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Effect of gypsum and polyacrylamides on water turbidity and infiltration in a sodic soil

S. Sivapalan

School of Agricultural and Veterinary Sciences, Charles Sturt University, Locked Bag 588, Wagga Wagga,
NSW 2678, Australia; Current address: School of Urban Development, Queensland University of Technology,
GPO Box 2434, Brisbane, Qld 4001, Australia. Email: s.sivapalan@qut.edu.au

Abstract. Water ponded on sodic soils can develop turbidity problems which seriously affect rice crop establishment. A total of 19 polyacrylamide products were assessed for their effectiveness to control water turbidity in a sodic soil under laboratory conditions. Anionic polyacrylamides were more effective than cationic or non-ionic polyacrylamides. When combined with gypsum, polyacrylamides were found to be more effective than when applied alone. A split application strategy was more efficient than continuous application of polyacrylamide treatments. Different rates of polyacrylamides at 2.5, 5, and 10 kg/ha did not show significant difference in controlling water turbidity. Selected polyacrylamides were also tested on soil columns to study their effect on infiltration and percolation of water through the soil. Results showed that polyacrylamides combined with low rates of gypsum did not modify the infiltration pattern to a greater extent. This study demonstrated that anionic polyacrylamides applied with small quantities of gypsum through a split application strategy would be an appropriate technique to overcome water turbidity problems in sodic soils.

Additional keywords: sodicity, nephelometric turbidity units, rice establishment.

Introduction

It has been observed that sodic soils in rice-growing areas create turbid water, and that this seriously affects the successful establishment of rice seedlings (Humphreys and Barrs 1998). Similar conditions were reported in the Wah Wah Irrigation District in the Murrumbidgee Irrigation Area of New South Wales (NSW), where irrigation water from the Barren Box Swamp was found to be often turbid (Jones 2004). The significance of the threshold and turbidity concentrations in relation to sodicity and microstructure has been investigated by Quirk (2001). Humphreys and Barrs (1998) found that lower temperatures were associated with turbidity, and the reduction in temperature at the soil surface in turbid water was large enough to seriously retard rice seedling growth.

Bacon (1978) found that at least 1.1 t/ha of gypsum was needed to prevent turbid water. However, Slavich *et al.* (1993) found that 2.5 t/ha of gypsum increased recharge by 3.3 ML/ha, while Humphreys and Barrs (1998) found that 1.25 t/ha of gypsum roughly doubled recharge. Rising watertables and the secondary effects of salinisation are major threats to the sustainability of irrigated agriculture in the rice-growing areas of southern NSW. Therefore, these findings are of major concern.

Humphreys and Barrs (1998) also found that alternatives to gypsum (aluminium sulfate and polyacrylamides) were effective when tested in the laboratory but failed in the field. The failure of polyacrylamides to clarify the water in the field was attributed to the lack of high valency cationic sources in the irrigation water, and not to adoption of split polyacrylamide application strategy as proposed by Sojka and Surapaneni (2000).

Polyacrylamides are commonly used for solid–liquid separations in clarification of potable and waste waters, dewatering of sludges, mining separations, food processing and paper making, as well as petroleum recovery, textile additives, friction reduction, personal care products, and cosmetics (Barvenik 1994). Polyacrylamide use in agriculture could have important environmental, soil conservation, and irrigation efficiency benefits (Sojka and Lentz 1994). Sojka *et al.* (1998) demonstrated the effect of polyacrylamide on infiltration of irrigated agriculture. Vacher *et al.* (2003) demonstrated the beneficial effects of polyacrylamides for the management and rehabilitation of disturbed lands in Australia. Polyacrylamide use in irrigation water for erosion control has also been shown to remove or immobilise microorganisms (Sojka and Entry 2000) and reduce runoff loss of weed seeds (Sojka *et al.* 2003).

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Polyacrylamides are characterised mainly by their molecular weight, molecular configuration, type of charge, and charge density. Barvenik (1994) proposed a classification of polyacrylamides according to their molecular weight (MW). Polyacrylamides with $<10^5$, 10^5–10^6, 1–5×10^6, and $>5 \times 10^6$ g/mol are classified as low MW, medium MW, high MW, and very high MW, respectively. The structure of the long chains in polyacrylamides can be either coiled (cross-linked) or stretched (linear). Most of the water soluble polyacrylamides have linear chain structure. Polyacrylamides can be cationic, non-ionic, or anionic. Proportions of charge in a polyacrylamide of <10%, 10–30%, and >30% are considered low, medium, and high charge density, respectively. Polyacrylamides are commonly available in solution, dry, and inverse emulsion forms. Several polyacrylamide, soil, and solution characteristics can influence polyacrylamide-soil interactions and these are reviewed by Letey (1994) and Levy and Ben-Hur (1997).

The objective of this study was to test, under laboratory conditions, the effectiveness of a range of polyacrylamides, gypsum, and their combination in reducing the turbidity of water in a sodic soil and to test the effect of selected treatments on water infiltration rate through the soil.

Materials and methods

Soil

Soil samples were collected from the 0–0.1 m layer of a sodic non-self mulching clay soil [Grey, Brown and Red Clays (Stace *et al.* 1968); Ug5.2 (Northcote 1979); Vertosol (Isbell 1996)] from 2 rice paddocks located 30 km north-west of Wakool in the Western Murray Valley, NSW, Australia. Some selected physical and chemical characteristics of the soil are given in Table 1. The selection of paddocks was based on farmer's observation of severe water turbidity problems under rice in previous years. The paddocks had not been treated with gypsum or any other soil amendments prior to soil sample collection. At the time of sample collection, Paddock 1 was under a pasture phase of a rice–pasture rotation, while Paddock 2 had been under wheat after a rice crop in previous 2 years. The soil was dried at 50°C for 72 h and ground to pass through a 2-mm sieve. Soil fractions <2 mm in size were used for further analyses.

Table 1. Physical and chemical properties of the soil (0–0.1 m)
Soil analyses performed by Incitec Ltd. Values are averages of 2 replicates

Parameter	Paddock 1	Paddock 2
Soil colour (Munsell)	Greyish brown	Greyish brown
Soil texture	Light clay	Light clay
pH (1 : 5 water)	6.7	6.6
pH (1 : 5 $CaCl_2$)	5.4	5.6
Organic C (%)	0.76	1.0
Nitrate-N (mg/kg)	7.8	1.5
S (MCP) (mg/kg)	19	28
P (Colwell) (mg/kg)	5.5	12
K (ammonium acetate) (cmol/kg)	0.81	0.98
Ca (ammonium acetate) (cmol/kg)	7.14	8.50
Mg (ammonium acetate) (cmol/kg)	10.94	12.38
Na (ammonium acetate) (cmol/kg)	2.40	3.00
Cl^- (mg/kg)	35	25
EC (dS/m)	0.09	0.16
Ca/Mg ratio	0.65[A]	0.69[A]
CEC (cmol/kg)	21.28[A]	24.85[A]
Exchang. Na percentage (ESP)	11.28[A]	12.07[A]
EC (saturation extract) (dS/m)	0.7[A]	1.2[A]

[A] Calculated values.

