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Environmental Pollution 121 (2003) 453–462

ENVIRONMENTAL POLLUTION

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Polyacrylamide + $Al_2(SO_4)_3$ and polyacrylamide + CaO remove coliform bacteria and nutrients from swine wastewater

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Received 21 January 2002; accepted 16 April 2002

"Capsule": *Polyacrylamide mixture may be able to reduce run-off of enteric bacteria from animal wastes.*

Abstract

Animal wastes are a major contributor of nutrients and enteric microorganisms to surface water and ground water. Polyacrylamide (PAM) mixtures are an effective flocculent, and we hypothesized that they would reduce transport of microorganisms in flowing water. After waste water running at 60.0 l min^{-1} flowed over PAM + $Al_2(SO_4)_3$, or PAM + CaO in furrows, total coliform bacteria (TC) and fecal coliform bacteria (FC) were reduced by 30–50% at 1 and 50 m downstream of the treatments compared to the control. In a column study, PAM + $Al_2(SO_4)_3$, and PAM + CaO applied to sandy, sandy loam, loam, and clay soils reduced NH_4^+ and ortho-P concentrations in leachate compared to the source waste water and the control. PAM + $Al_2(SO_4)_3$ and PAM + CaO applied to sandy, sandy loam and loam soils reduced both total and ortho-P, concentrations in leachate compared to the source wastewater and control treatment. In a field study, PAM + $Al_2(SO_4)_3$, or PAM + CaO treatments did not consistently reduce NH_4^+, NO_3^-, ortho-P, and total P concentrations in wastewater flowing over any soil compared to inflow wastewater or the control treatment. With proper application PAM + $Al_2(SO_4)_3$ and PAM + CaO may be able to reduce the numbers of enteric bacteria in slowly flowing wastewater running off animal confinement areas, reducing the amount of pollutants entering surface water and groundwater. Published by Elsevier Science Ltd.

Keywords: Runoff; Surface water; Soils; Australia; Groundwater; Pathogens

1. Introduction

In Australia pollution of surface flow and groundwater from the application of animal waste has been well documented (Imbeah, 1998; Eyre and Pepperell, 1999; McKee and Eyre, 2000; Sparrow et al., 2000). Liquid-waste discharge onto soil initiates solute and microbe movement into the soil that follows natural ground water drainage patterns and may contaminate adjoining surface water. These same bodies of water are often used for sources of drinking water and/or for recreational activities. Human contact with recreational waters containing intestinal pathogens is an effective method to spread disease. Therefore, it is critical to maintain the quality of our lakes and streams by keeping them free of intestinal pathogens and excess nutrients.

Increased N and P concentrations in water can alter the function and stability of many riparian and aquatic ecosystems. In the past few decades, intensive fertilization has contributed to the accumulation of these elements in aquatic environments (Vitousek et al., 1997; David and Gentry, 2000; Edwards et al., 2000; Sharpley et al., 2000). Changes in flora and fauna have been attributed to increased input of nutrients (Davis, 1991; Koch and Reddy, 1992; Cooper and Brush, 1993; Stevenson et al., 1993). Most aquatic ecosystems develop in conditions limited by N and P. Increased N and P in wetland ecosystems may also cause eutrophication, creating an abnormally high oxygen demand and often resulting in the death of many aquatic organisms (Cooper and Brush, 1993).

Management practices that are currently used to mitigate the input of pollutants from animal waste to surface and groundwater include control of animal

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0269-7491/02/$ - see front matter Published by Elsevier Science Ltd.
PII: S0269-7491(02)00225-7

numbers (Jawson et al., 1982; Gary et al., 1985), control of animal diet (Diez-Gonzalez et al., 1998), constructed wetlands, and riparian filterstrips (Walker et al., 1990; Young et al., 1980; Coyne et al., 1995; 1998). However, there are several problems with vegetative systems: (1) the establishment of vegetation in wetlands or riparian areas can take from months to years, (2) vegetative systems may not be effective when vegetation is not growing (Hubbard et al., 1998; Snyder et al., 1998, Jordan et al., 1993), (3) riparian filterstrips or constructed wetlands are effective for only small quantities of runoff (relatively infrequent or low intensity runoff events) since continuous application can quickly overload the system and nullify the ability of the vegetation to take up nutrients (Hubbard et al., 1998; Snyder et al., 1998, Jordan et al., 1993), and (4) vegetative systems cannot be transported to the site of a waste spill or runoff area. Therefore, even when best management practices are used, animal production operations can sometimes contribute large amounts of nutrients and enteric microorganisms to watercourses.

Polyacrylamide (PAM) has been used in furrow irrigated agriculture for erosion control and increased infiltration (Lentz et al., 1992; Lentz and Sojka, 1994; Sojka et al., 1998a,b). PAM-treatments reduce sediment loss rate over time with improvement of the runoff water quality parameters ortho-P, total-P, NO_3^-, and biological oxygen demand (Lentz and Sojka, 1994; Lentz et al., 1998, 2000). Runoff sediment reduction averaged 94% and infiltration increased 15% in a series of studies conducted over three years. Subsequent studies have further documented the capacity of PAM-treatment of furrow irrigation water to reduce sediments, nutrients, and pesticides in irrigation water (Agassi et al., 1995; Bahr et al., 1996; Singh et al., 1996; Sojka et al., 1998a, b).

