

## REDUCING MASS FLUX OF DRAINAGE SALTS

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### ABSTRACT

Irrigation of arid and semi-arid agricultural regions has produced salinization and waterlogging problems. Tile drainage systems will effectively lower the water table and transport salts out of the root zone. However, the salts exiting the irrigated soils via drains cause new problems, such as reducing groundwater quality and damaging wetlands habitat. This research investigates the simulation of management alternatives that control drainage and the mass flux of salts in the drainage water and demonstrates an improvement over the use of leaching fraction and leaching requirement as conceptual models.

HYDRUS\_2D, a two-dimensional Windows-based modeling environment, is used to simulate solute transport under the influence of alternative irrigation management practices for an alfalfa crop. HYDRUS\_2D uses a finite element technique that numerically solves the Richards equation for saturated/unsaturated flow, and the Fickian-based advection/dispersion equation for solute transport in variably saturated porous media. The response to management alternatives (depth of irrigations, using water sources of varying quality in irrigating a soil with varying salinity) allows managers to evaluate the influences on the mass flux of salts in drainage water before they put a new approach into practice. The results include graphical displays of water and solute fluxes and the salt distribution in the upper soil profile.

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## INTRODUCTION

The 1902 Reclamation Act created many western water projects, one of which is the Newlands Project. The goal of the Newlands Project was to "reclaim" arid lands in west central Nevada for human use. Construction of the Lahontan Dam created the Lahontan Reservoir that stores flows from the Carson and Truckee Rivers. Once the canals were in place, farmers began irrigating formerly non-productive lands with the high-quality river water. Irrigation dramatically raised the water table, creating salinity and waterlogging problems. Evapoconcentration increases the salinity in the root zone. Water above and beyond the crop's water requirements leaches salts out of the root zone, but increases drainage volumes and solute mass fluxes (Postel, 1999). Drain effluent and canal seepage water discharge into the neighboring Stillwater Marsh and Carson Lake wetlands. The canal diversions have not only reduced the quantity of water reaching the wetlands, but also the quality of the wetlands waters (Chambers and Guitjens, 1992).

## OBJECTIVES

The objective is to quantify and to demonstrate with HYDRUS\_2D the solute flux and the salt distribution in the soil profile under various irrigation management strategies.

## BACKGROUND

### NARC Site

In 1977, a system of perforated tile drains was installed in an experimental field at the Newlands Agricultural Research Center (NARC), with the twin goals of reducing the height of the water table and removing leached salts. The NARC study site is located in Fallon, Nevada, in the Lahontan Valley (Fig.1). The Carson Desert is a mid-latitude desert with cold winters and hot summers. The area receives an average of about 13 cm of natural precipitation annually, far less than the amount needed for crop production.

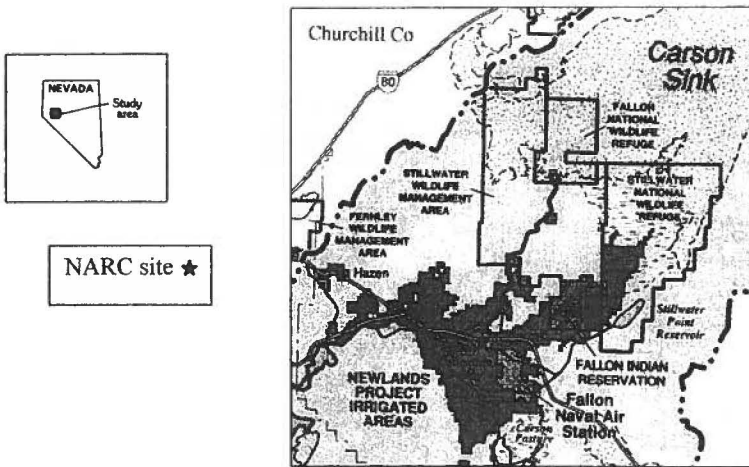


Fig.1. Location of Newlands Agricultural Research Center, Fallon, Nevada (Trionfante and Peltz, 1994)

