THE EFFECTIVENESS OF CAPILLARY BARRIERS TO HYDRAULICALLY ISOLATE SALT CONTAMINATED SOILS[*]

D. J. ROONEY, K. W. BROWN[**] and J. C. THOMAS
Texas A&M University, Soil and Crop Sciences Dept., College Station, TX 77843-2474, U.S.A.
E-mail: brown@tamu.edu

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Abstract. The use of capillary barriers overlayed with topsoil to hydraulically isolate highly saline soils was investigated in a greenhouse study. Capillary barriers of 8 cm or greater thickness effectively prevented salt from migrating upward into the topsoil, thus allowing vegetation to be established. The water which drained from the capillary barrier had electrical conductivities on the order of one third that of the underlying saline soil, and should be acceptable for stream discharge. The capillary barriers reduced the flux of water and salt to the groundwater to about one third of that of the control. The results of the study show that capillary barriers can be used effectively to contain salt contaminated soils.

Key words: capillary barrier, evaporation ponds, gravel barrier, salt brine, salt reclamation, salt remediation, saline soil

1. Introduction

Oil and gas production activities have generated large volumes of concentrated brine. The United States Environmental Protection Agency (USEPA, 1987) estimated that 1.4 billion tons of waste brines are produced annually. During the first half of the century, much of the produced brines were discharged to the surface or placed in unlined evaporation pits or surface impoundments. As late as 1984, the USEPA estimated that some 125 000 open oil and gas waste surface impoundments could be located in the USA (USEPA, 1986). These activities have resulted in hundreds of thousands of salt contaminated sites containing salt concentrations as high as several percent by weight. Although many of these contaminated areas are only a few hundred to a few thousand square meters in size and several meters to tens of meters deep, a few are much larger.

Soils contaminated with brines become sources of persistent contamination to both surface water and groundwater as the salts are washed from the surface and leached deeper. While classical reclamation procedures including treatment with calcium sources, organic residues, and leaching are effective for soils with electrical conductivities of 20 dSm^{-1} or lower, they are ineffective for soils with greater salt concentrations (Dutt *et al.*, 1972; Van Rooyen and Weber, 1977; Longenecker and Lyerly, 1974).

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[*] Contribution of the Texas Agricultural Experiment Station, Texas A&M University System, College Station, TX 77843, U.S.A.

[**] Author for all correspondence.

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While a cover layer of clean soil may temporarily decrease the salt concentration at the surface and allow reclamation, salts are soon brought to the surface by capillary rise, killing the vegetation, and negating the effect of the soil cover. Such a cover is, thus, ineffective in preventing contamination of either the surface soil, surface water, or the groundwater. While it might be possible to excavate highly salt-contaminated soils, such excavations would in some cases be very large and costly and there are few places where the excavated soil could be placed. Therefore, a method is needed to isolate salt-contaminated soils, preferably in-place, so that discharge to both surface water and groundwater is eliminated or at least greatly reduced.

McFarland (1988) suggested the use of a layer of gravel to act as a capillary barrier, overlain by a soil to serve as a rooting medium for the cover vegetation. A properly installed capillary barrier over highly salt-contaminated soil, should prevent the capillary rise of salt, and minimize the downward flow of water from the overlying soil layer. He conducted field tests of the capillary barriers, but unfortunately, his capillary barrier layer contained sufficient fines to allow salt to migrate through it and into the overlying soil. The present study was undertaken to determine the effectiveness of gravel capillary barriers in retarding both the upward and downward movement of salt from contaminated soils.

2. Materials and Methods

The effectiveness of capillary barriers was tested in 30 microcosms assembled in 208 L polyethylene barrels (Figure 1). A 15 cm thick layer of sandy clay soil was amended with 1% NaCl, which increased the electrical conductivity (EC) of the saturated paste extract to 55 dSm^{-1}, and was packed in the bottom of each container. Treatments included a control plus four thicknesses (0, 8, 15, 23 and 30 cm) of capillary barriers. The capillary barrier consisted of pea gravel which had 79.9% of the particles in the 2–6.3 mm diameter range, 18.7% in the 6.3–7.9 mm diameter range, 1% greater than 7.9 mm and 0.4% less than 2 mm in diameter. Six containers of each treatment were assembled. A 30 cm thick layer of unamended sandy clay top soil was placed over each capillary barrier and in the case of the control, the top soil was directly in contact with the saline soil. Three replications of each treatment were watered to simulate a wet climate and three were watered to simulate a dry climate. Common bermudagrass, *Cynodon dactylon*, was planted as a vegetative cover.

Each microcosm was equipped with two drainage ports; one to collect leachate from the bottom of the layer of saline soil and one to collect leachate from the bottom of the capillary barrier. The second drainage port represents lateral drainage which would normally need to be discharged or removed from the capillary barrier to prevent water buildup which would defeat the purpose of the gravel layer.

