but since such knowledge is usually available, this is rarely a problem. Equally, although all soils can be categorized within the guidelines, other factors may dictate that drainage is either inappropriate or impracticable. Again, local knowledge will help to eliminate the anomalies.

As indicated above, a successful drainage solution is dependent on site specific factors which cannot be included in the guidelines. They are not therefore intended as a substitute for a detailed site investigation. On the contrary, by providing a forewarning of the type of problem or combination of problems to be expected, they should encourage a more thorough site investigation than has often been undertaken in the past. In so doing they should also ensure that the most appropriate type of solution is adopted for the problem in hand. With the current financial pressures on the farming industry, it is absolutely essential that all farm investments are soundly based. If these guidelines can go some way towards ensuring that this criterion is met as far as field drainage is concerned, they should provide a useful tool in the agriculturalists' or farmers' armoury.

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Effects of gypsum-slotting on infiltration rates and moisture storage in a swelling clay soil

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Abstract. Previous studies have shown marked increases in wheat yields on a swelling clay soil due to gypsum-slotting compared to no-gypsum and surface gypsum applications, largely through improved aeration in the surface layers. In the present study, steady infiltration rates indicated 2-fold increases due to surface gypsum applications and 4- to 6-fold increases due to slotted gypsum. This should provide increased moisture storage and reduced soil erosion hazards during prolonged heavy rainfall periods, provided that a crust does not form under the impact of raindrops. However, gypsum-slotted lands should not be used in crop rotations which include ponded rice, due to increased potential water use and risk of rising watertables and salinization.

The effect of the 'throttle' in the upper B horizon which restricts moisture storage in the lower soil layers during short-term and prolonged ponding was reduced, but not eliminated, by surface and slotted gypsum applications. Thus the moisture contents of the lower depths in both the non-ameliorated and ameliorated soils were less than the moisture content at saturation or at −10 kPa potential even after flooding for 11 days.

INTRODUCTION

THE heavy clay soils in the Riverine plain in south-east Australia are well suited for ponded rice cultivation. However, recent reductions in rice prices, increased water charges and risks of rising watertable and salinization have necessitated changes to alternate crops. The average yields of upland row crops such as wheat, maize, sunflower and sorghum are low when compared to similar climatic areas overseas (Smith *et al.*, 1983). Loveday *et al.* (1970) indicated that the poor physical properties of the fine-textured soils of the area restricts water infiltration during irrigation with high-quality water and thereby also restricts growth due to the limited availability of soil water. The poor internal drainage properties of these soils also contributes to the low average yields. Slow internal drainage following flood irrigation results in poor root zone aeration and subsequent restriction in root growth and activity (Meyer *et al.*, 1985; Jayawardane & Meyer, 1985; Meyer & Barrs, 1985). Previous studies (McIntyre *et al.*, 1982a,b) indicate that the low infiltration rates of the transitional red brown earths, which cover 60% of the area, are caused by a 'throttle' with a very low hydraulic conductivity at a depth of 0.25–0.55 m. They also showed that application of gypsum increased the hydraulic conductivity of this layer.

While field experiments (Loveday *et al.*, 1970; Muirhead *et al.*, 1970) have shown that gypsum application can increase the infiltration rate and crop yields on these soils, it is not a widely adopted on-farm practice. This is possibly due to the cost of the repeated gypsum applications required to maintain the ameliorative effects. They also found that although deep tilling markedly improve these soils, the beneficial effects tend to decrease significantly in the following seasons.

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Another method of soil amelioration which involves the use of gypsum-enriched slots to increase the effectiveness of the applied gypsum was proposed by Jayawardane & Blackwell (1985). Moisture profiles measured under a sorghum crop in summer 1983/84 indicated preferential flow during irrigation through the slots, which have higher hydraulic conductivities. This resulted in deeper wetting in the slotted plots than in the plots with no-gypsum or surface gypsum applications. Consequently, the surface soil layers between the slots were subjected to less wetting and were better aerated than the corresponding depth in the non-slotted plots. The slots, which maintained high air-filled porosity values between irrigation due to faster moisture redistribution and greater root uptake, thus provide pathways for oxygen flow to the roots in the soil between slots and at lower depths. Similar changes in moisture and air-filled porosity profiles were observed under a wheat crop in winter 1984 (Jayawardane *et al.*, 1985). This resulted in increases in rates of phasic development, tillering, canopy closure, dry matter production and finally in higher yields in the slotted plots compared to the plots with surface gypsum and no-gypsum. Thus, in comparison to the control plot, surface gypsum increased yields by less than 1 t ha^{-1}, while slotted gypsum increased yields by 3 t ha^{-1}.

