Prediction and Control of Salt Accumulation in the Upper Root Zone Under Sub-Surface Drip Irrigation

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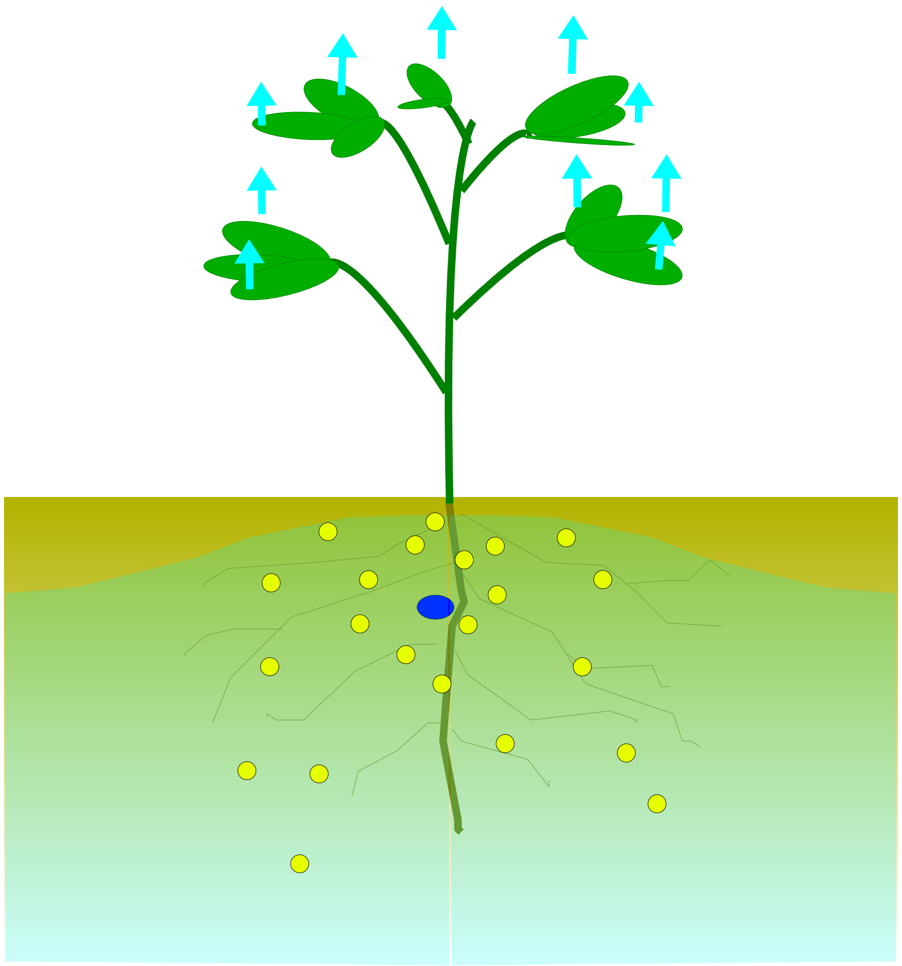
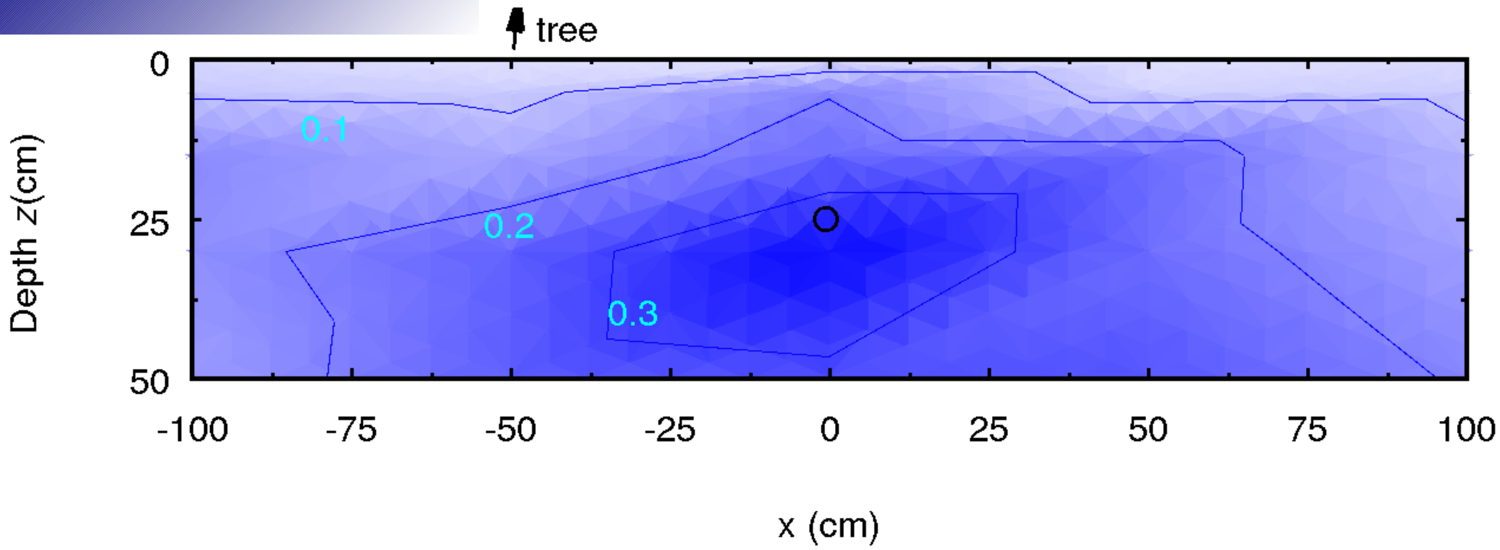
Introduction

Sub-surface drip irrigation (SSDI) is expected to play a key-role in arid regions as the ultimate water saving method.

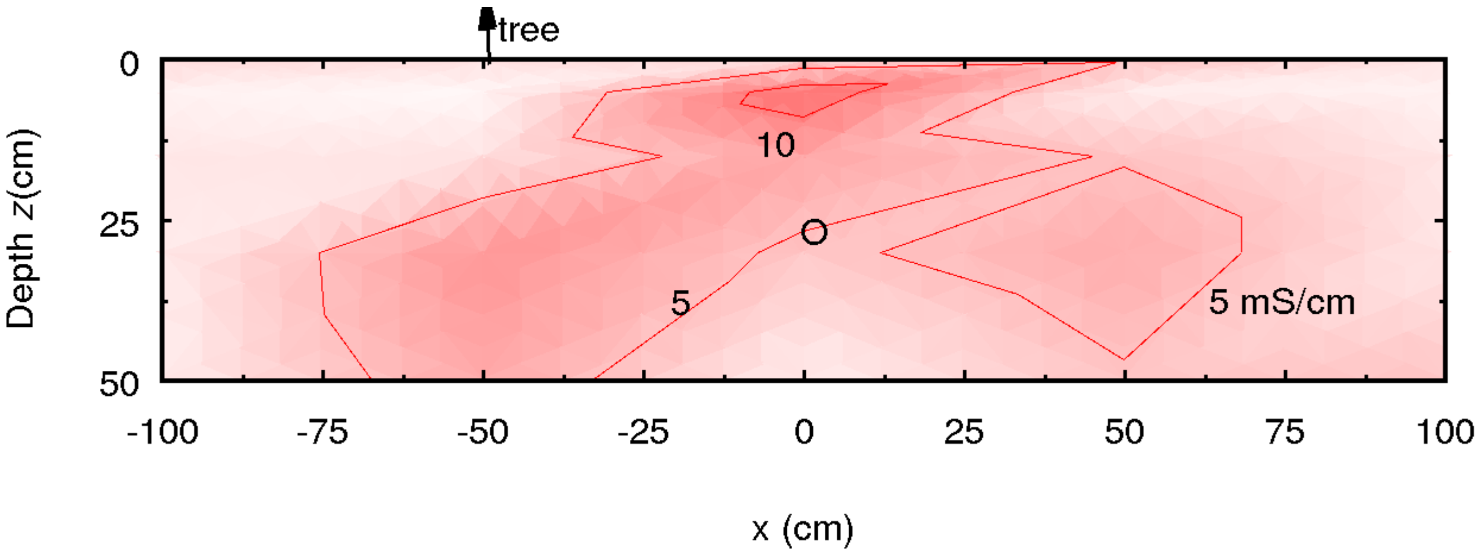


One of the drawback of SSDI: the accumulation of salt to the upper root zone and it cannot be leached out by water from emitter.

Introduction



Distribution of volumetric water content under subsurface drip irrigation in almond field (under vital tree) at Sa'as kibutsu, Israel



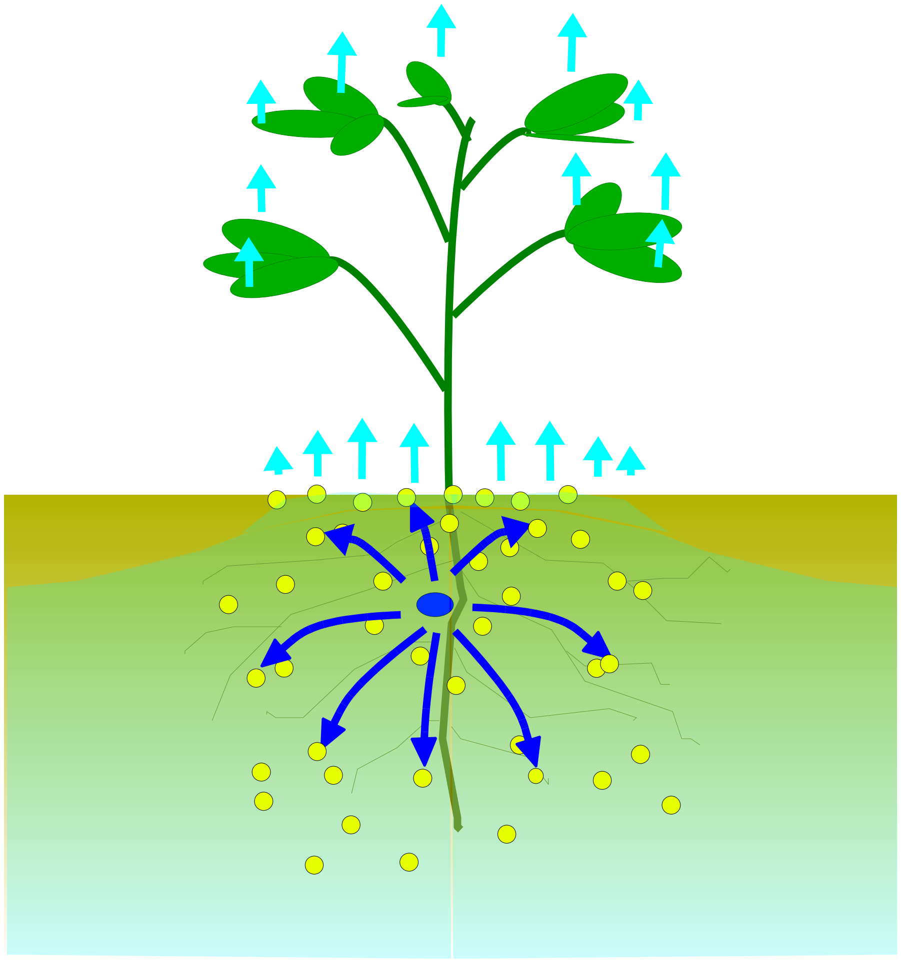
Distribution of electrical conductivity of saturated extract under subsurface drip irrigation in almond field (under vital tree) at Sa'as kibutsu, Israel

Introduction

Upward Leaching Method

1. Application of much water enough to make wetting front reach to the soil surface

2. Scraping of surface layer after salt accumulates due to evaporation



Objectives

- To develop a simulation model for predicting salt accumulation and leaching under sub-surface drip irrigation: i. e. two dimensional movement of water, heat and solute as well as evapotranspiration and root water uptake, considering the water vapor movement and effect of salt crust on evaporation.