Polyacrylamides

The polyacrylamides used in these studies were water-soluble and consisted of linear-type structural configuration. They are characterised mainly by their physical form, molecular weight, type of charge, and charge density, as shown in Table 2. Active polyacrylamide concentration of dry, inverse emulsion, and solution forms were 95, 42, and 20%, respectively. Consequently, the application rate of inverse emulsion and solution forms were adjusted, based on their active polyacrylamide concentrations, to represent the rate of the dry form. The dry-form polyacrylamide granules (2.5 g) were agitated gently in deionised water (500 mL) until fully dissolved in solution. These stock solutions were diluted in deionised water to the required concentrations to treat the soil.

Gypsum

Analytical grade calcium sulphate ($CaSO_4$) was used to represent gypsum treatments and the rate of application was based on an average content of 85% of $CaSO_4$ in commercial gypsum. Gypsum was applied to the soil by sprinkling the required amount on to the soil surface evenly to simulate conventional method of field application.

Turbidity experiments

For turbidity experiments, a 100-g soil sample was placed in a 400-mL glass jar with a plastic straw positioned in the middle extending from the bottom to the top of the jar. The use of straw minimised soil disturbance due to escaping air bubbles while the soil was being saturated and enabled the soil to become saturated without much air trapped. Two methods of polyacrylamide application were tested. As a 'split method' of application, 50 mL of solution containing polyacrylamide at the required rate in deionised water was added to the soil sample and left to stand for 16 h. A further 280 mL of deionised water was then added to the soil sample. As a 'continuous method' of application, 330 mL of solution containing polyacrylamide at the required rate in deionised water was added to the soil sample in the jar at a steady rate over 3 min. Both methods of application produced a solution that was 85 mm deep over the soil surface. In order to minimise soil disturbance, the solutions were poured onto a hand-held disk above the soil surface. After 24 h, the suspension was gently mixed for a fixed time interval using an electric motor to ensure the uniformity of clay particles in the suspension. The jars were allowed to stand for 30 s after the completion of the mixing and three 25-mL aliquots were taken from the suspension for turbidity measurements. Three turbidity measurements were made on each aliquot, in nephelometric turbidity units (NTU), using a Hach™ turbidimeter.

The rates of application of polyacrylamides and gypsum (in kg/ha or t/ha) were calculated based on the soil surface area (30.2 cm^2) in the glass jar for the turbidity experiments.

Turbidity experiment 1

The objective of this experiment was to assess the effect of method of application, type of polyacrylamide, gypsum, and their combinations on turbidity of water. Six polyacrylamides (1–6 in Table 2) representing anionic, non-ionic, and cationic charge with varying charge density were used in this experiment. Three rates (0, 5, 10 kg/ha) of polyacrylamides, 4 rates (0, 1.25, 2.5, 5 t/ha) of gypsum, and combinations of 5 kg/ha

Table 2. Characteristics of the polyacrylamides used in the study

Identification number	Product code	Source[A]	Physical form	Molecular wt ($\times 10^6$ g/mol)	Type of charge	Charge density (%)
1	AN905SH	SNF	Dry	11–14	Anionic	3
2	AN923SH	SNF	Dry	12–14	Anionic	20
3	AN990SH	SNF	Dry	5–8	Anionic	90
4	FA920SH	SNF	Dry	7–9	Non-ionic	0
5	FO4240SH	SNF	Dry	6–8	Cationic	15
6	FO4400SH	SNF	Dry	5–7	Cationic	30
7	AN910BPM	SNF	Dry	3–5	Anionic	10
8	AN956BPM	SNF	Dry	5–7	Anionic	50
9	AN910SH	SNF	Dry	12–14	Anionic	10
10	AN956SH	SNF	Dry	13–16	Anionic	50
11	02KOR059	Nalco	Dry	5–8	Anionic	5
12	X0211006	Nalco	Dry	5–8	Anionic	35
13	X0211003	Nalco	Dry	15–20	Anionic	5
14	X0211005	Nalco	Dry	15–20	Anionic	35
15	X0210072	Nalco	Emulsion	5–8	Anionic	5
16	X0211004	Nalco	Emulsion	5–8	Anionic	35
17	X0211002	Nalco	Emulsion	15–20	Anionic	5
18	99AUS133	Nalco	Emulsion	15–20	Anionic	35
19	00LT053	Nalco	Solution	15–20	Anionic	30

[A] SNF, SNF Australia Pty Ltd; Nalco, Nalco Australia Pty Ltd.

of polyacrylamide with 0.6 or 1.25 t/ha of gypsum constituted the treatments which were trialed under 2 (split and continuous) methods of application. Soil from paddock 1 was used for this experiment. The suspensions in the glass jars were stirred for 4 min.

Turbidity experiment 2

The objective of this experiment was to verify the results of turbidity experiment 1 using lower rates of polyacrylamides and gypsum. Four anionic polyacrylamides (7–10 in Table 2) at 3 rates (0, 2.5, 5 kg/ha) and gypsum at 7 rates (0, 25, 50, 75, 150, 300, 600 kg/ha) were used to treat the soil. However, gypsum at the rate of 75 kg/ha was used when it was combined with each polyacrylamide treatment. Polyacrylamide solutions were applied to the soil by the split method of application. Soil from paddock 1 was used for this experiment. The suspensions were stirred for 2 min.

Turbidity experiment 3

The objective of this experiment was to assess the effect of different formulations of polyacrylamide with varying molecular weight and charge density on the turbidity of water. The polyacrylamides used in this experiment were anionic in dry, emulsion, or solution formulations (11–19 in Table 2). Polyacrylamides at 2 rates (0, 5 kg/ha) and gypsum at 4 rates (0, 25, 50, 100 kg/ha) were used to treat the soil. However, gypsum at the rate of 25 kg/ha was used when it was combined with each polyacrylamide treatment. Soil from paddock 2 was used in this experiment. Polyacrylamide solutions were added to the soil by split method of application. The suspensions were stirred for 2 min.

Infiltration experiments

Infiltration experiments were conducted on soil columns packed to a bulk density of 1.31 g/cm^3 in transparent perspex tubes. The bottoms of the tubes were covered with cloth to prevent soil spilling out. The rates of application of polyacrylamides and gypsum were calculated based on the soil surface area in the tube for each of the infiltration experiments. The polyacrylamide solutions were added to the soil surface, in the manner described for turbidity experiments, by split method of application. A water column 80 mm deep was maintained above the soil surface in each tube using Mariotte bottles containing deionised water. The advancement of the wetting front below the soil surface was measured at frequent intervals.

