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Minimising off-site movement of contaminants in furrow irrigation using polyacrylamide (PAM). II. Phosphorus, nitrogen, carbon, and sediment

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Abstract. Off-site movement of nutrients and sediment from furrow-irrigated agriculture has been a concern in the Ord River Irrigation Area, Western Australia. After consultation with growers, a range of management strategies were tested to assess the effectiveness of various practices to minimise off-site movement of nutrients during irrigation. This paper reports on the effectiveness of the additions of high molecular weight, anionic, polyacrylamide (PAM) to irrigation water to minimise off-site movement of phosphorus, nitrogen, carbon, and sediment. Surface runoff water quantity and quality from 4 separate irrigation bays, which contained 25 furrows per irrigation bay, was monitored over time for a single irrigation 35 days after sowing.

Addition of PAM as a puck (cylindrical disc 55 mm diameter by 23 mm height) to the head of each irrigation furrow significantly ($P < 0.001$) decreased the average volume of surface runoff water leaving the irrigation bays by 54%, from 599 kL for the control irrigation bays to 277 kL for the PAM-treated irrigation bays. The addition of PAM also significantly ($P < 0.001$) decreased the average total suspended sediment load for the duration of the irrigation from 94.9 kg/ha for the control bays to 13.4 kg/ha for the PAM-treated irrigation bays. The concentrations of the different forms of N, P, and C measured in the runoff water were not significantly different between the 2 treatments. The amounts (g) of particulate ($>0.45\,\mu$m) P and dissolved organic C were significantly ($P < 0.01$) less from the PAM-treated bays than from the control bays.

There was a consistent trend for the addition of PAM to decrease the cumulative mass loss of all nutrients (N, P, and C) measured. However, significant decreases were only seen for particulate ($>0.45\,\mu$m) P (by 94%), unfiltered (or total) N (by 56%), and unfiltered (or total) C (by 60%). This experiment demonstrated that the addition of PAM to irrigation waters has the potential to decrease the off-site movement of nutrients bound to colloidal material. However, in this study off-site movement of contaminants present in the ‘soluble’ ($<0.45\,\mu$m) fraction is unlikely to be mitigated by the addition of PAM to irrigation water. The mode of application of PAM, however, may affect water infiltration and hence vertical movement of ‘soluble’ contaminants and requires further investigation to ensure that while off-site surface transport is being minimised, contamination of groundwater is not being increased. Other strategies to minimise off-site movement for contaminants in the dissolved phase also need investigation.

Additional keyword: contaminant movement.

Introduction

The Ord River Irrigation Area (ORIA) is one of the main horticultural production areas in Western Australia. Currently 14 000 ha of land is farmed using the Ord River dam as the main source of quality fresh water. About 60 crops are grown in the ORIA, with rockmelons (*Cucumis melo* var. cantalupensis), bananas (*Musa* spp.), honeydew melons (*Cucumis melo* var. inodorus), watermelons (*Cirtrullus lanatus*), and pumpkins (*Cucurbita* spp.) making up the bulk of production.

Currently, crops in the ORIA are grown in raised beds. The fields are furrow-irrigated and the surface runoff water is released from their paddocks into channels, which eventually flow back into the Ord River. One of the consequences of furrow irrigation is that erosion can become a major problem. In addition to the loss of topsoil, nutrients and contaminants bound to any particulate material may also move off-site and cause adverse effects on the downstream environment. A series of field experiments was conducted on farms in the area to assess the effectiveness of a range of management strategies to minimise nutrient and pesticide movement in runoff water. This paper reports on the effect of high molecular weight, anionic polyacrylamide (PAM) to the irrigation water on nutrient and sediment