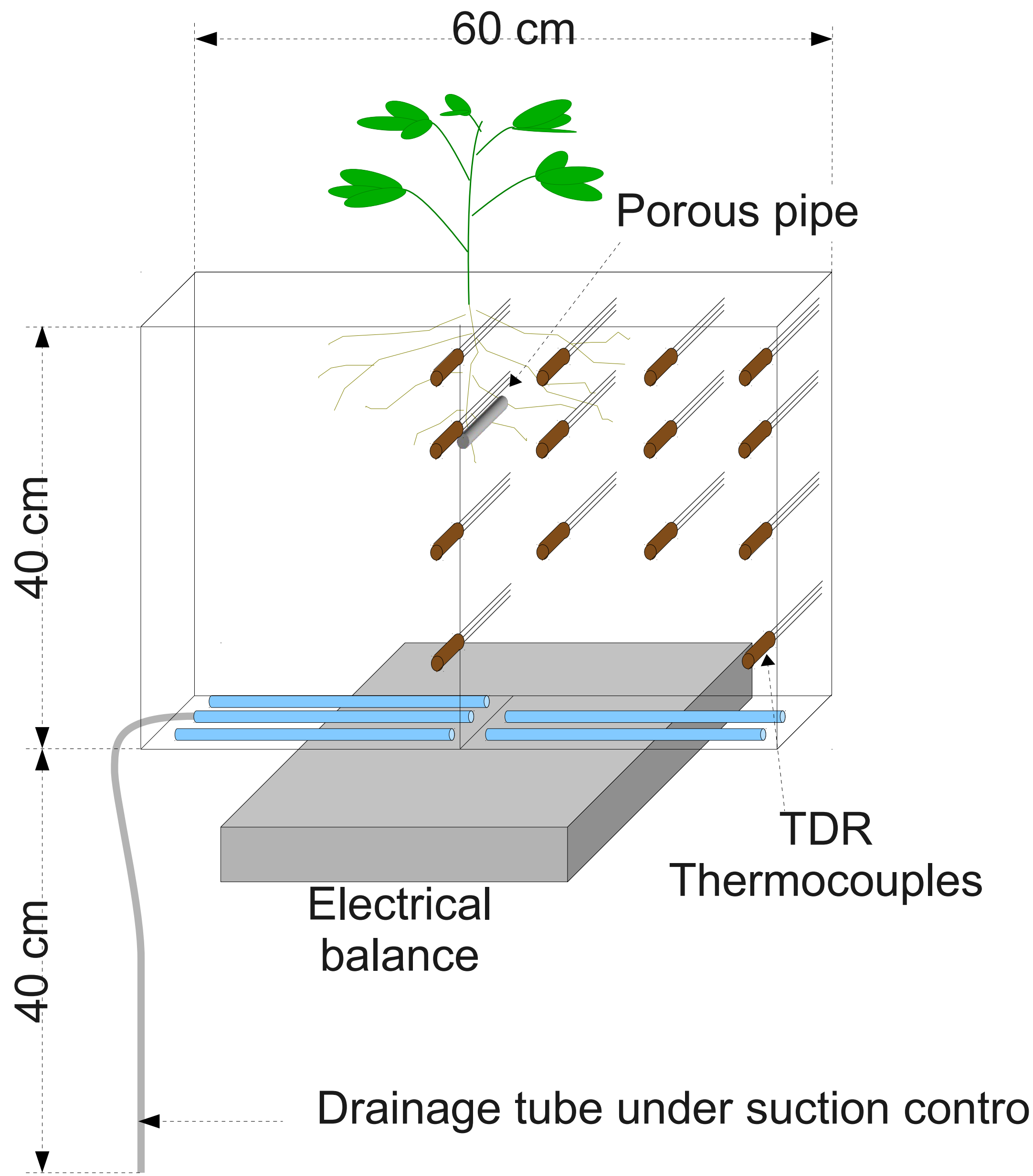
- To test the validity of the model by comparison with experimental results

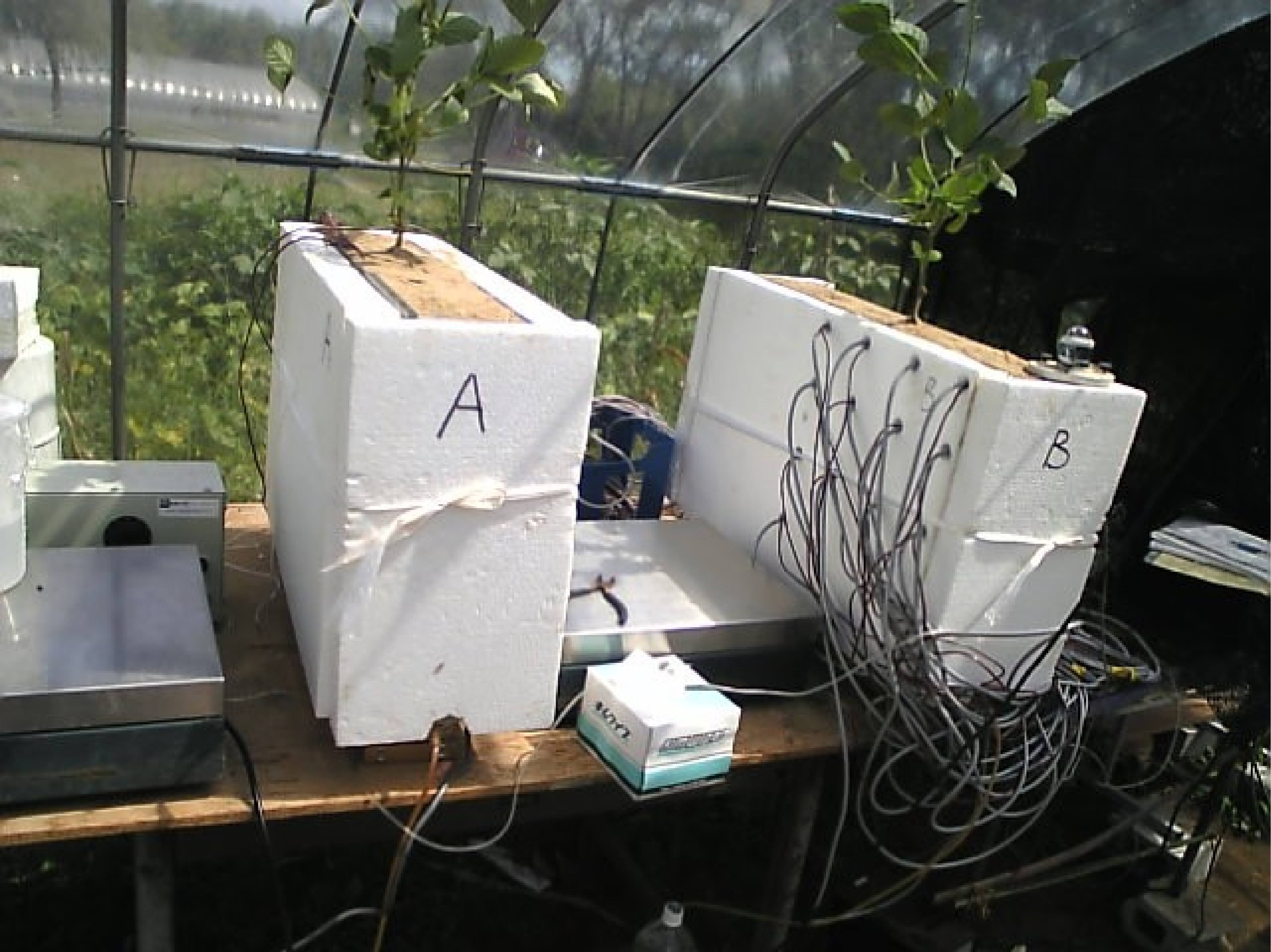
- To evaluate the upward leaching method to remove accumulated salt in the upper root zone.