Infiltration experiment 1

The objective of this experiment was to test the effect of different treatments on movement of water through a column of soil. Soil from paddock 1 was used to create 0.25-m-long columns inside tubes 0.35 m long and 25 mm in diameter. The polyacrylamide AN956BPM (8 in Table 2) was selected for this experiment based on the results obtained from the turbidity experiment 2 described above. Gypsum at 3 rates (0, 25, 1000 kg/ha) and polyacrylamide at 2 rates (0, 5 kg/ha) were used to treat the soil. Gypsum at the rate of 25 kg/ha was used when it was combined with the polyacrylamide treatments.

Infiltration experiment 2

The objective of this experiment was to verify the results of infiltration experiment 1 using different sets of treatments and a large diameter soil column. Soil from paddock 2 was used to create 0.50-m-long columns inside tubes 0.60 m long and 0.125 m in diameter. The tubes were laid on a flat plastic saucer in order to avoid movement of soil downward. The polyacrylamides X0211006, X0211005, and 99AUS133 (12, 14, and 18, respectively, in Table 2) were selected for this experiment based on the results obtained from turbidity experiment 3. Gypsum at 2 rates (0, 25 kg/ha) and polyacrylamide at 2 rates (0, 5 kg/ha) were used to treat the soil. Gypsum at the rate of 25 kg/ha was used when it was combined with the polyacrylamide treatments.

Statistical analyses

All treatments in the above experiments had 3 replicates each. In the case of turbidity experiments, the average of 9 observations for each replicate was used for further analysis. The combined data from turbidity experiment 1 were analysed by a 2-way ANOVA and subsequent analyses were carried out on 2 separate datasets (dataset 1 consisted of turbidity readings for the control and all polyacrylamide treatments, while dataset 2 consisted of turbidity readings for the gypsum and polyacrylamide plus gypsum treatments). The data from turbidity experiments 2 and 3 were analysed by 1-way ANOVA. Data on total time taken by the advancing wetting front to reach 0.25 m in infiltration experiment 1, and data on total depth of water front advancement at the end of 572 h in infiltration experiment 2, were also analysed by 1-way ANOVA. In general, data are presented as means with the relevant least significance difference ($P = 0.05$) and standard error of mean as error bars. Treatment means were separated by Duncan's multiple range test ($P = 0.05$).

Results

Effect of polyacrylamides and gypsum on water turbidity

A comparison of split method of application with the continuous method of application by analysis of variance of combined dataset from the turbidity experiment 1 indicated a significant difference ($P < 0.001$) between the 2 methods of application. Water turbidity values of treatments under the split method of application were generally lower than those under the continuous method of application.

The effect of gypsum and polyacrylamide plus gypsum treatments on turbidity was much greater than that of control and polyacrylamide alone treatments. Therefore, further analysis of data was carried out on 2 separate datasets, representing treatments of control and polyacrylamides alone (set 1) or gypsum and polyacrylamide plus gypsum combinations (set 2).

Mean turbidity readings for control and different polyacrylamide treatments under the split and continuous application methods are shown in Table 3. Analysis of variance of dataset 1 indicated significant differences between the two application methods ($P < 0.001$) and between the treatments ($P < 0.001$). Mean turbidity readings for the split and continuous application methods were about 255 and 355 NTU, respectively. Therefore, it became apparent that further experiments should be concentrated on the split application method only.

Table 3. Turbidity of suspensions subjected to different polyacrylamide treatments by 2 methods of application

Each value (NTU) is the mean of 3 replicates. The ANOVA for the comparison of the methods of application was a 2-way analysis based on the combined treatments; for treatments, separate 1-way ANOVAs were carried out for each method of application. Values in columns followed by the same letter are not significantly different at $P = 0.05$ according to Duncan's multiple range test

Treatment	Method of application	
	Split application	Continuous application
Control	357bc	677f
At 5 kg/ha		
AN905SH	204ab	278abc
AN923SH	255ab	271ab
AN990SH	120ab	292bcd
FA920SH	271ab	417e
FO4240SH	529c	377cde
FO4400SH	305abc	393de
At 10 kg/ha		
AN905SH	132ab	257ab
AN923SH	255ab	182a
AN990SH	62a	280abc
FA920SH	272ab	425e
FO4240SH	286ab	378cde
FO4400SH	270ab	391de
l.s.d. ($P = 0.05$)	210	90

A comparison of polyacrylamides with different charges indicated that the polyacrylamides with anionic charge (AN905SH, AN923SH, AN990SH) were more effective than those with cationic (FO4240SH, FO4400SH) or non-ionic (FA920SH) charges. Under the split method of application, high charge density polyacrylamides (AN990SH, FO4400SH) reduced the turbidity of water to a greater extent than their low charge density counterparts. However, the opposite occurred when a continuous method of application was used. Obviously, a higher rate (10 kg/ha) of application of polyacrylamides was more effective than a lower rate (5 kg/ha). The high charge density anionic polyacrylamide (AN990SH) at the rate of 10 kg/ha reduced the turbidity of water by 82.6% compared with that of the control under the split method of application.

Mean turbidity readings for different rates of gypsum and polyacrylamide plus gypsum combination treatments under the split and continuous application methods are shown in Table 4. The turbidity values for these treatments

Table 4. Turbidity of suspensions subjected to different polyacrylamide and gypsum treatments by 2 methods of application

Each value (NTU) is the mean of 3 replicates. The ANOVA for the comparison of the methods of application was a 2-way analysis based on the combined treatments; for treatments, separate 1-way ANOVAs were carried out for each method of application. Values in columns followed by the same letter are not significantly different at $P = 0.05$ according to Duncan's multiple range test

