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Chloride Movement in a De-Watered Saline Soil Profile

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Abstract

Surface ripping affected the downward movement of water and solutes within a saline de-watered duplex soil profile near Kellerberrin. Prior to ripping, 63% of the total rainfall ended up as runoff and there was little evidence from tensiometric measurements and soil solution samples of significant downward flows of water below a depth of 0.3m. Following ripping to a depth of 0.2m to break a near surface hard layer: runoff was reduced to around 13%; there was some change in soil matrix potential; some leaching of the surface soil occurred; and several preferred water fluxes were intercepted at a depth of 1.5m. These intercepted fluxes were recorded shortly after (<1hr) high intensity rainfall greater than 20mm, suggesting post ripping flow through macropores. The initial chloride storage in the profile was 162t ha^{-1}, approximately 5t ha^{-1} chloride was leached during the field study (3%). The main leaching mechanism before ripping was runoff (0.5t ha^{-1}). After ripping, flow through macropores and mesopores accounted for 0.5t ha^{-1}, runoff 0.09t ha^{-1} with the rest redistributed through the soil matrix.

Introduction

The duplex nature of many wheatbelt soils, combined with the loss of deep-rooted vegetative cover, has resulted in increased recharge and elevated groundwater levels (Peck and Williamson, 1987). Salinised soils are formed following the discharge of groundwater at the soil surface. When this saline discharge is eliminated either artificially through groundwater pumping or by better management of water upslope in the catchment, leaching of accumulated salt is required to complete rehabilitation. This leaching can be achieved artificially through some form of irrigation or by natural rainfall.

In agricultural situations the degree and depth of cultivation has a large impact on the infiltration and redistribution of water into and within the soil. The amount of solute movement is also affected. Smith and Stoneman (1970) showed that cultivation in the dryland agricultural regions of Western Australia could increase infiltration rates in winter but had little effect in aiding and maintaining downward salt leaching, simply because the amount of rainfall was not sufficient to continue the downward leaching. With the potential evaporative flux exceeding the rainfall for most of the year there is a net unsaturated, upward flux of water and solutes.

Water and solute movement is largely governed by the intensity and quantity of rainfall (or irrigation) and the physical properties of the soil. A factor emphasised in this paper is the degree of macroporosity of the soil. The flux of water through a clay soil matrix that contains a population of macropores may be greater than the flux through the matrix alone, as a result of preferred flow through the macropores (Beven and Germann, 1982).

Research under irrigated conditions or in areas of high rainfall has shown that macropores can conduct up to 96% of the total water flux (Watson and Luxmoore, 1986); however, macropores tend to transport only small quantities of solute (Jardine *et al*, 1990). The preferred pathways reported by Johnston *et al* (1983) provided direct recharge of groundwater by rainfall in forested lateritic soils in wetter areas of Western Australia.

Materials and Methods

The research site was located at "Wimmera" farm 20km north of Kellerberrin, in the wheatbelt of Western Australia. The site was within the West Wallatin Creek sub-catchment (Salama *et al*, 1993) and conformed with the Booraan Surface as described by Bettenay and Hingston (1964). The site was devoid of vegetation and the groundwater level artificially held at > 1.8m by a windmill for the duration of the project (Salama *et al*, 1993).

To investigate the flux of water and solute at the site, field measurements of chloride content of the soil and soil solution were measured along with water movement. A soil pedon was constructed and instrumented as shown in Figure 1. During the exposure of the side wall, core samples of soil were taken at various depths for the determination of volumetric water content (θ_v), gravimetric water content (θ_g), bulk density (ρ) and soil chloride content (tonnes Cl^- per hectare). The structure and texture of the soil was described, including the observation of macropores within the B and C horizons.

Rainfall was monitored daily with a tipping bucket rain gauge. A storage rain gauge was installed and the chloride concentration was determined on a monthly basis from a bulk rain water sample. All runoff from the 2m x 3m pedon surface was collected and the quantity logged every three hours. Samples of the bulk runoff water were taken monthly for chloride analysis.

Soil matrix suction (ψ) at various depths was measured directly with 18 tensiometers installed through the side wall of the pedon (see Figure 1). The middle row of tensiometers was logged every three hours, and the rest were monitored manually every month. Soil water storage was estimated from these tensiometric measurements. Details of the installation procedures are given by Bourgault du Coudray (1994).