Materials and Methods

soil: Masa loamy sand
placed in a greenhouse
plant: soybean

7/16: seeding
8/15: saturation with tap water
9/ 1: irrigation with 5000ppm $CaCl_2$ solution started
irrigation depth = ET
9/25: upward leaching with 1.7 cm
10/1: scraping and sampling




A
B

Numerical Simulation

Governing equation for water flow

$$\frac{\partial \theta}{\partial t} = -\left(\frac{\partial q_{lx}}{\partial x} + \frac{\partial q_{lz}}{\partial z}\right) - \left(\frac{\partial q_{vx}}{\partial x} + \frac{\partial q_{vz}}{\partial z}\right) + S$$

$$q_{lx} = -K \frac{\partial \psi}{\partial x}$$

$$q_{lz} = -K \left(\frac{\partial \psi}{\partial z} - 1\right)$$

$$q_{vx} = -a \tau \rho_w^{-1} h_r D_{va} \left\{\frac{\rho_v *}{R_v T_s} \frac{\partial \psi_w}{\partial x} + \eta \frac{\partial \rho_v *}{\partial T_s} \frac{\partial T_s}{\partial x}\right\}$$

$$q_{vz} = -a \tau \rho_w^{-1} h_r D_{va} \left\{\frac{\rho_v *}{R_v T_s} \frac{\partial \psi_w}{\partial z} + \eta \frac{\partial \rho_v *}{\partial T_s} \frac{\partial T_s}{\partial z}\right\}$$

θ: volumetric water content
q_l : liquid water flux (cm/s)
q_v : water vapor flux (cm/s)
K: hydraulic conductivity (cm/s)
ψ: pressure head (cm)
ψ: matric potential (cm)
ψ_w: water potential(cm)
a: air-filled porosity
τ: tortuosity
D_{va} : water vapor diffusion coefficient in air (cm²/s)
η: enhancement factor for thermal vapor diffusion
T_{ls}: soil temperature (K)
ρ_v^* : saturated water vapor density (g/cm³)
h_r : relative humidity
R_v : the gas constant for water vapor (4697 cm/K)
S : root water uptake (s^{-1})

Numerical Method: Alternative Direction Implicit FDM (ADI) with Celia(1990)'s mass-conservative iteration scheme

Transpiration Rate

Potential Transpiration Rate (T_{rp})

$$T_{rp} = W\, E_p\, K_c$$

W: width of the target region (cm)

E_p: ET by Penman equation (cm/s)

K_c: crop coefficient for transpiration

$$K_c = a_{kc}[1 - \exp(b_{kc} \Sigma T\, dt)] + c_{kc}$$

a_{Kc}, b_{Kc} : plant-specific parameters

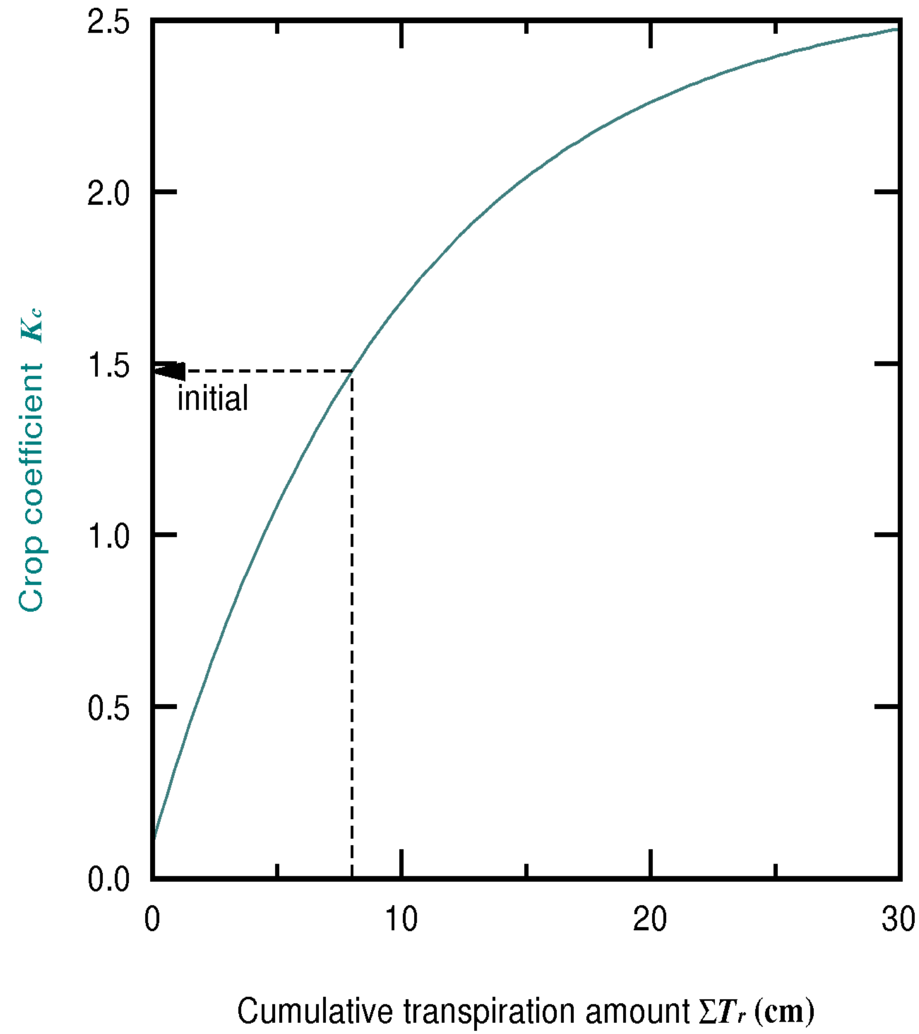
Actual Transpiration Rate (T_r)

$$T_r = \int_0^{drt} \int_0^{W} S\, dxdz$$

$$S = T_{rp}\, \beta\, \alpha_w\, \alpha_s$$

α_w: reduction coefficient for water stress

α_s: reduction coefficient for salinity stress



Crop coefficient as a function of cumulative transpiration amount

Root Water Uptake

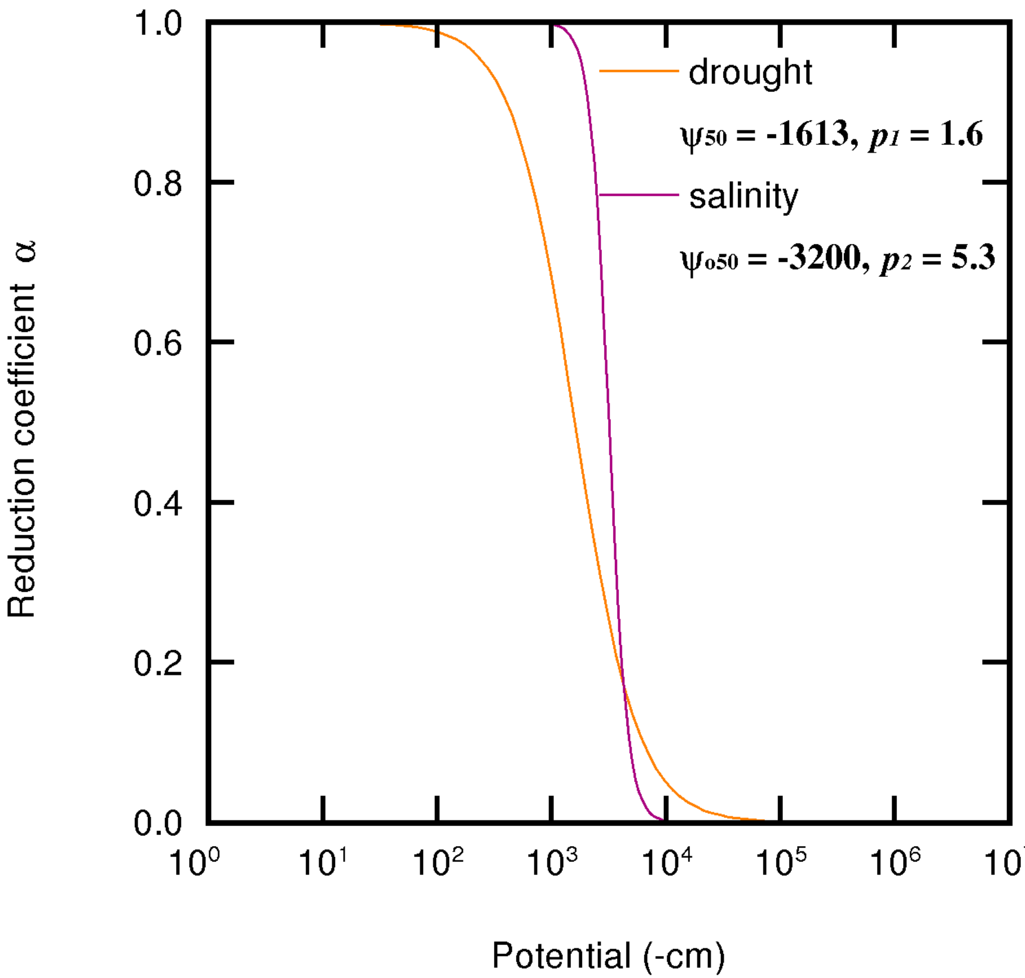
van Genuchten's response function (1987)

$$\alpha = \alpha_w \alpha_s = \frac{1}{1+\left(\frac{\psi}{\psi_{50}}\right)^{p_1}} \times \frac{1}{1+\left(\frac{\psi_o}{\psi_{o50}}\right)^{p_2}}$$

fitting parameters

reduction due to salinity stress

reduction due to water stress



Drought and salinity stress response function for soybean

Governing equation for solute movement

$$\frac{\partial(\theta c)}{\partial t} = -\left(\frac{\partial q_{sx}}{\partial x} + \frac{\partial q_{sz}}{\partial z}\right) + S_c$$

$$q_{sx} = -\theta D_{xx}\frac{\partial c}{\partial x} - \theta D_{xz}\frac{\partial c}{\partial z} + q_{lx} c$$

$$q_{sz} = -\theta D_{zz}\frac{\partial c}{\partial z} - \theta D_{xz}\frac{\partial c}{\partial x} + q_{lz} c$$

$$\theta D_{xx} = \theta D_{iw}\tau_s + \frac{\lambda_L q_{lx}^2 + \lambda_T q_{lz}^2}{|q_l|}$$

$$\theta D_{zz} = \theta D_{iw}\tau_s + \frac{\lambda_L q_{lz}^2 + \lambda_T q_{lx}^2}{|q_l|}$$

$$\theta D_{xz} = \theta D_{zx} = \frac{(\lambda_L - \lambda_T) q_{lx} q_{lz}}{|q_l|}$$

c : solute concentration (mg/cm^3)
q_s : solute flux (mg/cm^2/s)
S_c: sink/source for solute (mg/cm^3/s)
D : dispersion coefficient (cm^2/s)
D_{iw} : diffusion coefficient in free water(cm^2/s)
τ_s : tortuosity factor for ionic diffusion
λ_L : longitudinal dispersivity (cm)
λ_T : traversal dispersivity (cm)