Sojka and Entry (2000) documented large reductions in microorganisms in water flowing in 1–30 m of furrows in irrigated crop land after applying 15–30 g of PAM directly to the soil in the first 1.0 m of the furrow. Entry and Sojka (2000) found that after water flowed over three manure sources and then PAM, PAM + $Al_2(SO_4)_3$, or PAM + CaO in furrows, total coliform bacteria, fecal coliform bacteria, and fecal streptococci were reduced by 10–1000-fold in water flowing 1 and 27 m downstream of the treatments compared to the control treatment.

The water soluble PAMs used in this study have been developed for use in erosion control are very large anionic molecules that have been shown to be safe for a variety of food, pharmaceutical and sensitive environmental applications (Barvenik, 1994). They should not be confused with gel forming cross linked PAM, or evaluated with other PAM formulations, especially cationic PAMs, which have known safety concerns related to their specific chemistries (Barvenik, 1994). Environmental regulation, safety and toxicity issues related to PAM-use have been extensively reviewed (Barvenik, 1994; Seybold, 1994). Although the precise mechanism is not fully understood, polyacrylamide compounds are used in many industrial processes to accelerate flocculation.

PAM degradation in soil is approximately 10% year $^{-1}$ (Barvenik, 1994). Degradation of the acrylamide monomer (AMD) is fairly rapid (Lande et al., 1979; Shanker et al., 1990; Kay-Shoemake et al., 1998a). AMD was completely degraded within 5 days after applying 500 mg PAM kg^{-1} garden soil (Shanker et al., 1990). Lande et al. (1979) applied 25 mg PAM kg^{-1} soil and reported that half life of an AMD in agricultural soils was 18–45 h. Enrichment cultures showed that bacteria are capable of utilizing PAM as a sole source of N, but not C (Kay-Shoemake et al., 1998b). The effect of PAM application to water or soils has been shown to both increase and decrease soil microbial biomass (Nadler and Steinberger, 1993; Steinberger et al., 1993; Kay-Shoemake et al., 1998a, b).

In this study we used Superfloc A836, which is an extremely large negatively charged molecule (Barvenik, 1994; Lentz et al., 2000). When PAM is combined with either $Al_2(SO_4)_3$ or CaO and then added to water, $Al_2(SO_4)_3$ or CaO quickly disassociate, freeing Al^{+3} and Ca^{+2} to bind with anionic nutrients such as $H_2PO_4^-$ and NO_3^-. Free Al^{+3} and Ca^{+2} are thought to bind with anionic sites on the PAM molecule, forming a bridge with anionic nutrients such as $H_2PO_4^-$ and NO_3^-. The anionic charges on PAM attract not only minerals, but also microorganisms, and possibly positively charged nutrients in wastewater.

The objective of the study was to: (1) determine the efficacy of PAM + $Al_2(SO_4)_3$ and PAM + CaO to remove total coliform bacteria (TC) and fecal coliform bacteria (FC), total P, ortho-P, NH_4^+ and, NO_3^- from three sources of swine wastewater leached through a range of soil types in columns and (2) determine the efficacy of PAM + $Al_2(SO_4)_3$ and PAM + CaO to remove TC and FC, total P, ortho-P, NH_4^+ and NO_3^- from swine wastewater flowing over three different Australian soil types in tilled fields.

2. Materials and methods

2.1. Column study

The column study was designed to simulate water movement downward through each soil, emulating water moving microorganisms and nutrients from the soil surface into shallow ground water. The column studies allowed us to determine downward flow of water through each soil type under the same conditions in a controlled environment.

Table 1

Concentration of total (TC) and (FC) coliform bacteria, total P, ortho-P, NO_3^- and NH_4^+ in three sources of swine wastewater

Waste source	Total coliforms (colonies/ 100 ml water)	Fecal coliforms (colonies/ 100 ml water)	Total P (mg element/ l water)	ortho-P (mg element/ l water)	NO_3^- (mg element/ l water)	NH_4^+ (mg element/ l water)
Toohey Farm	5.8×10^7a	6.2×10^6a	39.4a	2.30a	9.5a	14.6a
Nobby Farm	6.3×10^7a	6.8×10^6a	24.8a	3.42a	1.4a	14.6a
Warick Farm	5.1×10^7a	6.6×10^6a	43.4a	6.23a	3.7a	15.2a

In each column, values followed by the same letter are not significantly different as determined by the Least Square Means Test ($P\leq0.05$) ($n=9$).

2.1.1. Experimental design

The column study was arranged in a completely random design (Kirk, 1982) consisting of three treatments which were (1) PAM + $Al_2(SO_4)_3$, (2) PAM + CaO and (3) a control having no amendment with four different soil types (1) sandy (Warick), (2) sandy loam, (Toohey), (3) loam (Hawksbury) and (4) clay (Warick). Swine waste from three different farms (1) Nobby farm, (2) Toohey farm and (3) Warick farm was applied as a slurry to each treatment type×soil combination. Thirty-six columns were prepared for the study. There were three replications (columns) with three observations (three samples taken from each leachate sample as sampling error) for each treatment×soil types×waste source combination (3 treatments ×4 soil types×3 waste sources×3 replications×3 observations per column).