Twelve solution samplers (two rows of six) were installed through the pedon side wall (see Figure 1). These samplers were monitored monthly (sometimes daily) and the solution analysed for chloride. Also installed at the base of the pedon at a depth of 1.5m were six leachate interceptor trays. The chloride concentration of the outflow was determined whenever water was collected. The volume of the outflow to tray 5 was logged with a tipping bucket. The six trays together covered an area of $1.047m^2$.

For ease of data analysis, time was presented in Julian days, starting at day 1 on 1 January 1992. The pedon was constructed on day 147 (26 May 1992); from that time until day 511 (25 May 1993) monitoring was conducted with a bare soil surface. On day 511, the fracturing of the compacted layer was carried out with the intention of increasing infiltration and leaching. This was done using a pick to simulate agricultural ripping by a tyned implement to a depth of 0.2m.

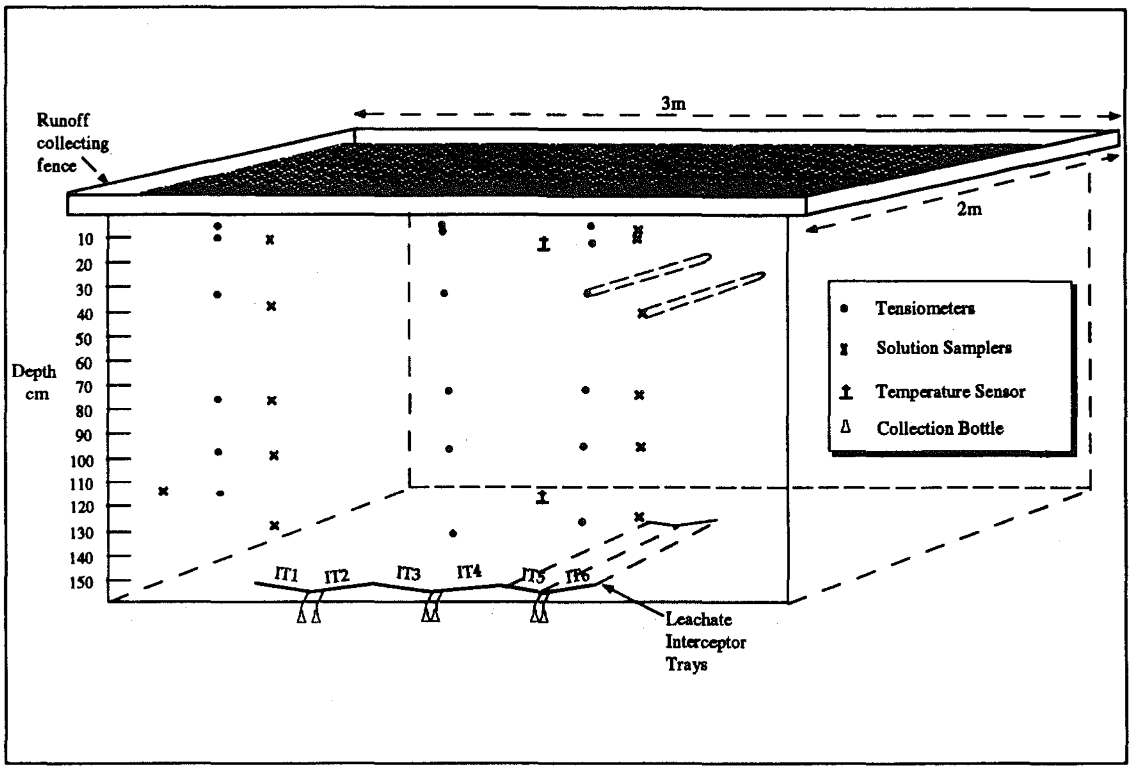

Figure 1 The soil pedon showing the location of tensiometers, soil solution samplers, leachate interceptor trays and runoff collecting fence.

Results and discussion

Soil profile description

The soil profile was classified as a Solonchak (Stace *et al*, 1968) or using Northcote (1979) as a Dy3.31. In general it consisted of four distinct horizons: A surface A1 horizon of greyish brown, apedal, sandy loam to a depth of 0.025m; an A2 horizon of brown, massive, dispersed, hard-setting sandy loam between 0.025m and 0.3m depth; a B horizon of yellowish brown, medium blocky, sandy clay between 0.3m and 0.8m; and a C horizon of freshly weathered gneiss containing alternating bands of dark brown, blocky medium to heavy clays and yellowish brown, apedal, coarse loamy sand characteristic of the freshly weathered bedrock. These horizons are subsequently referred to as the surface, hard layer, clay layer and banded region, respectively. Particle size distributions are given for each horizon in Table 1; they show a duplex profile. Duplex soils such as these are subject to water logging and the development of secondary salinity (Peck, 1978).