Treatment	Method of application	
	Split application	Continuous application
Gypsum at 1.25 t/ha	2.75g	2.17bc
Gypsum at 2.5 t/ha	2.08f	1.95abc
Gypsum at 5 t/ha	1.39de	1.54abc
Combined with gypsum at 0.6 t/ha		
AN905SH	0.65ab	0.95ab
AN923SH	0.38a	0.51ab
AN990SH	0.90abcd	2.73c
FA920SH	1.17bcde	1.57abc
FO4240SH	0.78ab	1.44abc
FO4400SH	1.46e	0.59ab
Combined with gypsum at 1.25 t/ha		
AN905SH	0.81abc	0.28a
AN923SH	0.46a	0.38a
AN990SH	0.81abc	2.16bc
FA920SH	0.84abc	1.33abc
FO4240SH	1.15bcde	0.42a
FO4400SH	1.33cde	1.89abc
l.s.d. ($P = 0.05$)	0.45	1.39

were much lower than those of control and polyacrylamide-alone treatments as presented in Table 3. Analysis of variance of dataset 2 indicated a significant difference ($P < 0.001$) between the treatments. However, the difference between the 2 application methods was not significant. As expected, higher rates of gypsum application resulted in lower turbidity levels. The results of this study also indicated that gypsum at the rate of 0.6 or 1.25 t/ha combined with polyacrylamides could achieve turbidity levels lower than that resulting from 1.25, 2.5, or 5 t/ha of gypsum applied alone. All polyacrylamide plus gypsum combinations reduced the turbidity by 99.7% compared with that of the control under the split method of application. Anionic polyacrylamides were generally more effective than cationic or non-ionic polyacrylamides in controlling turbidity. For anionic polyacrylamides, low charge (AN905SH) and medium charge (AN923SH) density were more effective than high charge (AN990SH) density when combined with gypsum in controlling turbidity. However, analysis of data indicated that the difference in turbidity for 0.6 and 1.25 t/ha of gypsum combined with polyacrylamides was not significant.

The results from turbidity experiment 2 indicated that all treatments reduced turbidity significantly ($P < 0.001$) below that of the control (252 NTU) (Fig. 1). Furthermore, these treatments kept the turbidity levels below the threshold level (170 NTU, cited by Humphreys and Barrs 1998) required to facilitate rice seedling establishment. AN956BPM at the rate of 5 kg/ha was as the most effective polyacrylamide treatment, reducing turbidity to the same level as the lowest rate (25 kg/ha) of gypsum. Consequently, AN956BPM at the rate of 5 kg/ha was used in a subsequent infiltration experiment 1. As expected, increasing levels of gypsum applications were associated with decreasing levels of turbidity. Gypsum at the rate of 75 kg/ha in combination with polyacrylamides was more effective than when applied alone. The 2 lower molecular weight polyacrylamides (AN910BPM, AN956BPM) were more effective than the 2 higher molecular weight polyacrylamides (AN910SH, AN956SH). In terms of charge density, AN956SH appeared more effective than AN910SH; however, there was no difference between AN956BPM and AN910BPM. The application rate of 5 kg/ha of polyacrylamides was not different than 2.5 kg/ha in reducing the turbidity of water. However, when polyacrylamides were combined with 75 kg/ha of gypsum, the application rate of 5 kg/ha was more effective than 2.5 kg/ha.

The results from turbidity experiment 3 indicated that high turbidity level in untreated soil (control) was progressively reduced by increasing amounts of gypsum. Gypsum at the rate of 100 kg/ha reduced the turbidity below the threshold level (170 NTU) required for successful rice seedling establishment (Fig. 2). Reduction in average turbidity for all polyacrylamide treatments was similar to that achieved by gypsum application at the rate of 25 kg/ha. However, polyacrylamides combined with gypsum reduced turbidity to a level comparable to that achieved by a gypsum application at the rate of 100 kg/ha.

Different polyacrylamide products reduced turbidity to varying extents, as shown in Fig. 3. Even though all the 9 polyacrylamide products tested alone in this experiment greatly reduced water turbidity levels, they failed to reduce the turbidity below the threshold level (170 NTU). However, 6 of the polyacrylamides reduced the turbidity below 170 NTU when these products were applied with gypsum at the rate of 25 kg/ha. Applied alone or in

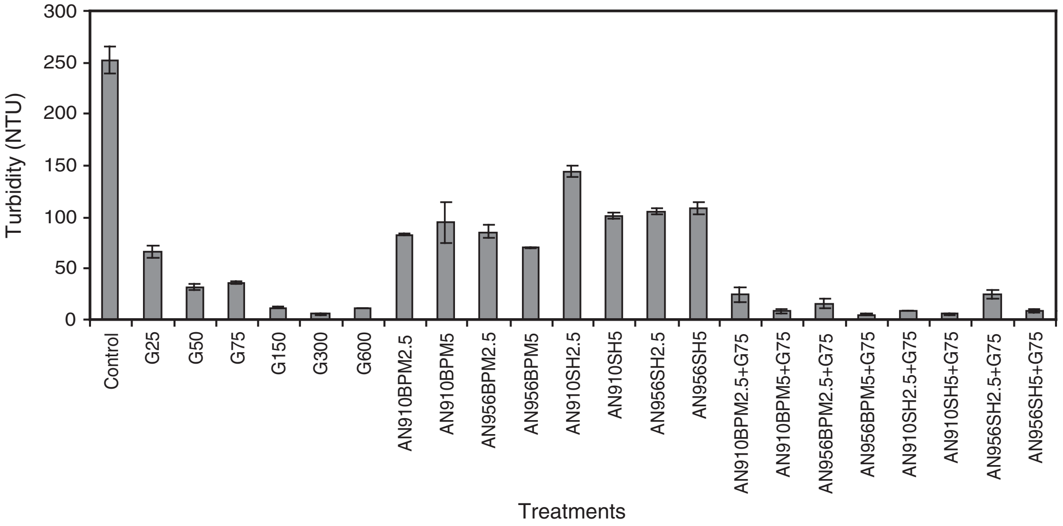

Fig. 1. Turbidity of water under different treatments. G, gypsum; numbers represent rate of application in kg/ha. Error bars are standard error of mean; l.s.d. ($P = 0.05$) between treatments, 33.2.

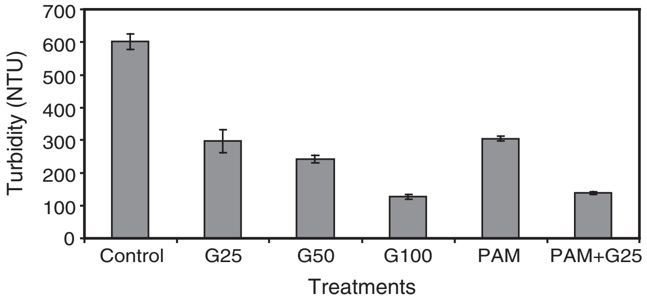

Fig. 2. Effect of gypsum and polyacrylamide treatments on water turbidity. G, gypsum; PAM, polyacrylamides; numbers represent rate of application in kg/ha. Error bars are standard error of mean; l.s.d. ($P = 0.05$) between treatments, 104.1.

combination with gypsum, dry formulations were more effective than emulsion or solution forms of these products. In addition, higher molecular weight (15–20 × 10^6 g/mol) polyacrylamides were generally more effective than lower molecular weight (5–8 × 10^6 g/mol). High charge (35%) density polyacrylamides were found to be more effective than their counterparts with low charge (5%) density. It should be noted that the 2 most efficient formulations, X0211006 and X0211005, were the dry formulations with high anionic charge (35%). The third-most efficient, 99AUS133, is an emulsion formulation also with high anionic charge (35%). These 3 products were identified as the most effective polyacrylamides to reduce turbidity levels when they were used with gypsum and were therefore used in the subsequent infiltration experiment 2.