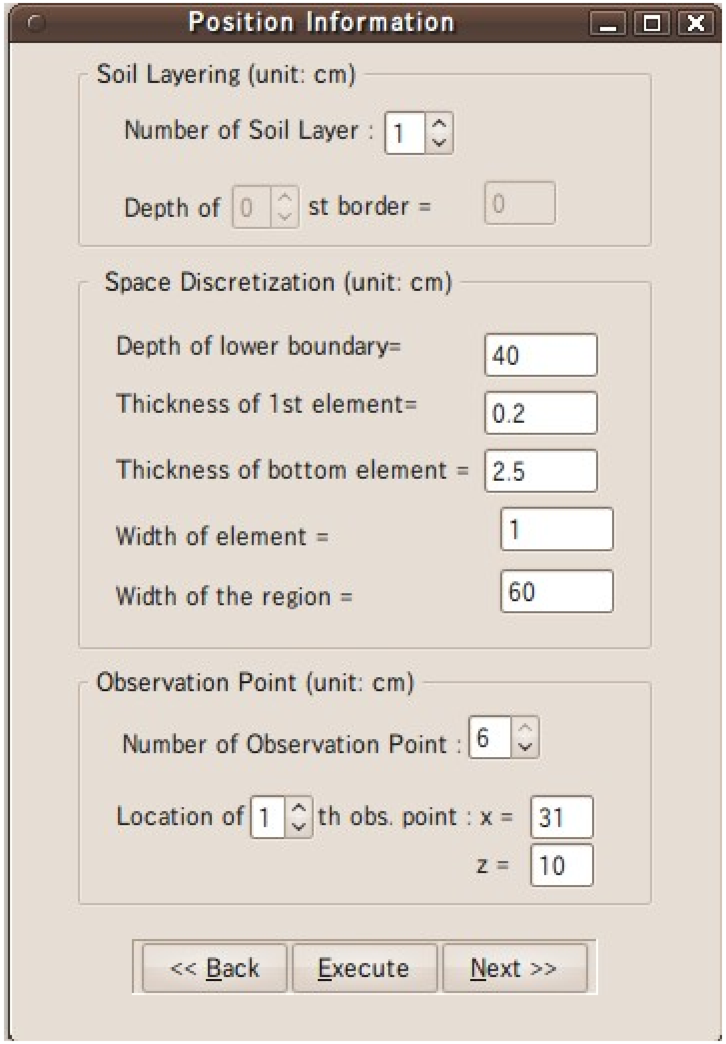
Conditions for Numerical Simulationon

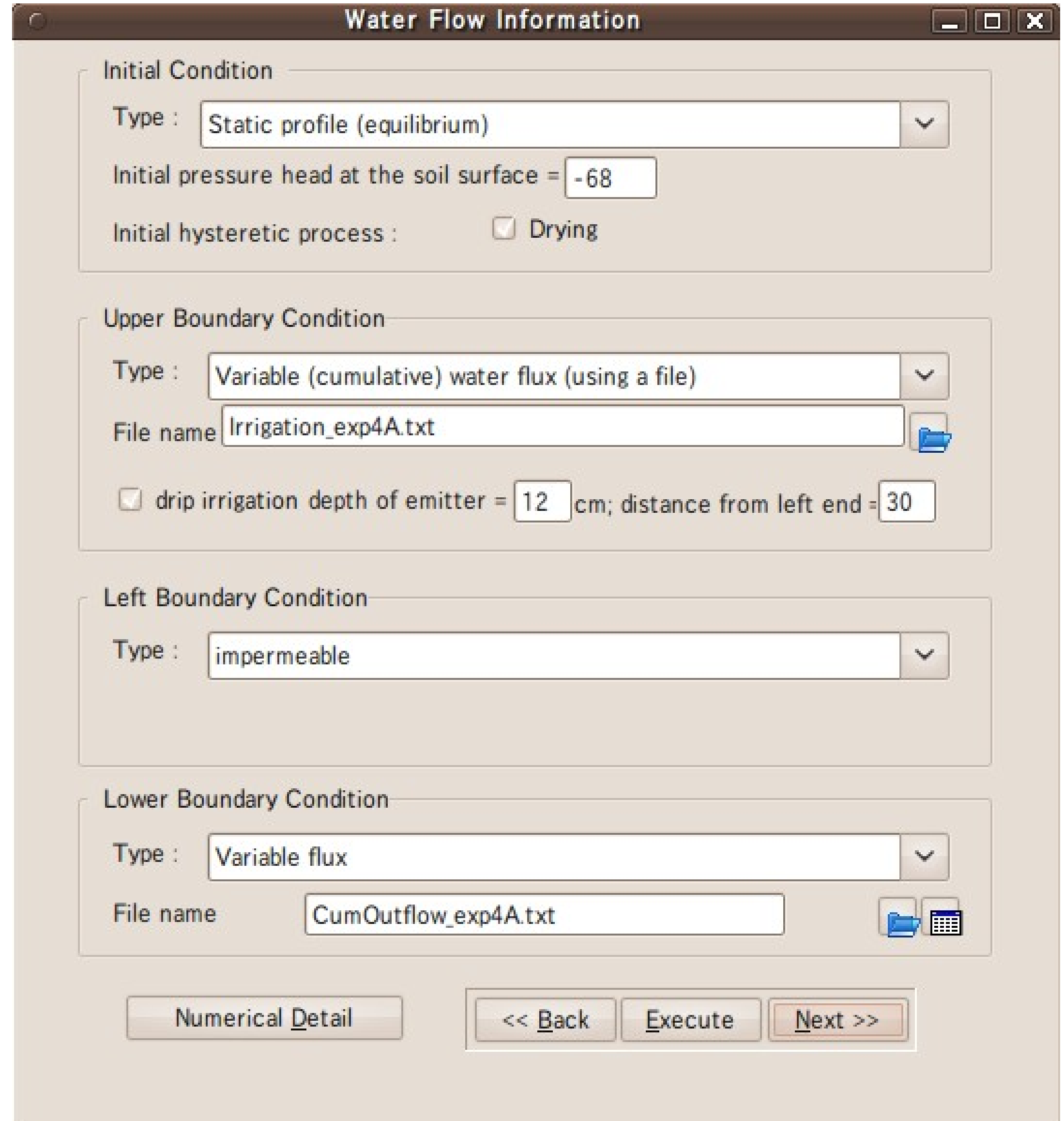
root density distribution: measured one

lower BC: daily-measured cumulative outflow

Thermal vapor diffusion was incorporated by plainly inter/extrapolating measured soil temperature.

Aerodynamic resistance:
given from hourly wind velocity at the nearest weather station with correction factor such that aerodynamic resistance gives daily evaporation rate from wet soil beside the lysimeter.


Position Information
Soil Layering (unit: cm)
Number of Soil Layer : 1
Depth of 0 st border = 0
Space Discretization (unit: cm)
Depth of lower boundary= 40
Thickness of 1st element= 0.2
Thickness of bottom element = 2.5
Width of element = 1
Width of the region = 60
Observation Point (unit: cm)
Number of Observation Point : 6
Location of 1 th obs. point : x = 31
z = 10
<< Back
Execute
Next >>

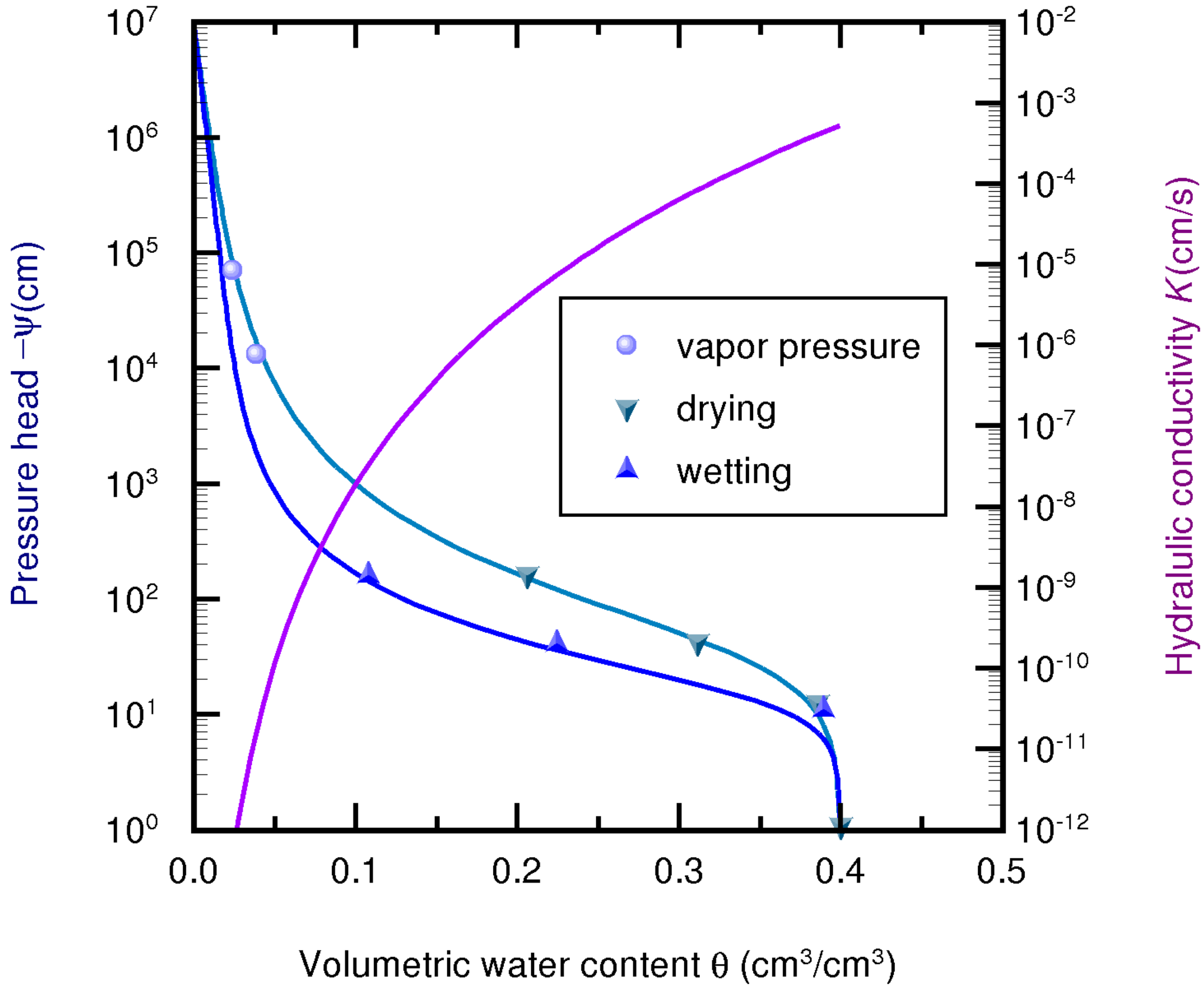

Water Flow Information
Initial Condition
Type : Static profile (equilibrium)
Initial pressure head at the soil surface = -68
Initial hysteretic process : Drying
Upper Boundary Condition
Type : Variable (cumulative) water flux (using a file)
File name Irrigation_exp4A.txt
drip irrigation depth of emitter = 12 cm; distance from left end = 30
Left Boundary Condition
Type : impermeable
Lower Boundary Condition
Type : Variable flux
File name CumOutflow_exp4A.txt
Numerical Detail
<< Back
Execute
Next >>

Hydraulic Properties :

independently measured using the hanging water method, the vapor equilibrium method, the transient evaporation method

