and PAM treatments (table 2). Despite causing an increase in average ortho–P concentration, the straw cover treatment significantly reduced ortho–P loss by 37% for the first storm through runoff reduction. Reduction in ortho–P loss was greater than 50% for the two PAM treatments (table 3). Ortho–P losses for the two PAM rates were not significantly different from one another for any combination of slope and cover treatment (table 4). On the 8% slope, the 10 ppm PAM treatment reduced ortho–P total loss on uncovered soil by 64%. On straw-covered soil, the two PAM treatments reduced losses of ortho–P by more than 55% (table 4).

Since ammonium and orthophosphate are readily adsorbed to soils, the effects of increasing slope that were previously discussed with regards to TON concentration may not have caused the same changes in NH_4^+–N and ortho–P concentrations. Cover treatment tended to cause increases in soluble nutrient concentrations during the first storm. This may be a result of nutrients naturally present in the organic matter of the straw being released during the rainfall. Another possible reason for this is that the straw could have drawn in the lagoon effluent as it was applied to the soil surface. Thus, some of the nutrients in the lagoon effluent would not have been allowed to adsorb onto soil clays, but would have instead been stored within the straw until the application of rainfall, at which point the nutrients would have contributed to the nutrient loading in the runoff. Despite the increase in soluble nutrient concentrations, the presence of straw cover significantly reduced total loss of ortho–P and NH_4^+–N during the first storm by controlling runoff. PAM was very effective at reducing dissolved nutrient losses from straw-covered soils.

Table 5 presents ANOVA results for the total nitrogen and phosphorus concentration and transport data from the first simulated storm. Each of the main treatments (slope, cover, and PAM) had very significant effects on both concentration and total loss of TKN (table 5). Interactions between the main

Table 5. ANOVA significance of treatment main effects and interactions of slope, cover, and PAM on total nutrient concentration and loss for storm 1.

	Total Kjeldahl N		Total P	
Source	Conc.	Loss	Conc.	Loss
Model R^2	0.92	0.97	0.93	0.98
Slope	***	***	***	***
Cover	***	***	***	***
Slope × Cover	***	***	***	***
PAM	***	***	***	***
Slope × PAM	**	***	ns	ns
Cover × PAM	***	***	*	**
Slope × Cover × PAM	***	**	ns	ns

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

treatments were also significant. Increasing slope caused increases in average TKN concentration, while cover and PAM treatment caused decreases (table 6). Cover treatment reduced the factor-level mean loss by 77% (table 6). Averaging results from both concentration levels, PAM treatment reduced the factor-level mean TKN loss by about 55% (table 6). Although PAM treatment significantly reduced TKN concentrations in only one of the four different combinations of slope and cover level, it resulted in significant reductions in total loss of TKN in three of the four slope-cover combinations because of its ability to reduce total runoff (table 7). No significant differences in TKN loss between the two PAM treatment levels were observed.

Average TP concentrations and losses were significantly affected by the main treatment factors of slope, cover, and PAM application (table 5). The 8% slope treatments had a factor-level mean TP concentration that was 34% higher than that of the 4% slope treatments (table 6). Cover treatment lowered the factor-level mean TP concentration by more than 50% (table 6). Generally, PAM treatment significantly reduced TP concentrations for most combinations of slope and cover treatment (table 7). On bare soils, the 10 ppm PAM treatment reduced TP concentrations approximately 30% at both slope gradients. The 20 ppm PAM treatment on straw-covered soils at 4% slope reduced the average TP concentration by 41% (table 7).

Cover treatment caused the most dramatic differences in TP loss, decreasing the factor-level mean TP loss from 1030 g ha^{-1} on bare soils to 230 g ha^{-1} on straw-covered soils, a reduction of about 80% (table 6). Treatment with 10 ppm of PAM reduced the factor-level mean TP loss from 920 g ha^{-1} for PAM-free control treatments to 419 g ha^{-1}, a reduction of >50% (table 6). Analysis of PAM effects on different combinations of slope and cover treatment showed that the PAM treatment always had significantly lower TP losses than the control (table 7), with reductions ranging from 22% to 72%. TP losses were not significantly different between the two levels of PAM treatment.