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concentrations and loads in surface runoff water. PAM has been in use in the USA since 1995 but its use in Australia is very limited. Sivapalan (2002, 2003) has reported on glasshouse experiments with PAM and observed increased water retention by sandy soils, but no field experiments in Australia have been reported. The addition of PAM to irrigation water has been extensively studied in USA to assess its effectiveness to minimise off-site movement of soil (Lentz *et al*. 1992) and, to a lesser extent, nutrients (Bahr and Stieber 1996; Lentz *et al*. 1998*a*, 1998*b*; Bjorneberg *et al*. 2002; Entry and Sojka 2003). PAM is a water-soluble polymer with the ability to enhance soil stabilisation. High molecular weight PAMs have increased length of the polymer and increased viscosity of the PAM solution and tend to be more effective in decreasing soil movement off-site (Levy and Agassi 1995). Anionic PAM stabilises soil surface structure and pore continuity by binding to negatively charged sites on the clay surface through divalent cations. The presence of divalent calcium or magnesium cations in solution is imperative for effective soil stabilisation because they have a double charge and small hydrated radius which favours flocculation (Green and Stott 2001; Entry *et al*. 2002). Also, they act as bridging cations between negatively charged soil surfaces and negatively charged soil particles (Laird 1997). In this study the aim of the addition of PAM to the water supply was to flocculate out any sediment in the irrigation water with the proposed added benefit of decreased off-site transport of any nutrients that bind to any particulate material.

Materials and methods

Field experiment

Details of the field experiment are given in Oliver and Kookana (2006) and are briefly described here. The field experiment involved 2 treatments that were replicated twice in a randomised block design: PAM applied to irrigation water, and no PAM (conventional or control treatment). Irrigation water was applied to a paddock 35 days after being sown to melons (*Cucumis melo* var. cantalupensis). The irrigation water inflow rate was approximately 60 L/min. In both experiments the irrigation water applied had a pH of 7.9, an EC of 27 811 µS/m, and a sodium adsorption ration (SAR) of 0.5.

The soil was a Typic Haplotorrert with a total organic carbon content of 0.7%, a clay (<0.002 mm) content of 52%, a sand (0.02–2 mm) content of 36%, and pH (1 : 5, 0.01 M $CaCl_2$) of 6.6. The total N of the soil was 0.03% (Matejovic 1997), NH_4-N was 1.4 mg/kg (ISO 1977), NO_3-N was 4.4 mg/kg (APHA/AWWA/WEF 1992*b*), bicarbonate-extractable P was 37 mg/kg (Rayment and Higginson 1992), and total P was 190 mg/kg (USEPA 1998). The EC of the soil was 0.19 dS/m; the concentrations (mg/kg) of soluble salts were 66 Ca, 20 K, 26 Mg, 76 Na, 38 S, and 58 Cl; and the SAR of the soil was 0.90 mg/L (Rayment and Higginson 1992). The soil parameters were determined by mid-infrared analysis (Haaland and Thomas 1988; Janik *et al*. 1998) except where indicated otherwise. The furrows were 300 m long with an average slope of 1%. The amount of water leaving each irrigation bay (1.35 ha) was determined using a Doppler flow meter (Unidata America, Lake Oswego, OR, USA) that was placed in a rectangular, open-channel weir at the end of the tail drain. Each bay was irrigated separately starting with the bay closest to the weir and moving up the paddock in the opposite direction of the water flow in the tail drain. The same number and size of irrigation siphons were used for each irrigation bay. The duration of the irrigation was the same for each bay and the height of water in the supply channel was approximately the same for each irrigation bay. The approximate inflow rate into each furrow was 60 L/min. The PAM was applied to irrigation bays 2 and 4 as the commercial product, Flobond^{TM}, at the rate of 1.11 kg/ha as cylindrical discs (55 mm diam. by 23 mm height) in the top of each furrow closest to the irrigation siphon. This ensured that both field replicates of the PAM treatment received the same amount of PAM. Flobond^{TM} is a 40% active PAM powder with a charge density of 30% and a molecular weight of 12–15 Mg/mol.

The following fertilisers were applied to the soil prior to the crop being sown (kg/ha): 250 diammonium phosphate (DAP), 150 sulfate of ammonia, 100 sulfate of potash, 10 zinc, and 5 boron.