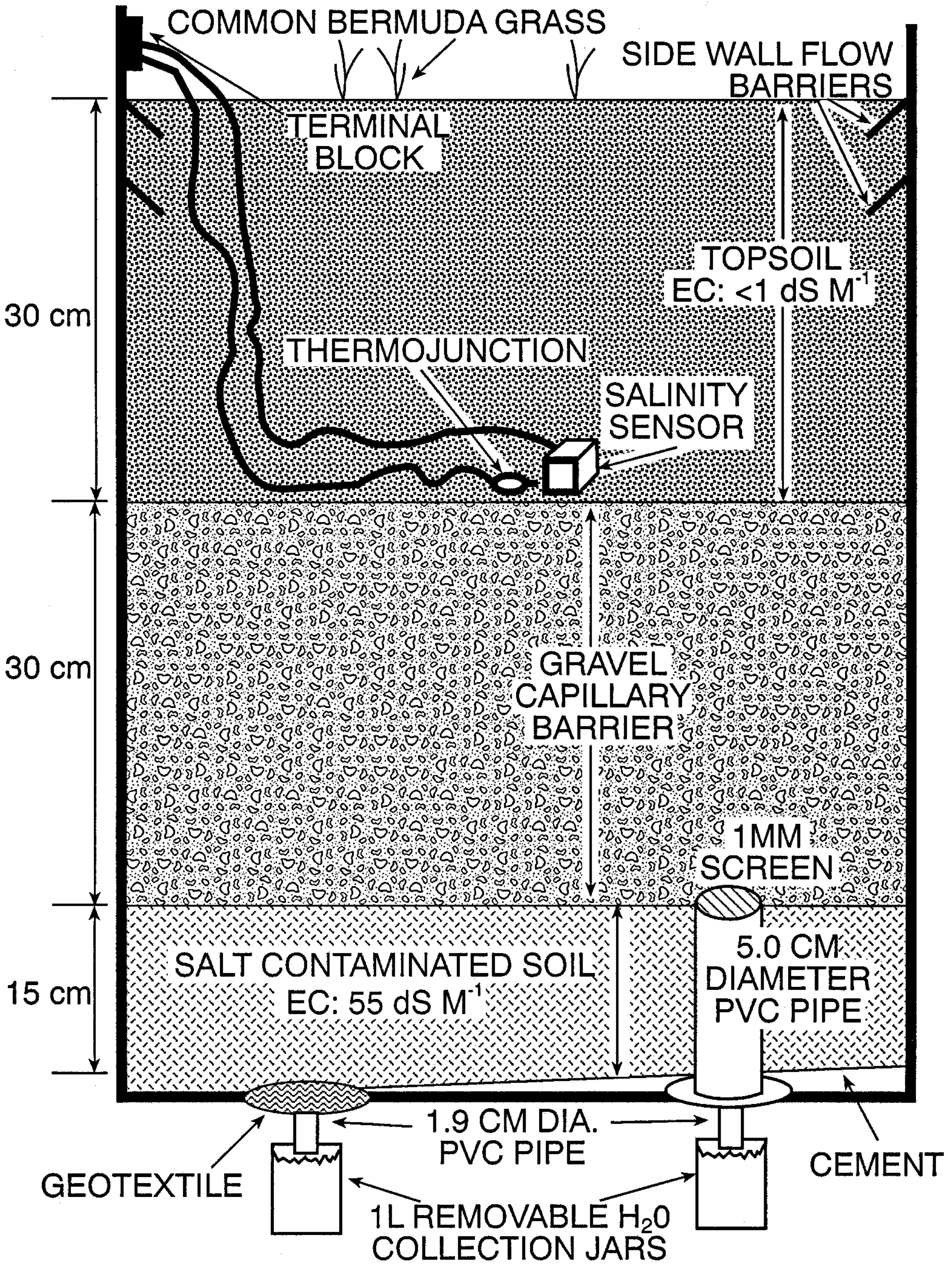

Figure 1. Schematic diagram of 208 L microcosms used to evaluate the effectiveness of capillary barriers. The thickness of the gravel barrier was varied.