As expected, TKN and TP losses were well correlated with total sediment loss (fig. 1). Total nutrient analysis measures

Table 6. Overall total nutrient concentration and loss factor-level means for storm 1.[a]

		Total Kjeldahl N		Total P	
Treatment		Conc. (mg L^{-1})	Loss (g ha^{-1})	Conc. (mg L^{-1})	Loss (g ha^{-1})
Slope	4%	8.14 b	2270 a	1.81 b	497 a
	8%	10.9 a	3340 a	2.45 a	764 a
Cover	0%	12.8 a	4560 a	2.87 a	1030 a
	30%	6.25 b	1050 b	1.40 b	230 b
PAM	0 ppm	11.9 a	4430 a	2.56 a	920 a
	10 ppm	8.46 a	1910 b	1.85 a	419 b
	20 ppm	8.16 a	2080 b	2.00 a	553 ab

[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. Total nutrient average concentrations and total losses for storm 1.[a]

Slope (%)	Surface Cover (%)	PAM Conc. (ppm)	Total Kjeldahl N Conc. (mg L^{-1})	Total Kjeldahl N Loss (g ha^{-1})	Total P Conc. (mg L^{-1})	Total P Loss (g ha^{-1})
4	0	0	11.9 a	4720 a	2.74 a	1090 a
4	0	10	9.15 a	2610 b	1.82 b	505 b
4	0	20	10.1 a	3500 ab	2.10 b	723 b
8	0	0	22.1 a	9050 a	4.17 a	1710 a
8	0	10	12.6 b	4030 b	3.00 b	955 b
8	0	20	11.0 b	4170 b	3.40 ab	1340 b
4	30	0	6.75 a	1340 a	1.86 a	365 a
4	30	10	5.75 a	438 b	1.27 ab	101 b
4	30	20	5.27 a	604 ab	1.09 b	126 b
8	30	0	7.09 a	1940 a	1.47 a	396 a
8	30	10	6.30 a	721 a	1.29 a	144 b
8	30	20	6.36 a	515 a	1.40 a	111 b

[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.

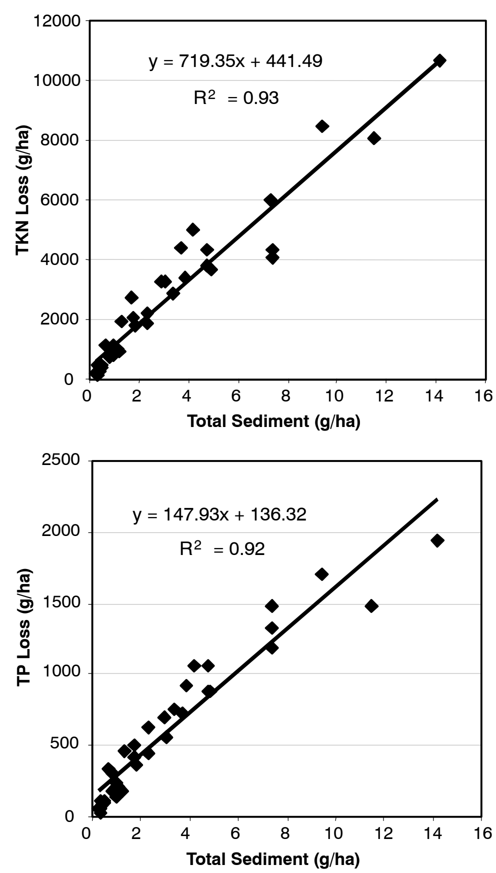

Figure 1. Total nutrient loss as a function of sediment loss for all treatments during storm 1.

Table 8. ANOVA significance of treatment main effects and interactions of slope, cover, and PAM on soluble nutrient concentration and loss for storm 2.

Source	TON Conc.	TON Loss	NH_4^+–N Conc.	NH_4^+–N Loss	Ortho–P Conc.	Ortho–P Loss
Model R^2	0.69	0.71	0.72	0.67	0.79	0.63
Slope	***	***	ns	ns	ns	ns
Cover	ns	ns	ns	ns	***	ns
Slope × Cover	***	***	**	***	ns	ns
PAM	ns	ns	***	***	***	***
Slope × PAM	ns	ns	**	ns	***	ns
Cover × PAM	ns	ns	ns	ns	**	**
Slope × Cover × PAM	ns	ns	ns	ns	**	ns

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

Table 9. Overall soluble nutrient concentration and loss factor-level means for storm 2.[a]

Treatment	TON Conc. (mg L^{-1})	TON Loss (g ha^{-1})	NH_4^+–N Conc. (mg L^{-1})	NH_4^+–N Loss (g ha^{-1})	Ortho–P Conc. (mg L^{-1})	Ortho–P Loss (g ha^{-1})
Slope						
4%	0.09 b	43.4 b	0.18	90.5	0.21	108
8%	0.17 a	84.9 a	0.16	85.1	0.23	116
Cover						
0%	0.13	67.4	0.17	92.7	0.20 b	108
30%	0.13	60.9	0.17	82.9	0.24 a	116
PAM						
0 ppm	0.13	65.5	0.25 a	129 a	0.26 a	134 a
10 ppm	0.14	69.7	0.16 b	78.9 b	0.20 b	101 b
20 ppm	0.11	57.3	0.10 b	55.2 b	0.19 b	101 b

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

nutrients that are attached to soil clay and organic particles, and this data indicate that management practices that are used to control erosion are important for reducing nutrient inputs into water bodies.