The Carson Desert, a typical closed basin, is composed of mostly late Tertiary and Quaternary deposits, and lacustrine sedimentary deposits. These valley sediments were derived from the surrounding NE-trending fault-block mountains composed predominantly of olivine-basalts, rhyolites, hornblende and pyroxene andesites, mostly occurring as tuffs (Willden and Speed, 1974). They are easily weathered, contributing to the rapid salt dissolution. Glancy (1986) identified 4 principal aquifers based on chemical properties and physical boundaries (Fig. 2). The figure illustrates the interconnectedness of the aquifer system, and the close proximity to the wetlands.

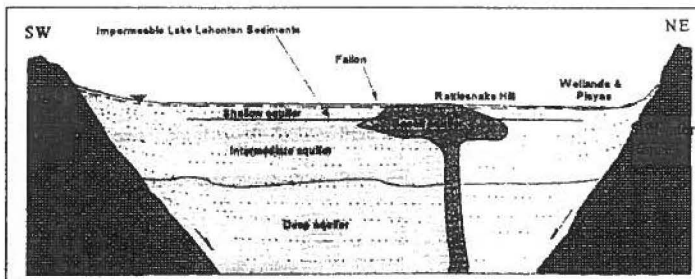


Fig. 2. Vertical Cross-Section of the Lahontan Valley Aquifer System

Three of the four aquifers are highly variable sedimentary (alluvial) formations found at shallow (0-15 m), intermediate (15-300 m), and greater (below 150 to 300 m) depths. The fourth aquifer is a mushroom-shaped basalt formation, 60-300 meters deep that is surficially exposed at Rattlesnake Hill. All four are interconnected and function as a single system, though each has distinct hydraulic and solute transport properties. The shallow aquifer is maintained by irrigation drainage.

### Field, Drains and Borehole Sampling

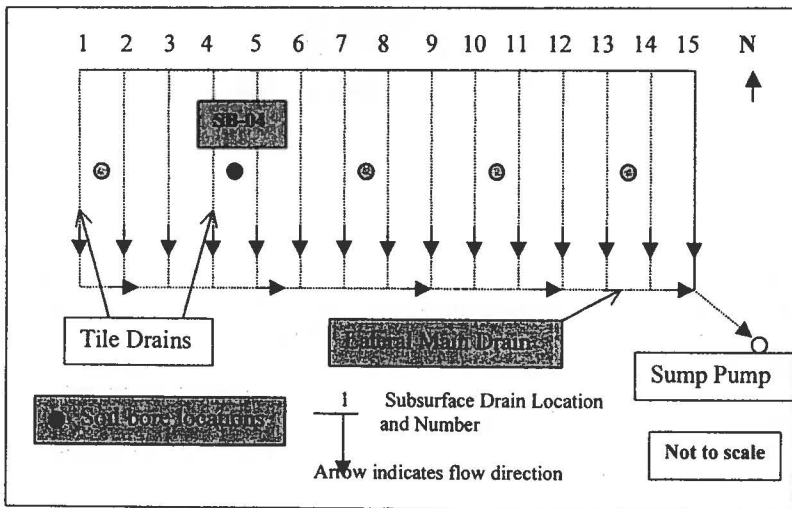


Fig. 3. Plan View of NARC Field

The study site (Fig. 3) consists of a 22-acre field, drained by a system of 15 perforated tile drains, 10 cm in diameter, spaced 37 meters apart at a 2-meter depth. The 15 drains connect to a lateral main drain that discharges into a sump. Five soil borings were drilled in the field in 1994 to average depths of 22 m. The borings were located along the east-west centerline and extended through the shallow aquifer and into the lower confining unit. Soil borings were evaluated for texture and salinity (Mathis, 1995). From the results the field depth was partitioned into 8 distinct soil layers.