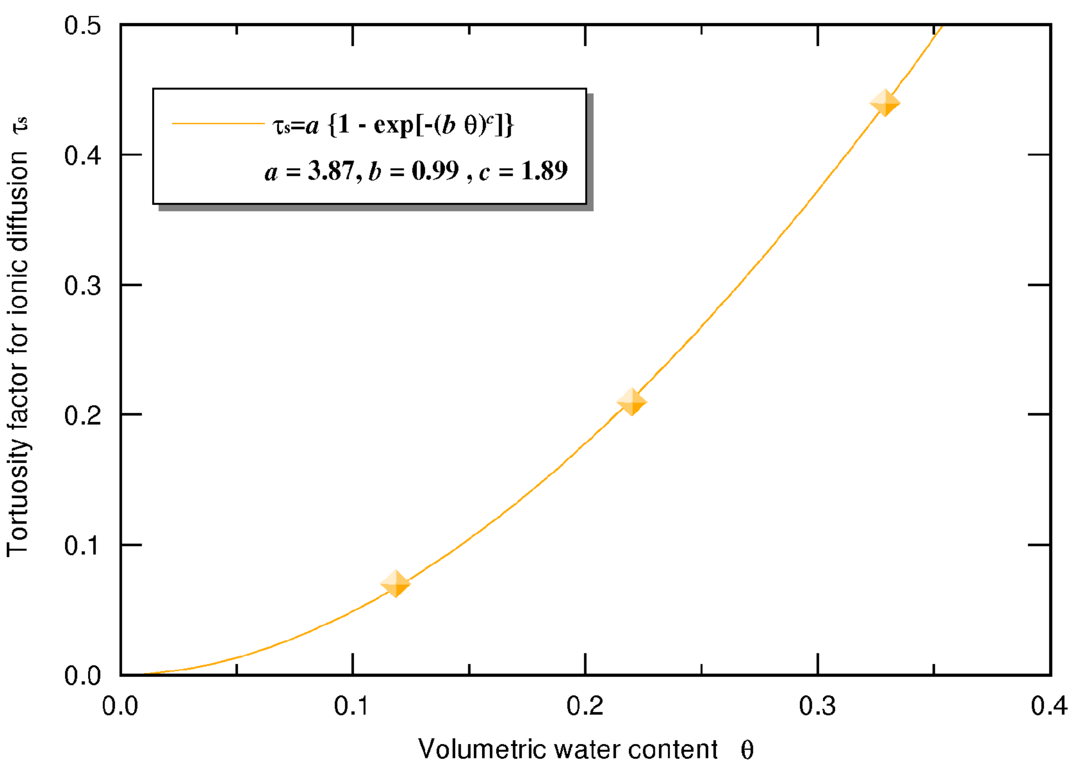
$$\theta = \frac{\theta_{sat} - \zeta}{\left[1 + (-\alpha \psi_m)^n\right]^m} + \zeta \left\{ 1 - \left[\frac{\ln(-\psi_m + 1)}{\ln(-\psi_0 + 1)} \right]^2 \right\}$$

$$K = K_{sat} \left(\frac{\theta}{\theta_{sat}} \right)^{\omega}$$

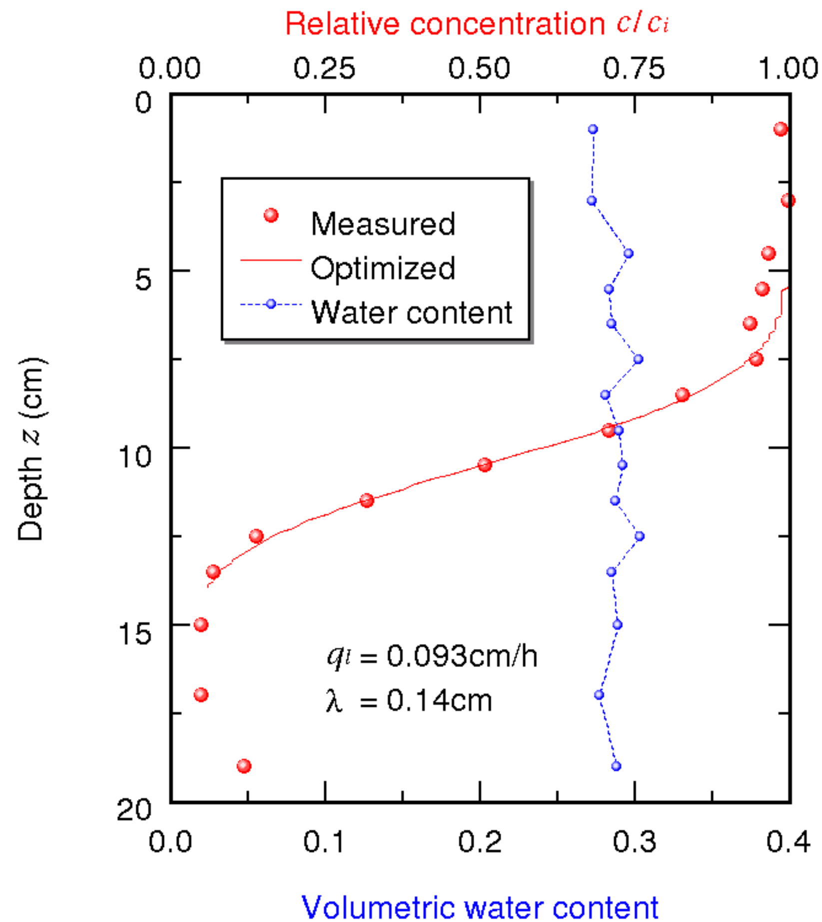


Soil water retention curve of Masa loamy sand

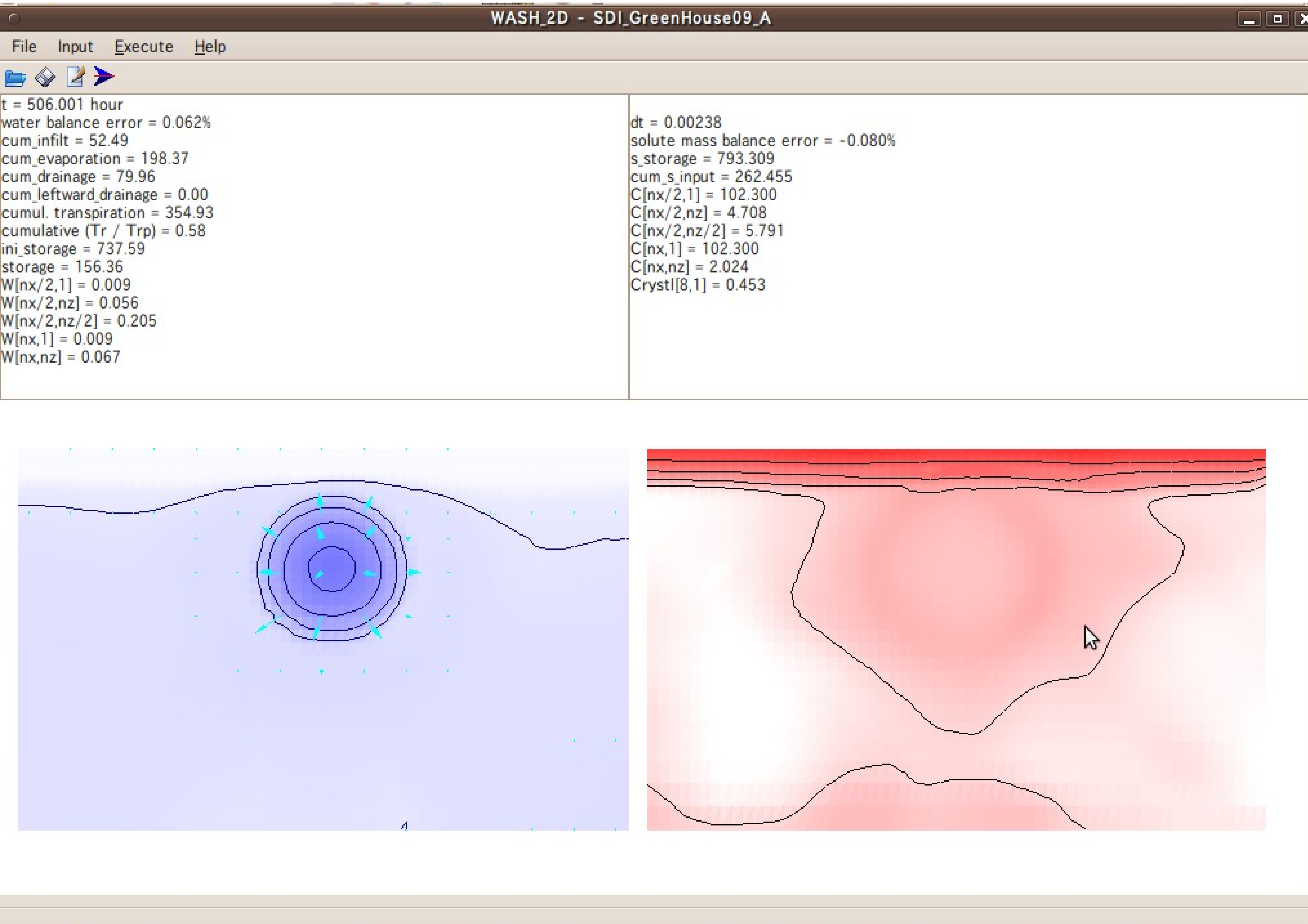
Solute Transport Properties :
independently measured using the half cell method and the long column method (c vs z).