Storm 2 Results

Similar to the first storm, slope was the only main treatment effect to be significant on TON concentration and losses during the second, multiple rainfall intensity storm (table 8). Increasing slope caused an increase in average TON concentration. The factor-level mean TON concentration at 8% slope was 89% greater than that at 4% slope, and TON loss nearly doubled for the higher slope gradient (table 9).

PAM treatments significantly affected the average concentration of NH_4^+–N in runoff during the second storm (table 8). Average NH_4^+–N concentration for boxes not treated with PAM was 0.25 mg L^{-1} (table 9). Treatment with 10 ppm PAM reduced this level by 36% to 0.16 mg L^{-1}, and treatment with 20 ppm PAM reduced the factor-level mean NH_4^+–N concentration by 60% to 0.10 mg L^{-1} (table 9). The straw cover treatment no longer affected the concentration of NH_4^+–N during the second storm, as it did during the first.

Second storm soluble nutrient concentration and loss results for each treatment are presented in table 10. The 20 ppm PAM treatment significantly reduced the average NH_4^+–N concentration for each level of slope and cover treatment. For boxes with no straw surface cover, the 20 ppm PAM treatment reduced the average NH_4^+–N concentration by a little over half on both slope treatments, whereas on straw-covered boxes, the 20 ppm PAM treatment reduced the average NH_4^+–N concentration by 53% and 68% on the 4% and 8% slopes, respectively.

The total loss of NH_4^+–N during the second storm was affected only by PAM treatment (table 8). The 10 ppm PAM treatment reduced the factor-level mean NH_4^+–N loss by 39% in comparison to the control treatments, while the 20 ppm PAM treatment reduced loss by more than 50% (table 9). PAM treatments effectively reduced NH_4^+–N losses during the second storm in three of the four different slope and cover combinations (table 10). On bare soil at 8% slope, the 10 ppm PAM treatment reduced NH_4^+–N loss by over 80%. Treatment with 20 ppm of PAM was more effective on straw-covered soils and reduced total loss of soluble NH_4^+–N by more than 55%.

Similar to the first storm, the second storm concentrations of soluble orthophosphate were affected significantly by the cover and PAM treatments (table 8). The factor-level mean ortho–P concentration increased slightly from 0.20 mg L^{-1} for bare soil treatments to 0.24 mg L^{-1} for treatments that had 30% straw cover (table 9). Both PAM application rates were equally effective at reducing the factor-level mean ortho–P concentration by about 25%.

PAM treatment did not have a significant effect on ortho–P concentration on bare soils at 4% slope (table 10). However,

Table 10. Soluble nutrient average concentrations and total losses for storm 2.[a]

Slope (%)	Surface Cover (%)	PAM Conc. (ppm)	TON Conc. (mg L^{-1})	TON Loss (g ha^{-1})	NH_4^+–N Conc. (mg L^{-1})	NH_4^+–N Loss (g ha^{-1})	Ortho–P Conc. (mg L^{-1})	Ortho–P Loss (g ha^{-1})
4	0	0	0.04 a	21.3 a	0.25 a	145 a	0.20 a	115 a
4	0	10	0.03 a	15.7 a	0.23 ab	121 a	0.19 a	98.0 a
4	0	20	0.04 a	22.4 a	0.12 b	72.3 a	0.19 a	114 a
8	0	0	0.23 a	107 a	0.25 a	126 a	0.28 a	136 a
8	0	10	0.28 a	145 a	0.04 b	22.9 b	0.15 b	78.2 b
8	0	20	0.16 a	93.0 a	0.12 b	69.6 ab	0.19 b	109 ab
4	30	0	0.19 a	90.3 a	0.19 a	93.3 a	0.27 a	133 a
4	30	10	0.15 a	60.1 a	0.16 a	70.3 ab	0.24 ab	103 a
4	30	20	0.11 a	50.8 a	0.09 b	41.5 b	0.19 b	86.0 a
8	30	0	0.08 a	43.4 a	0.28 a	153 a	0.28 a	153 a
8	30	10	0.11 a	57.9 a	0.19 ab	102 ab	0.24 b	125 ab
8	30	20	0.14 a	62.9 a	0.09 b	37.5 b	0.21 b	96.6 b

[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.