### Solute Transport

Salts are primarily transported with moving water. It is assumed that they do not sorb onto mineral surfaces to change their relative concentrations in the profile. Two processes for moving solutes are diffusion and advection. Diffusion occurs as waters of varying concentration mix and seek equilibrium (Fetter, 1994). Steady state diffusion follows Fick's First Law (Eq. 1), and for systems where the concentrations are changing over time diffusion follows Fick's Second Law (Eq. 2).

$$F = -D (dC/dx) \quad (1)$$

$$\delta C/\delta t = D \delta^2 C/\delta x^2 \quad (2)$$

F is the mass flux of solute ( $ML^{-2}t^{-1}$ ), D is the diffusion coefficient ( $L^2t^{-1}$ ),  $dC/dx$  is the concentration gradient ( $ML^{-3}L^{-1}$ ),  $\delta C/\delta t$  is the change in concentration over time ( $ML^{-3}t^{-1}$ ) and  $\delta^2 C/\delta x^2$  is the change in the concentration gradient.

Advection is the process by which moving water carries with it dissolved solutes. Equation 3 shows the advection form of Darcy's Law.

$$v_x = (K/\theta) dh/dl \quad (3)$$

The darcy velocity  $v_x$  is the average linear velocity of the water ( $L t^{-1}$ ), K is the hydraulic conductivity of the medium ( $L t^{-1}$ ),  $\theta$  is the volumetric water content ( $L^3 L^{-3}$ ), and  $dh/dl$  is the hydraulic gradient. Mechanical dispersion caused by soil heterogeneity further complicates the modeling of solute transport problems. SWMS\_2D (Simunek et al., 1996), the source code for HYDRUS\_2D, combines three factors into the dispersion tensor,  $D_{ij}$  (Eq. 4).

$$\theta D_{ij} = D_T |q| \delta_{ij} + (D_L - D_T) q_i q_j / |q| + \theta D_d \tau \delta_{ij} \quad (4)$$

$\theta$  is the volumetric water content ( $L^3 L^{-3}$ ),  $D_T$  and  $D_L$  are the transverse and longitudinal dispersion coefficients ( $L$ ), respectively,  $q$  is the fluid flux ( $L t^{-1}$ ),  $\tau$  is the tortuosity factor ( $-$ ),  $D_d$  is the molecular diffusion coefficient ( $L^2 t^{-1}$ ), and  $\delta_{ij}$  is the Kronecker delta function.

Total dissolved solids (TDS) were modeled. Electrical conductivity (EC) in  $dS m^{-1}$  was converted to  $mg L^{-1}$  (Eq. 5) (Bohn et al., 1985).

$$640 \text{ EC } (dS m^{-1}) = \text{TDS } (mg L^{-1}) \quad (5)$$

In HYDRUS\_2D the units were converted to  $cm^3 L^{-1}$ .

## METHODS

The irrigation manager must balance several competing goals: minimizing water usage, drainage (both water and salts), salt accumulations in the root zone (beyond the crop's tolerance levels) and decline in quality of groundwater supplies and degradation of wetlands habitats.

### Conceptual Model

The leaching fraction (LF) and leaching requirement (LR) conceptually calculate the amount of water needed beyond the plants' ET requirements for a steady state salt balance and leaching salts out of a specific crop's root zone, respectively (Eqs. 6 and 7).

$$LF = D_d / D_i = EC_i / EC_d \quad (6)$$

$$LR = D_d^* / D_i = EC_i / EC_d^* \quad (7)$$

$D_d$  = depth of drainage water (cm) and  $D_i$  = depth of irrigation water (cm);  $EC_i$  = EC of the irrigation water ( $\text{dS m}^{-1}$ );  $EC_d$  = EC of the drainage water (Hoffman, 1990); and  $D_d^*$  is the depth of drainage based on the crop salt tolerance threshold ( $EC_d^*$ ). The conversion to  $EC_d^*$  is shown in Eq. 8.

$$EC_d^* = (5 EC_e) - EC_i \quad (8)$$

$EC_e$  = EC of the soil water extract ( $\text{dS m}^{-1}$ ).

