

Replicated lysimeter measurements of tracer transport in clayey soils: Effects of irrigation water salinity

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ABSTRACT

Recent studies suggest that standard guidelines for managing salinity in irrigated agriculture overestimate the leaching requirement. Transient-state, process-based model analyses offer the possibility of more efficient water and salinity management, but data are needed to evaluate the accuracy of various subcomponents of the models. In this study, tracer (Br) transport in twelve lysimeters identically packed with clayey soil materials was monitored at eight soil depths and in drainage waters. In the first phase of the experiment (the salinization phase), six of the lysimeters were irrigated with high EC waters (8.1 dS m^{-1}) and six with low EC waters (0.4 dS m^{-1}). In the second phase, all lysimeters were leached with low EC waters (0.4 dS m^{-1}). Tracer transport was very different in the high and low EC irrigation treatments, with the high EC treatment exhibiting significant tailing in the breakthrough curves. Due to the replicated experimental design, it was possible to confirm that the differences between the experimental treatments were significant and not due to random deviation. Future research aimed at placing realistic confidence levels on model predictions will allow transient-state models to reach their full potential as water and salinity management tools.

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1. Introduction

For many decades, guidelines for managing salinity in irrigated agriculture have emphasized the leaching fraction (LF) and leaching requirement (LR) concepts, where LF is the fraction of irrigation water that percolates below the root zone during a growing season and LR is the minimum LF that is required to maintain the root zone salinity at a level that does not reduce yields (U.S. Salinity Laboratory Staff, 1954; Rhoades, 1974; Ayers and Westcot, 1985). Several recent articles (e.g., Letey and Feng, 2007; Corwin et al., 2007; Dudley et al., 2008; Ben-Gal et al., 2008; Letey et al., 2011; Suarez, 2012) have noted various shortcomings associated with the LR approach to salinity and water management, many of which stem from the fact that the LR approach is based on a steady-state analysis of irrigation, drainage, crop salt tolerance, and root water uptake. Recently, a University of California Center for Water Resources workgroup concluded that steady-state analyses overestimate both leaching requirements and the negative impacts of irrigating with saline waters (Letey et al., 2011). Thus the guidelines

encourage overirrigation, which wastes water and increases contaminant transport to groundwater. The workgroup recommended that transient-state analyses be developed to promote more effective water and salinity management (Letey et al., 2011).

Transient-state analyses of leaching requirements can be generated using computer simulation models such as UNSATCHEM (Suarez and Simunek, 1997), HYDRUS (Šimunek et al., 2005), ENVIRO-GRO (Pang and Letey, 1998), SWAP (van Dam et al., 2008), and MACRO (Jarvis, 1994). These mathematical models simulate water flow and chemical transport processes in irrigated soils, and can account for dynamic factors such as irrigation scheduling and seasonally variable irrigation water quality and crop salt tolerance (Oster et al., 2012).

From a macro-perspective, reducing leaching fractions and making greater use of marginal quality waters should lead to water savings and reduced groundwater pollution. From a micro-perspective, water (and cost) savings should also result, but it will involve operating farms at salinity levels that are closer to the margin where yields (and revenues) are expected to diminish. In this context, it is reasonable to consider the accuracy of transient-state model predictions and the precision with which the outcomes of different management scenarios can be predicted. If a transient model predicts growth conditions that will just allow for maximum or acceptably high yields, how much confidence should be placed in that prediction?

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This paper is motivated by the relative scarcity of data for testing the accuracy of transient state model predictions and the difficulty of obtaining such data. Over the years, a number of studies, employing varying degrees of model fitting and prediction, have reported reasonable agreement between experimental data and model calculations (e.g., Crescimanno and Garofalo, 2005; Gonçalves et al., 2006; Letey and Feng, 2007; Ramos et al., 2011). But considering the variety of biogeochemical processes included in transient models, as well as the potential range of environmental and agronomic settings, the testing has been fairly limited. In particular, comparatively little work has been done in clayey soils. Yet clayey soils with low infiltration rates and limited potential for overirrigation are among those most likely to be impacted by salinity. Modeling of transport processes in clayey soils poses significant challenges due to the strong effect that the surface charge of clay particles has on soil hydraulic properties and on the mobility of solutes (Nielsen et al., 1986). In clayey soils, charged particles produce phenomena such as anion exclusion (Bresler, 1973), salt sieving (Kemper and Maasland, 1964), streaming potentials (Revil and Pezard, 1999), and swelling pressures (Iwata et al., 1995) which are typically negligible in coarser textured soils. Data are needed for evaluating mechanistic transport models in clayey soils.

Obtaining detailed measurements of chemical transport in soils is difficult. Field experiments are hard to perform and interpret due to the difficulty of controlling or even monitoring basic experimental parameters (Skaggs et al., 2002). Replicated trials are very difficult or impossible due to spatially and temporal variable soil properties. Additionally, large scale field research is often prohibitively expensive. Small laboratory columns offer greater control and lower costs, but considerable uncertainty exists about how to “scale-up” the results to the field scale. An alternative that is intermediate to field and laboratory studies is large, well-instrumented column lysimeters (e.g., Schoen et al., 1999). Large lysimeters permit a relatively high degree of control over experimental conditions and transport distances comparable to the root zone depth.

Our objective was to make experimental observations of tracer transport that could be used test model predictions and evaluate assumptions underlying model process descriptions. In this work, we describe the design and construction of a large column lysimeter installation and report data from a salinization and leaching experiment conducted on layered, clayey soil materials.

2. Methods and materials

2.1. Lysimeter design and construction

Twelve cylindrical lysimeters, measuring 197 cm tall and 46 cm in diameter, were constructed from large diameter PVC pipe (Fig. 1). The lower ends of the lysimeters were sealed and the bottom 10 cm packed with 90 mesh sand to a dry bulk density of 1.6 g cm^{-3} . The sand layer served as an envelope for a vacuum drainage system that consisted of six 15 cm long ceramic candles inserted into the sand through equispaced openings in the sidewalls, 4 cm above the bottom (Fig. 1). The ceramic candles had a 1 bar bubbling pressure and were attached to a constant vacuum source (35 kPa).