Table 11. ANOVA significance of treatment main effects and interactions of slope, cover, and PAM on total nutrient concentration and loss for storm 2.

Source	Total Kjeldahl N Conc.	Total Kjeldahl N Loss	Total P Conc.	Total P Loss
Model R^2	0.90	0.93	0.91	0.93
Slope	***	***	***	***
Cover	***	***	***	***
Slope × Cover	***	ns	***	ns
PAM	***	***	***	***
Slope × PAM	ns	ns	ns	ns
Cover × PAM	***	**	*	**
Slope × Cover × PAM	ns	ns	ns	ns

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

PAM reduced the ortho−P concentration by more than 32% on bare soils at 8% slope. For soils with a straw surface cover, treatment with 20 ppm of PAM in the applied effluent resulted in average runoff concentration reductions of ortho−P by 25% at both slope gradients.

Application of PAM with lagoon irrigation water was the only treatment to have a significant effect on total loss of soluble P during the second storm (table 8). The two PAM rates performed similarly; both reduced the factor-level mean ortho−P loss from 134 g ha^{-1} for the control treatment to 101 g ha^{-1}, a reduction of 25% (table 9).

Second storm average TKN concentrations were significantly affected by all factors studied (table 11). Factor-level mean TKN concentrations were lower in the second storm than in the first storm (table 12). The 10 and 20 ppm PAM treatments reduced TKN concentration by >30% compared to the control treatments (table 12). On boxes with no straw cover or with straw at 8% slope, the 20 ppm PAM treatment resulted in average TKN concentration reductions of about 40% (table 13).

Each of the main treatment factors had very significant effects on the total loss of TKN during the second storm (table 11). By increasing the slope from 4% to 8%, the second storm factor-level mean TKN loss was increased from 2740 to 3730 g ha^{-1} (table 12). Using straw cover during the second storm cut the factor-level mean TKN loss in half (table 12). The two PAM treatment levels performed equally well, reducing the factor-level mean TKN loss by 35% compared to the control (table 12).

Comparison of PAM treatments at the various combinations of surface cover and slope level revealed significant reductions of TKN loss due to PAM treatment in several cases

Table 12. Overall total nutrient concentration and loss factor-level means for storm 2.[a]

Treatment		Total Kjeldahl N Conc. (mg L^{-1})	Total Kjeldahl N Loss (g ha^{-1})	Total P Conc. (mg L^{-1})	Total P Loss (g ha^{-1})
Slope	4%	5.23 b	2740 b	1.23 b	631 a
	8%	7.26 a	3730 a	1.60 a	829 a
Cover	0%	8.08 a	4320 a	1.93 a	1020 a
	30%	4.41 b	2160 b	0.91 b	442 b
PAM	0 ppm	8.13 a	4220 a	1.69 a	881 a
	10 ppm	5.50 b	2750 b	1.27 ab	636 a
	20 ppm	5.11 b	2740 b	1.30 ab	674 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 13. Total nutrient average concentrations and total losses for storm 2.[a]

Slope (%)	Surface Cover (%)	PAM Conc. (ppm)	Total Kjeldahl N Conc. (mg L^{-1})	Total Kjeldahl N Loss (g ha^{-1})	Total P Conc. (mg L^{-1})	Total P Loss (g ha^{-1})
4	0	0	8.55 a	4960 a	2.00 a	1170 a
4	0	10	5.98 ab	2990 b	1.30 b	653 b
4	0	20	5.11 b	3100 b	1.34 ab	949 a
8	0	0	13.1 a	6240 a	2.59 a	1240 a
8	0	10	7.93 b	4110 b	2.03 b	1050 a
8	0	20	7.82 b	4490 b	2.07 ab	1180 a
4	30	0	4.54 a	2250 a	0.98 a	484 a
4	30	10	3.59 a	1500 a	0.77 a	329 a
4	30	20	3.59 a	1610 a	0.75 a	342 a
8	30	0	6.33 a	3410 a	1.17 a	631 a
8	30	10	4.51 b	2410 b	0.96 a	511 ab
8	30	20	3.90 b	1760 b	0.80 a	358 b

[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.

(table 13). Treatment with 10 ppm of PAM reduced TKN losses by >30% on bare soils. Treatment with PAM caused an average reduction in TKN loss of 39% on straw-covered boxes set to 8% slope (table 13).