2.1.2. Soil descriptions

The Hawksbury soil is a deep, well drained, Aridic Haploboroll (Isbell, 1996). This soil is moderately to highly erodible with poor structure. Its particle size distribution is 35% sand, 45% silt and 15% clay. It has a saturated hydraulic conductivity of 7–5 m s^{-1}. Organic matter content varies from 1 to 2%. The soil had a pH 6.0 when measured in a 1:5 soil:water (weight:weight) mixture. Cation exchange capacity was 38 meq/100g. Concentrations of elements in the soil were $NO_3 = 56.0$, $PO_4 = 58.0$, total P = 203, K = 336, Ca = 344, Mg = 126, Fe = 22.0, Mn = 3.0 Cu = 0.8, Zn = 0.8 mg element kg^{-1} soil. The soil from Nobby was classified as a Vertic Haploboroll by (Isbell, 1996). This is a clay soil (76% clay, 18% silt, 6% sand) with shrink-swell properties. This soil is had a field saturated hydraulic conductivity of 10–6 m s^{-1}. The soil had a pH 6.5 when measured in a 1:5 soil:water (weight:weight) mixture. Organic carbon ranged from 2.4% in the surface 10 cm to < 0.8% below 30 cm. Cation exchange capacity was 21 meq/100 g. Concentrations of elements in the soil were $NO_3 = 23.0$, $PO_4 = 34.0$, total P = 133, K = 222, Ca = 552, Mg = 137, Fe = 21.0, Mn = 3.0 Cu = 0.8, Zn = 0.9 mg element kg^{-1} soil. The Warick soil was classified as a Arenic Paleudult by (Isbell, 1996). This is a loamy sand (13% clay, 3% silt, 84% sand) with a major texture contrast at a depth of 65 cm. Below 65 cm the soil is a dense structure-less clay. The soil had a pH < 4.0 when measured in a 1:5 soil:water (weight:weight) mixture. The upper profile was well-drained (ksat = 5.4–5 m s^{-1}.) but water flow was restricted below 65 cm. Soil organic carbon ranged from about 2% in the upper profile to < 1% below 65 cm. Cation exchange capacity was 43 meq/100 g. Concentrations of elements in the soil were $NO_3 = 19.0$, $PO_4 = 18.0$, total P = 47, K = 145, Ca = 321, Mg = 128, Fe = 19.0, Mn = 2.0 Cu = 0.8, Zn = 0.7 mg element kg^{-1} soil. The Soil from the Toohey Forest, Griffith University, was a Typic Albaqualf (Isbell, 1996). Particle size distribution in this soil is 30–45% sand, 30–45% silt and 10–15% clay. The soil represents mixtures of sands and muds, and contains large amounts of organic matter. The soil had a pH 5.0 when measured in a 1:5 soil:water (weight:weight) mixture. Organic carbon ranged from 4% in the surface 10 cm to < 1.2% below 30 cm. The soil experiences an alternating wetting and drying environment, and exhibited "gleying" throughout the profile. This gleying effect was more pronounced at depth with the upper profile displaying more sandy texture. Cation exchange capacity was 42 meq/100 g. Concentrations of elements in the soil were $NO_3 = 16.0$, $PO_4 = 28.0$, total P = 97, K = 144, Ca = 402, Mg = 112, Fe = 12.0, Mn = 2.0 Cu = 0.7, Zn = 0.8 mg element kg^{-1} soil.

2.1.3. Waste material

Swine (*Suis scrofa*) waste were fine grained materials obtained from animals on three local farms (Nobby, Toohey and Warick) given feed rations with dietary supplements. Concentrations of TC and FC bacteria and nutrients for each waste source are listed in Table 1. Input values for TC and FC bacteria and nutrients that was added to the top of each soil for the column are listed as "input" in Table 2 and as "inflow" Table 3 for the surface flow study.

2.1.4. Column description

Nine, 4.0 cm diameter×40.0 cm long polyvinyl chloride cylinders were tapped into each soil type. Columns were inserted into each soil type to 30 cm leaving a 10 cm space at the top of each column. Soil was removed from around the outside of each cylinder, the cylinders were tipped to a horizontal position and both ends were labeled and capped. Cylinders were then taken to the

Table 2
Efficacy of polyacrylamide (PAM) + $Al_2(SO_4)_3$ and PAM + CaO to remove total (TC) and (FC)coliform bacteria, total P, PO_4, NO_3 and NH_4 in swine fecal wastewater and swine wastewater leachate flushed through columns of four different soil types