Soil materials for the lysimeters were excavated from the surface (0–45 cm) of two locations near the city of Firebaugh in western San Joaquin Valley, California. The sites, which are both mapped as Lillis series (very-fine, smectitic, thermic, Halic Haploxerert), yielded materials with clay contents of 33% and 43%. The predominant soil mineralogy was smectite (>50%), illite, and chlorite. The two soil materials were spread out separately on a paved surface and air-dried; subsequently, they were ground and passed through a 6 mm wire mesh.

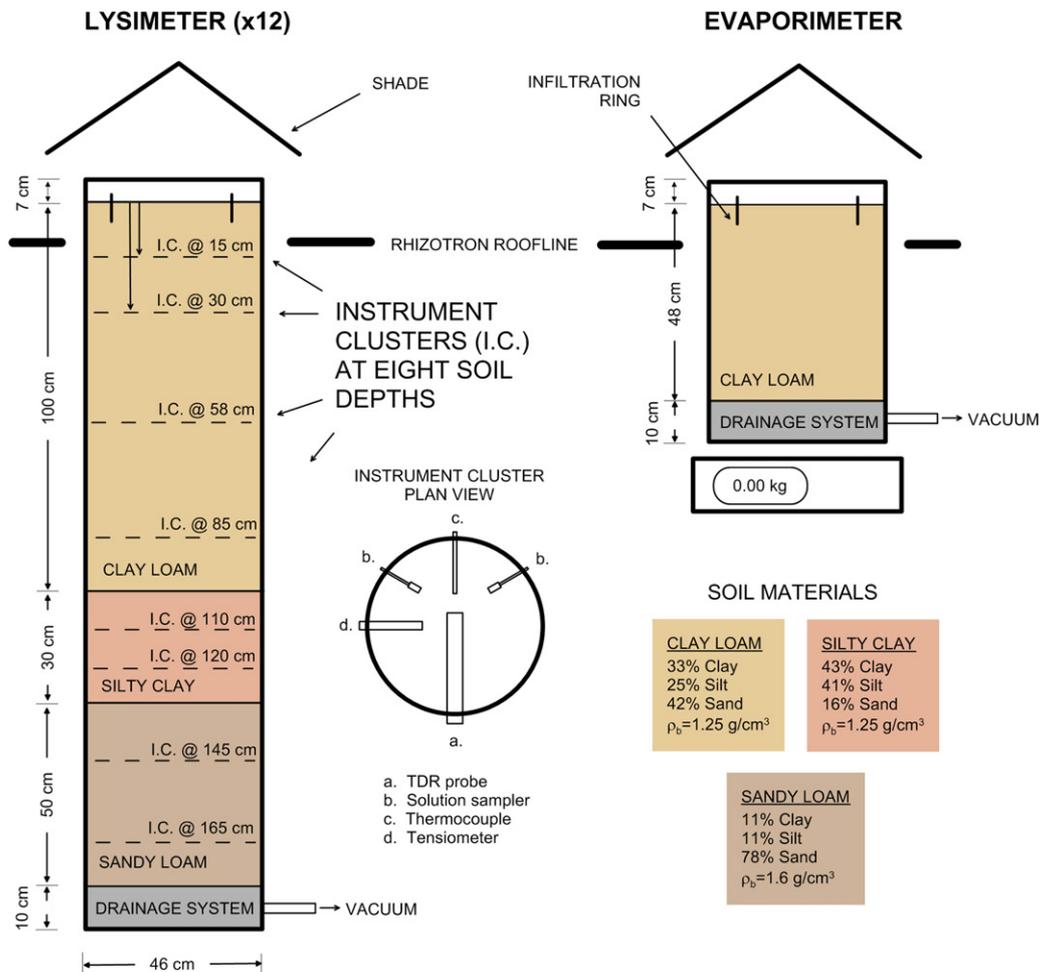
The lysimeter design objective was to create a layered soil medium patterned after a textural profile that exists in agricultural lands on the west side of San Joaquin Valley (Shouse et al., 2006): a fine-textured (e.g., clay loam) surface layer, a thinner second layer with higher clay content, and a deeper layer with a coarser texture. With this goal in mind, the 12 lysimeters were packed identically using the homogenized 33% clay soil material for the 0–100 cm layer, the homogenized 43% clay material for the 100–130 cm layer, and a homogenized mixture of blasting sands and 33% clay material for the 130–180 cm layer. The soil for the second layer was treated with boron laden water to bring the salt and adsorbed boron concentrations in line with those observed in the field by Shouse et al. (2006). The treatment consisted of mixing the soil with drainage water collected from sumps near the soil excavation sites. The chemical composition of the water was very similar to that measured by Shouse et al. (2006) for the 100–130 cm layer, albeit about four times more concentrated. The soil was mixed with diluted (1:4) drainage water and left to settle for 48 h. Clear water was decanted from the mixing tub and another cycle of soil washing commenced. Once the second wash was completed, the soil was allowed to air dry for several days and was ground and sieved. The material for the third layer was synthesized by thoroughly mixing 60 mesh sand, 90 mesh sand, and the 33% clay material in a ratio of 3:3:2 by weight. The mixture, which had a final a clay content of 11%, was passed through a 6 mm wire mesh before packing.

Soil material was packed into the columns in 10 cm segments to achieve the dry bulk density targeted for each soil layer: 1.25 g cm^{-3} in the top two layers and 1.6 g cm^{-3} in the bottom layer (Fig. 1). After each segment was packed, Riverside tap water (Table 1) was sprinkled onto the surface and allowed to redistribute for 24–48 h, such that the final gravimetric water content of the packed material was about 20%. No shrink-swell behavior was observed in the soil during this time. The 12 columns were packed concurrently by a single technician, with the same segment being added to all columns on the same day; every effort was made to produce 12 identical columns (Tables 2 and 3).

During packing, each column was fitted with a cluster of instruments at eight depths (Fig. 1). Each cluster consisted of two solution samplers, one TDR probe, one tensiometer, one thermocouple, and one soil gas port. At each depth, the cluster orientation was rotated 15° from the previous one so that instruments were not aligned on top of one another (Fig. 1). The TDR probes, gas ports, and thermocouple instruments were not utilized in the current study and will not be discussed further. The solution samplers were based on the design of Suarez (1986) which specifies a reduced interior air space and flushing of the sample chamber such that CO_2 degassing during sampling is minimized and reliable measurement of soil solution pH is possible. During sampling, the samplers were connected to a constant vacuum source of 35 kPa. The samplers were constructed with porous stainless steel and Teflon materials that were tested and found to be chemically inert to boron and other elements of interest.