Surface runoff water collection

Water samples were collected from the outlet of each bay at the following time intervals after water started to flow over the Doppler flow meter: 15 min, 1, 3, 6, and 10 h. Since the PAM-treated bays stopped flowing after 8 h, all loads of nutrients moving off-site were determined up to 6 h only. All samples were collected into acid-washed plastic bottles and stored on ice until transported to the cold room, where they were kept at 4°C and then transported to the laboratory. In the field 2 samples were unfiltered and 2 were filtered through Gelman Supor Acrodisk 0.45 µm filters. In the field, all samples were acidified after collection with 2 drops of concentrated HCl. Samples of supply water and tail water were also spiked with known concentrations of N, P, and C to check the effect of the transport process on recovery. Duplicate samples were also collected at each time for measuring total suspended sediment (APHA/AWWA/WEF 1992*a*).

Nutrient analyses

Total N and C were determined on the filtered (<0.45 µm; termed 'soluble' in the text) and unfiltered (total sample composed of 'particulate' (>0.45 µm) + 'soluble' (<0.45 µm fraction)) samples using the Skalar Formacs High Temperature TOC/TN Analyser. The inorganic C in the filtered sample was determined by adding additional acid to the filtered sample to evolve the inorganic C and measuring the CO_2 released. The dissolved organic C in the filtered sample was determined as the difference between the total dissolved C and the inorganic C in the filtered sample. Total P was measured using inductively coupled plasma (ICP). Ammonium nitrogen was measured using ISO Method 11732 (ISO 1977), which involves mixing the water sample with a continuous flow of an EDTA/sodium hydroxide solution. The ammonia produced is determined colourimetrically. Nitrate-nitrogen was measured using Method 4500-NO_3-F (APHA/AWWA/WEF 1992*b*), which involves the reduction of NO_3^- to NO_2^- using Cd. The NO_2^- produced is then measured colourimetrically.

Determining nutrient loads

Runoff volumes were calculated from water velocity and depth measured using the Doppler flow meter, and cross-sectional area of the open-channel weir (installed at the end of the tail drain) in which the meter was installed.

Amounts (mg) of nutrients leaving each bay for the designated time intervals were determined by multiplying concentrations (mg/L) by the total volume (L) of water leaving the bay during that time interval. The total volume of runoff water leaving the field over a designated time increment was determined by calculating the area under the hydrograph. The cumulative load for the irrigation of each bay was then determined by the summation of the amounts for each time interval. The hydrograph for bays 2 and 3 overlapped (Oliver and Kookana 2006) so the volumes of water leaving bay 2 at the conclusion of irrigation and that leaving bay 3 at the start of irrigation were determined by extrapolating the hydrograph for bay 2 forward and for bay 3 backwards. Data were statistically analysed by ANOVA using the commercially available software package, GENSTAT.

Results and discussion

Water leaving the irrigation bays and total suspended sediment

Details of the total water leaving the bays and total suspended sediment loads are covered in more detail in Oliver and Kookana (2006). Briefly, the addition of PAM decreased the average volume of water leaving the irrigation bays by 54%. The average volume of water leaving the PAM-treated irrigation bays was 277 kL, which was significantly ($P < 0.001$) less than the average volume leaving the control irrigation bays (i.e. 599 kL). Since approximately the same volume of water was added to each irrigation bay this suggested that the addition of PAM increased water infiltration, which in turn would be expected to increase water use efficiency. However, increased water infiltration may cause potential problems with groundwater contamination, particularly with highly soluble nutrients such as nitrate. Others have found enhanced water infiltration following the addition of PAM to soil (Lentz and Sojka 1994). Lentz *et al.* (2001) studied soil water percolating below 1.20 m during the irrigation season for conventional and PAM-treated irrigation furrows. They found no statistical difference between control and PAM-treated furrows in the cumulative amount (kg/ha) of nitrate-N or chloride in the soil water collected over the season.