This study examines the effects of surface and slotted gypsum on infiltration rates and moisture profile changes in the soil during infiltration.

MATERIALS AND METHODS

Description of the site and soil ameliorative treatments

The experiment was carried out at a research site near Whitton, 40 km south-east of Griffith in New South Wales, Australia. The soil profile consists of a sandy loam to sandy clay loam surface layer underlain by a swelling clay subsoil. In a soil survey of the area (van Dijk, 1961), the soils were mapped as Mundiwa clay loam. This soil belongs to the transitional red brown earths and is classified as a Dr 2.33 (Northcote, 1971) due to the presence of a sodic subsoil. In the Soil Taxonomy (Soil Survey Staff, 1975) they are classified as Natrixeralfs. Morphological and physical characteristics of the soil cores extracted for neutron probe access tube installation, indicated that the soils within the experimental area (15 × 18 m) are uniform except for slight variations in depth of the lighter textured surface layer (0.13 to 0.18 m).

The experimental area of four plots was subjected to the following ameliorative treatments on 13 December 1983, as described in detail by Jayawardane & Blackwell (1985).

(i) Plot C – no gypsum;
(ii) Plot G broadcast gypsum (8 t ha^{-1});
(iii) Plot SG_1 – gypsum-enriched slots spaced 0.66 m apart;
(iv) Plot SG_2 – gypsum-enriched slots placed 1.0 m apart.

The gypsum-enriched slots (Fig. 1) were prepared by laying the gypsum in parallel bands at the appropriate spacings at a

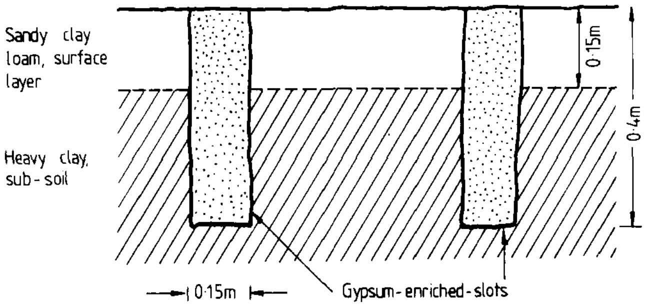

Fig. 1. Sketch of soil profile showing gypsum-enriched slots.

rate of 8 t ha^{-1} (calculated on the basis of the whole plot surface area) and running a trench digger on the bands to mix the gypsum into the excavated soil. This soil was shovelled back into the 0.15-m-wide and 0.40-m-deep trenches. The excess gypsum-enriched soil spread over the surface had a gypsum content of around 2 t ha^{-1}. Since the slots constitute only a 1/5 and 1/7 of the surface area in plots SG_1 and SG_2, respectively, the gypsum within the slots is concentrated 5 to 7 times.

During the first season (summer 1983/84) a sorghum crop was grown in the experimental area (Jayawardane *et al.*, 1984b). During the second season (winter, 1984) a wheat crop was grown and harvested on 12 December 1984 (Jayawardane *et al.*, 1985).

Measurement of infiltration rates and moisture profile changes during infiltration

Measurements were made in February 1985. In the non-slotted plots (C and G) infiltration measurements were carried out in large infiltration rings of 1.17 m diameter. Moisture profile changes during infiltration were measured in previously installed neutron probe access tubes, located at the centre of the rings.

In the slotted plots (SG_1 and SG_2) square infiltrometers were used, with the slots located along the middle of the measurement area. To obtain representative proportions of slot/non-slot surface areas the infiltrometers were 1.0 by 1.0 m in plot SG_2 and 0.66 by 1.0 m in plot SG_1. Three neutron probe access tubes were located inside the infiltrometers in each of the slotted plots. One access tube was located in the slot and another at the centre point between two slots. A third tube, installed midway between these two tubes, represented the undisturbed soil volume adjacent to the slots.

During the infiltration run the water level was maintained at 5 cm inside the infiltrometer and in the surrounding guard rings, using float valves. The tops of the infiltrometers were covered to prevent evaporation losses. Cumulative infiltration was measured over a period of 2–3 weeks. The irrigation water used had an electrical conductivity of 0.27 dS m^{-1}.