Average bulk density, initial gravimetric water content (θ_g), initial volumetric water content (θ_v), and soil chloride content for samples from each of the different textural horizons noted during excavation are given in Table 2. These initial results show a profile to 1.5m with a relatively high bulk density and consequently low porosity, a corresponding low volumetric water content and water storage capacity and a high level of salt storage (~ 162 t ha^{-1}). Initial chloride storage in the A1 horizon was about 2.6 t ha^{-1}. Bulk density values ranged from 1.45 g cm^{-3} at the surface to 1.9 g cm^{-3} in the hard layer. The surface values were significantly lower than the underlying material, despite the material having

Table 1 Particle size distribution for the pedon soil profile.

Profile Type	Horizon	Sampled Depth (m)	% Gravel	% Sand	% Silt	% Clay
Sandy Loam	A1	0 - 0.05	1	65	24	10
Hard layer 1	A2	0.05 - 0.1	0	70	18	12
Hard layer 2	A2	0.25 - 0.3	1	60	13	27
Clay layer 1	B	0.35 - 0.4	4	52	10	34
Clay layer 2	B	0.65 - 0.7	7	43	11	39
Coarse band	C	0.9 - 0.95	8	71	10	11
Clay band	C	1.0 - 1.1	5	23	11	61

a similar particle size distribution. This hard layer is considered typical of the Booraan surface, which tends to be hard-setting (Grealish, Sholtz, personal communications[1]). The structural problems were further aggravated by the sodicity resulting in the complete dispersion of clay aggregates. Vehicle and livestock traffic may have assisted the compaction and re-cementation processes.

Table 2 Initial average values for water content, bulk density and soil chloride content determined from soil cores taken during pedon construction (*n* = 5 for each depth).

Depth (m)	Horizon	θ_g (g g^{-1})	θ_v (cm^3 cm^{-3})	ρ (g cm^{-3})	[Cl$^-$] (t ha^{-1})
0.025	A1	0.04	0.06	1.53	2.6
0.085	A2	0.06	0.1	1.82	5.5
0.325	B	0.15	0.26	1.77	32.8
0.575	B	0.16	0.27	1.75	20.9
1.025	C	0.12	0.22	1.79	22.7
1.545	C	0.13	0.22	1.68	77.8

Rainfall and Runoff

The quantity of rainfall and runoff during the project is presented in Table 3. This clearly shows that the fraction of runoff has reduced since surface cultivation. Before ripping 63% of rainfall ended up as runoff whereas after ripping runoff accounted for only 13%. Although there was six times less runoff after ripping, only five times less chloride was removed. Before ripping 0.5t ha^{-1} (19%) of the chloride was leached in runoff from the A1 horizon, leaving 2.1t ha^{-1}. After ripping a further 0.09t ha^{-1} (4%) was removed. The average chloride concentration over the entire monitoring period was 0.004g l^{-1} for rainfall and 0.2 g l^{-1} for runoff (50 times more), indicating leaching losses from the A1 horizon. The chloride concentration of the rainfall was insignificant compared to the average chloride concentration of the soil solution (~ 16g l^{-1}).

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Table 3 Rainfall and runoff quantity before and after surface ripping.

	Total Quantity	Before Ripping	After Ripping
Rainfall (mm)	624	357	266
Runoff (mm)	262	226	36
Runoff/Rainfall	0.42	0.63	0.13

Tensiometric data and water movement

The average and standard deviation (in brackets) of the daily 9am recording of soil matrix suction (ψ), is given in Table 4. The data was obtained by continuously logging tensiometers at depths of 0.08m, 0.36m and 0.73m; the depth increments shown in the table correspond to the regions of soil of similar texture. The estimation of the volumetric water content is based on the drying water characteristic curves for each texture.

Table 4 Volumetric water contents (θ_v) and the soil matrix suction (ψ) from tensiometric measurements. Average values are reported with standard deviations in parentheses.