In the first hour, the concentration of the total suspended sediment (TSS) leaving the control irrigation bays was significantly ($P < 0.01$) greater than that leaving the PAM-treated bays (Fig. 1*a*). For the duration of the irrigation the TSS concentration continued to decline in the control bays. The addition of PAM significantly ($P < 0.001$) decreased the average cumulative amount (kg) of TSS leaving the irrigation bays by 86%, from 128 kg or 94.9 kg/ha for the control bays to 19 kg or 13.4 kg/ha for the PAM-treated bays. Others have also recorded a decrease in total sediment losses following the application of PAM. Lentz *et al.* (1998*a*) measured total sediment losses over 4 irrigations of 3061 kg/ha for the control compared with 334 and 242 kg/ha for furrows treated with PAM only until runoff commenced, and for furrows treated continuously with PAM, respectively. In a 12-h irrigation experiment, Lentz *et al.* (2001) found a cumulative sediment loss per control furrow of 609 kg/ha compared with 59 kg/ha for furrows treated with 10 mg/L of PAM applied in advance only (i.e. PAM not supplied continuously). This is a 90% reduction in sediment load, which is similar to that found in this study.

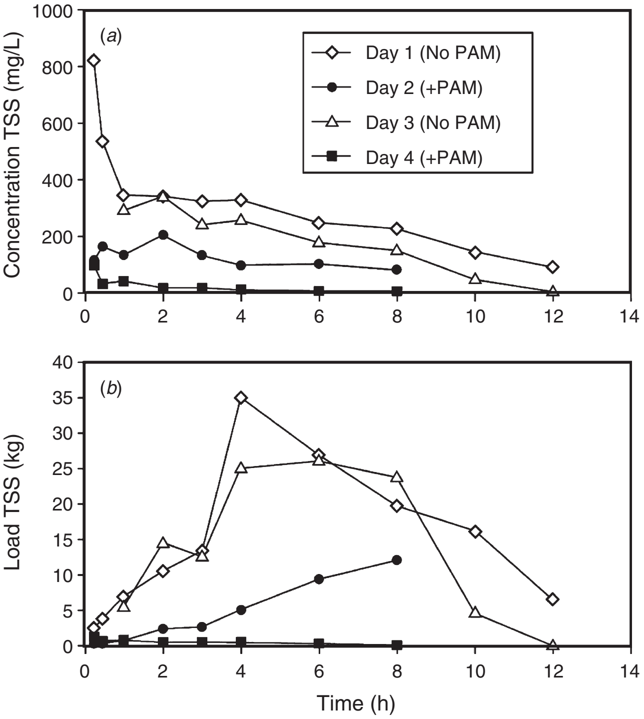

Fig. 1. (*a*) Concentration (mg/L) and (*b*) load (kg) of total suspended sediment (TSS) at each time interval from each bay for the irrigation period.

Concentration of nitrogen, phosphorus and carbon

The concentrations of the different forms of N, P, and C measured at each sampling time over the irrigation period generally decreased with time, with maximum decline during the first hour (Fig. 2). However, there were no significant differences in the concentrations of the different forms of N, P, and C between the PAM-treated irrigation bays and the conventional irrigation bays. The range of concentrations of N, P, and C in runoff water over the 8-h irrigation period is given in Table 1. The greatest range for N, P, and C was in the unfiltered (total) measurement. At any given sampling time, for both treatments, the lowest concentration for P and N was in the particulate (>0.45 µm) fraction (Fig. 2*a*, *b*). In this study the highest and median concentrations were 0.29 and 0.20 mg/L for total P, and 1.52 and 0.9 mg/L for total N, respectively. Carter *et al.* (1974) found sediment eroded from irrigated agricultural soils in US typically contained 900–1200 mg total P/kg soil. The average total P concentration in irrigation runoff from control fields measured over 2 years ranged from 0.95 to 3.47 mg/L (Westermann *et al.* 2001). Lentz *et al.* (1998*a*) found that neither continuous PAM application to water during irrigation nor application of PAM only until runoff began decreased the mean NO_3-N concentrations in furrow runoff compared with control treatments. However, they found that both PAM treatments decreased total P and ortho-P (soluble P)