Slope, cover, and PAM treatments had significant effects on TP concentration in runoff during the second storm (table 11). In general, TP concentrations were lower in the second storm, and the magnitudes of treatment effects were also less than during the first storm. Increasing slope resulted in a 30% increase in the factor-level mean TP concentration, while increasing cover caused a 53% reduction (table 12). PAM treatment did not affect TP concentrations on straw-covered boxes, but significantly reduced average TP concentrations on bare soils (table 13). Straw cover treatment brought about the most notable differences in TP transport, reducing the factor-level mean TP loss by 57% (table 12). On specific combinations of cover and slope level, PAM treatment significantly reduced TP losses in two of four different combinations. The 10 ppm PAM treatment had approximately 40% less TP loss than the control on bare soils at 4% slope, while the 20 ppm PAM treatment also had about 40% less TP loss on straw-covered soils at 8% slope (table 13).

During the second storm, PAM treatments often caused significant reductions in total nutrient concentrations and cumulative losses, but in some cases (4% slope, 30% cover) no significant PAM-induced reductions were observed. Since cover treatment alone caused such a large reduction in total nutrient losses, PAM-induced reductions in TKN and TP losses were of less magnitude and were therefore more difficult to detect within the level of replication and variability in this study when cover was present. Less significant treatment differences during the second storm could also have been caused by a reduction in the supply of easily transportable sediment by the time of the second storm, so that control treatment nutrient losses were reduced to levels that were similar to PAM treatment losses.

Second Storm Rainfall Rate Effects

In order to determine whether the rainfall intensity had any effect on nutrient concentrations, the average nutrient concentration during each rainfall intensity period was

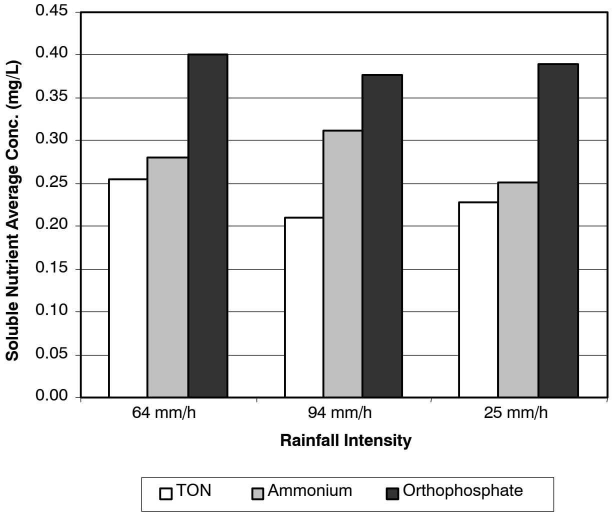

Figure 2. Average soluble nutrient concentrations for three rainfall intensities. For a given nutrient, there were no significant differences in nutrient concentration caused by rainfall intensity (Tukey-Kramer HSD, α = 0.10).

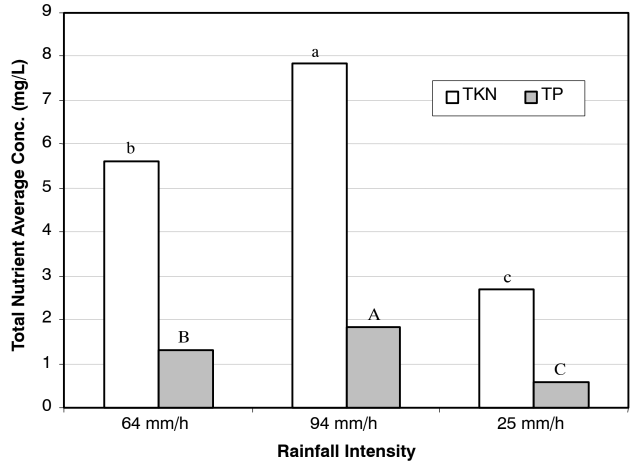

Figure 3. Average total nutrient concentrations for three rainfall intensities. Bars labeled with the same letter for a given nutrient are not significantly different (Tukey-Kramer HSD, α = 0.10).

determined for each replicate, and then the mean nutrient concentrations for all treatments were compared across rainfall intensities. Changing the rainfall intensity did not significantly change the concentration of any of the soluble nutrients during the second storm (fig. 2), probably due to developed seal formation. For TON and NH_4^+−N, the significance of main effects during each rainfall intensity period closely matched the overall results presented in table 8. For ortho−P concentration, cover had a significant effect for all of the rainfall rates. PAM treatment significantly impacted ortho−P concentration during the medium and high rainfall rates, but not during the low-intensity rainfall.