Polyacrylamide (PAM) treatment	Soil type	Total coliform bacteria (colonies/ 100 ml water)	Fecal coliform bacteria (colonies/ 100 ml water)	total P (mg element/ l water)	ortho-P (mg element/ l water)	NO_3^- (mg element/ l water)	NH_4^+ (mg element/ l water)
Input	Hawksbury	8.7×10^7a	3.9×10^6a	17.40a	2.30a	6.2b	59.1a
	Nobby	6.7×10^7a	4.0×10^6a	17.60a	2.29a	6.6b	64.0a
	Toohey	7.1×10^7a	3.9×10^6a	19.20a	2.79a	5.7b	51.8a
	Warick	5.5×10^7a	3.0×10^6a	20.50a	1.92a	5.3b	58.7a
Control	Hawksbury	2.9×10^6b	2.3×10^5b	1.71b	2.39a	3.5c	32.2b
	Nobby	1.6×10^6b	2.7×10^5b	1.89b	0.57b	0.9d	47.3ab
	Toohey	2.1×10^6b	2.7×10^5b	3.21b	3.00a	11.6a	25.3b
	Warick	2.3×10^6b	1.1×10^5b	2.10b	1.68a	7.5ab	48.7ab
PAM + $Al_2(SO_4)_3$	Hawksbury	6.9×10^4c	6.2×10^4c	0.81c	0.17c	3.4b	21.6b
	Nobby	7.1×10^4c	2.7×10^3d	0.45c	0.40b	7.2ab	2.9c
	Toohey	5.1×10^4c	6.2×10^3cd	0.67c	0.52b	10.2a	3.8c
	Warick	5.9×10^4c	5.7×10^3cd	1.69b	0.41b	13.7a	4.3c
PAM + CaO	Hawksbury	1.9×10^3d	1.5×10^2e	0.23c	0.03c	1.4c	3.5c
	Nobby	2.3×10^4cd	4.5×10^3de	0.46c	0.36b	0.9d	13.9bc
	Toohey	$1.6.\times10^3$d	3.2×10^3de	0.47c	0.37b	1.3d	3.1c
	Warick	1.9×10^3d	2.3×10^3de	0.37c	0.20bc	1.9d	6.0c

In each column, values followed by the same letter are not significantly different as determined by the Least Square Means Test ($P \leqslant 0.05$) ($n = 27$).

Table 3
Efficacy of polyacrylamide (PAM) + $Al(SO_4)_3$ and PAM + CaO to remove total (TC) and fecal (FC) coliform bacteria, total P, PO_4, NO_3 and NH_4 from swine wastewater flowing over three different soil types at 60 l min^{-1}

Treatment	Distance	Soil type	Total coliform bacteria (bacteria/ 100 ml water)	Fecal coliform bacteria (bacteria/ 100 ml water)	Total P (mg element l water)	ortho-P (mg element/ l water)	NO_3^- (mg element/ l water)	NH_4^+ (mg element/ l water)
Inflow	0	Sand	3.3×10^5a	9.2×10^4a	3.0b	2.08b	0.18a	2.7b
		Loam	3.6×10^5a	9.5×10^4a	1.0b	0.3b	0.12bc	1.1b
		Clay	4.9×10^5a	5.2×10^4a	22.31a	20.2a	1.00a	31.0a
Control	1	Sand	2.6×10^5a	4.3×10^4a	16.6a	19.2a	0.09a	21.1a
		Loam	3.4×10^5a	5.7×10^4a	1.2b	0.3b	0.17a	0.9b
		Clay	4.9×10^5a	5.4×10^4a	20.4a	24.2a	0.12a	28.5a
PAM + $Al_2(SO_4)_3$	1	Sand	5.6×10^4b	1.8×10^4b	22.7a	24.9a	0.10a	30.3a
		Loam	1.3×10^4b	1.7×10^4b	0.8b	0.4b	0.12a	1.7b
		Clay	7.6×10^4b	2.2×10^4b	20.5a	17.8a	0.12a	33.6a
PAM + CaO	1	Sand	3.0×10^4b	1.3×10^4b	19.1a	20.6a	0.14a	25.1a
		Loam	3.8×10^4b	2.1×10^4b	1.4b	0.4b	0.10a	1.6b
		Clay	4.8×10^4b	2.2×10^4b	17.4a	24.5a	0.20a	33.5a
Control	50	Sand	2.3×10^5a	6.0×10^4a	24.9a	24.0a	0.16a	37.4a
		Loam	3.6×10^5a	7.6×10^4a	0.8b	0.2	0.13a	0.8b
		Clay	3.2×10^5a	5.9×10^4a	19.0a	20.5a	0.24a	29.2a
PAM + $Al_2(SO_4)_3$	50	Sand	7.5×10^3c	1.5×10^4b	21.3a	24.9a	0.14a	36.5a
		Loam	8.3×10^3c	2.2×10^4b	0.3b	0.7b	0.13a	1.1b
		Clay	10.8×10^3c	1.6×10^4b	28.8a	18.1a	0.12a	28.4a
PAM + CaO	50	Sand	3.5×10^4b	1.3×10^4b	22.3a	23.2a	0.10a	36.1a
		Loam	4.3×10^4b	1.7×10^4b	3.1b	0.2b	0.16a	0.8b
		Clay	5.6×10^4b	1.5×10^4b	19.6a	27.9a	0.12a	29.2a

In each column, values followed by the same letter are not significantly different as determined by the Least Square Means Test ($P \leqslant 0.05$) ($n = 24$).