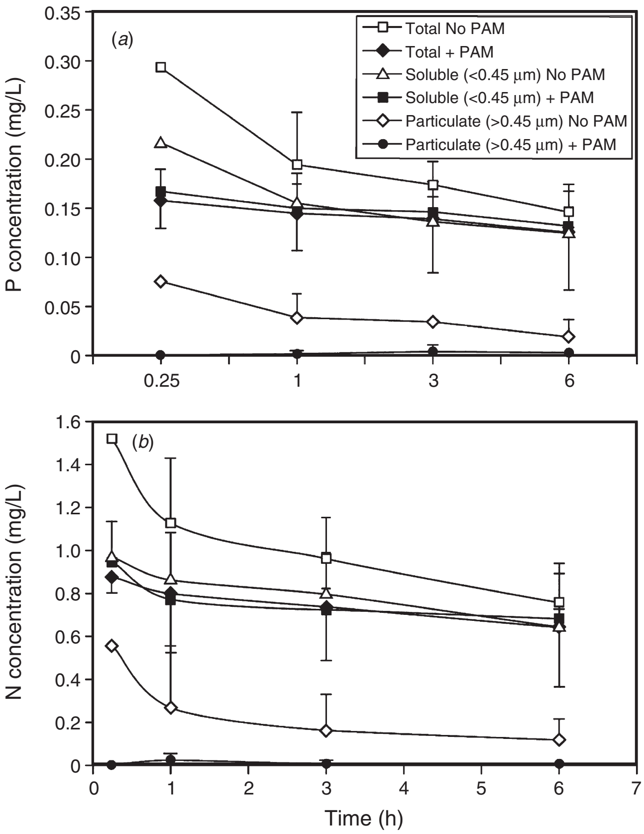

Fig. 2. Average concentrations (±s.d.) at each sampling interval of (*a*) total, soluble (<0.45 µm) and particulate (>0.45 um) P and (*b*) total, soluble (<0.45 µm) and particulate (>0.45 µm) N, over time for the irrigation period.

concentrations in furrow runoff. They found runoff from control furrow streams contained 5–7 times higher total P and ortho-P concentrations than the runoff from the PAM-treated furrows. Others have found the addition of PAM as a granular powder spread over 0.1 m^2 adjacent to the inflow siphon decreased total N, NO_3^-, and total P and K in runoff water, which was attributed to a decrease in both the nutrients dissolved in irrigation water and nutrients contained in sediment (Entry and Sojka 2003). However, a field study investigating the efficacy of PAM + $Al_2(SO_4)_3$ or PAM + CaO to remove coliform bacteria and nutrients from swine wastewater did not consistently decrease NH_4^+, NO_3^-, ortho-P, or total P concentrations in wastewater compared to the control treatment (Entry *et al.* 2003).

Amounts of nitrogen, phosphorus, and carbon

Generally the amounts of N, P, and C leaving the bays at each sampling interval were not significantly different between treatments (data not shown). The exceptions to this were the amounts at each sampling interval of particulate P and DOC (Fig. 3*a*, *b*) in the surface runoff water. The average load (g) at each sampling interval of particulate (>0.45 µm) P leaving the control irrigation bays increased for the first 3 h of irrigation but then started to decline by 6 h (Fig. 3*a*). By contrast, the average load at each sampling interval of particulate (>0.45 µm) P leaving the PAM-treated irrigation bays was significantly ($P < 0.01$) lower than the control bays and remained fairly low throughout the irrigation period (Fig. 3*a*). The average load at each sampling interval of DOC (g) leaving both the control and PAM-treated irrigation bays increased over time for the duration of the irrigation. However, the average load at each sampling interval of DOC (g) leaving the PAM-treated bays was significantly ($P < 0.01$) less than that leaving the control bays (Fig. 3*b*).