Calibration equations to obtain volumetric moisture contents (θ_v mm^3 mm^{-3}) from the neutron counts at different depths in this swelling soil were derived using the procedure described previously (Jayawardane *et al.*, 1984). A separate

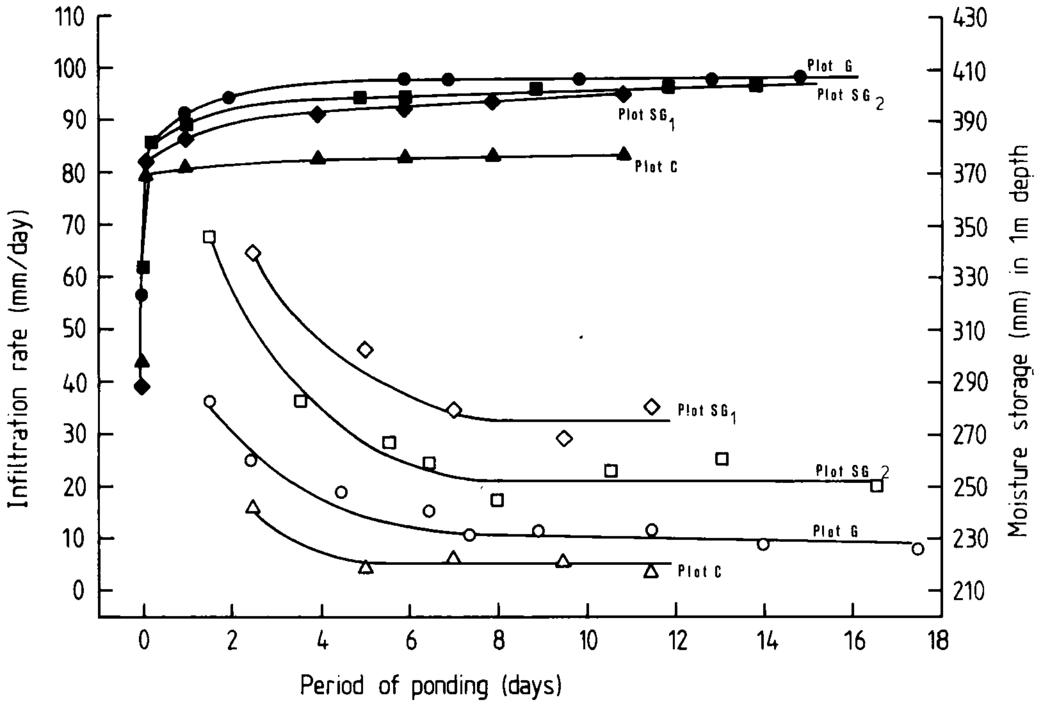

Fig. 2. Infiltration rates (open symbols) and cumulative moisture storage in 1 m depth of soil (closed symbols) during ponding of plots C, G, SG_1 and SG_2.

set of calibration equations was used to obtain θ_v for the disturbed soil in the slots. Two 32-s neutron counts were taken at depths of 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80 and 1.00 m before flooding and on days 0.1, 1, 6 and 11 of the infiltration run.

RESULTS AND DISCUSSION

Infiltration rates

In the non-ameliorated, surface-gypsum and the slotted plots, fairly steady infiltration rates were reached after approximately 4, 6 and 8 days, respectively (Fig. 2). The steady infiltration rate of 4 mm day^{-1} in the non-ameliorated plot was increased twofold by surface-gypsum applications, while the plots with slotted gypsum showed a 4- to 6-fold increase. Therefore, during periods of prolonged rainfall the gypsum ameliorated plots could store more moisture in the soil, provided that crusting due to the impact of raindrops does not occur. The reduced runoff should decrease the risk of soil erosion during rainstorms and reduce the need for soil conservation measures. Gypsum slotting increased the effectiveness of the applied gypsum.

The data also indicate the potential risk of using gypsum-slotted lands in crop rotations which include ponded rice cultivation because of increased deep percolation losses beyond the root zone leading to excessive water use, which could result in the rise of saline ground watertables and consequent increases in the rate of salinization of the land.