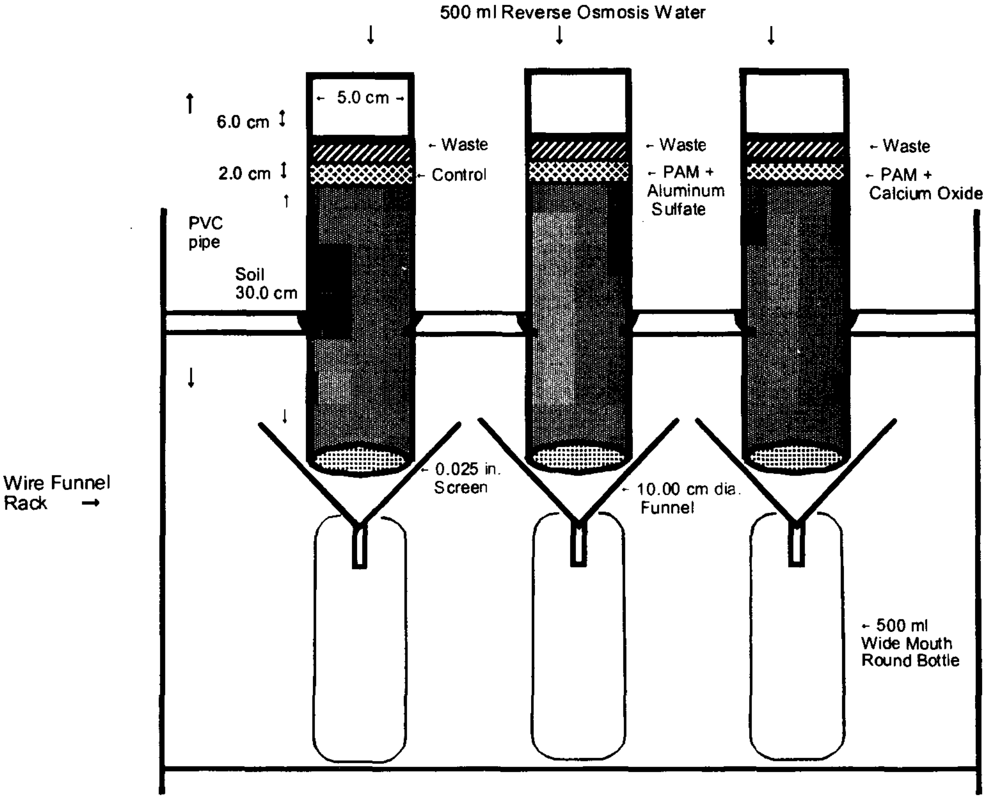


Fig. 1. Diagram of column apparatus showing distilled water poured over animal waste which overlies the PAM + $Al(SO_4)_3$ or PAM + CaO treatments draining through sandy, sandy loam, loam and clay soils into a 500 ml sterile container.

laboratory. A 2.00 mm wire screen was cut into squares (125×125 mm) and secured to the bottom of each (Fig. 1). A 10 cm diameter funnel was placed below each column and the apparatus was secured to a funnel rack. Prior to waste application, 10 replications of 500 ml of distilled water was passed through each to flush microorganisms and nutrients that could be loosely held to soil particles. After the final wash, columns were allowed to drain for 1 hr prior to the start of the experiment. One cm thick PAM + $Al_2(SO_4)_3$ or PAM + CaO mixtures were spread on the surface of each soil column. A solid wet swine waste slurry 2.5 cm thick was placed over the control, PAM + $Al_2(SO_4)_3$ or PAM + CaO mixtures. A 7.5 cm head space at the top of each column was left so that distilled water could be poured over the animal waste. A 10 cm diameter funnel was placed under each column and into a 500 ml erlenmeyer flask below.

2.1.5. Polyacrylamide

The polyacrylamide copolymer used was a dry granular material having an approximate molecular weight of 12–15 mg/mole, with an 18% negative charge density (provided by CYTEC Industries of Wayne, NJ and marketed in the USA under the trade name Superfloc 836A). The same product is marked in Australia under the trade name Irrigaid.