Horizon	**Before Ripping**		**After Ripping**	
Depth (m)	**θ_v (cm^3 cm^{-3})**	**ψ (kPa)**	**θ_v (cm^3 cm^{-3})**	**ψ (kPa)**
A2 0.05 - 0.3	0.19 (0.05)	-24 (25)	0.23 (0.03)	-5 (4)
B 0.3 - 0.5	0.31 (0.1)	-8 (4)	0.32 (0.13)	-5 (2)
B 0.5 - 0.8	0.31 (0.08)	-8 (3)	0.33 (0.06)	-6 (1)

After ripping, the water storage in the upper 0.3m of the profile increased. The standard deviations show variability in the water content and soil suction between 0.05m and 0.3m. This variation was attributable to the periodic nature of rain events. Ripping the surface did not greatly affect the moisture status of the soil profile below a depth of about 0.3m. The tensiometer data also allowed the estimation of the soil-limited evaporative flux (Whistler *et al*, 1970), calculated to be less than 1mm per day.

Chloride concentration and movement

The chloride concentrations obtained for the soil solution ranged between 1 and 32 g l^{-1}. Table 5 shows the average and standard deviation of the chloride concentrations from samples taken before and after the surface ripping. Results show that there was near surface leaching and chloride redistribution, and that it was not horizontally uniform. After surface ripping, samplers on the left side of the pedon face showed a degree of leaching at depths of 0.09m and 0.34m and accumulation at depths of 1.02m and 1.15m. This change could be the result of piston type displacement of chloride from the near saturated A2 horizon above. Alternatively there could be a direct redistribution of chloride from the saturated A2 horizon to the C horizon via macropores (bypassing the B horizon) with little interaction with the clay matrix. The first explanation is the most likely as tensiometers did not indicate the presence of a perched water table that would be required to initiate macropore flow.

Table 5 Average and standard deviations (in brackets) of chloride concentrations determined from sampled soil solution.

Position	Depth (m)	Horizon	Chloride concentration Before Ripping ($g\ l^{-1}$)	Chloride concentration After Ripping ($g\ l^{-1}$)
Left	0.09	A2	13.3 (4.0)	3.4 (0.9)
Side	0.34	A2	28.0 (1.5)	16.8 (2.3)
of	0.78	B	24.5 (1.6)	25.9 (1.1)
Pedon	1.02	C	18.6 (1.5)	23.1 (1.3)
	1.15	C	17.0 (0.7)	21.5 (1.6)
Right	0.11	A2	5.6 (1.1)	4.7 (1.0)
Side	0.13	A2	8.5 (1.7)	8.0 (1.4)
of	0.42	B	18.2 (0.5)	
Pedon	0.73	B	14.7 (0.8)	14.7 (0.7)
	0.96	C	13.3 (0.6)	13.6 (0.5)
	1.25	C	13.3 (0.7)	13.7 (0.5)

Samples taken on the right-hand side of the pedon showed a small amount of leaching from depths of 0.11m and 0.13m with little change at greater depth. Several outflows of leachate were captured by interceptor tray 5 immediately below these samplers following heavy rain. It is hypothesised that the leaching noted after cultivation from the former hard layer bypassed the B and C horizons entirely. A total of 52.2 grams of chloride or 0.5t ha^{-1} of chloride was removed to all interceptor trays after ripping. At the time of ripping 2.1t ha^{-1} of chloride remained within the A1 horizon. The amount leached to the trays would have removed about 25% of this chloride. At the end of the field study about 2.4t ha^{-1} of chloride remained in the A horizon (0.3m). A total of ~ 5.7t ha^{-1} of chloride was leached from this horizon during the entire study period. Runoff losses accounted for almost 0.6t ha^{-1}, with the rest redistributed lower down the profile, either through piston displacement or preferred flow (0.5t ha^{-1}). The six interceptor trays measured macropore flow for only 17% of the pedon area. The variation in volume and duration of flow to each tray highlighted the importance of the spatial variability of macropores and mesopores.

Intercepted preferred flow

High intensity rain events greater than 20mm produced no outflow to the interceptor trays before ripping, however, after ripping, water outflows (preferred flows) were recorded three occasions. The amount of outflow that was recorded was horizontally variable, with outflow from tray IT5 exceeding the outflow from the other 5 trays combined. The results of flow intercepted by tray 5 during a 22.8mm rainfall event, lasting 2 hours on day 680, are shown in Figure 2. During this storm, 5mm was runoff and the 1.6l of measured macropore flow was extrapolated to 1.5mm for the whole pedon (0.87mm over tray 5). The balance would have been stored within the soil matrix. Changes in tensiometer values near the surface suggest an increase in soil storage of at least 12mm. A total of 17g of chloride was leached to the trays during this storm (~ 0.16t ha^{-1}).