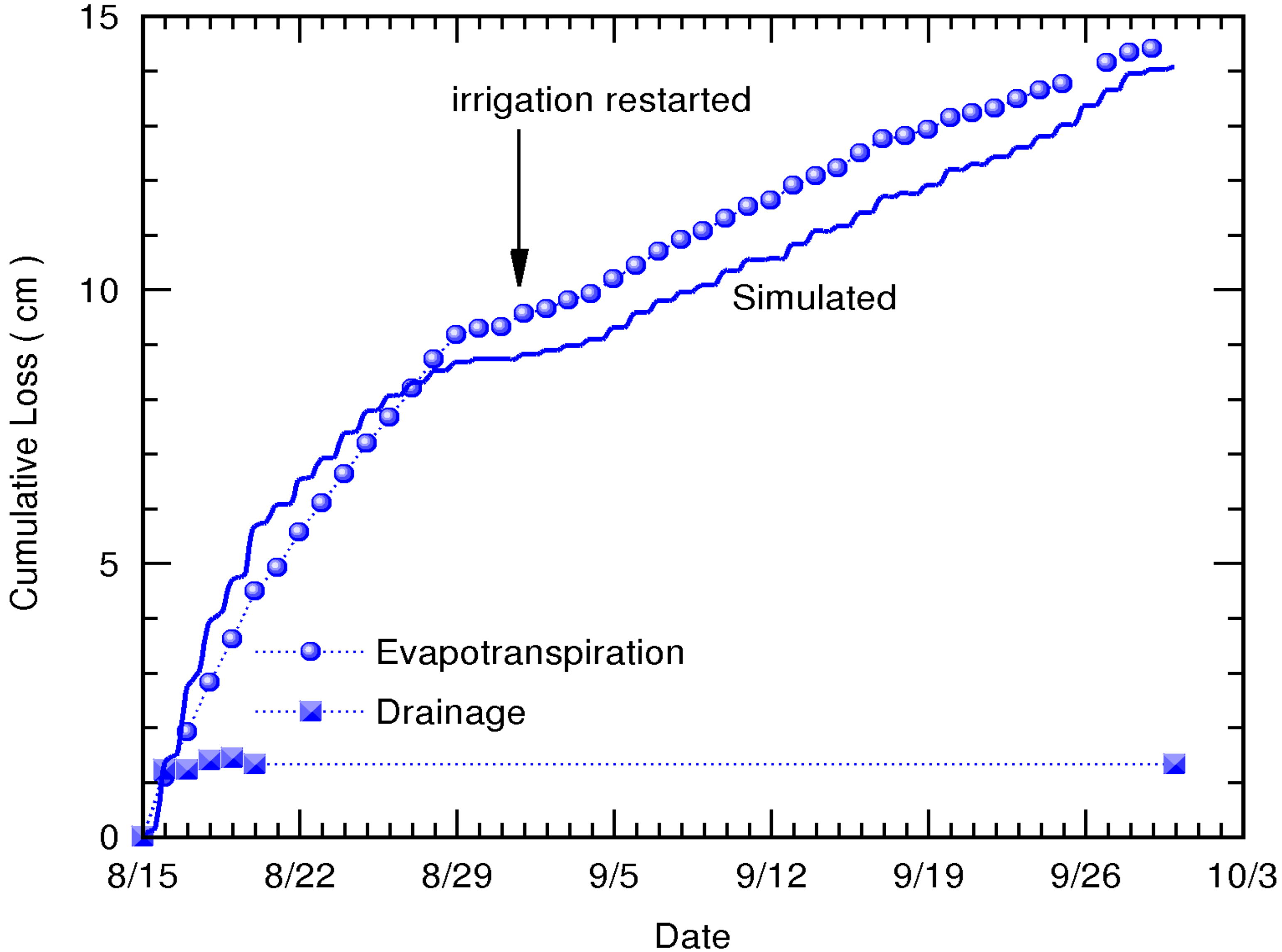
Tortuosity factor for ionic diffusion as a function of water content



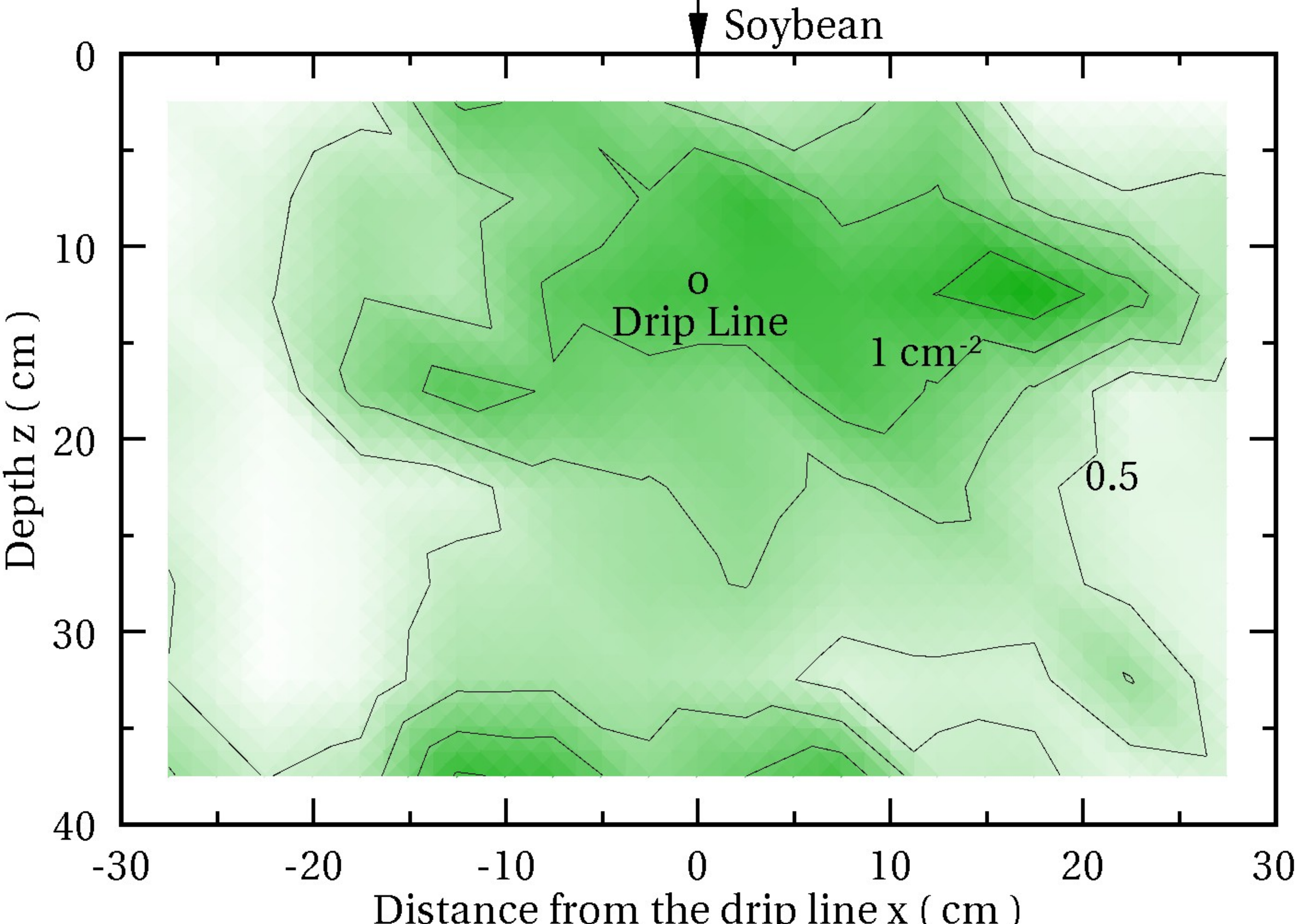
Concentration and water content profiles
under the displacement experiment for Masa loamy sand


WASH_2D - SDI_GreenHouse09_A
File
Input
Execute
Help
t = 506.001 hour
water balance error = 0.062%
cum_infilt = 52.49
cum_evaporation = 198.37
cum_drainage = 79.96
cum_leftward_drainage = 0.00
cumul. transpiration = 354.93
cumulative (Tr / Trp) = 0.58
ini_storage = 737.59
storage = 156.36
W[nx/2,1] = 0.009
W[nx/2,nz] = 0.056
W[nx/2,nz/2] = 0.205
W[nx,1] = 0.009
W[nx,nz] = 0.067
dt = 0.00238
solute mass balance error = -0.080%
s_storage = 793.309
cum_s_input = 262.455
C[nx/2,1] = 102.300
C[nx/2,nz] = 4.708
C[nx/2,nz/2] = 5.791
C[nx,1] = 102.300
C[nx,nz] = 2.024
Crystl[8,1] = 0.453