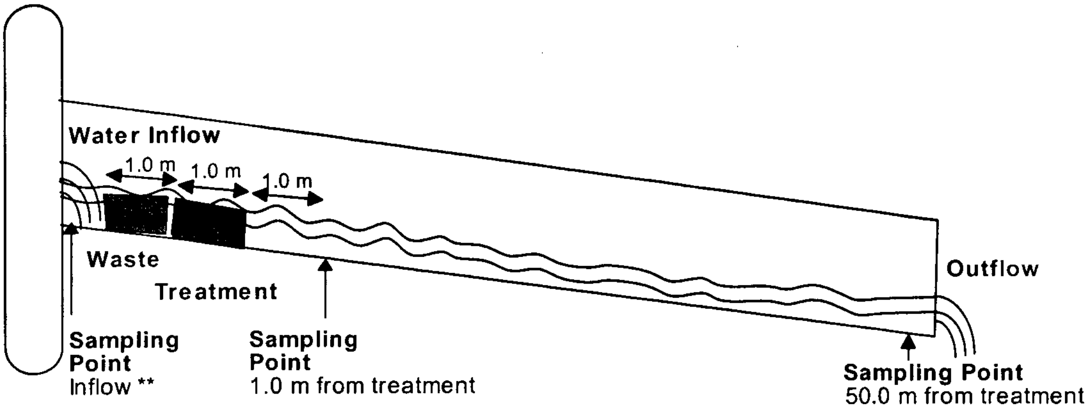
2.1.6. Treatments

Polyacrylamide treatments consisted of: 10 g PAM + $Al(SO_4)_3$ (1 g PAM mixed with 9 g $Al_2(SO_4)_3$ or 10 g PAM + CaO (1 g PAM mixed with 9 g CaO spread over the surface of the soil). Then 30 ml solid:wet 1:1 semisolid (slurry) animal waste was poured over the various PAM treatments (Fig. 1). The control treatment did not have a PAM mixture placed on the soil surface. After animal waste was applied over the PAM mixtures, 500 ml distilled water was poured over the top of the animal waste. Water flowed through the swine waste, then through the PAM mixtures and finally through washed soils. Leachate was collected in a 500 ml erlenmeyer flask. Columns were allowed to drain until leachate filled the 500 ml erlenmeyer flask below each column (24 h).

2.2. Field study

2.2.1. Soil descriptions

The field study was conducted at Alister Park Farms near Dalby, Queensland, Australia. Soils in the field plots were (1) heavy clay, (2) loam and (3) light sandy loam. Slopes on all sites were 1.0–1.5%. The heavy clay soil is a Vertic Haploboroll with a texture of 75% clay, 15% silt, 10% sand with shrink-swell properties. This soil had a field saturated hydraulic conductivity of 10 m



* Rill was 10 cm deep by 10 cm wide with a 2% slope. Illustration is not to scale

**Inflow was sampled prior to flowing over waste and treatments

Fig. 2. Diagram of rill showing irrigation swine wastewater flowing over manure then a PAM + $Al(SO_4)_3$ or PAM + CaO treatments in sand, silt or clay dominated soils with collection points at 1 and 50 m from the inflow point.

sec^{-1}. The soil had a pH 7.9 when measured in a 1:5 soil:water (weight:weight). Organic carbon was 1.2% in the surface 10 cm. Cation exchange capacity was 32.74 meq/100 g. Concentrations of elements in the soil were NO_3 = 26.0, PO_4 = 38.0, total P = 100, K = 232, Ca = 471, Mg = 165, Fe = 19.0, Mn = 2.0 Cu = 0.8, Zn = 1.2 mg element kg^{-1} soil. The loam soil is Typic Haploboroll with a particle size distribution of 25% sand, 60% silt and 15% clay. It has a saturated hydraulic conductivity of 6–5 m s^{-1}. Organic matter content was 1.2%. The soil had a pH 7.3 when measured in a 1:5 soil:water (weight:weight) mixture. Cation exchange capacity was 25.33 meq/100 g. Concentrations of elements in the soil were NO_3 = 20.2, PO_4 = 57.0, total P = 101, K = 340, Ca = 355, Mg = 127, Fe = 25.0, Mn = 4.0, Cu = 0.9, Zn = 1.8 mg element kg^{-1} soil. The sandy soil was classified as a Typic Paleudult with a particle size distribution of 10% clay, 15% silt, 75% sand. The soil had a pH 5.5 when measured in a 1:5 soil:water (weight:weight) mixture. Soil organic carbon was 1.0%. Concentrations of elements in the soil were NO_3 = 20.2, PO_4 = 57.0, total P = 101, K = 340, Ca = 355, Mg = 127, Fe = 25.0, Mn = 4.0Cu = 0.9, Zn = 1.8 mg element kg^{-1} soil.

2.2.2. Experimental design

The field type study was arranged in a completely randomized design consisting of three treatments: (1) PAM + $Al(SO_4)_3$, (2) PAM + CaO and (3) control (no treatment). Each treatment had swine waste water flowing over three soils with three different textures. Water was sampled at three distances along the furrows: at the inflow point and at 1 and 50 m down slope of the above treatments and times during flow (1/2, and 3 1/2 h). We analyzed three sub-samples for TC and FC. We took 162 samples for the study (three treatments × 3 soil textures × 3 × furrows × 3 sampling points along each furrow × 2 sampling times during each water application × 3 samples from each water collection as sampling error).

2.2.3. Treatment application

Furrows were 0.3 m wide × 0.2 m deep × 50 m long. We placed a mixture of 35 g PAM + 750 g $Al_2(SO_4)_3$, a mixture of 35 g PAM + 750 g CaO in a 0.2 m wide × 0.2 m deep × 1.0 m long area or no chemical (control) treatment. Application of PAM + $Al_2(SO_4)_3$, and PAM + CaO involved the spread of granular PAM on the surface of the soil (Fig. 2.). Irrigation water came from the Swine wash water which was first in a storage pond and pumped to the 0.2 m wide × 0.2 m deep × 50 m long furrows at a rate of approximately 60.0 l min^{-1}.