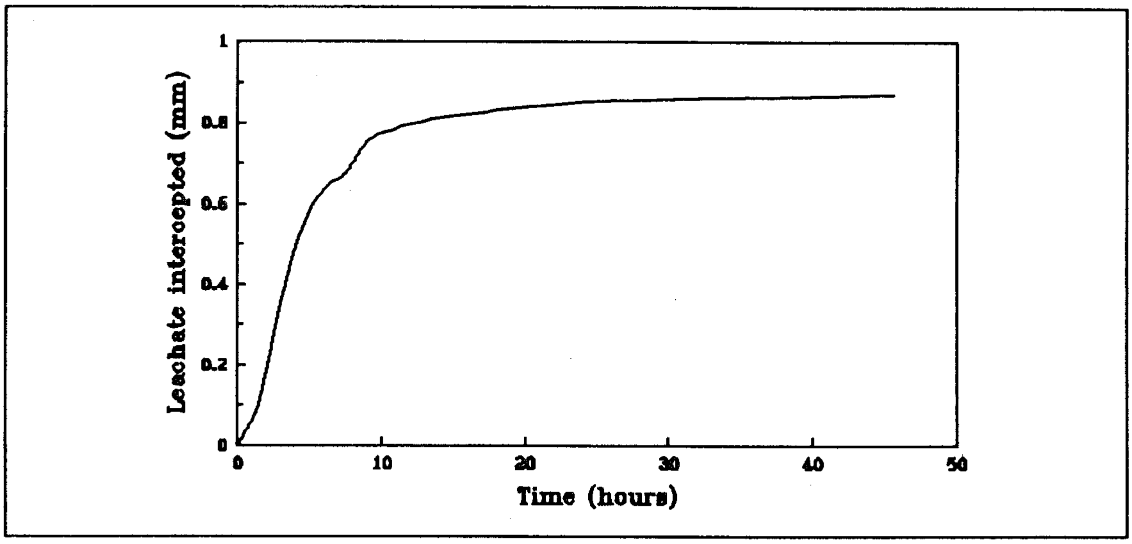

Figure 2 Cumulative outflow intercepted by Tray IT5 on day 680.

Observation of the clay matrix at the "Wimmera" site revealed the presence of both macropores and mesopores. The rapid (<1 hr) response at the trays after this rainfall suggests rapid macropore flow. It is possible that the preferred flow observed at the pedon site occurred within both these pore types. The use of a simple model based on the Hagan-Poiseuille equation for laminar flow allows the curve in Figure 2 to be broken into a number of straight line segments, each of which can be assigned a pore size that theoretically could produce the flux recorded. For example, 10 cylindrical pores of 6mm radius or 1 plannar slit of 4mm diameter would provide 56% of the recorded flow. It is feasible that the rapid response part of the curve in Figure 2 carried less chloride than the later stage of the flow. Luxmoore (1991), comments that high concentrations of solutes have been recorded in preferred pathways during rain events as a result of diffusive transfer of chlorides from the stagnant matrix water into the rain-fed percolating water moving through the mesopores. These mesopores are drained at field capacity but are less than 1mm in diameter and have a large surface area that allows chemical transfer.

Conclusions

Ripping of the soil surface to remove the dispersed hard layer aided the natural leaching of the soil profile. Macropore and mesopore flow in the B and C horizon was not observed until after ripping. Ripping resulted in increased infiltration and chloride redistribution. The rip fractures filled with water saturating the soil above the clay layer (B horizon). Mixing between the percolating water and the ripped soil matrix occurred. On the right side of the pedon, the hydraulic head was sufficient to allow the saline water to flow down past the clay layer via preferred pathways. On the left side, piston displacement of chloride was apparent, with chloride in the A horizon displacing chloride in the B horizon. Water content profiles before ripping showed little change in the short term, whereas after ripping the water content in the upper 0.3m of soil increased marginally. The depletion of the chloride content in the A horizon would take only a few years at the observed leaching rate, whereas, leaching of the B and C horizons may take a considerable time. During the field study the chloride content in the 1.8m profile was reduced from an estimated 162t ha^{-1} to 156t ha^{-1}.

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