### Physical Model

Figure 4 shows a vertical cross-section of the simulated profile, with drain and piezometer locations, soil layers and boundary information. The physical model is based upon a half-drain spacing between two parallel drains, assuming a mirror image to the left of the drain (Guitjens, 1999). The half-width was 1850 cm and the half-drain size 5 cm by 10 cm. The depth of the modeled profile was 2195 cm. The soil layers reflect the bore hole information. A ninth material (loamy sand) was added around the drain to simulate the backfill material (identified in Fig. 4 as the drain box). It measures approximately 24 cm by 54 cm.

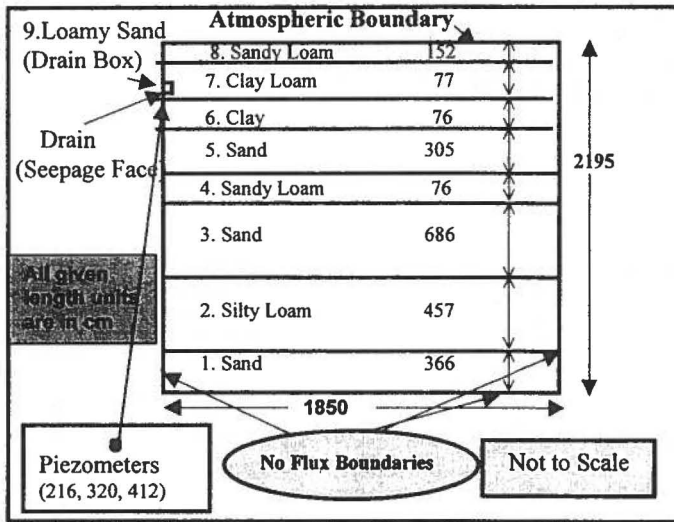


Figure 4. Soil Profile Vertical Cross-section

The mesh generator in HYDRUS\_2D created a triangular element mesh composed of 3989 points, 11762 edges, and 7774 triangles. HYDRUS\_2D solved the groundwater flow and solute transport equations at each node at incremental time steps.

Irrigation and evapotranspiration (ET) occurred across the surface boundary. The drain was modeled as a seepage face boundary, which allows water to move into the drain. The remaining three profile boundaries (the two vertical sides and the bottom) were designated as no flux boundaries. The left vertical boundary was chosen as no flux because it was assumed the flow paths on one side of the drain are mirror images of the flow paths on the other side of the drain. The other vertical boundary was chosen as a no-flux boundary because of the groundwater divide created by the midpoint of the flow patterns between two adjacent drains, again assuming identical conditions exist on either side of this groundwater divide.

The model simulated a root zone depth of 130 cm. Initial ( $t=0$ ) pressure head distribution was based on simulating a water table at 130 cm ( $h = -130$  cm at the surface,  $h = 0$  cm at the 130 cm depth, and  $h = 2065$  cm at the bottom of the profile). The pressures were linearly distributed throughout the profile. Initial

profile salinity ( $EC_e$ ) of the 8 layers originated from bore log data (Mathis, 1995). The observation nodes at 216, 320, and 412 cm depths below ground surface simulated the depths of the field piezometers (Pohll and Guitjens, 1994). Table 1 shows the HYDRUS\_2D catalog of those soils that were identified in the 1994 bore log and the hydraulic parameters and values. The final column in Table 1 lists the layers in the soil profile.