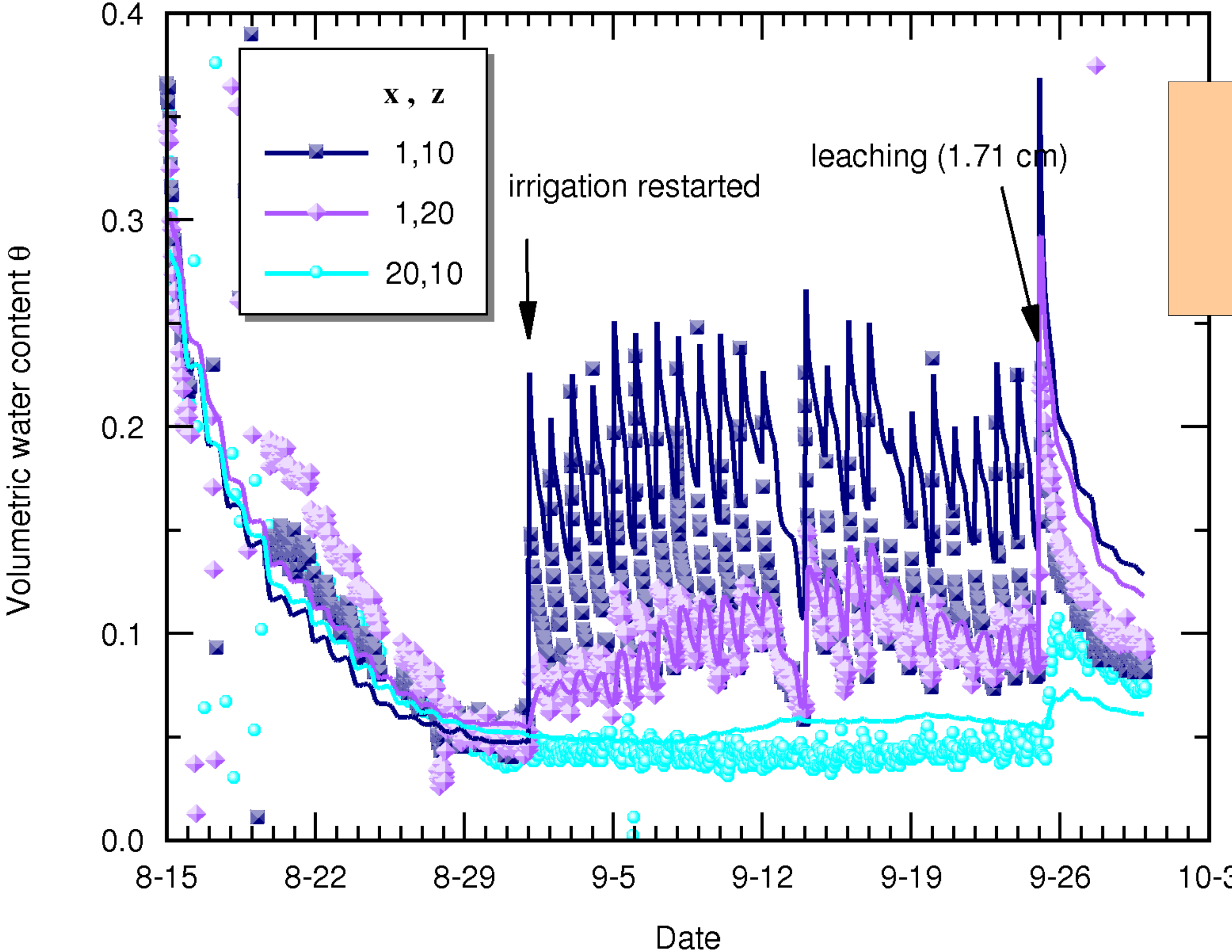
Results and Discussion

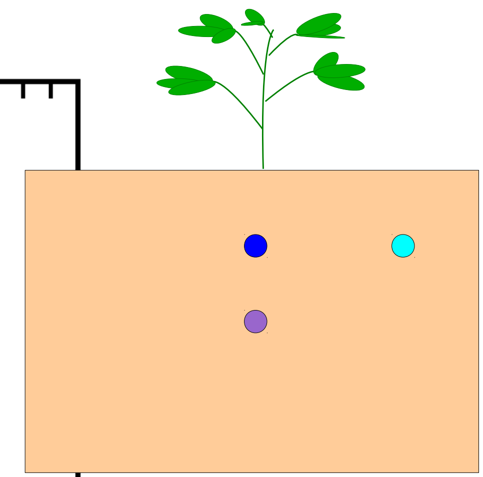


Comparison of measured and simulated time evolutions of



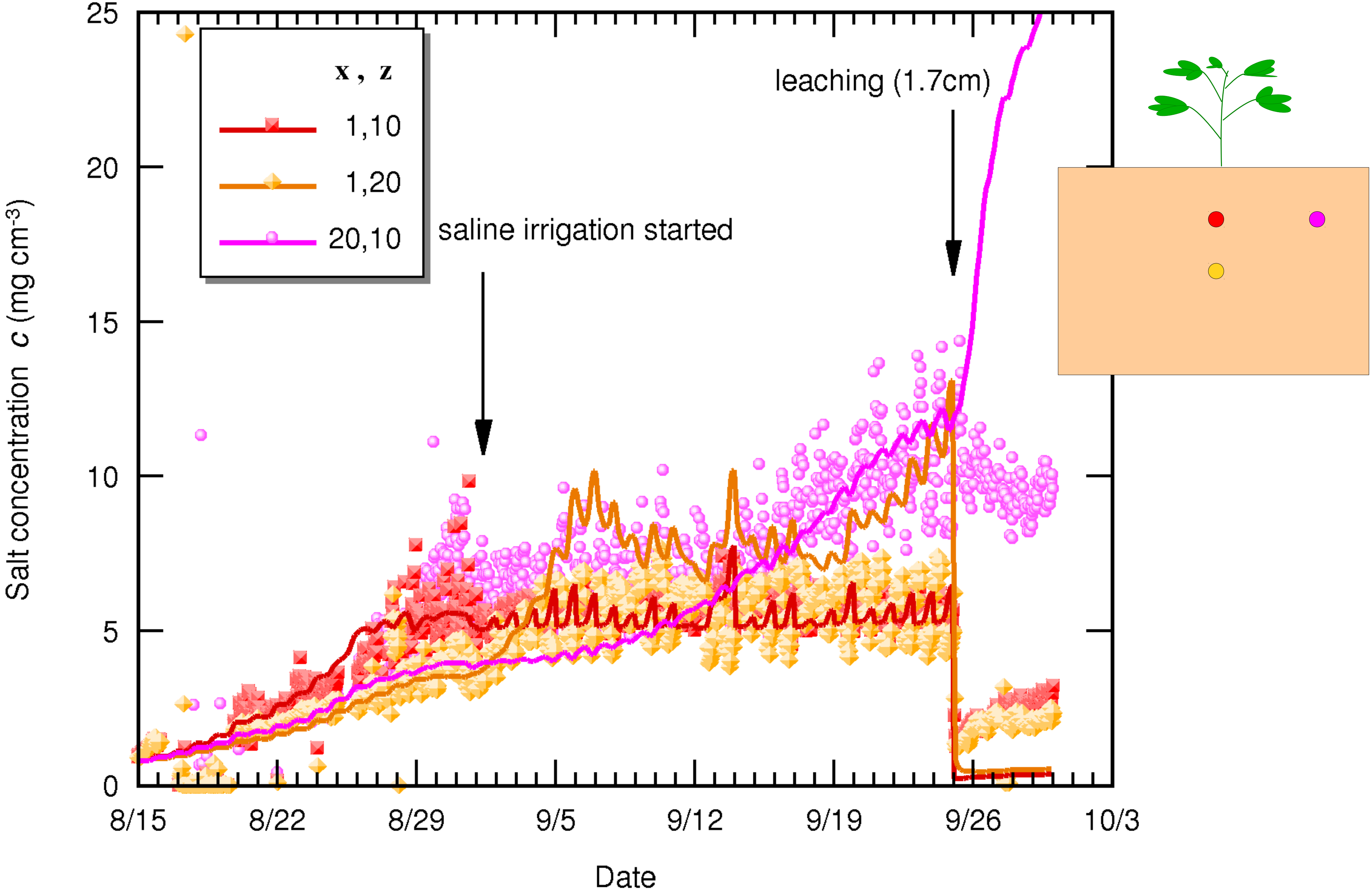
Root length density distribution
in a vertical section at the end of the experiment 09A.



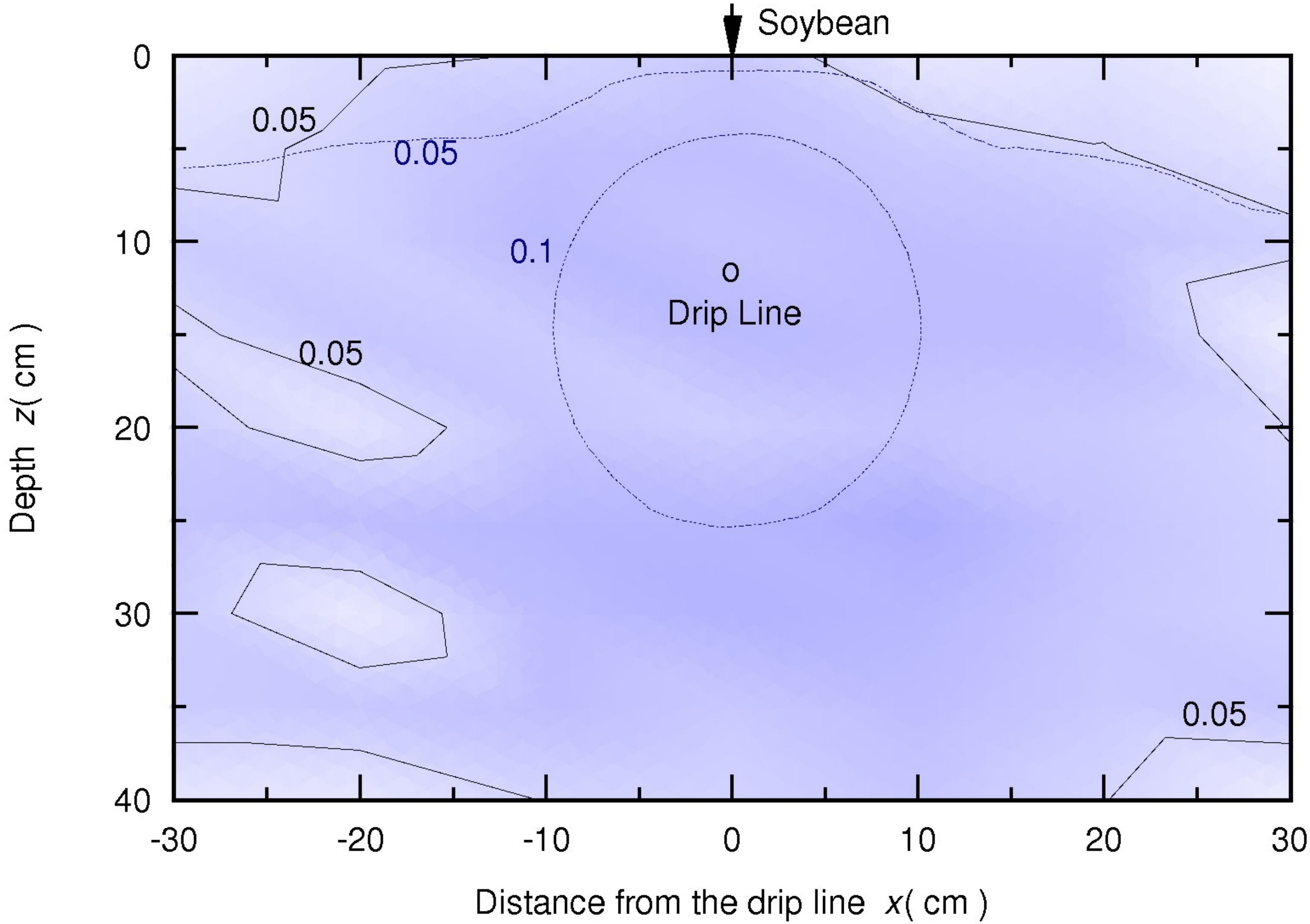


computation time: 88 min at 1.6GHz CPU

Comparison of measured (markers) and simulated (lines) time evolution of water content