Effect of polyacrylamides and gypsum on water infiltration rates

The results from infiltration experiment 1 indicated that the time taken for the wetting front to reach a depth of 0.25 m in the soil column was significantly ($P < 0.01$) faster for gypsum application at the rate of 1000 kg/ha than the other treatments (Fig. 4). However, when data for gypsum 1000 kg/ha treatment were omitted, there were no significant differences among the other treatments for this parameter. The initial rate of wetting front movement through the soil column was faster for all treatments than that in the control (Fig. 5). After about 25 h, the rate of wetting front movement for gypsum at 25 kg/ha, polyacrylamide, and polyacrylamide plus gypsum treatments became almost equal to that in the control.

The results of the infiltration experiment 2 showed that the advancement of water through a column of soil was similar for the control and the soil treated with 25 kg/ha of gypsum (Fig. 6). Most of the other treatments where the soils were treated with polyacrylamides or polyacrylamides combined with gypsum showed initially a higher rate of water advancement through the soil. The analysis of data of depth of infiltration at the end of 20 h revealed a significant ($P < 0.05$) difference between the treatments. However, the rate of water advancement through the soil became almost equal after 200–300 h of infiltration for the control and all treatments, and therefore the initial difference in infiltration remained the same throughout the experiment. Analysis of the data revealed a significant difference ($P < 0.05$) between the treatments for their final depth of infiltration

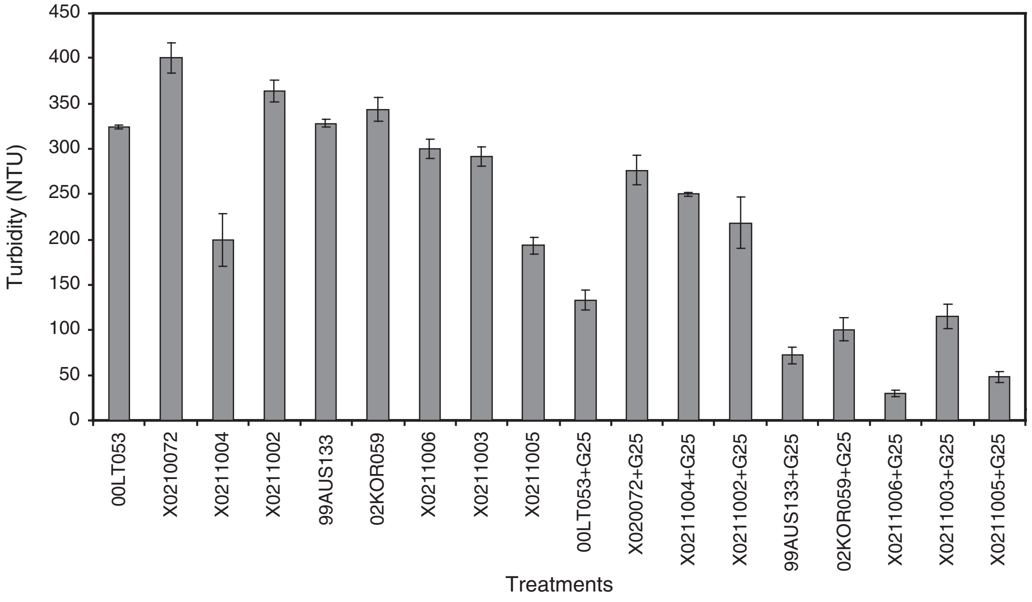

Fig. 3. Effect of different polyacrylamide products used alone or combined with gypsum on water turbidity. Error bars are standard error of mean; l.s.d. ($P = 0.05$) between treatments, 78.7.

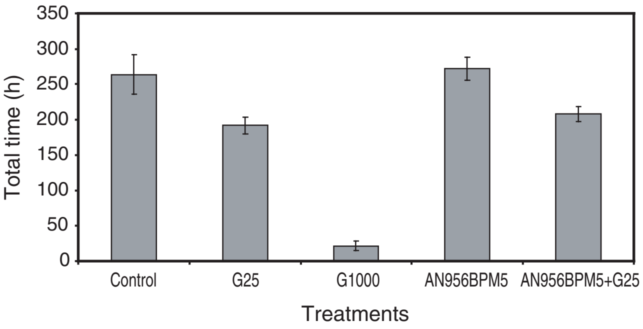

Fig. 4. Total time taken by the wetting front to reach 0.25 m. G, gypsum; numbers represent rate of application in kg/ha. Error bars are standard error of mean; l.s.d. ($P = 0.05$) between treatments, 92.07.

after 572 h (Fig. 7). However, the increase in depth of infiltration between 452 and 572 h was not significant for the treatments.

Discussion

The high turbidity of water (>350 NTU) in the control treatment in turbidity experiment 1 showed the highly dispersive nature of the soil. Most of the polyacrylamide treatments did not reach the required minimum turbidity levels in water for rice seedling establishment. However, low charge density anionic polyacrylamide (AN905SH) at the rate of 10 kg/ha and high charge density anionic polyacrylamide (AN990SH) at rates of 5 and 10 kg/ha were found to reduce turbidity of water less than the critical level under the split application strategy. Overall, turbidity readings under the split application strategy were lower than under the continuous application strategy.

All of the polyacrylamide and gypsum combinations reduced the turbidity of water in turbidity experiment 1 by >99.7%. Therefore, polyacrylamides combined with gypsum were highly successful in reducing the turbidity of water lower than critical levels required for successful rice seedling establishment. Different rates (5 and 10 kg/ha) of application of polyacrylamides alone and different rates (0.6 and 1.25 t/ha) of gypsum combined with polyacrylamides failed to show significant differences in controlling the turbidity of water. It is possible that the concentrations of polyacrylamides used in this experiment would be adequate to reduce the turbidity of water to levels required for better rice seedling establishment. Hence, turbidity experiments 2 and 3 were designed to find the optimal proportion of polyacrylamide and gypsum in reducing turbidity of water. A range of alternative polyacrylamides were also evaluated for their performance.

Turbidity experiment 2 looked at the effect of anionic polyacrylamides and gypsum on reducing the turbidity of water and found that all treatments reduced turbidity significantly below that of the control or the level required for optimal rice growth. Infiltration experiment 1 demonstrated that the polyacrylamide AN956BPM at the rate of 5 kg/ha and gypsum at the rate of 25 kg/ha, alone or in combination, did not significantly change the wetting front movement compared to the control. A gypsum rate of 25 kg/ha is much lower than current application rates used by farmers. AN956BPM at 5 kg/ha applied with gypsum at 25 kg/ha could be a treatment for reducing rice water turbidity without increasing water infiltration rates in the rice field.