Table 1. Soil Profile and Hydrologic Parameters

| Soil Type  | $\theta_r$ | $\theta_s$ | $K_s$ (cm hr <sup>-1</sup> ) | Profile layer |
|------------|------------|------------|------------------------------|---------------|
| Sand       | 0.045      | 0.43       | 29.700                       | 1, 3, 5       |
| Loamy sand | 0.057      | 0.41       | 14.592                       | 9             |
| Sandy loam | 0.065      | 0.41       | 4.421                        | 4, 8          |
| Clay loam  | 0.100      | 0.39       | 1.310                        | 7             |
| Silty loam | 0.034      | 0.46       | 0.250                        | 2             |
| Clay       | 0.070      | 0.36       | 0.020                        | 6             |

The default HYDRUS\_2D values for the Feddes Root Water Uptake Parameters were changed to allow water to be fully taken up by plant roots and thereby allowed the simulations to run to completion.

### Irrigation Schedule

A one-year irrigation and ET schedule was put into a time-variable boundary record (TVBR) table of HYDRUS\_2D. For the growing season, March 16–October 11, time steps of 12 hours allowed the depths of evapotranspiration, irrigation and natural precipitation ( $D_{et}$ ,  $D_i$  and  $D_n$ , respectively) to be evenly spread over 12 hours, the ET occurring during daylight hours. The dormant season, October 12–March 14, began at  $t=5148$  hours. Time steps of 168 hours allowed the weekly  $D_{et}$  and  $D_i$  to be evenly spread over 168 hours. The final day of the dormant season, March 15, completed the full-year schedule, for a total of 8868 hours. The concentration of the irrigation water ( $C_i$ ) was initially set at 0.25 mg cm<sup>-3</sup>. The  $D_{et}$  was based on Eq. 9 (Guitjens, 1987). Reference ET ( $ET_o$ ) values were based on measured Class A pan evaporation adjusted for wind speed and relative humidity.

$$D_{et} = K_{crop} ET_o \quad (9)$$

Site-specific crop coefficients ( $K_{crop}$ ) were from Guitjens (1987). The TVBR consisted of 446 time periods for a 5148-hour growing season schedule.

### Model Calibration and Sensitivity Analysis

The model was calibrated to the piezometer data of Pohll and Guitjens (1994). Calibration was accomplished by comparing field and modeled-output pressures. Hydraulic parameters of layers 6, 7 and 8 (those closest to the drain) were adjusted to obtain an acceptable agreement. After calibration, a sensitivity analysis was performed to determine the response to changes in  $D_i$  and  $D_{et}$ . The "best" schedule for meeting the ET allowed for approximately a 25% LF and became the basis for all subsequent simulations of management alternatives.

### Management Scenarios

In order to minimize drainage effluent and mass salt flux in the drainwater, four alternative irrigation management practices were considered. The management alternatives included varying  $D_i$  and  $C_i$ .

Table 2. Management Alternatives and Initial Conditions

| Mgmt.<br>Alt.<br>(#) |                                  |                  |                                     | Initial conditions (I.C.) ( $\text{mg cm}^{-3}$ ) |                         |                         |
|----------------------|----------------------------------|------------------|-------------------------------------|---------------------------------------------------|-------------------------|-------------------------|
|                      | $C_i$<br>( $\text{mg cm}^{-3}$ ) | $D_i$<br>(ratio) | $C_{sw}$<br>( $\text{mg cm}^{-3}$ ) | Layer 8<br>G.S. to 152cm                          | Layer 7<br>153 to 229cm | Layer 6<br>230 to 305cm |
| 1                    | 0.25                             | $1.00D_i$        | I.C.                                | 0.576                                             | 0.768                   | 0.640                   |
| 2                    | 2.50                             | $1.00D_i$        | I.C.                                | "                                                 | "                       | "                       |
| 3                    | 0.25                             | $0.75D_i$        | I.C.                                | "                                                 | "                       | "                       |
| 4                    | 2.50                             | $0.75D_i$        | I.C.                                | "                                                 | "                       | "                       |

For example, the first irrigation application of the season (at  $t=324$  hrs.) was 22.86 cm; this amount exceeded the  $D_{et}$ , the remainder going to  $D_d$ . To decrease drainage  $D_i$  was multiplied by 0.75, yielding 17.15 cm.