The tensiometers were constructed with 1 bar ceramic cups and were fitted with electronic pressure transducers which permitted automated readings at regular intervals using data loggers. Also installed on the inside of the lysimeter walls were annular bypass rings measuring 5 cm tall and 0.75 cm thick. The rings were affixed every 35 cm and were intended to divert water away from the lysimeter walls (Corwin, 2000).

The lysimeters were installed in a rhizotron facility at the U.S. Salinity Laboratory in Riverside, CA. The tops of the lysimeters protruded through openings in the rhizotron roof, extending 18 cm above the surface grade (Fig. 1). Cone shaped tarp coverings were placed above each column and removed only during irrigation. The tarps shaded the columns at all times and prevented any rainfall from reaching the soil.



Above grade view of shaded (grey) lysimeters. In lower-right corner, one lysimeter is shown unshaded. The green tanks are irrigation water storage.



Below grade view of lysimeters.

Fig. 1. Illustration of the lysimeter installation.

The lysimeter lower boundary was defined by the interface between the sandy loam soil layer and the sand layer that enveloped the vacuum drainage system (Fig. 1). That interface was not directly controlled or monitored, but it was indirectly affected by the constant vacuum drainage system and the prevailing pressure head in the sand envelope. Tensiometer measurements made on a limited basis indicated that the pressure head in the sand envelope at the bottom of the columns was between -50 and -100 cm during the course of the experiment.

A 13th lysimeter, called the evaporimeter, was constructed and similarly installed in the rhizotron. The evaporimeter was shorter, measuring 70 cm tall, and contained only the 33% clay soil surface layer and a drainage layer (Fig. 1). Being relatively lightweight, the evaporimeter was installed directly on an electronic balance and an automated system was used to record changes in the evaporimeter weight. Evaporimeter drainage was also monitored on a second balance. From the measured changes in evaporimeter and drainage masses, it was possible to calculate by difference daily

Table 1
Water compositions.

Lysimeter	EC (dS m ⁻¹)	SAR	Br (mg L ⁻¹)	B (mg L ⁻¹)	pH	Na (mmol _c L ⁻¹)	K (mmol _c L ⁻¹)	Ca (mmol _c L ⁻¹)	Mg (mmol _c L ⁻¹)	Cl (mmol _c L ⁻¹)	SO ₄ (mmol _c L ⁻¹)	NO ₃ (mmol _c L ⁻¹)	NO ₂ (mmol _c L ⁻¹)	ALK (mmol _c L ⁻¹)
Phase 1 irrigation water: salinization (804 days)														
1, 4	0.4	2	20	0.2	7	1.7	0.05	0.8	0.8	1.3	0.3	0	0	1.5
2, 5	0.4	2	20	5	7	1.7	0.05	0.8	0.8	1.3	0.3	0	0	1.5
3, 6	0.4	2	20	20	7	1.7	0.05	0.8	0.8	1.3	0.3	0	0	1.5
7, 10	8.3	25	20	0.2	7	75	0.9	6.5	12	30	54	0.8	0.8	10.4
8, 11	8.3	25	20	5	7	75	0.9	6.5	12	30	54	0.8	0.8	10.4
9, 12	8.3	25	20	20	7	75	0.9	6.5	12	30	54	0.8	0.8	10.4
Phase 2 irrigation water: leaching (696 days)														
1–3, 7–9	0.4	2	0.3	0.06	8.2	1.6	0.05	0.8	0.8	1.3	0.3	0	0	1.5
4–6, 10–12	0.4	2	0.3	0.06	5.7	1.6	0.05	0.8	0.8	1.3	0.3	0	0	1.5
Riverside, CA tap water	0.6	1	0.16	0.08	7.5	1.6	0.1	3.3	0.8	0.8	1.2	0.5	0.5	3.7

Table 2
Initial soil chemical properties.

Property	Clay loam Layer 1	Silty clay Layer 2	Sandy loam Layer 3
Organic carbon content (%)	0.76	0.73	0.17
Inorganic carbon content (%)	0.25	0.25	0.059
Gypsum content (%)	0.19	0.25	0.11
Aluminum oxide content (%)	0.083	0.077	0.027
Iron oxide content (%)	1.1	1.2	0.34
Surface area (m ² g ⁻¹)	168	173	43.3
Cation exchange capacity (mmol _c kg ⁻¹)	350	337	6.35
Saturation percentage (%)	68	73	31
Exchangeable sodium percentage ^a (%)	5	7	7

^a Estimated from saturation extract concentrations (U.S. Salinity Laboratory Staff, 1954).

evaporation for the shaded surface conditions used in the lysimeter installation.

Infiltration rings made of galvanized sheet metal and measuring 36 cm in diameter and 15 cm tall were installed in the surface of each lysimeter and the evaporimeter. The rings were inserted 8 cm into the soil, leaving a 7 cm lip in which irrigation water could pond before infiltrating the soil. Irrigation was accomplished by slowly pouring a measured volume of water into the ring. The purpose of the ring was to keep infiltrating water away from the column wall. Preliminary investigations using a mockup lysimeter found that for the irrigation volumes and frequencies being considered, saturated flow conditions existed only briefly within the interior of the infiltration ring and did not initiate wall flow.

2.2. Salinization and leaching experiment

A two-phase study of salt accumulation and leaching was initiated in May 2006. The first phase was termed the salinization phase and ran from May 2006 through August 2008. During this phase, lysimeters were irrigated with one of six synthetic irrigation waters (Table 1) varying in salinity (0.4 or 8.3 dS m⁻¹) and B concentration (0.2, 5, or 20 mg L⁻¹). All waters contained the same concentration of Br tracer (20 mg L⁻¹). The high EC irrigation waters were patterned after the shallow groundwater composition observed by Shouse et al. (2006) in western San Joaquin Valley. Note that although we refer to Phase 1 as the “salinization” phase, the six lysimeters receiving low EC irrigation waters during this time were actually being leached with respect total salt content owing to the high salinity of the packed soil material. However, Br and – in the case of the medium and high B waters – B concentrations were increasing in those lysimeters during Phase 1 even as the total salts decreased.