2.2.4. Coliform procedures

In both studies, water was collected and stored in sterile, 125 ml bottles and prepared for coliform testing within 24 h of collection (Greenberg et al., 1992). Samples were stored at 4 °C (West et al., 1986) to minimize the effects of storage on microbial activity. Total coliform and FC bacteria were analyzed using the membrane filter technique (Greenberg et al., 1992). One ml of water was diluted in a series of 2–5. One hundred milliliters of final dilution of each sample was vacuum-filtered through a sterile 0.45 μm filter and placed on Em endo medium to determine TC and placed on mFC medium to determine FC. Total coliform bacteria were incubated at 35.0 ± 0.02 °C; FC bacteria were incubated at 44.5 ± 0.02 °C for 24 h.

2.2.5. Soil chemical analysis

Nitrate and ammonium were determined using a Lachat autoanalyzer (Lachat Quickchem Systems, Milwaukee, WI) using methods described by Keeney and Nelson (1996). Phosphate and total P were estimated using methods described by Olsen and Sommers (1996).

2.3. Statistical analyses

All dependent variables were tested for normal distribution using univariate procedures in SAS programs (SAS Institute, 1996). The number of total and fecal coliform bacteria were transformed using logarithms to achieve normal distributions. Data were then analyzed using general linear models (GLM) procedures for a completely random design with SAS (SAS Institute, 1996). For the column study, statistical comparisons were made of total coliform and fecal coliform bacteria, NH_4^+, NO_3^-, ortho-P and total P in water by PAM mixtures×soil type because the interaction was significant in nearly all of the GLM models. In the surface flow study, statistical comparisons for total and fecal coliform bacteria, ammonium, nitrate ortho P and total P in water by PAM mixtures×soil type×distance from inflow because GLM models showed these interactions were significant at $P \leqslant 0.05$ (Snedecor and Cochran, 1980; Kirk, 1982). In all analysis, residuals were equally distributed with constant variances. Differences reported throughout are significant at $P \leqslant 0.05$, as determined by the Least Squares Means test. Total and fecal coliform bacteria are reported in untransformed numbers.

3. Results

Concentrations of TC, FC, NH_4^+, NO_3^-, ortho-P and total P in source waste water did not differ among waste water collected from Toohey, Nobby and Warick swine farms (Table 1).

3.1. Column study

Interactions in GLM models of PAM mixtures×soil type×manure type×leachate runs were not significant, therefore, statistical comparisons of TC, FC, NH_4^+, NO_3^-, ortho-P and total P are presented for PAM mixtures×manure type because GLM models showed these interactions were significant at $P \leqslant 0.05$ (Snedecor and Cochran, 1980). All soil columns reduced populations of TC and FC in leachate by approximately 10 fold in all three swine waste sources compared to the waste (Table 2). The PAM + $Al_2(SO_4)_3$, and PAM + CaO treatments reduced populations of TC and FC in leachate 100-fold in all three manure sources compared to the control treatment and from 1000-fold compared to the source waste.

Columns containing sandy loam and loam soils that did not receive PAM + $Al_2(SO_4)_3$ or PAM + CaO reduced NH_4^+ concentrations in leachate (Table 2). The PAM + $Al_2(SO_4)_3$, and PAM + CaO treatments reduced NH_4^+ concentrations in leachate compared to the source waste and control treatment. The PAM + CaO treatment reduced NO_3^+ concentrations in leachate compared to the source waste and control treatment. The PAM + $Al_2(SO_4)_3$ and PAM + CaO treatments applied to sandy loam, loam and clay soils reduced ortho-P, concentrations in leachate compared to the source waste and control treatment. Columns containing sandy loam, loam and clay soils without PAM + $Al_2(SO_4)_3$ or PAM + CaO reduced total P concentrations in leachate compared to source waste. PAM + $Al_2(SO_4)_3$ and PAM + CaO treatments reduced total P concentrations in leachate compared to the source waste and control treatment.

3.2. Field study

In the surface flow study, statistical comparisons for TC, FC, NH_4^+, NO_3^-, ortho- P and total P by PAM mixtures×soil type×distance from inflow×time of sampling are not presented because GLM models showed these interactions were not significant at $P \leqslant 0.05$ (Snedecor and Cochran 1980; Kirk, 1982). No difference in the numbers of TC and FC in wastewater was found at 1 m downstream compared to the organisms in water 50 m downstream of the treatments (Table 3). As swine wastewater flowed over PAM + $Al_2(SO_4)_3$, or PAM + CaO, TC were reduced by approximately 10 fold at 1 and 50 m downstream of the treatments compared to the source swine waste (input) in all three soil types. As swine waste water flowed over PAM + $Al_2(SO_4)_3$ and PAM + CaO, TC and FC were reduced by approximately 30–50% at 1 and 50 m downstream of the treatments compared to the control treatment in all three soil types. The PAM + $Al_2(SO_4)_3$, or PAM + CaO treatments did not consistently reduce NH_4^+, NO_3^-, ortho-P and total P concentrations in wastewater flowing over any soil compared to inflow wastewater or the control treatment.