## RESULTS AND DISCUSSION

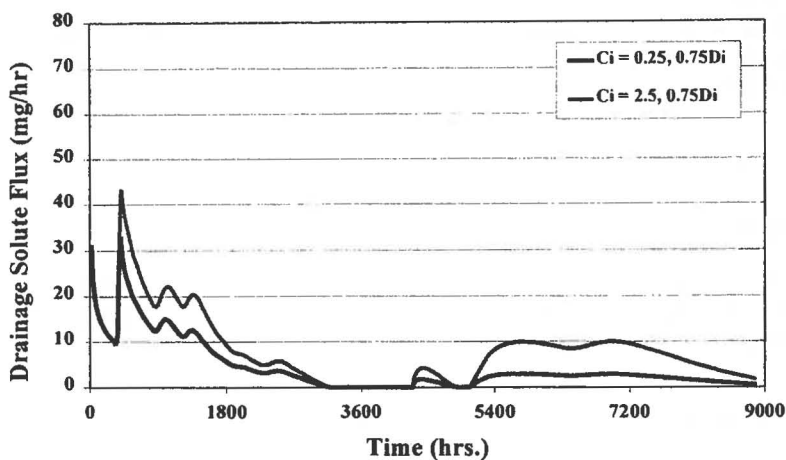


Fig. 5. Drainage Solute Flux for  $C_i = 0.25$  and  $2.50 \text{ mg cm}^{-3}$  and  $0.75D_i$

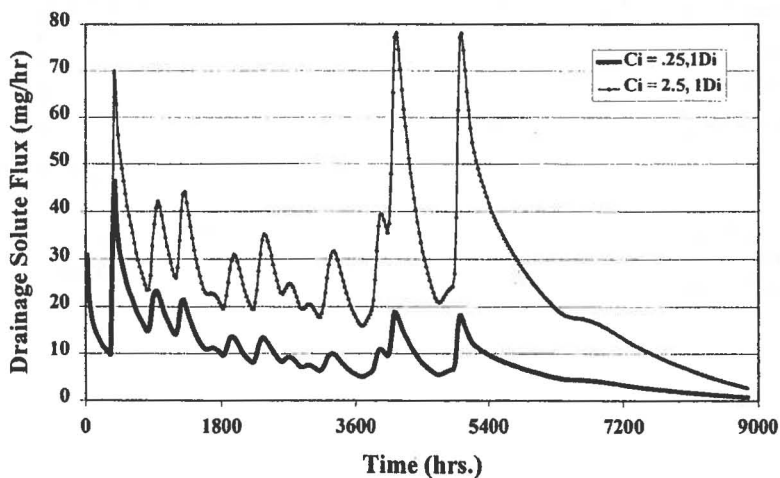


Fig. 6. Drainage Solute Flux for  $C_i = 0.25$  and  $2.50 \text{ mg cm}^{-3}$  and  $1.00D_i$

Figures 5 and 6 illustrate the effects of  $C_i$  and  $D_i$  on the drainage solute mass flux. Comparing Figs. 5 and 6, the  $1.00D_i$  increased the drainage solute flux and the peaks at irrigation events. Furthermore, the effect of  $C_i = 2.50$  was very pronounced. Fig. 7 shows the changes in  $C_{sw}$  at the beginning of the season ( $t=0$  hrs.), at the end of the growing season ( $t=5148$  hrs.) and at the end of the year ( $t=8800$  hrs.) for two  $D_i$  levels. More leaching occurred for  $1.00D_i$ . The concentrations in the unsaturated zone are also affected by the water content.