Phase 2, or the leaching phase, ran from August 2008 through July 2010. Two synthetic low EC irrigation waters were used which differed in their pH, 8.2 or 5.7. Both leaching phase waters contained only small amounts of Br or B (Table 1). During both phases,

Table 3
Chemical composition of initial soil saturation extracts.

Chemical characteristic	Clay loam Layer 1	Silty clay Layer 2	Sandy loam Layer 3
EC _e (dS m ⁻¹)	1.8	3.6	3.8
pH _e	8.30	8.45	8.35
Na (mmol _c L ⁻¹)	9.96	19.6	21.1
K (mmol _c L ⁻¹)	0.61	0.79	0.65
Ca (mmol _c L ⁻¹)	7.38	15.8	16.4
Mg (mmol _c L ⁻¹)	2.40	5.45	5.70
Cl (mmol _c L ⁻¹)	4.22	12.5	13.1
SO ₄ (mmol _c L ⁻¹)	8.01	24.8	27.5
B (mg L ⁻¹)	1.17	1.40	1.47
SAR	4.5	6.0	6.3

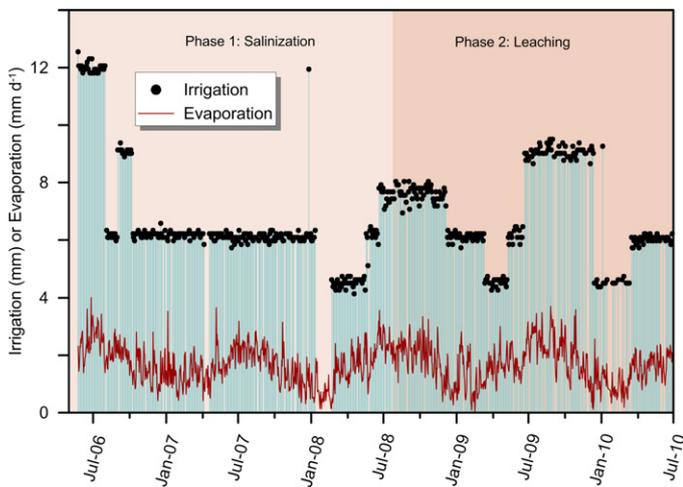


Fig. 2. Implemented irrigation regime and measured evaporation rate.

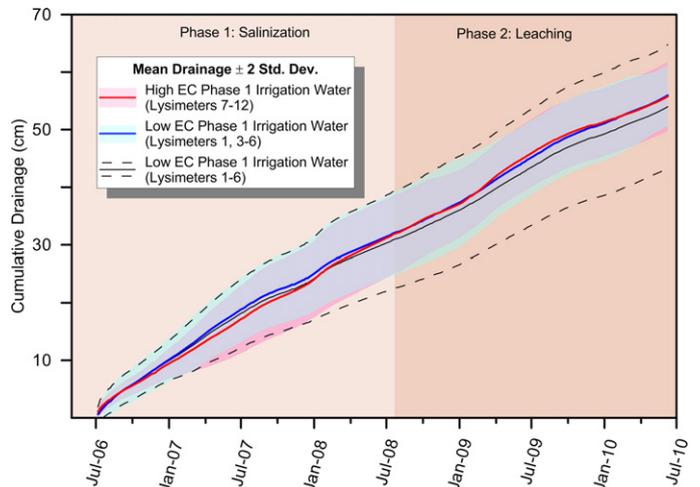


Fig. 3. Measured average cumulative drainage and variability for the low and high EC irrigation water treatments.

the irrigation waters were stored in sealed tanks and were periodically analyzed. As necessary, the pH of the irrigation water was maintained by bubbling CO_2 or adding acid or base.

As will be detailed in the results section, the rate of irrigation varied during the experiment. Most often, irrigation occurred three times a week (Monday, Wednesday, Friday). Throughout the experiment, the irrigation volumes and timing were identical for all lysimeters and the evaporimeter. The evaporimeter was irrigated during both phases with Riverside, CA tap water ($\text{EC} \approx 0.6 \text{ dS m}^{-1}$; Table 1).

At irregular intervals, soil solution samples were extracted using the vacuum solution samplers. Samples collected from the two samplers at a single depth in the same lysimeter (Fig. 1) were combined and analyzed as a composite sample. The sampling frequency ranged from several times a week early in the experiment to once every two weeks toward the end. The samples were analyzed for electrical conductivity and Br, B, and Cl concentration. Samples of collected drainage waters were also analyzed. On a limited number of occasions the soil solution sampling protocol was altered to permit the determination of solution pH on non-composite samples using the method described by (Suarez, 1986, 1987).

3. Results

During the experiment, irrigation was managed with the goal of achieving as high a water application rate as possible while still maintaining unsaturated soil conditions. The tensiometers installed at eight depths within each lysimeter were used to monitor soil water contents during the experiment and the irrigation rate (I) was reduced if the soils approached saturation, or was increased if it appeared the soils could take more water; generally, irrigation adjustments were necessary in response to seasonal changes in evaporation (E). Because of the low permeability of the soil materials, particularly the middle silty clay layer, the highest net infiltration rate ($I - E$) that could be maintained turned out to be quite low, with the experiment average being less than 1 mm day^{-1} . The implemented irrigation regime is plotted in Fig. 2, which shows each individual water application as well as the evaporation rate measured with the evaporimeter. On some occasions the irrigation rate was too high and soils became saturated, typically above the silty clay layer. Whenever that happened, irrigation was halted until drainage and water redistribution resolved the saturated condition, whereupon irrigation was resumed, usually at a lower rate. The most significant saturation episode occurred near the end of 2007. During the last third of 2007, evaporative demand decreased

steadily while the irrigation rate remained constant (Fig. 2). By the end of 2007, tensiometer readings were indicating saturated conditions at multiple depths within several lysimeters. Starting in January 2008, irrigation was halted for 41 days (Fig. 2). Thereafter, irrigation adjustments were made more frequently to maintain tighter control on the water content (Fig. 2).

The data in Fig. 2 show that the net applied water rate, $I - E$, varied throughout the experiment. Thus, although the irrigation water compositions were constant during the two phases, the leaching concentrations, resulting from the evapoconcentration of the applied water at the soil surface, varied throughout the experiment, similar to field conditions where leaching is generally reduced during periods of high ET. The surface boundary conditions therefore had time-varying fluxes and concentrations and were more complex (and realistic) than those typically imposed in controlled solute transport experiments.