The overall trend for the average cumulative mass loss of all nutrients measured was that the addition of PAM decreased the total nutrient load leaving the irrigation bay (Table 1). However, significant decreases were only seen for particulate

Table 1. Concentration (mg/L) range and average (±s.d.) cumulative amounts (g/ha) of N, P, and C in the unfiltered, filtered and particulate samples leaving the PAM and conventionally treated bays
The median concentrations are given in parentheses

	Conc. range		Amount		% Decrease, amount	*P*-value[C]
	No PAM	+ PAM	No PAM	+ PAM		
Unfiltered P (total)	0.12–0.29 (0.20)	0.08–0.18 (0.15)	52.1 ± 6.9	23.5 ± 10.8	55	0.088 n.s.
Filtered P[A]	0.12–0.22 (0.10)	0.10–0.18 (0.16)	44.2 ± 9.2	24.4 ± 8.0	45	0.150 n.s.
Particulate P[B]	0–0.08 (0)	0–0.01 (0)	7.9 ± 2.3	0.5 ± 0.8	94	0.050*
Unfiltered N (total)	0.63–1.52 (0.90)	0.47–1.06 (0.75)	276 ± 15	122 ± 51	56	0.050*
Filtered N[A]	0.52–0.96 (0.80)	0.45–1.06 (0.87)	230 ± 47	126 ± 56	45	0.178 n.s.
Particulate N[B]	0.04–0.56 (0.10)	0–0.05 (0)	45.9 ± 31.7	0 ± 0	100	0.177 n.s.
NH_4-N	0.01–0.07 (0)	0.01–0.06 (0.03)	7.1 ± 0.2	4.6 ± 2.0	57	0.222 n.s.
NO_3-N	0.09–0.30 (0.20)	0.05–0.35 (0.20)	62 ± 0.4	29 ± 23	54	0.176 n.s.
Unfiltered TC (total)	4.20–11.64 (6.10)	3.51–6.98 (4.82)	1953 ± 256	773 ± 253	60	0.043*

[A] Filtered P = fraction <0.45 µm.
[B] Particulate fraction (>0.45 µm) = (Concentration in unfiltered sample (i.e. total concentration) – concentration in filtered sample, i.e. <0.45 µm).
[C] The *P* value has been determined from ANOVA of cumulative amounts data.
*$P < 0.05$.

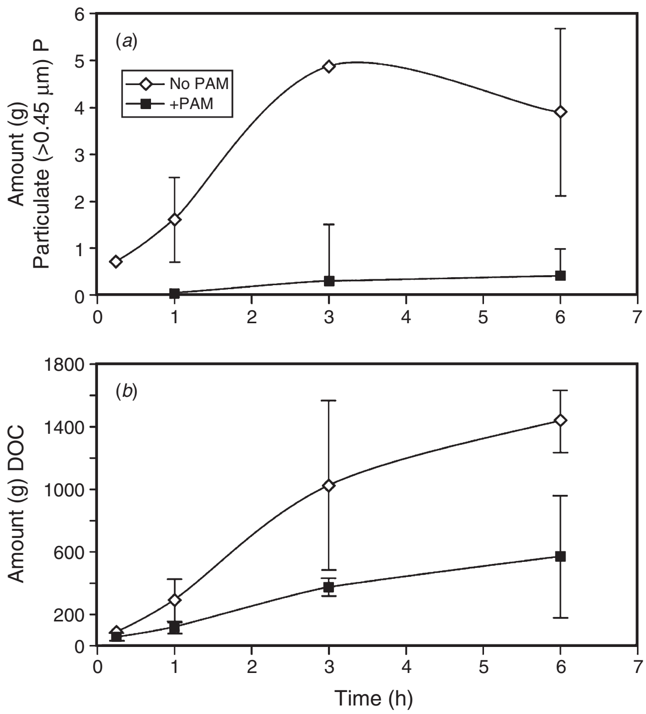

Fig. 3. Average amount (±s.d.) of (*a*) particulate P (>0.45 µm) (P in unfiltered sample – P in filtered sample) and (*b*) DOC, leaving the irrigation bays at each time interval from each bay for the irrigation period.