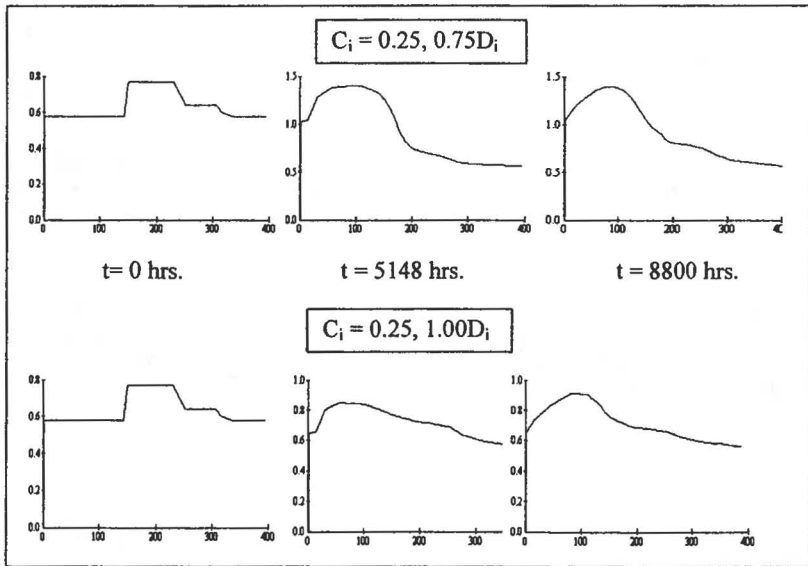


Fig. 7.  $C_{sw}$  along a line 18 cm parallel to the left vertical boundary from the soil surface to a depth of 400 cm, for  $0.75D_i$  and  $1.00D_i$ , at  $C_i = 0.25 \text{ mg cm}^{-3}$ , at  $t = 0, 5148$  and  $8800$  hrs.

The same trend also occurred when  $C_i$  was increased to  $2.50 \text{ mg cm}^{-3}$  (Fig. 8). These trends follow the trends of Rhoades and Loveday (1990).

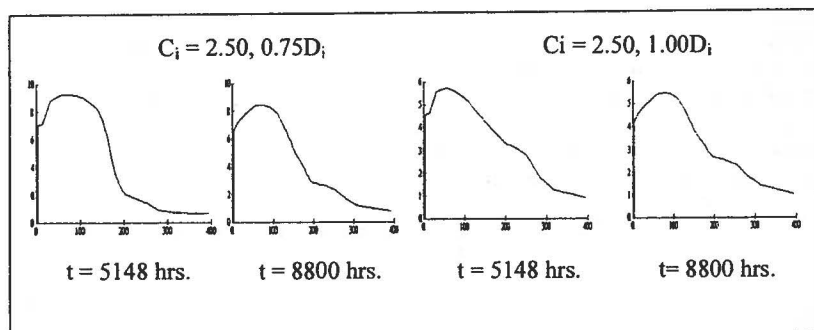


Fig. 8.  $C_{sw}$  along a line 18 cm parallel to the left vertical boundary from the soil surface to a depth of 400 cm, for  $0.75D_i$  and  $1.00D_i$ , at  $C_i = 2.50 \text{ mg cm}^{-3}$ , at  $t = 5148$  and  $8800$  hrs.

Figure 8 shows similar trends for  $C_i = 2.50$ , but note the dramatic increase in  $C_{sw}$ . After just one season of applying saline water ( $C_i = 2.50$ ), the salinity in the root zone was high enough to reduce the yields of most alfalfa crops by 80% or more (Rhoades and Loveday, 1990).

## CONCLUSIONS

HYDRUS\_2D was used to demonstrate the effects of management changes in irrigation quantity and salinity on solute flux and the salt distribution in the upper soil profile. This approach differs from the concepts LF and LR. HYDRUS\_2D, a physically-based model, provides a simulation technique that allows more realistic manager-control of drainage quantity and salinity.

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