The apparent net water fluxes – as evidenced by measured lysimeter drainage rates – exhibited relatively low variability among the twelve lysimeters, but the variability appeared random and did not correlate with the irrigation water treatments. When we assess the solute transport data below, it will be useful to distinguish the group of lysimeters irrigated in Phase 1 with low EC water (Lysimeters 1–6, $\text{EC} = 0.4 \text{ dS m}^{-1}$) and those irrigated with high EC water (Lysimeters 7–12, $\text{EC} = 8.3 \text{ dS m}^{-1}$). Fig. 3 shows the average cumulative drainage measured for those two sets of lysimeters over the course of the whole experiment. The variability that existed is indicated by filled areas about the mean curves which correspond to plus-or-minus two standard deviations of the measured values. If Lysimeter 2 – which produced relatively low drainage volumes and appeared to be an outlier – is excluded, the mean and variability of the cumulative drainage in the high and low EC treatments were nearly identical (Fig. 3). If Lysimeter 2 is included, the observed variability in the second half of the study is considerably larger in the low EC treatment and the mean is slightly lower than, though still not statistically significantly different from, the mean of the high EC treatment (Fig. 3).

The overall patterns of salinization and leaching that occurred in the lysimeters during the experiment are illustrated in Fig. 4, which shows the time variation (or breakthrough curve) of the soil solution EC and the Cl and Br concentrations for the eight monitoring depths and the drainage water. Again, mean values and variability are shown for the sets of lysimeters receiving high and low EC irrigation water treatments during Phase 1. Recall (Table 1) that the high EC irrigation waters also had a high Phase 1 Cl concentration

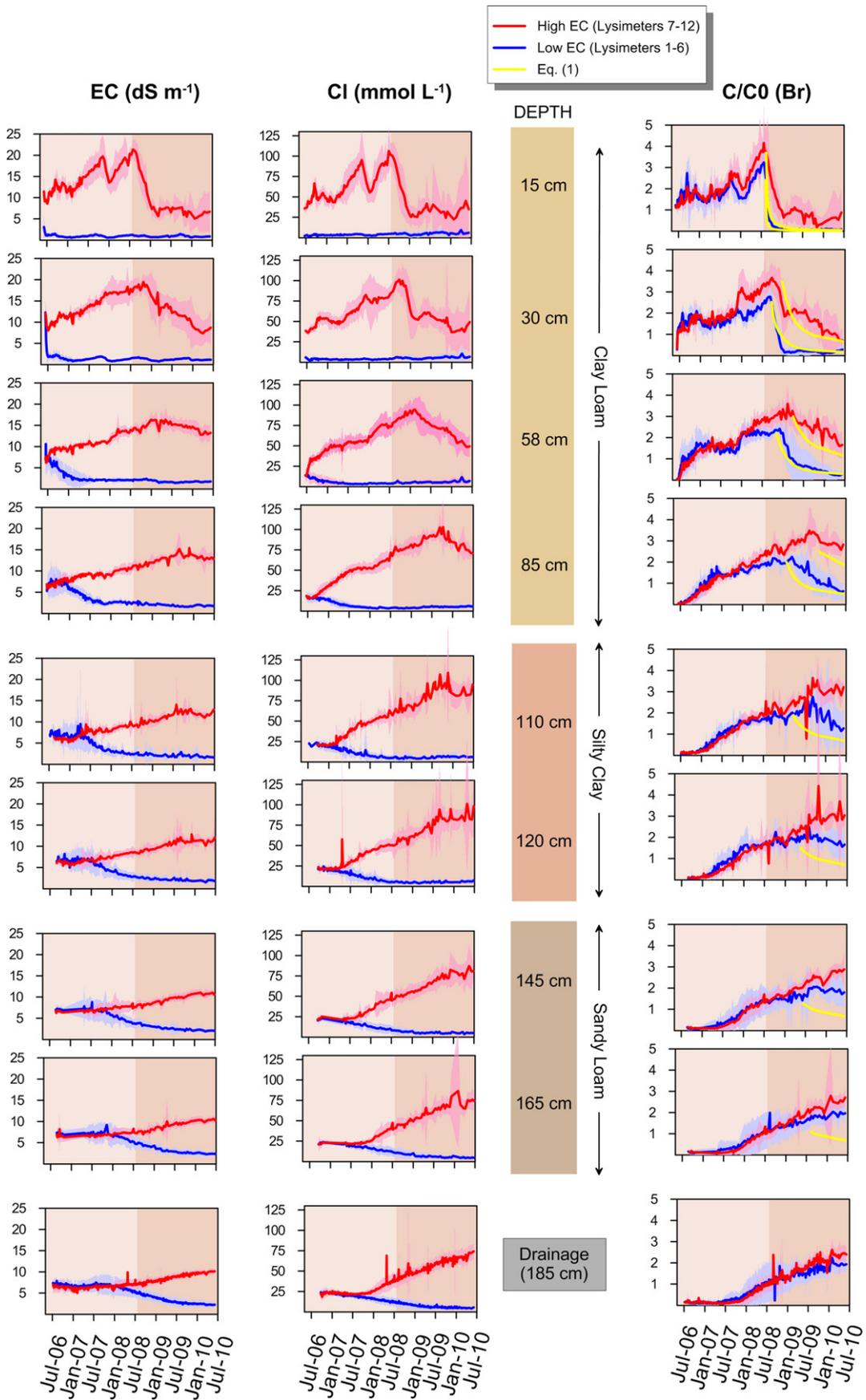


Fig. 4. Measured EC, Cl, and Br breakthrough data for the eight observation depths and drainage water.

(30 mmol L⁻¹), and that the low EC waters had a low Phase 1 Cl concentration (1.3 mmol L⁻¹).