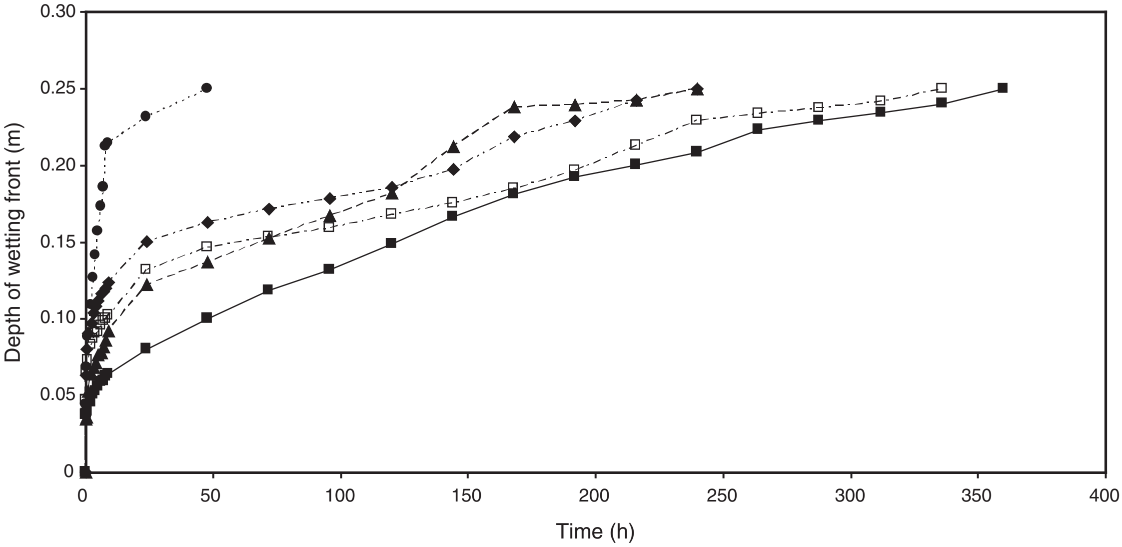

Fig. 5. Time taken by the wetting front to reach different depths in the soil column. ■ Control; ▲ G25; ● G1000; ☐ AN956BPM5; ◆ AN956BPM5+G25.

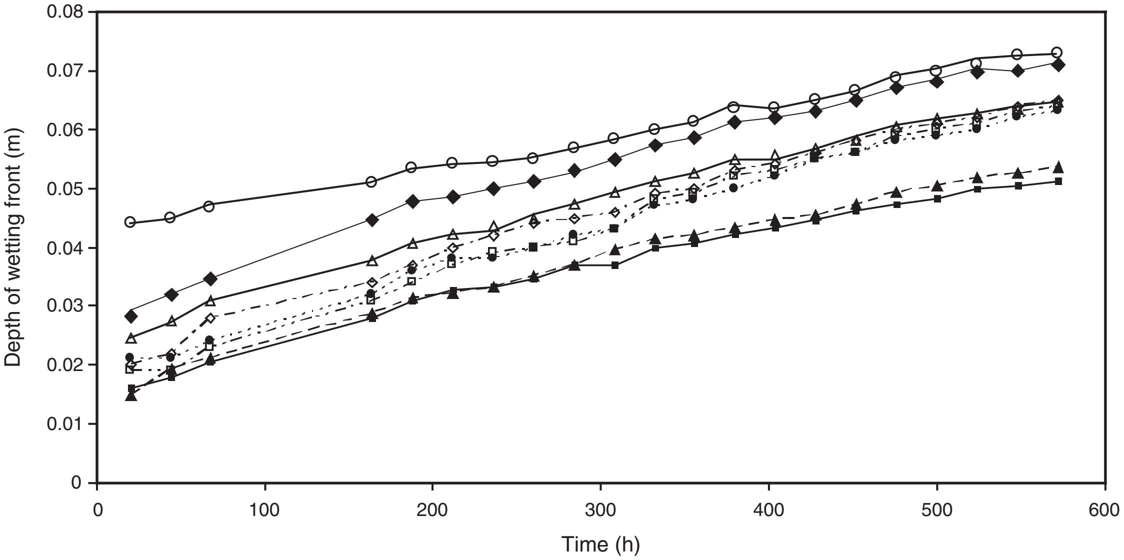

Fig. 6. The effect of different treatments on advancement of wetting front through the soil column. ■ Control; ▲ G25; ● 99AUS133; × X0211006; □ X0211005; Δ 99AUS133+G25; ○ X0211006+G25; + X0211005+G25.

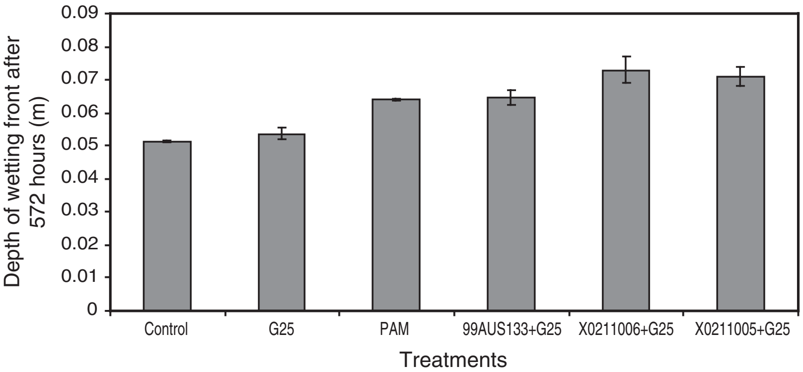

Fig. 7. Total depth of wetting front at the end of 572 h of infiltration. G, gypsum; PAM, mean for 99AUS133, X0211006, and X0211005; numbers represent rate of application in kg/ha. Error bars are standard error of mean; l.s.d. ($P = 0.05$) between treatments, 1.296.

The potential use of polyacrylamide applied with irrigation water to control rice water turbidity problems has also been demonstrated from turbidity experiment 3. Three polyacrylamide products have been identified as effective. Polyacrylamide at the rate of 5 kg/ha combined with gypsum at the rate of 25 kg/ha was effective in controlling water turbidity. Infiltration experiment 2 confirmed that these treatments do not affect infiltration or percolation of water through the soil.