Rainfall intensity had a definite effect on the concentration of total nutrients during the second storm, as soil loss was dependent on rainfall intensity (Flanagan and Canady, 2006). On average, TKN concentrations were about 40% higher during the high rainfall intensity, and about 52% lower during the low rainfall intensity, than concentrations from the medium intensity rainfall period (fig. 3). The high-intensity rainfall raised average TP concentrations by 38% relative to the medium-intensity rainfall, while the low-intensity rainfall periods resulted in TP concentrations that were 55% lower on average (fig. 3). For TKN, all three main treatment effects remained significant throughout the varying rainfall intensities except for slope, which caused no effect during the final, low-intensity level. Slope and cover effects were consistent across all rainfall intensity levels for TP concentration; however, PAM's effect was only significant during the high-intensity rainfall period.

Comparison of De-Ionized Water and Lagoon Effluent Irrigations

Comparisons of nutrient concentration and losses in runoff were made between soil boxes irrigated with de-ionized water and soil boxes irrigated with lagoon effluent (both with and without PAM) for bare soils at 4% slope (table 14). As would be expected, addition of lagoon effluent to the soil caused significantly large increases in the concentration and total loss of nutrients in runoff from the soil in subsequent rainfall events.

For the combined storms, lagoon effluent treatments with 20 ppm of PAM had significantly lower NH_4^+−N concentration than the lagoon effluent control treatment (table 14). There were no significant differences in NH_4^+−N concentration between water irrigation treatments and lagoon effluent

Table 14. Comparison of soluble nutrient losses for lagoon effluent and water-only simulated irrigations.[a]

		TON		NH_4^+−N		Ortho−P	
Storm	Treatment[b]	Conc. ($mg\ L^{-1}$)	Loss ($g\ ha^{-1}$)	Conc. ($mg\ L^{-1}$)	Loss ($g\ ha^{-1}$)	Conc. ($mg\ L^{-1}$)	Loss ($g\ ha^{-1}$)
Storm 1	L	0.12 a	46.1 a	0.49 a	191 a	0.49 a	196 a
	LPAM10	0.07 a	17.7 a	0.44 ab	126 abc	0.47 ab	133 a
	LPAM20	0.10 a	33.8 a	0.19 bc	64.7 bc	0.39 b	136 a
	W	0.02 a	8.80 a	0.06 c	34.8 c	0.14 c	55.9 b
Storm 2	L	0.03 a	21.3 a	0.25 a	145 a	0.20 a	115 a
	LPAM10	0.02 a	15.7 ab	0.23 a	121 ab	0.19 a	98.0 a
	LPAM20	0.03 a	22.4 a	0.12 b	72.3 bc	0.19 a	114 a
	W	0 a	5.82 b	0.04 b	19.8 c	0.07 b	42.5 b
Combined	L	0.04 a	67.4 a	0.35 a	336 a	0.32 a	310 a
	LPAM10	0.03 ab	33.3 ab	0.30 ab	246 a	0.29 a	231 a
	LPAM20	0.02 ab	56.2 ab	0.14 bc	137 a	0.26 a	250 a
	W	0 b	14.6 b	0.05 c	54.6 b	0.10 b	98.4 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.

treatments with 20 ppm PAM. Runoff NH_4^+–N losses from the lagoon effluent treatment were more than six times higher than from the de-ionized water for the combined storms. For storms 1 and 2 individually, boxes receiving lagoon effluent with 20 ppm of dissolved PAM did not have significantly different total losses of NH_4^+–N than boxes receiving only water.

All of the boxes irrigated with lagoon effluent had significantly higher average runoff ortho–P concentrations than the boxes that received water irrigation (table 14). The total loss of soluble P from the lagoon-treated control boxes was approximately three times greater than that from the water-irrigated boxes. Losses of ortho–P from PAM treated soils were significantly greater than those from the de-ionized water.

Generally, the TKN and TP results were similar, especially during the second storm (table 15). During the first storm, TKN concentration from the water-treated boxes was significantly lesser than that from the lagoon effluent treatment, while losses were not different. The 10 ppm PAM reduced TKN loss by 45%. TP concentrations and losses were similar for the PAM and de-ionized water treatments for the first storm, and all were less than the lagoon effluent treatment.

During the second storm and for the combined storm overall results, generally both TKN and TP concentrations and cumulative losses from water-irrigated soils were significantly lower than the lagoon effluent-irrigated PAM-free treatments. In each case, the 10 ppm PAM application lowered losses to values that were not significantly different from the water-irrigated results (table 15).