The general trends shown in Fig. 4 for EC and Cl during Phase 1 are as expected. Before irrigation, the EC and Cl concentrations in the soil solution were highly uniform with depth, being about 7 dS m⁻¹ and 22 mmol L⁻¹, respectively. (The plots for the 15 and 30 cm depths appear to show different values at the earliest times, but the first irrigations had penetrated those depths before the samples were collected, so those data are not representative of the initial conditions.) As Phase 1 progressed, EC and Cl increased in lysimeters receiving high EC water and decreased in those receiving low EC water, with the salinizing/leaching front progressing downward over time. However, because of the time-varying net infiltration rate and evapoconcentration noted above, the increases/decreases in concentration were not strictly monotonic during Phase 1. At the 15 cm depth in the high EC lysimeters (red curves), EC and Cl grew to a maximum in November 2007, decreased significantly to a minimum in February 2008, and then increased again through the end of Phase 1 in the Summer of 2008 (Fig. 4). The same variation occurred also in the low EC lysimeters (blue curves), although it is difficult to see at the scale of the plots in Fig. 4. The concentration fluctuations, caused by a decreasing effective inlet concentration during Fall 2007, were mostly damped by the time the water and salts reached the 58 cm depth (Fig. 4).

With the initiation of Phase 2 in August 2008, all lysimeters were irrigated with low EC (0.4 dS m⁻¹) waters (Table 1). The pH irrigation water treatment imposed in Phase 2 (Table 1) did not have an appreciable effect on any data that were measured subsequently, including the soil solution pH. The buffering capacity of the calcareous soil materials was sufficient to raise the pH of the lower pH irrigation water by calcite dissolution and release of alkalinity in the near surface (a forthcoming article will give a detailed accounting of the soil pH measurements). Thus the most significant changes made at the initiation of Phase 2 were the switch to low EC irrigation waters in Lysimeters 7–12 and the switch to waters with negligible Br and B concentrations in all lysimeters.

The general trends shown in Fig. 4 for EC and Cl during Phase 2 are also mostly as expected. In the lysimeters that had been salinized in Phase 1 (red curves), EC and Cl decreased, with the leaching front progressing downward over time, having just reached the middle (silty clay) layer at the end of the study. In the top (clay loam) layer, an initially rapid decrease in EC and Cl was followed by fairly extensive tailing in the breakthrough curves. In the low EC lysimeters (blue curves), leaching continued at the deeper depths, whereas at the shallow depths, where a quasi-equilibrium with the irrigation water had been reached in Phase 1, the concentration was essentially constant, exhibiting relatively minor fluctuations in response to changes in the evapoconcentration rate at the soil surface.

Although the general trends noted thus far were mostly as expected, an examination of the Br tracer data suggests that some transport processes deviated significantly from what would be expected based on transport in an inert rigid porous medium. Recall that during Phase 1, all irrigation waters had the same Br concentration (20 mg L⁻¹). During the first part of Phase 1, Br concentrations increased uniformly across all lysimeters, as expected (Fig. 4). However, during the fall of 2007, the period in Phase 1 in which the time-varying boundary condition led to a brief period of salt leaching near the surface, the Br breakthrough curves measured in the high (red) and low (blue) EC lysimeters diverged at the 15 cm depth, with the mean values becoming statistically significantly different (Fig. 4). After a short period, the Br breakthrough curves tracked each other but remained separated for the remainder of Phase 1. With the initiation of Phase 2, Br was quickly leached from the 15 cm depth in the low EC treatment but significant tailing occurred in the high EC treatments. The same trends occurred

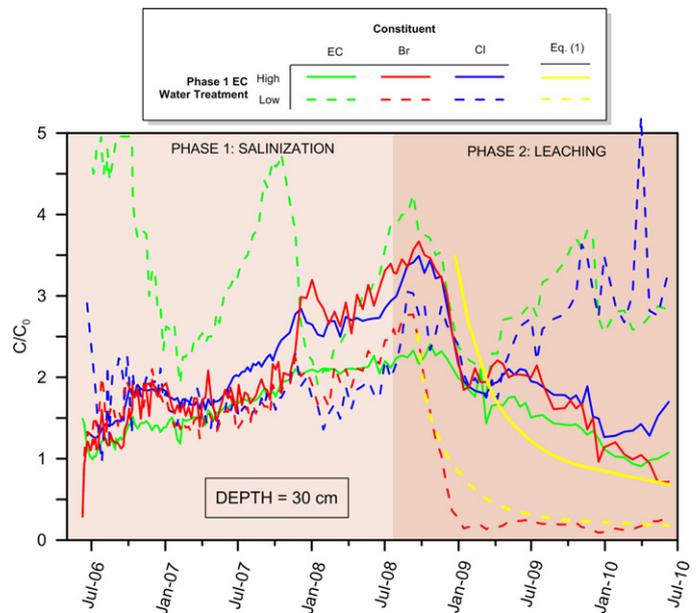


Fig. 5. Measured EC, Cl, and Br breakthrough data for the 30 cm depth.

at deeper depths, with significantly more tailing occurring in the high EC treatments. The B breakthrough curves exhibited a comparable Phase 2 bifurcation between low and high EC treatments (not shown). A detailed analysis of the B transport data in terms of sorption and transport mechanisms will be the subject of a forthcoming publication.

The Phase 2 portions of the Fig. 5 Br plots also show the generalized soil reclamation relationship of Hoffman (1986),

$$\left(\frac{C}{C_0}\right) \left(\frac{d_w}{d_s}\right) = K' \quad (1)$$

where C is (in the present context) the Br concentration, C_0 is the Br concentration at the start of Phase 2, d_w is the depth of net applied water, d_s is the soil depth, and K' is a constant that is related to the leaching efficiency, with a lower K' value corresponding to a higher efficiency. For continuous ponded irrigation, the value of K' has been found to range approximately from 0.1 to 0.45 depending on soil type, with $K' = 0.3$ being typical for clay loam soil (Oster et al., 1999). For intermittent ponded irrigation, a value of $K' = 0.1$ has been shown to describe leaching very well over a range of soil textures (Oster et al., 1999). Sprinkler irrigation, which is perhaps more comparable to the irrigation method used in the present work, was found by Oster et al. (1972) to have a leaching efficiency that was intermediate to that of continuous and intermittent ponding. Fig. 5 shows Eq. (1) plotted for two values of K' , $K' = 0.1$ and $K' = 0.3$. We estimated $d_w(t)$ to be equal to the measured Phase 2 cumulative drainage (Fig. 3). Eq. (1) is applicable (and plotted in Fig. 5) only for $d_w/d_s > K'$.