With the split application method, after the first phase of the application, soil particles would reorient to settle down with the infiltrating water, and in the case of polyacrylamide and/or gypsum treatments, most of these chemicals would be in the soil, causing clay particles to flocculate. During the second phase of application, there would be some chance for the clay particles to move back into the standing water. However, there was little opportunity for this to happen under the continuous application method. Moreover, dilution of chemicals in the solution may be another reason for the poor performance with the continuous method. Therefore, a split application strategy similar to the one used in this study would result in more effective control of turbidity than a continuous method of application. However, in gypsum treatments, gypsum was applied first directly to the soil surface before adding solutions by split or continuous method of application. The gypsum reacted with soil during the application of solutions, and therefore, the 2 application strategies failed to show any significant difference in their effects on the turbidity of water.

The reverse strategy of applying untreated water followed by polyacrylamide-treated water was not attempted in this study. During the application of untreated water, soil dispersion would occur, bringing clay particles into the suspension. Subsequent addition of polyacrylamide-treated water would flocculate the suspended clay particles depositing them as a blanket over the soil surface. This layer of clay would interfere with successful establishment of rice seedlings, as reported by Humphreys and Barrs (1998) who applied gypsum into very turbid water. Thus, the aim of the split application strategy in this study is to stabilise soil structure in an attempt to prevent dispersion.

Although the same soil was used for both turbidity experiments 1 and 2, the turbidity values in turbidity experiment 2 were generally lower than those of experiment 1, possibly due to the lesser stirring time used in experiment 2. On the other hand, the soil used in experiment 3 was obtained from paddock 2, which had slightly higher exchangeable sodium percentage (ESP) than soil from paddock 1 (Table 1). Soil with higher ESP can disperse more than a soil with lower ESP. This could be a reason for higher turbidity values reported in turbidity experiment 3 than that in experiments 1 or 2.

The important polyacrylamide characteristics that affect their adsorption onto clay particles are molecular weight, electrostatic charge, and charge density. The results of this study showed that higher molecular weight polyacrylamides were more effective than those of lower molecular weight. DeBoodt (1972) demonstrated that the greater the chain length, the more effective was the soil conditioning. However, the charge type and density can mask the effect of molecular weight as noted in this study.

Non-ionic polyacrylamides are believed to attach to clay by hydrogen bonding (Harris *et al*. 1966; De Boodt 1972) and this adsorption onto a clay surface is an entropy-driven process (Theng 1982). The adsorption of cationic polyacrylamides by clays occurs through electrostatic (Coulombic) interactions between the cationic groups on the polyacrylamide and the negatively charged sites on the clay surface (Harris *et al*. 1966). Adsorption of negatively charged polyacrylamides on clay surface occurs by fixation of the anionic charges to the cationic charges on the edges of clay (Harris *et al*. 1966; Russell 1973) and sharing of the charges of polyvalent mineral cations with the negative charges of clay and polyacrylamides (Harris *et al*. 1966).

The results of this study have shown that negatively charged polyacrylamides are more effective than neutral or positively charged ones. Cationic polyacrylamides compete with exchangeable and electrolyte cations for exchange sites on the clay (Letey 1994). Hence, adsorption of these polyacrylamides by clay increases with a decrease in the valency of the exchangeable cation (Gu and Doner 1992) and decreases with an increase in the electrolyte concentration of the solution (Aly and Letey 1988). On the other hand, adsorption of anionic polyacrylamides is promoted by the presence of polyvalent cations that act as ‘bridges’ between the anionic groups on the polyacrylamide and the negatively charged sites on the clay (Mortensen 1962; Letey 1994). This justifies the need to provide a calcium (divalent cation) source such as gypsum for the anionic polyacrylamides to promote complete flocculation of clay particles. Wallace *et al*. (1986) believed that this salt effect is important in bringing clay particles close enough together so that several of them could be bound with a common polyanion.

This study has demonstrated that anionic polyacrylamides with high charge density were more effective than low charge density ones. The negative charges along the molecule cause the chain to stretch out (Letey 1994). Polyacrylamides with low charge would tend to form a coil rather than a chain. On the other hand, the extended chain of polyacrylamides with high charge density would possibly enable more adsorption to clay particles.

Previous work on polyacrylamides has also shown that polyacrylamides were useful for decreasing clay dispersion (Cook and Nelson 1986; Terry and Nelson 1986; Aly and Letey 1988; Helalia and Letey 1988). However, a benefit was found when gypsum and polyacrylamide applications were combined (Shainberg *et al*. 1990; Zahow and Amrhein 1992). Orts *et al*. (1999) also noted that the polyacrylamide and calcium had a greater effect than calcium alone in reducing suspended solids in runoff.

Soil from paddock 1 was used in infiltration experiment 1, while soil from paddock 2 was used in experiment 2. The ESP of soil from paddock 2 was higher than that of soil from paddock 1 (Table 1). Soil with higher ESP can disperse to a greater extent than a soil with lower ESP. Higher dispersion can reduce the rate of water infiltration, as observed in infiltration experiment 2. The soil columns in infiltration experiment 1 were packed in a 25-mm-diameter pipe, while soil columns in experiment 2 were packed in a 0.125-m-diameter pipe. The packing and arrangement of soil particles in a smaller diameter pipe may leave considerable space along the edge of the tube, which can contribute to a higher rate of water infiltration. This might be another reason for the observed higher rate of infiltration in experiment 1 compared with experiment 2.

The higher initial infiltration rates observed in both experiments 1 and 2 may be attributed to polyacrylamide, gypsum, and their combinations which can cause flocculation at the soil surface. This will enhance the entry of water into the soil through the soil surface. The strong adsorption of polyacrylamides to the surface of soil particles results in limited penetration of polyacrylamides through clay soils (Nadler *et al*. 1994). The quantity of polyacrylamides (5 kg/ha) applied to the soil in these studies was small, and hence most of the polyacrylamide might be adsorbed by the clay particles within the first few mm of the soil. The soil layers below may not be affected by the polyacrylamide application. Therefore, the movement of the wetting front slows down as the water moves into untreated soil. The implication of these results is that polyacrylamide at 5 kg/ha, gypsum at 25 kg/ha, or both combined used to control turbidity of water would not significantly influence the rate of infiltration of water and hence the amount of water percolating towards groundwater.

Mitchell (1986) added an anionic polyacrylamide to irrigation water in an attempt to increase the hydraulic conductivity of a silty clay loam soil with a high percentage of swelling clay. He found that the final infiltration rate and total amount of infiltrated water were not increased by the polyacrylamide. Swelling was found to be more important than dispersion in reducing hydraulic conductivity (McNeal *et al*. 1966). Zahow and Amrhein (1992) found that polyacrylamides do not reduce soil swelling even at an application rate of 50 mg/kg. It should be noted that the soil used in this study also exhibited swelling properties upon wetting.