Moisture profiles during infiltration

The changes in moisture profiles during the infiltration runs on plots C, G and SG_1 are shown in Figs 3 and 4. The volumetric moisture content at saturation (θ_s) at different depths, based on field measured swelling characteristics of this transitional red brown earth soil (Jayawardane *et al.*, 1984a; Jayawardane, 1984), are also shown. These values of θ_s show good agreement with θ_s values measured in the laboratory on undisturbed soil cores taken from the experi-

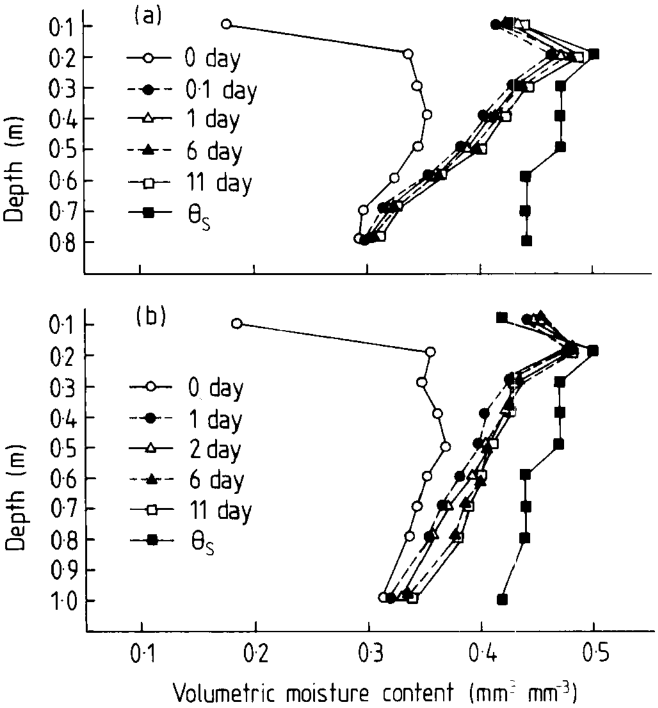

Fig. 3. Changes in moisture profiles during ponding in (a) Plot C and (b) Plot G.

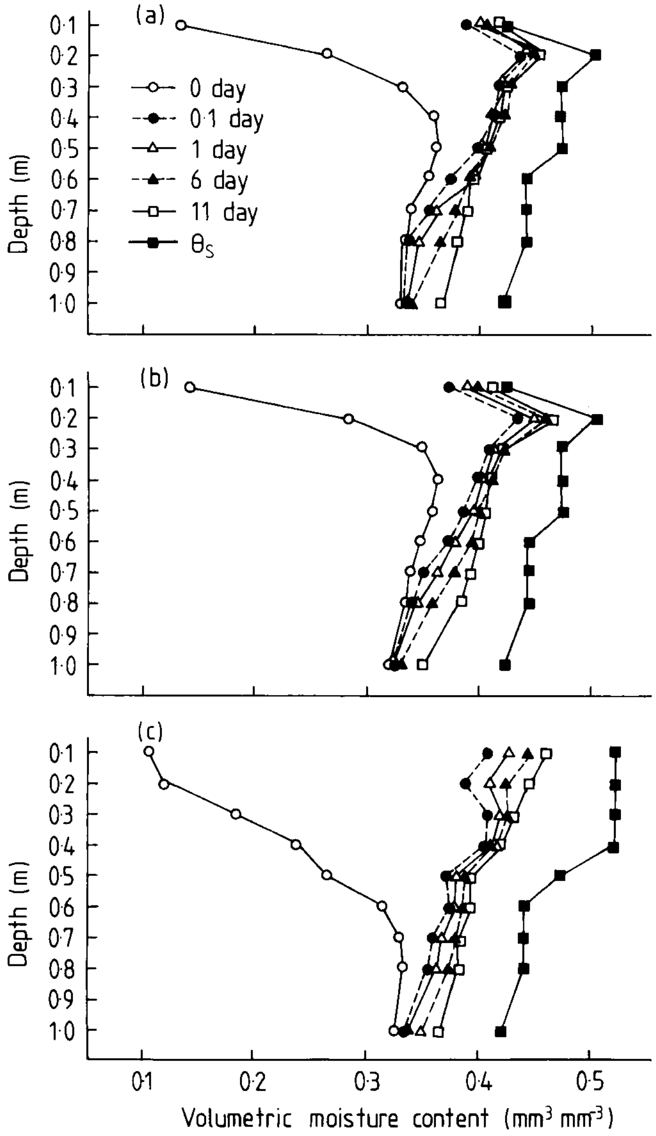

Fig. 4. Changes in moisture profiles during ponding in plot SG_1 (a) between slots. (b) adjacent to slots and (c) in the slots.

mental site (Table 1).