Table I

Annual rainfall amounts by month in cm for both the wet and dry moisture regimes. The corresponding water additions in liters for each microcosm are also included. No additions were made to the 0 cm capillary barrier treatment in January, March, and April due to saturated conditions

Month	Wet moisture regime		Dry moisture regime	
	Annual rainfall (cm)	Water addition (L)	Annual rainfall (cm)	Water addition (L)
July	6.1	15.8	5.9	15.3
August	5.8	15.1	5.6	14.6
September	12.5	32.5	5.2	13.5
October	8.7	22.6	4.6	12.0
November	7.5	19.5	1.5	3.9
December	7.5	19.5	1.1	2.9
January	6.3	16.4	1.0	2.6
February	7.5	19.5	1.5	3.9
March	6.1	15.8	2.3	6.0
April	11.0	28.6	2.7	7.0
May	11.1	28.6	6.6	17.2
June	8.2	21.3	7.1	18.5
Total	99.1	257.6	45.1	117.3

Salt migration into the topsoil was determined by salinity sensors installed 3 cm above the capillary barrier. After 130 days, the study was terminated and soil samples were collected from 0–8, 9–15, 15–23 and 24–30 cm depths of each microcosm and tested for salinity by measuring the electrical conductivity of a saturated paste extract. Population means were tested using Fisher's Least Significant Difference Method (Ott, 1988). A confidence level of 0.05 was used in all cases.

The moisture regimes selected were for College Station and Lubbock, Texas and represented wet and dry moisture regimes, respectively. Irrigation equivalent to the 30 year mean monthly precipitation (National Oceanic and Atmospheric Administration, 1990) for each site was applied to the treatments (Table I). College Station receives an average of 99.1 cm precipitation per year spread throughout the year, while Lubbock receives 45.1 cm per year, mostly between May and October. The mean monthly precipitation was applied every 10 days allowing simulation of a 13 month period in the 130 day study period.

The salinity sensors were made in our laboratory and were similar to those used by Richards (1966). Fifteen bar ceramic pressure plates (Soil Moisture Corp., Santa Barbara, CA) were cut into 2 cm square pieces. Small parallel incisions, one cm long, were made on one face of a pair of 2 cm plates to hold the 2 cm long, 30-gauge platinum wires. One strand of an insulated multiple conductor copper wire was silver soldered to each platinum electrode to act as a lead wire. The edges

Table II

Mean electrical conductivity values of saturated paste extracts of soil samples collected at the end of the study

Treatment	0–8 cm	9–15 cm	16–23 cm	24–30 cm	Mean*
	(dSm^{-1})				
0 cm – Wet	4.0	4.0	9.0	10.0	6.8 b
0 cm – Dry	8.0	8.0	14.0	17.0	11.8 a
8 cm – Wet	0.6	0.4	0.3	0.3	0.4 c
8 cm – Dry	0.8	0.4	0.5	0.8	0.6 c
15 cm – Wet	0.7	0.5	0.4	0.4	0.5 c
15 cm – Dry	0.8	0.4	0.3	0.3	0.5 c
23 cm – Wet	0.6	0.3	0.2	0.3	0.4 c
23 cm – Dry	0.8	0.4	0.3	0.3	0.5 c
30 cm – Wet	0.5	0.5	0.5	0.5	0.5 c
30 cm – Dry	0.8	0.5	0.3	0.3	0.5 c

* Values for the mean followed by the same letter do not differ significantly at P = 0.05 in the Fishers Least Significant Difference Test.

of the plates were held together with Armstrong A-34 epoxy. The sensors were calibrated in known salt solutions. Readings were made using an ohm meter. A copper-constantan thermojunction was installed next to each salinity sensor and read using a digital thermometer. The temperature measurements were used to correct the salinity sensor measurements to 25 °C.

3. Results and Discussion

The electrical conductivity data from the saturated paste extracts of the soil samples collected at the end of the study (Table II) showed significantly greater electrical conductivity values for the control which indicates that the salt had migrated from the underlying contaminated soil into the surface soil which was not protected by a capillary barrier. The electrical conductivities had risen from the original value of 0.4 dSm^{-1} to as great as 17 dSm^{-1} in the bottom layer of the surface soil in the dry moisture regime. The salt which had been transported into the profile of the control treatment would be sufficient to retard the growth of most plants under simulated dry conditions (Bresler *et al.*, 1982). The electrical conductivity of the 24–30 cm layer of soil with capillary barriers ranging from 8 to 30 cm in thickness were low and statistically similar indicating that the capillary barriers were effective in preventing the upward migration of salts.

Table III

Average electrical resistance (ohms × 10^3) readings for sensors located 27 cm below the soil surface. Values are the mean of three replications followed by the standard deviation

	Thickness of capillary barrier									
	0 cm		8 cm		15 cm		23 cm		30 cm	
Date	wet	dry	wet	dry	wet	dry	wet	dry	wet	dry
June 15	956±103	973±52	1160±33	377±208	N/A	767±214	N/A	957±147	N/A	N/A
July 1	334±415	99±21	657±178	408±163	N/A	759±102	N/A	789±154	N/A	1047±0
July 15	70±52	87±30	320±72	306±178	491±448	411±272	624±660	446±233	597±410	374±75
December 1	85±49	76±62	618±339	1137±348	499±163	349±309	146±87	419±237	496±277	155±20
May 1	66±20	94±19	586±291	742±420	290±141	348±208	321±183	386±227	638±546	147±27