In the Fig. 5 Br plots, the curves for $K' = 0.1$ fall below those for $K' = 0.3$. At the top four depths, the agreement between the low EC leaching data and Eq. (1) with $K' = 0.1$ is quite good, whereas the high EC treatment data are closer to the curve for $K' = 0.3$, although the agreement is not nearly as good. At the deeper four depths, the agreement with the lower EC data diminishes. Curves for $K' = 0.3$ are not shown at those depths because d_w/d_s was not greater than 0.3. Oster et al. (1972, 1999) note that lower leaching efficiencies (higher K' values) are generally attributable to bypass flow in large cracks and macropores.

Fig. 5 shows a close-up of the dynamics measured at the 30 cm depth. In the figure, each plotted constituent (EC, Br, Cl) is scaled by the respective value of the Phase 1 irrigation water. So, for example,

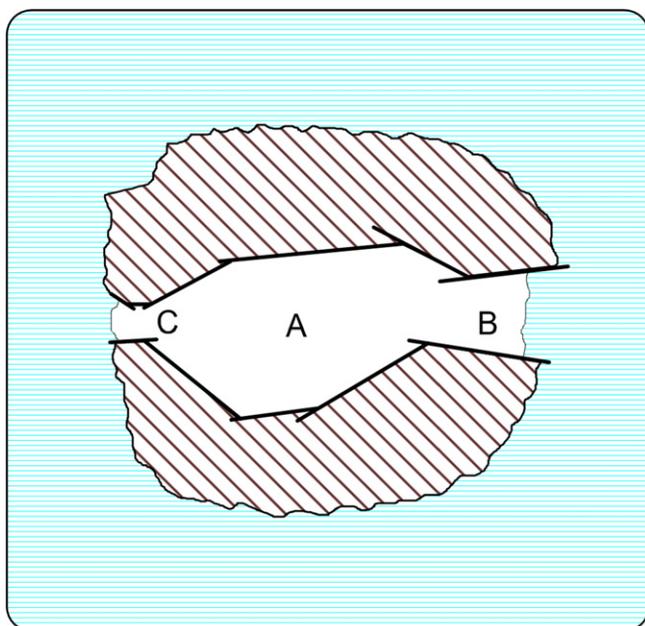


Fig. 6. Diagram of the Blackmore (1976) clay-bounded pore sequence containing salt solution and immersed in water (after Blackmore, 1976).

the average EC measurements for the low EC treatment are scaled by 0.4 dS m^{-1} and those for the high EC treatment by 8.3 dS m^{-1} (Table 1). The EC evapoconcentration fluctuations in the low EC treatments, which were not easy to see in Fig. 4, are clearly visible in Fig. 5.

The percent recovery of the applied Br mass was calculated from the measured Br in the drainage waters and an estimate of the Br contained in the soil based on the Br concentrations measured with the solution samplers. At the end of Phase 1, the calculated mass recovery was about 78% for the high EC treatment and 65% for the low EC treatment. At the end of Phase 2, the values were 90% for the high EC treatment and 47% for the low EC treatment. Calculated estimates for Cl mass balance were comparable: 67% and 73% in the low and high EC treatments, respectively, at the end of Phase 1, and 70% and 80% at the end of Phase 2.

4. Discussion

The most striking experimental results were the observed differences in the measured Br breakthrough curves for the high and low EC treatments. The calculated mass balance was better in the high EC treatment, suggesting possible experimental difficulties with the low EC treatment. In the low EC treatment, where the mass recovery appeared too small, it is possible that salts were being retained in the soil and were not reflected in the solution sampler data.

In soils that have a range of pore sizes, sections of the pore space will be connected to the rest of the pore space by pathways which traverse small pores (e.g., Hunt and Ewing, 2009; Skaggs, 2011). Blackmore (1976) noted that such a pore arrangement could produce a mechanism for salt sieving within clayey soils. To illustrate, Blackmore (1976) considered the two-dimensional pore space diagrammed in Fig. 6. The pore space is assumed to be stable with clay pore faces fixed relative to one another. If the interior pore space labeled “A” in Fig. 6 contained a salt solution and the system were immersed in water, salt would diffuse out of the pore space by passing through the narrow regions labeled “B” and “C”. The extent of an anion exclusion volume at the surfaces of B and C would depend on the salt concentration of the pore water and on

the cation composition of the exchange surfaces and diffuse layers. Blackmore (1976) reasoned that as salts diffused out of the pore and the salt concentration decreased, the diffuse layers would expand and the exclusion volume would increase; if the layers at B and C became large enough to overlap, anions in the pore would be trapped, or sieved.

It is interesting to consider whether a similar mechanism could have contributed to the observed differences in Br transport and to the possible retention of salts in the low EC treatments. The key features of the Br transport data at the shallowest depths were: (1) Br concentrations increased identically for about the first 1.5 years of the study; (2) in the latter part of 2007, during a period of leaching brought about by a diminishing evapoconcentration rate, the Br breakthrough data from the two treatments diverged for the first time; (3) when the irrigation rate was subsequently adjusted and salinization resumed, the Br breakthrough data from the two treatments remained separated but tracked each other for the remainder of Phase 1; and (4) with the initiation of Phase 2, Br decreased readily in the low EC treatments whereas in the high EC treatments an initial rapid decrease in Br was followed by a lengthy period of tailing. At deeper depths, these features were also present, albeit with the expected time-lag and dampening.

A conceptual picture that is consistent with these data is as follows. In both EC treatments, it is likely that a multi-region flow field (e.g., mobile-immobile) existed. Certainly, the tailing seen in the high EC treatments is consistent with multi-region flow. A possible difference, though, was that in the low EC treatment the transition to leaching affected pores connecting mobile and immobile regions, leading to the isolation of salts in immobile regions during leaching. Whereas Blackmore (1976) focused only on fixed, rigid media, we leave open the possibility that in the smectitic soils of the current study some small amount of swelling or particle rearrangement may have also been a factor. Any chemistry induced changes in micropore connectivity or structure were apparently relatively subtle as they did not lead to any differences in the apparent macroscopic water flow properties as evidenced by the drainage data (Fig. 3) and informal visual observations of infiltration (although it should be noted that the low water flow rates may have masked changes in macroscopic hydraulic properties).