In plot C (Fig. 3a) there were rapid increases in θ_v in the first 2.5 h, smaller increases up to 1 day and only slight changes over the next 10 days. Thus, even after 11 days of continuous ponding, θ_v at all depths except the surface were much less than θ_s, apparently due to the presence of a 'throttle' in the upper portion of the clay subsoil (McIntyre *et al.*, 1982a,b). The difference between θ_v and θ_s increased with depth. The moisture content at any given depth after the same period of flooding was greater in this soil compared to the non-ameliorated transitional red brown earth (Marah clay loam) previously studied by McIntyre *et al.* (1982a,b). This may be due to the presence of a more permeable, lighter textured surface layer in this soil.

In plot G, the θ_v at depths less than 0.3 m showed marked increases on day 1 after flooding, but little change thereafter (Fig. 3b). At depths greater than 0.4 m θ_v showed gradual increases up to day 6 in contrast to plot C, in spite of the initial θ_v being higher than in plot C. The θ_v values on day 1 and 6 at depths greater than 0.4 m were shifted closer to θ_s indicating that the gypsum addition had reduced, but not eliminated, the effect of the 'throttle'. There was little change in θ_v profiles from day 6 to 11.

In plot SG_1, the most marked increases in θ_v following the flooding occurred within and below the slots (Fig. 4c), largely due to the lower pre-flooding θ_v and faster moisture flow. Previous studies (Jayawardane & Blackwell, 1985) indicate that the θ_v in the slots tend to decrease rapidly between irrigations due to faster internal drainage and moisture uptake by roots. Between slots and adjacent to the slots in plot SG_1 (Fig. 4a and b) the increase in θ_v at depths less than 0.30 m after any given period of ponding was less than in plots C and G, but the extent of wetting at soil depths greater than 0.40 m was larger than in plot C and comparable to plot G, indicating lateral flow from the slots. This wetting of the lower soil layers between the slots in plot SG_1 also continued till the end of the flooding period. However, the θ_v values in the lower depth were still less then θ_s due to the slow rate of moisture flow through the clay layers below and between the slots. Surprisingly the θ_v values within the slots were also less than θ_s, even after 11 days of flooding. This may be partly due to surface crusting and air entrapment. These values of θ_s were calculated from bulk densities measured within the slot when the soil was dry and it was assumed that the volume of the slot remained constant. However, it is very likely that the swelling of the undisturbed soil between the slots during the flooding could have reduced the volume and hence the total porosity of the slot at saturation. Studies are being planned to measure such changes.

In plot SG_2, the patterns of moisture profile changes measured within, adjacent to and midway between slots were similar to those observed in plot SG_1 (unpublished data). However the changes in moisture profiles midway between two slots were intermediate to those observed in plot SG_1 and in plot C. This is possibly due to the reduced effects of lateral flow from the slots in plot SG_2, where the slots are further apart.

The total moisture stored in 1 m depth of the soil profile after different periods of ponding (Fig. 2) were calculated from Figs 3 and 4. The total moisture in 1 m soil depth after ponding for more than 1 day was the least in plot C, pri-

Table 1. Moisture contents (mm^3 mm^{-3}) at saturation and −10 kPa moisture potential measured on soil cores (12 replicates) from the Whitton experimental site (Loveday *et al.*, personal communications)

Depth (m)	Moisture potential	
	Saturation	−10 kPa
Surface	0.38	0.30
0.30	0.47	0.45
0.60	0.44	0.40

marily due to the restricted moisture storage below 0.5 m depth. Plot G showed the greatest moisture storage. However, the high θ_v values in the surface layers (depths less than 0.25 m) and slower redistribution rates after an irrigation (Jayawardane & Blackwell, 1985) could restrict oxygen flow in the upper layers (and hence also to the lower layer) in plot G as well as in plot C. This could cause reductions in root growth, unless drainage is provided to remove excess water from the upper layers. The larger differences between the daily infiltration rate and the rate of increase in moisture stored in 1 m depth in the slotted plots (Fig. 2) indicate greater moisture flow to depths below 1 m, which may be used by deep rooting crops.

The post-infiltration θ_v values of the subsurface layers were not only less than the θ_s values of each layer (Figs 3 and 4) but they were even smaller than the laboratory measured θ_v values at -10 kPa potential on undisturbed core samples (Table 1), which are commonly used as an estimate of post-irrigation θ_v profiles. Therefore the post-irrigation moisture storage profiles required in irrigation scheduling need to be measured directly in the field in both non-ameliorated and ameliorated transitional red brown earth soils.

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