4. Discussion

In the field study, the efficacy of PAM + $Al_2(SO_4)_3$, and PAM + CaO to remove TC and FC from waste water did not vary with soil type. The efficiency of PAM + $Al_2(SO_4)_3$, and PAM + CaO at removing bacteria from water in this study is similar to values reported by Entry and Sojka (2000). Results from this study and studies on PAM alone (Sojka and Entry, 2000) and a previous study with PAM + $Al_2(SO_4)_3$, and PAM + CaO (Entry and Sojka, 2000) suggest that PAM, PAM + $Al_2(SO_4)_3$, and PAM + CaO are indiscriminate to the type and species of microorganisms removed from water. It might be expected that these mixtures could potentially remove a large range of pathogenic bacteria and fungi as well as parasitic protozoa, including *Cryptosporidum parvum* and *Giardia lamblia* from flowing water. The PAM mixtures should not be expected to sterilize water, but they should be able to substantially reduce the numbers of pathogenic bacteria in waste water prior to entering public water systems.

To achieve maximum benefit, we speculate that these compounds need only be spread in a narrow strip around an animal confinement area prior to rainfall during periods of risk. If the compounds are allowed to accumulate on the soil surface, they could be removed from the soil surface and composted. Sojka (unpublished data) has incorporated up to 5600 kg PAM ha^{-1} into soil without noticeable ill effects on soil properties or plant growth. Further studies investigating the use of PAM mixtures on and around animal confinement operations are necessary before we can fully determine if these mixtures are effective.

The efficacy of PAM compounds at removing TC and FC from water in the soil type study was much lower than the values in the manure type study. The main difference between the two studies was that water was flowing at 8.6 l min^{-1} when manure types were varied and at 60 l min^{-1} when soil types were varied. When water was flowing over PAM + $Al_2(SO_4)_3$ or PAM + CaO patches at 60 l min^{-1}, the PAM granules most likely did not get throughly mixed throughout the water column. Sojka and Entry (2000) showed that bacteria were effectively removed from water at rates flowing from 7.5 to 22.5 l min^{-1}. As flow rates increased, PAM + $Al_2(SO_4)_3$ or PAM + CaO removed a smaller percentage of bacteria from water. PAM + $Al_2(SO_4)_3$ or PAM + CaO patches are increasingly effective at lower flow rates. When PAM molecules are dissolved in water and adhere to microorganisms or nutrients, they may stay dissolved until the molecule adheres to an object that is heavy enough to settle out of the flow. This would explain why PAM + $Al_2(SO_4)_3$ and PAM + CaO in faster flowing water is not as effective as the same treatments in slower flowing water. The effectiveness of these compounds may be increased if clay or silt size particles are added into the water flow.

The anionic charges on PAM would not only flocculate microorganisms, but also positively charged nutrients in wastewater. The reduction of NH_4^+ in Toohey and Hawkesbury soils in the control columns could be due to adsorption on the ion exchange sites or fixation.

The values for NH_4, total P and ortho-P are higher in the soil than in the swine waste water input.

The producer irrigates crops with swine waste water on a weekly basis. We think that these nutrients may be accumulating in the soil as each irrigation is adding large amounts of NH_4, total P and ortho-P to the soil.

We hypothesize that when PAM is combined with either $Al_2(SO_4)_3$ or CaO and then added to water, $Al_2(SO_4)_3$ or CaO should quickly disassociate, freeing Al^{+3} and Ca $^{+2}$ to bind with anionic nutrients such as $H_2PO_4^-$ and NO_3^-. Free Al^{+3} and Ca $^{+2}$ most likely bind with anionic sites on the PAM molecule, forming a bridge with anionic nutrients such as $H_2PO_4^-$ and NO_3^-. In basic soils the addition of CaO could raise the pH of runoff water contributing to precipitation of hydroxyapatite minerals which should decrease ortho-P availability. The pH of soils and waste water used in this study ranged from 6.5 to 7.9. Further investigation to determine the efficacy of PAM + $Al_2(SO_4)_3$ or PAM + CaO to remove microorganisms and nutrients from waste water should include acidic soils and their combined effect with vegetative filters. Using PAM + $Al_2(SO_4)_3$ or PAM + CaO to remove microorganisms and nutrients from waste water may produce different results in acidic soils, especially when considering binding properties in ortho-P and total P.

Potential benefits of PAM + $Al(SO_4)_3$, and PAM + CaO compounds to animal production operations are: (1) they are inexpensive; (2) they can be quickly spread on the soil surface and (3) they can be used along with other techniques and management strategies such as riparian vegetation (Hubbard et al., 1998; Entry et al, 2000a, b) and denitrification walls (Schipper and Vojvodic-Vukovic, 1998) to reduce the input of pollutants from animal confinement areas to water resources. Cost analysis and testing of the use of these two compounds in various animal operations is necessary, but our research demonstrates the potential of PAM + $Al_2(SO_4)_3$, and PAM + CaO as a valuable tool to allow animal producers to control pollution from their operations. Animal production operators should not expect the development PAM + $Al_2(SO_4)_3$, and PAM + CaO products or new technologies, to help them to suspend best management practices or common sense. Best results of new pollution mitigation technologies will most likely be achieved by combining them with best management practices and sound animal management practices.

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