Conclusions

A comparison of 2 application strategies indicated that the split application strategy is more effective than the continuous application strategy to treat the soil with polyacrylamide. This study confirmed earlier findings that higher molecular weight polyacrylamides are more efficient than lower molecular weight polyacrylamides in reducing the turbidity of water. The results also showed that anionic polyacrylamides are more effective than cationic or non-ionic types. High charge density anionic polyacrylamides were more effective than those of low charge density. The application of polyacrylamide with gypsum had a significant beneficial effect compared with their application alone. The application of polyacrylamide with a small quantity of gypsum did not have a significant effect on the infiltration or percolation of water through the soil. Hence, polyacrylamides combined with gypsum seem to have potential implications for the amelioration of sodic soils and recharge management under the rice cultivation. Smaller quantities of gypsum can be dissolved in irrigation water together with polyacrylamides for treating the soil. With a current (2005) price of polyacrylamide at AU$6–8/kg and farm gate value of rice (2003) at AU$280/t, the adoption of the above technique seems economical to the rice growers in New South Wales. However, these results need to be verified under commercial field conditions.

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References

Aly SM, Letey J (1988) Polymer and water quality effects on flocculation of montmorillonite. *Soil Science Society of America Journal* **52**, 1453–1458.

Bacon P (1978) Progress in controlling muddy water. *Farmers' Newsletter Large Area*, 26–28.

Barvenik FW (1994) Polyacrylamide characteristics related to soil applications. *Soil Science* **158**, 235–243.

Cook DF, Nelson SD (1986) Effect of seedling emergence in crust forming soils. *Soil Science* **141**, 328–333.

De Boodt M (1972) Improvement of soil structure by chemical means. In 'Optimizing the soil physical environment toward greater crop yields'. (Ed. D Hillel) pp. 43–55. (Academic Press: New York)

Gu B, Doner HE (1992) The interaction of polysaccharides with Silver-Hill illite. *Clays and Clay Minerals* **40**, 151–156.

Harris RF, Chesters G, Allen ON (1966) Dynamics of soil aggregation. In 'Advances in agronomy'. Vol 18. (Ed. AG Norman) pp. 107–169. (Academic Press: New York)

Helalia AM, Letey J (1988) Polymer type and water quality effects on soil dispersion. *Soil Science Society of America Journal* **52**, 243–246.

Humphreys E, Barrs HD (1998) Constraints to rice establishment and yield in the Western Murray Valley. Rural Industries Research and Development Corporation, Publication No. 99/32.

Isbell RF (1996) 'The Australian Soil Classification.' (CSIRO Publishing: Collingwood, Vic.)

Jones S (2004) Irrigation based farming in an environment of reduced water supplies. In 'Paper presented at the ABARE Annual National Outlook 2004 Conference'. National Convention Centre, Canberra. (Australian Bureau of Agricultural and Resource Economics (ABARE): Canberra, ACT)

Letey J (1994) Adsorption and desorption of polymers on soil. *Soil Science* **158**, 244–248.

Levy GJ, Ben-Hur M (1997) Some uses of water-soluble polymers in soil. In 'Handbook of soil conditioners: Substances that enhance the physical properties of soil'. (Eds A Wallace, RE Terry) pp. 363–384. (Marcel Dekker, Inc.: New York)

McNeal BL, Novell WA, Coleman NT (1966) Effect of solution composition on the swelling of extracted soil clays. *Soil Science Society of America Journal* **30**, 313–317.

Mitchell AR (1986) Polyacrylamide application in irrigation water to increase infiltration. *Soil Science* **141**, 353–358.

Mortensen JL (1962) Adsorption of hydrolysed polysaccharide on kaolinite. *Clays and Clay Minerals* **10**, 530–554.

Nadler A, Magaritz M, Leib L (1994) PAM application techniques and mobility in soil. *Soil Science* **158**, 249–254.

Northcote KH (1979) 'A factual key for the recognition of Australian soils.' 4th edn (Rellim Technical Publications: Glenside, S. Aust.)

Orts WJ, Sojka RE, Glenn GM, Gross RA (1999) Preventing soil erosion with polymer additives. *Polymer News* **24**, 406–413.

Quirk JP (2001) The significance of the threshold and turbidity concentrations in relation to sodicity and microstructure. *Australian Journal of Soil Research* **39**, 1185–1217. doi: 10.1071/SR00050

Russell EW (1973) The stabilization of structural pores. In 'Soil conditions and plant growth'. 10th edn, p. 495. (Longman: London)

Shainberg I, Warrington DN, Rengasamy P (1990) Water quality and PAM interactions in reducing surface sealing. *Soil Science* **149**, 301–307.

Slavich P, Thompson J, Petterson G, Griffin D (1993) Gypsum and groundwater use in rice rotations. Rural Industries Research and Development Corporation, Final Report.

Sojka RE, Entry JA (2000) Influence of polyacrylamide application to soil on movement of microorganisms in runoff water. *Environmental Pollution* **108**, 405–412. doi: 10.1016/S0269-7491(99)00194-3

Sojka RE, Lentz RD (1994) Time for yet another look at soil conditioners. *Soil Science* **158**, 233–234.

Sojka RE, Lentz RD, Ross CW, Trout TJ, Bjorneberg DL, Aase JK (1998) Polyacrylamide effects on infiltration in irrigated agriculture. *Journal of Soil Water Conservation* **53**, 325–331.

Sojka RE, Morishita DW, Foerster JA, Wille MJ (2003) Weed seed transport and weed establishment as affected by polyacrylamide in furrow-irrigated corn. *Journal of Soil and Water Conservation* **58**, 319–326.

Sojka RE, Surapaneni A (2000) Potential use of polyacrylamides in Australian agriculture to improve off and on-site environmental impacts and infiltration management. Institute for Sustainable Irrigated Agriculture, Final Report, Tatura.

Stace HCT, Hubble GD, Brewer R, Northcote KH, Sleeman JR, Mulcahy MJ, Hallsworth EG (1968) 'A handbook of Australian soils'. (Rellim Technical Publications: Glenside, S. Aust.)

Terry RE, Nelson SD (1986) Effects of polyacrylamide and irrigation method on soil physical properties. *Soil Science* **141**, 317–320.

Theng BKG (1982) Clay-polymer interactions: summary and perspectives. *Clays and Clay Minerals* **30**, 1–10.

Vacher CA, Loch RJ, Raine SR (2003) Effect of polyacrylamide additions on infiltration and erosion of disturbed lands. *Australian Journal of Soil Research* **41**, 1509–1520. doi: 10.1071/SR02114

Wallace A, Wallace GA, Cha JW (1986) Mechanisms involved in soil conditioning by polymers. *Soil Science* **141**, 381–386.

Zahow MF, Amrhein C (1992) Reclamation of a saline sodic soil using synthetic polymers and gypsum. *Soil Science Society of America Journal* **56**, 1257–1260.

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