In considering the possibility of such a salt sieving mechanism, recall what is known about the effects of irrigation water quality on soil hydraulic properties. Soil hydraulic conductivity and infiltration rates are affected by the amount and types of salt in the pore water and on the clay exchange surfaces. A high percentage of exchangeable Na (ESP) promotes expansion of the double layer and clay swelling, whereas a high salt concentration in the pore water tends to counter those effects. Thus for a fixed ESP, infiltration and hydraulic conductivity generally decrease with a decrease in the EC of the irrigation water.

Irrigation water quality recommendations are often given in terms of combinations of irrigation water SAR and EC values that are expected to avoid damaging soil permeability. However, such recommendations assume the water and soil are in equilibrium, when in fact there is a dynamic aspect to the interactions of irrigation water SAR and EC. When a saline soil is irrigated with low EC water (i.e., when the soil is leached), the pore water EC near the surface tends to drop rapidly while the ESP is slower to react (Oster, 1994; Suarez et al., 2006). If the EC becomes too low relative to the ESP, clay swelling and reductions in permeability can occur.

Although the provided explanation of the data is speculative and cannot be proven, we made some additional measurements that appear qualitatively consistent with the presented theory. If the salt sieving explanation were correct, then significant Br should have remained in the surface soils of the low EC treatments at the end of the experiment in July 2010. In September 2011, we took soil cores through the sidewalls of Lysimeters 6 (low EC) and 12 (high

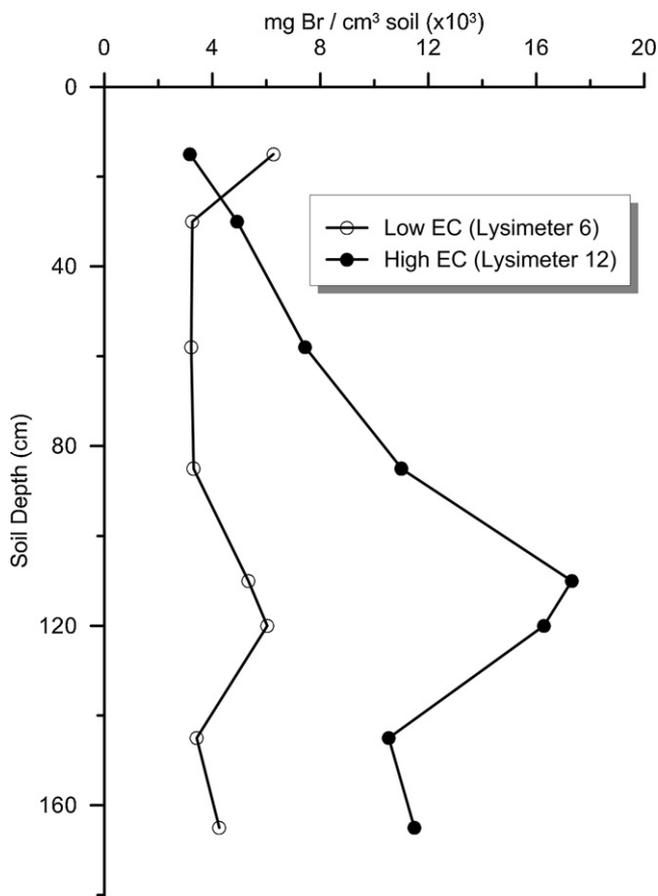


Fig. 7. Soil Br content determined soil saturation extracts.

EC) at the eight observation depths and analyzed the Br content of saturation extracts made from the samples. The results presented in Fig. 7 indeed show that whereas the solution sampler data (Fig. 4) indicated that the Br had long ago leached from the surface depths of the low EC treatment, the saturated extracts found elevated Br concentrations at the 15 cm depth in Lysimeter 6.

A complication in interpreting the extraction data is that between July 2010 and September 2011, the columns were leached with Phase 2 waters for about 8 months and then allowed to dry for several months. Consequently, it is not possible to quantitatively compare the data with solution samples taken at the end of the experiment. However, all lysimeters were treated identically, so it remains significant that an elevated Br concentration existed near the surface of the low EC lysimeter and not in the high EC lysimeter.

Whatever the cause, it is clear that differences in irrigation water chemistry led to very different transport behavior in the two sets of lysimeters. Because of the replicated experimental design, it was possible to verify that observed differences were significant and not the result of (apparently) random variation that will be present in transport in any relatively large volume of soil.

Many of the transient-state simulation models noted above have provisions for bypass or multi-region flow and transport, and it is likely that by adjusting certain model parameters, it would be possible to reproduce the observed tracer transport. It is not clear, however, whether it would ever be possible to quantitatively predict the transport behavior without calibration, which is not realistic for routine salinity management. When used in a purely predictive mode, transient-state model predictions will invariably carry significant uncertainty. Future research aimed at putting realistic confidence levels on model predictions would greatly enhance

the potential use of transient-state model as a management and decision support tools.

5. Summary and conclusions

Transient-state model analyses offer the possibility of more efficient water and salinity management, but data are needed to evaluate the accuracy of various subcomponents of the models, including solute transport in clayey, salt-affected soils.

Twelve large lysimeters identically packed with layered, homogenized clayey soil materials were irrigated in two phases. In the first (or salinization) phase, half the lysimeters were irrigated with high EC water (8.3 dS m^{-1}) and half with low EC water (0.4 dS m^{-1}). Both irrigation waters contained the same amount of Br tracer. In the second phase, all lysimeters were leached with low EC water (0.4 dS m^{-1}) containing negligible Br tracer. The soil solution concentration was monitored throughout the experiment at eight soil depths and in the drainage waters.

Br leaching during Phase 2 was very different in the high and low EC irrigation treatments. In the low EC treatment, Br appeared to leach relatively easily, with the decrease in concentration being in fairly good agreement with the prediction of a general soil reclamation equation. However, there was some indication that salt may have been held up in the soil and was not reflected in the leaching data. The apparent Br leaching in the high EC treatment was much slower, with the Br breakthrough curves exhibiting significant tailing. Due to the replicated experimental design (unusual in solute transport experiments), it was possible to confirm that the differences between the experimental treatments were significant and not due to random deviation.

Solute transport in clayey soils is highly complex due to the effects of charged clay particles on solute mobility, and consequently model predictions will always carry significant uncertainty. Future research aimed at placing realistic confidence level on model predictions will allow transient-state models to reach their full potential as water and salinity management tools.

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