P, unfiltered N, and unfiltered C. The addition of PAM to the irrigation water significantly ($P < 0.05$) decreased the total amount of particulate (>0.45 µm) P by 94%, the total amount of unfiltered N by 56%, and the total amount of unfiltered C by 60% (Table 1). Although the total amount of particulate N in water leaving the PAM-treated irrigation bays appeared to decrease by 100% compared with the water from the control irrigation bays, there was such a large variation between replicates for the particulate N measurements for the PAM-treated bays that the decrease was not significant. Lentz *et al.* (1998*a*) found across 4 irrigations that applying liquid PAM to irrigation water until runoff began, or applying liquid PAM continuously, decreased total P losses by 86 or 91%, respectively, compared with a decrease of 55% in our study. Lentz *et al.* (1998*a*) found that NO_3-N losses were low and neither PAM treatment significantly decreased the cumulative losses compared with the control treatments, consistent with our findings.

The average load of total P (unfiltered P) moving off-site in irrigation water for the duration of the irrigation event was 52.1 g/ha from the control bays and 23.5 g/ha from the PAM-treated bays, which was significant ($P = 0.09$, Table 1). By comparison, Westermann *et al.* (2001) found total P loss in runoff from a furrow-irrigated field for an entire irrigation event was between 2800 and 19 300 g P/ha, with a median load of 7300 g P/ha for a single irrigation event. However, some of the plots in their study had manure applied 4–7 years prior to the run-off experiment being conducted. The bicarbonate-extractable inorganic P in the bottom of the furrows in their experiment ranged from 10 to 125 mg/kg with a median of 48 mg/kg (Westermann *et al.* 2001). The amount of P in the top 0.30 m in their experiment was higher than in our experiment, which may explain the larger load of P leaving their experiment.

Phosphorus (P) is one of the least mobile plant nutrients in soil but it is transferred from agricultural lands to water bodies dissolved in surface runoff, attached to eroded sediment, and leached through the soil profile (Lemunyon and Daniel 2002). A major mechanism for losses of P is off-site transport by sediment as part of erosion processes (Barrows and Kilmer 1963). Of the various forms of irrigation the greatest erosion occurs with surface irrigation where concentrated flow in the furrows produces shear forces that detach and transport soil particles and any contaminants attached to those particles (Lentz *et al.* 1998*a*).

Although the addition of PAM to irrigation water in this furrow irrigation setup appears to be an effective way to minimise off-site transport of particulate P, unfiltered N, and unfiltered C, ecotoxicological studies will need to be conducted with Australian fauna to ensure there are no detrimental effects on aquatic organisms from the use of PAM. In USA anionic PAMs exhibit high LC_{50} values (>100 mg/L), i.e. low toxicity to fish (Barvenik 1994), and preliminary studies with waterflea (*Ceriodaphnia dubia*) indicate low toxicity (Anu Kumar, pers. comm.).

Distribution of N and P

In this study, irrespective of the treatment, the majority of the total average load of N and P was in the 'soluble' (<0.45 µm) fraction. The average proportion of P in the 'soluble' (<0.45 µm) fraction was 85% for runoff water leaving the control bays and 98% for the PAM-treated bays, while for N it was 83 and 100%, respectively. The average proportion of P in the 'particulate' (>0.45 µm) fraction was 15% for the control bays and 2% for the PAM-treated bays, while for N it was 17% for the control bays and 0% for the PAM-treated bays (Fig. 4). The addition of PAM to the irrigation water decreased the cumulative mass loss of P and N moving off-site and also decreased proportion of both P and N in the 'particulate' (>0.45 µm) fraction. This is in accordance with the mode of action of PAM and the observed effect of PAM to decrease the load of sediment moving off-site (Fig. 1*b*). By comparison, a study of seasonal P lost from 32 surface-irrigated agricultural fields found median soluble P lost was only 3% of the total P lost (Berg and Carter 1980).