Economic Considerations

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). A PAM concentration of 10 ppm in surface-applied water is a standard level for furrow irrigation erosion control practices.

Table 15. Comparison of total nutrient losses for lagoon effluent and water-only simulated irrigations.[a]

	Total Kjeldahl N		Total P	
Treatment[b]	Conc. (mg L^{-1})	Loss (g ha^{-1})	Conc. (mg L^{-1})	Loss (g ha^{-1})
Storm 1				
L	11.9 a	4720 a	2.74 a	1090 a
LPAM10	9.15 ab	2610 b	1.82 bc	505 b
LPAM20	10.1 ab	3500 ab	2.10 b	723 b
W	9.02 b	3380 ab	1.61 c	618 b
Storm 2				
L	8.55 a	4960 a	2.00 a	1170 a
LPAM10	5.98 ab	2990 b	1.30 b	653 b
LPAM20	5.11 b	3100 b	1.56 ab	949 a
W	5.23 b	3000 b	1.23 b	693 b
Combined				
L	9.91 a	9680 a	2.30 a	2250 a
LPAM10	7.12 b	5600 b	1.48 b	1160 c
LPAM20	6.91 b	6600 b	1.61 b	1540 b
W	6.71 b	6380 b	1.39 b	1310 c

[a] Quantities within a given storm followed by the same letter are not significantly different at $\alpha = 0.10$ 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.

There appears to be little added benefit of using a higher concentration for reducing nutrient losses in the application examined in this study; therefore, this concentration is recommended. Using a concentration of 10 ppm and a median PAM price of $5.00 kg^{-1}, surface application of lagoon effluent would cost $5.00 ha^{-1} per centimeter of applied depth. The purchase or construction of equipment designed to properly meter and mix PAM into lagoon effluent before land application would contribute further to startup costs. However, application of PAM during lagoon effluent irrigation appears to be a relatively inexpensive method to gain significant reductions in nutrient losses during rainfall events.

The primary benefit of using PAM with surface irrigation of lagoon effluent is the conservation of soil and the protection of water bodies from excess sediment and nutrient loadings. PAM use therefore results in the preservation of future agricultural production, ecological diversity, recreational use of water bodies, or other benefits that are often highly intangible or not immediately profitable to the PAM user. Soluble NH_4^+–N and ortho–P are both nutrients that are readily available for uptake by plants, while a portion of TKN and TP are nutrients present in organic matter or sorbed to soil surfaces that may later become available for crop consumption. All of these nutrients had cumulative losses that were reduced significantly by PAM treatment during this study.

Although often volatile, recent prices of fertilizers in the Midwest U.S. are about $0.63 kg^{-1} for N (based on the use of anhydrous ammonia) and $0.80 kg^{-1} for P (based on the use of triple super phosphate or diammonium phosphate) (personal communication with a representative of Heartland Co-op, Inc., Lafayette, Ind., March 2005). Nutrient conservation through PAM use during the two simulated storms was most dramatic on bare, 8% slope treatments. For this treatment, PAM use at a concentration of 10 ppm conserved $0.17 ha^{-1} worth of ammonium nitrogen and $0.18 ha^{-1} worth of orthophosphate. Assuming that the factor-level mean losses of nutrients for combined storms represent an average effectiveness of PAM treatment under a range of slope and cover conditions, PAM use might result in an average savings of $0.24 ha^{-1} in soluble N and P costs during a storm of similar duration and intensity as the storms simulated in this study. If TKN and TP savings are considered, the value of the nutrients conserved by PAM use was about $3.09 ha^{-1} for combined storms, but these nutrients are not immediately available for plant use. It is also worth noting that the value of dissolved nutrients applied to the soil in the lagoon effluent was about $4.87 ha^{-1} for an application depth of 0.7 cm. In a real-world field setting, actual nutrient losses and the effectiveness of PAM control might be greater (due to active rilling and PAM control of rill detachment) or lesser (due to deposition where overland flow slopes decrease, or due to less intense rain storm characteristics).

The economic analysis can be extended slightly further, if one takes the cost of the 10 ppm PAM application used here ($7 ha^{-1}) and divides it by the summed soluble and sediment-borne nutrients saved by the PAM treatment for the two storms (4.178 kg N saved, and 0.895 kg P saved). From these two storm events, the average cost of preventing the loss of a kilogram of N is $1.68, and the average cost of preventing the loss of a kilogram of P is $7.82. If the PAM continued to be effective in subsequent additional storms, with the cost of application constant and increasing nutrients conserved, then the average cost to prevent the nutrient losses would decrease from these values.