Table IV

The total annual equivalent depth of leachate and percent of applied precipitation which drained from the capillary barrier and from below the saline soil for each treatment. Values are the mean of three replications followed by the standard deviation

Thickness of Capillary Barrier	Drainage from Capillary Barrier			
	cm		%	
	wet	dry	wet	dry
8	47.2±0.3	9.5±0.4	48±0.3	21±0.9
15	54.6±5.0	11.7±0.9	55±5.0	26±2.0
23	45.3±1.2	9.6±0.1	46±1.2	21±0.3
30	37.0±1.9	6.7±0.1	37±1.9	15±0.3
Average	46.0	9.4	46	21

Thickness of Capillary Barrier	Drainage from below the saline soil			
	cm		%	
	wet	dry	wet	dry
0	9.0±0.7	2.9±0.1	9.1±0.7	6.4±0.2
8	3.2±0.9	0.6±0.2	3.2±0.9	1.3±0.4
15	4.9±0.8	0.8±0.6	4.9±0.8	1.7±1.3
23	1.9±1.0	0.6±0.1	1.9±1.0	1.3±0.3
30	4.7±0.4	0.6±0.5	4.8±0.4	1.2±1.2
Average	4.7	1.1	4.8	2.4

These results were consistent with the readings from the salinity sensors which indicated that the electrical conductivity of the topsoil 3 cm above the saline soil increased markedly in both the wet and dry treatments within the first month after irrigation began (Table III). The readings also indicated that the electrical conductivity of the dry treatments capillary barriers of 8 to 30 cm in thickness remained low indicating the absence of salts.

In all treatments, water drained from the topsoil. In those treatments which had capillary barriers, the majority of the drainage was collected from the capillary barrier and much less penetrated through the underlying layer of contaminated soil. Small amounts of water drained from the wet moisture regime treatments every month, but water did not drain from the dry moisture regime from any of the treatments for 4–6 months during the dry season. A summary of the total annual drainage, from the capillary barriers and from below the salt contaminated soil expressed in equivalent depth and percent of the applied precipitation is presented in Table IV. Nearly half of the applied water drained from the capillary barrier in the wet moisture regime, while an average of only 20.8% of the applied water

Table V

Average electrical conductivity of the drainage water from the capillary barrier and from below the saline soil

Date	Capillary barrier	Contaminant drain
	($\mathrm{dSm^{-1}}$)	
August	4	37
September	6	40
October	6	39
November	6	50
December	8	42
January	7	40
February	6	47
March	6	45
April	7	37
May	5	35
June	6	45
Average	6	41
Standard deviation	±1.4	±6.2

drained from this layer in the dry moisture regime. This water would need to be discharged horizontally through drains or otherwise disposed to prevent saturation of the capillary barrier. Much less water penetrated the underlying saline soil. For the wet moisture regime treatments, an average of 4.8% of the applied water was collected from the bottom drains while only 2.4% was collected from the bottom drains located in the dry moisture regime treatments. In this experiment the average monthly precipitation was added to each treatment every 10 days which resulted in a higher hydraulic loading rate than would have occurred in a typical year had the precipitation been spread out over the full 13 month period. Thus, the volumes of drainage water are likely slightly greater than might occur under typical field conditions since there would be more time available for evapotranspirational losses resulting in greater amounts of water being stored in the soil. Based on this, one may expect a field installation to be even slightly more protective of surface and ground water reserves than indicated herein.

Only a very small fraction of the applied water drained through the underlying saline soil indicating that the cap was effective in decreasing the flux of salt toward the groundwater. The capillary barrier cover did not provide complete hydraulic isolation of the saline soil, but did prevent upward migration of the salt, allowing revegetation of the surface and did decrease the flux of salt contaminated water toward the groundwater to about one third of that measured in the control.

The electrical conductivity of the drainage from the capillary barrier did not differ between treatments. The same was true for the leachate which passed through the salt contaminated soil. Thus, each data set was pooled and the averages for each month are shown in Table V. There was no apparent trend in concentration with time for either the drainage from the capillary barrier or from beneath the saline soil. The electrical conductivity of the drainage water from the capillary barrier in all treatments over time averaged 6 ± 1.4 dSm^{-1}. This was significantly lower than the electrical conductivity of the saline soil (55 dSm^{-1}), and depending on the circumstances, particularly if the leachate volumes were low, it may be practical to discharge this drainage directly to a stream. Drainage from many agricultural fields, in areas where saline water is used to irrigate, exceed this electrical conductivity (Rhoades *et al.*, 1973) and are routinely discharged into receiving streams. The deep leachate averaged 41 ± 6.2 dSm^{-1}, however, since the leachate was a very small fraction of the precipitation, it actually transported very little salt from the contaminated soil toward the groundwater.

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