Australian and New Zealand Water Quality Guidelines

The range of average nitrate-N concentrations in the runoff water from both control bays was 0.09–0.3 mg/L and from

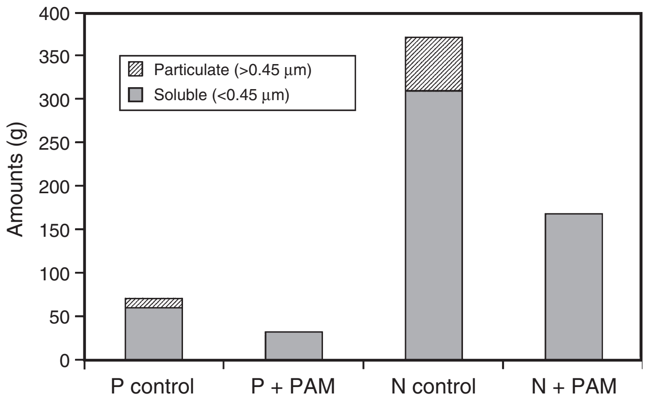

Fig. 4. Distribution of average total amounts (g) of P and N (determined from summation of amounts at each sampling interval) between particulate (>0.45 µm) and soluble (<0.45 µm) fractions for the control and PAM-treated irrigation bays.

the PAM-treated bays 0.05–0.35 mg/L (Table 1), which were well below the ANZECC long-term trigger values for nitrate-N of 5 mg/L and the short-term trigger values of 25–125 mg/L (ANZECC/ARMCANZ 2000). The default trigger values for chemical stressors for tropical Australian aquatic ecosystems range from 0.01 to 0.05 mg/L for total P and from 0.15 to 1.2 mg/L for total N (ANZECC/ARMCANZ 2000). The short-term trigger values have been developed to ensure that groundwater and surface water nitrogen does not exceed guidelines for drinking water, while long-term trigger values are based on maintaining crop yield and minimising off-site impacts (NHMRC/ARMCANZ 1996). The range of concentration of total (unfiltered) P in runoff water in this study was 0.12–0.29 mg/L for control bays and 0.08–0.18 mg/L for PAM-treated bays. These values do not exceed the short-term trigger values for P in irrigation water of 0.8–12 mg/L but do exceed the long-term values of 0.05 mg/L. The long-term values have been set to prevent algal growth in irrigation water (ANZECC/ARMCANZ 2000). The total P concentrations do, however, exceed the limit of 0.1 mg/L suggested by the USEPA for water flowing to streams and rivers (USEPA 1986).

Conclusions

This study demonstrated that the addition of PAM to irrigation water significantly ($P < 0.05$) decreased the volume of water, cumulative mass loss of TSS, particulate P, unfiltered total N, and unfiltered total C moving off-site for the duration of the runoff period associated with a single furrow irrigation event. The decrease in P movement is most likely due to the decreased sediment movement off-site following the addition of PAM to irrigation water. This resulted in a decrease in the average proportion of N and P in the ‘particulate’ (>0.45 µm) fraction in the PAM-treated irrigation bays compared with the controls. The addition of PAM to furrow irrigation was an effective treatment for minimising off-site transport of nutrients associated with colloidal material; however, there was no effect on the off-site movement of more soluble nutrients such as nitrate. The increased water efficiency following the addition of PAM to irrigation water, as evidenced by decreased water movement off-site, does raise a concern, however, about the potential for increased movement of soluble nutrients through the soil profile. This may pose a problem of groundwater contamination. However, a second field study has shown that a highly soluble pesticide, atrazine, did not move any further into the soil profile than the top 0.10 m following the addition of liquid PAM (Oliver and Kookana 2006). Further work is required to assess the impact of PAM on water and nutrient leaching through the soil profile and ensure that the use of PAM does not create groundwater problems. Before widespread use of PAM is promoted in Australia thorough assessment of its potential environmental impact needs to be made.

Acknowledgments

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