Summary and Conclusions

This study examined the practice of dissolving anionic polyacrylamide in swine lagoon effluent to determine its effect on runoff, erosion, and nutrient loss during rainfall events that occur after effluent application. The effects of straw surface cover and slope were examined in addition to the PAM treatment. Average concentration and total losses of nitrates and nitrites, ammonium nitrogen, orthophosphate, total Kjeldahl nitrogen, and total phosphorus were measured. It was hypothesized that: (1) anionic PAM application with the lagoon effluent would help to reduce the surface loss of soluble nutrients in runoff by sorption of nutrients to anionic sites on the PAM molecule and by PAM's ability to reduce runoff through inhibition of crusting and sealing, and (2) total nutrient movement would be affected by the treatment factors in a manner similar to sediment loss. Most of the nutrients in the total digests are associated with soil materials, either in the form of ammonium and orthophosphate ions, P bound to clay surfaces, or N and P nutrients present as structural components of organic and mineral materials. PAM and cover treatments would be expected to reduce total nutrient losses by decreasing aggregate degradation and inhibiting movement of soil aggregates in surface runoff. Higher slope treatments would be expected to increase total nutrient losses by increasing the magnitude of the forces driving runoff water and soil aggregates across the soil surface.

Concentration and surface transport of TON were affected primarily by slope during both the first and second storms. High slopes created considerably more TON loss on bare soils, but cover treatment controlled slope effects very effectively for this nutrient. PAM had no effect on TON concentrations, but in one case a combination of PAM and cover helped to control net surface loss of TON. Cover treatment did not significantly affect TON concentration during the first storm, but helped to control net surface loss of TON by reducing runoff. During the second storm, cover treatment did not affect either the concentration or cumulative transport of TON. Cover treatment did cause increases in the concentration of NH_4^+–N and ortho–P during both storms, but usually decreased total losses of these nutrients by reducing runoff. PAM treatment generally helped to reduce the concentration of NH_4^+–N and ortho–P in runoff. The highest concentration PAM treatment (20 ppm) was usually more effective at reducing NH_4^+–N concentration than the 10 ppm treatment, probably because the positively charged NH_4^+ ion could interact directly with the anionic sites of the PAM molecule. Moreover, the results were also affected by the flocculation effect of PAM. However, this high concentration PAM treatment did not offer further benefit for reduction of ortho–P concentration than the 10 ppm PAM treatment. Overall, PAM was an effective tool for reducing the loss of soluble NH_4^+ and ortho–P nutrients in runoff from lagoon-irrigated soils.

The concentrations and therefore cumulative loss of TKN and TP in runoff were strongly associated with sediment concentration during both of the simulated storms. Total nutrient loss was therefore affected by the treatment factors in the same way as sediment loss, and results for both nutrients were very similar. Cover and PAM treatments used separately were effective for reducing total nutrient losses relative to their associated control treatments. Furthermore, total nutrient loss was the only measured variable in this study, in which significantly beneficial effects beyond those provided by straw cover alone were often observed with the application of PAM in addition to cover treatment. Total nutrient concentrations were found to be dependent on rainfall intensity. The main treatments usually maintained their effects on total nutrient concentration throughout the various rainfall intensities. Treatment with 20 ppm of PAM did not result in lower TKN and TP loss than PAM treatments of 10 ppm concentration.

Comparisons of nutrient losses were also made between soils that received lagoon effluent and soils that received an application of de-ionized water instead of lagoon effluent. Soluble and total nutrient losses were significantly higher on boxes treated with lagoon effluent. Cumulative surface losses of TP and TKN from lagoon-treated soils were not significantly different from those of the water-irrigated soils when 10 ppm of PAM was applied with the effluent. While PAM treatment did not bring ortho–P losses from lagoon-treated soils to levels similar to the de-ionized water irrigation treatments, PAM in lagoon effluent often did not have significantly different concentrations or cumulative losses of TON and NH_4^+–N nutrients compared to the fresh water losses.

This study showed that the practice of dissolving anionic PAM in lagoon effluents before land application can help to protect surface water bodies and conserve nutrients during the critical periods of time immediately following land application. The use of PAM was shown to successfully inhibit the surface losses of NH_4^+–N, ortho–P, particulate N, and particulate P during storms occurring 24 h after land application of swine lagoon effluent. The treatment is especially appropriate on areas with relatively high slopes or low surface cover, but PAM was also very effective at reducing nutrient losses from soil with moderate (30%) residue cover.

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