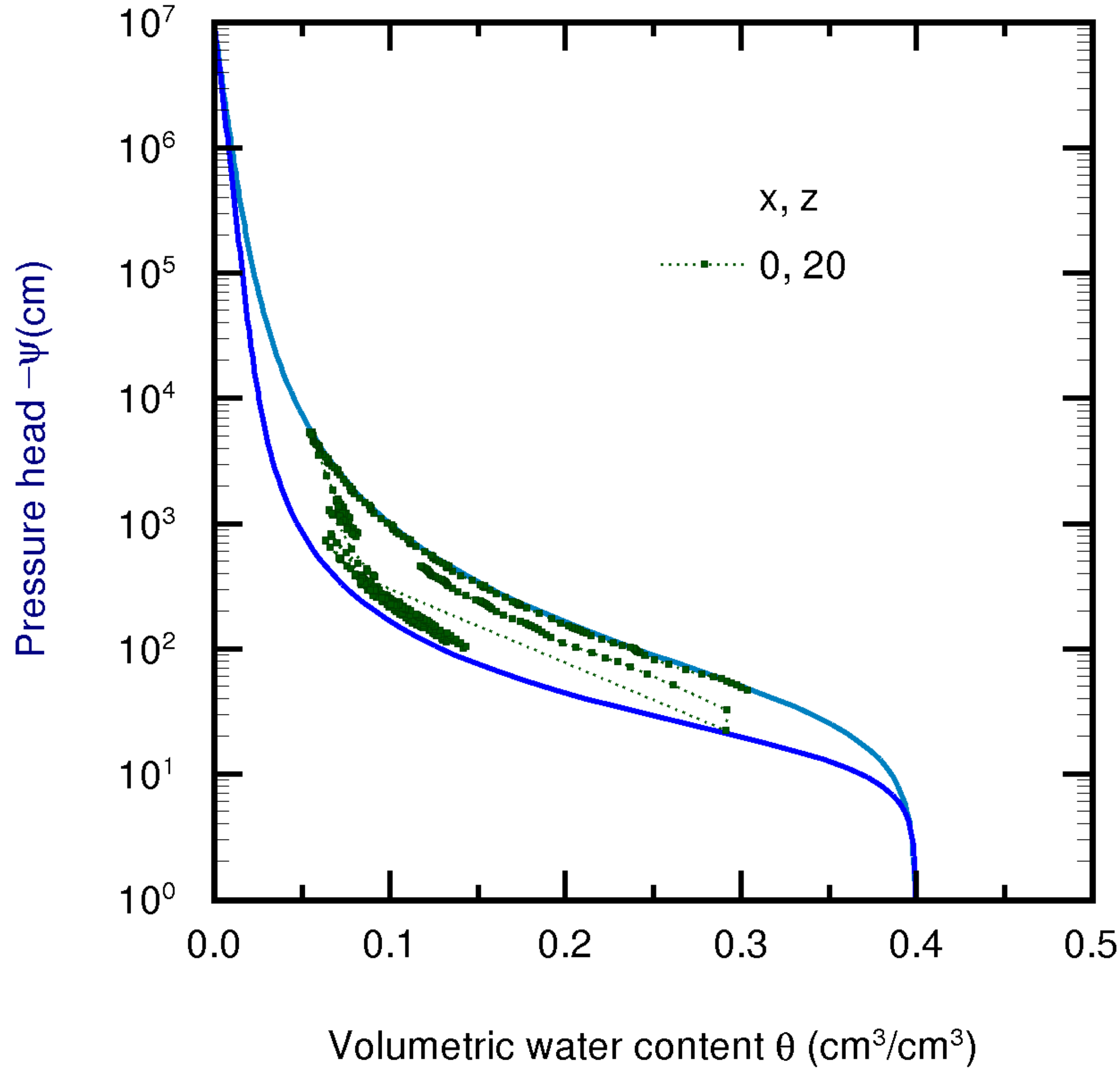


Comparison of measured (markers) and simulated (lines) time evolution of salinity



mass balance error = 0.3%

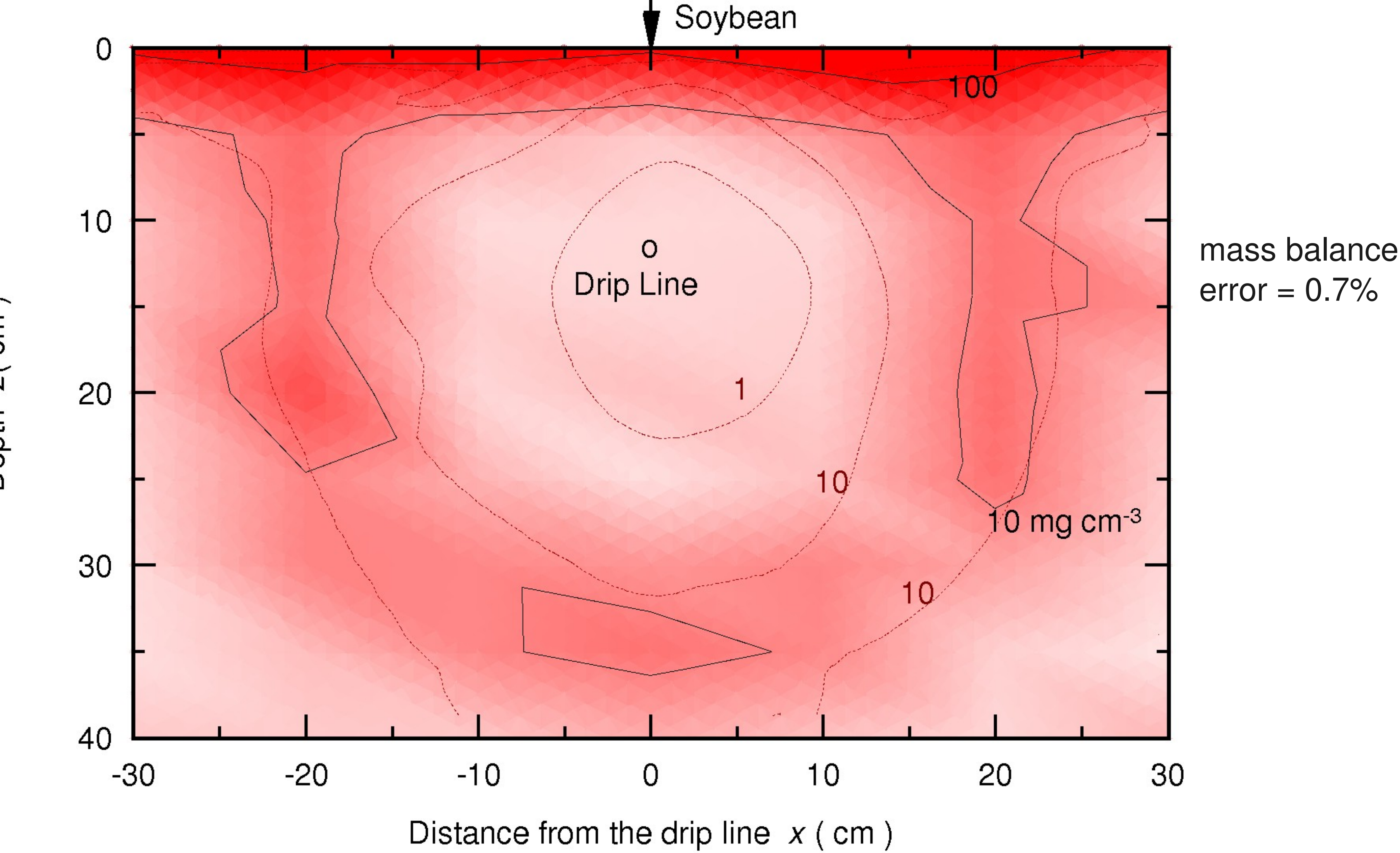
Comparison of measured and simulated volumetric water content distribution in a vertical section at the end of the experiment



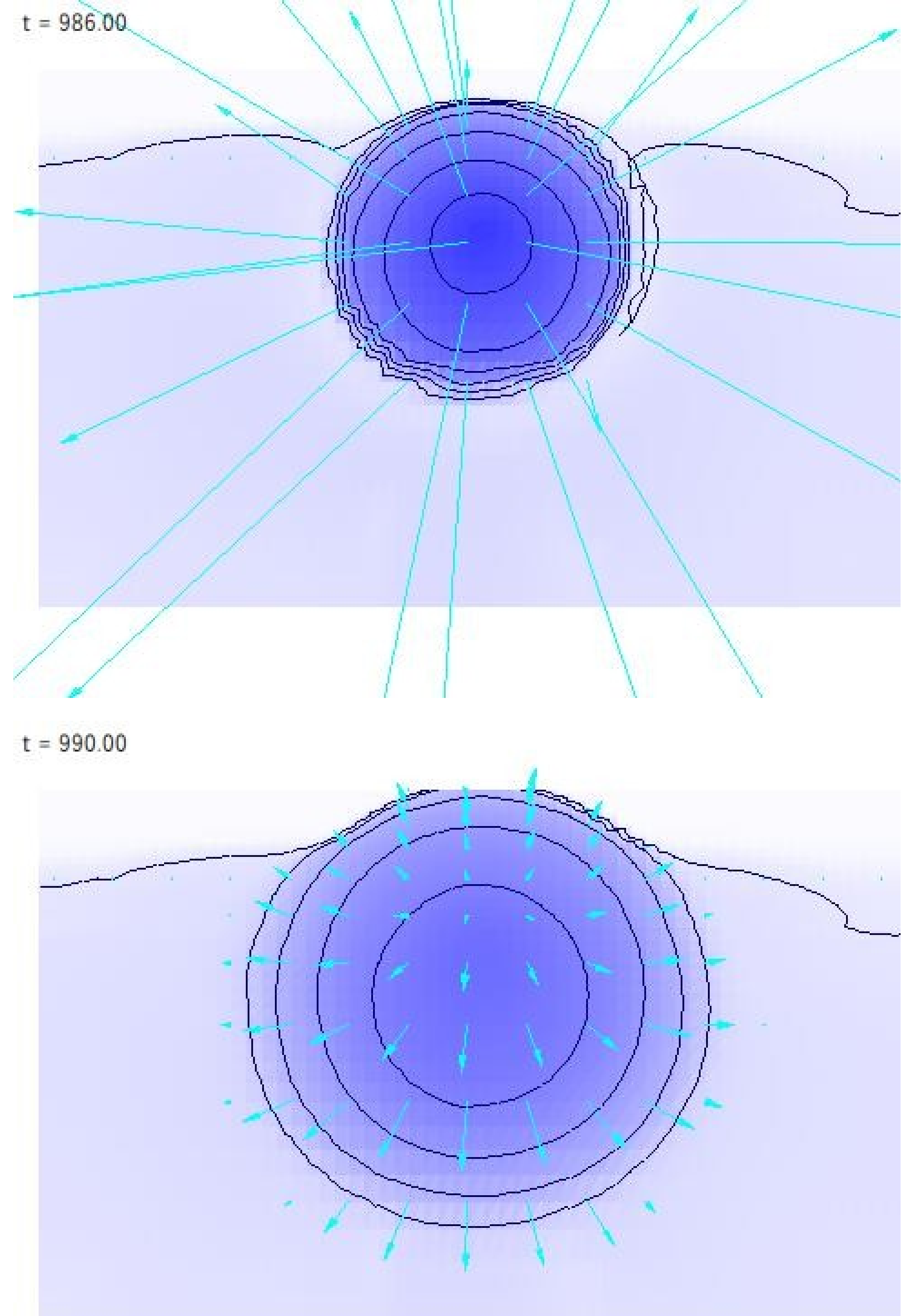
Simulated scanning curve at for Masa loamy sand

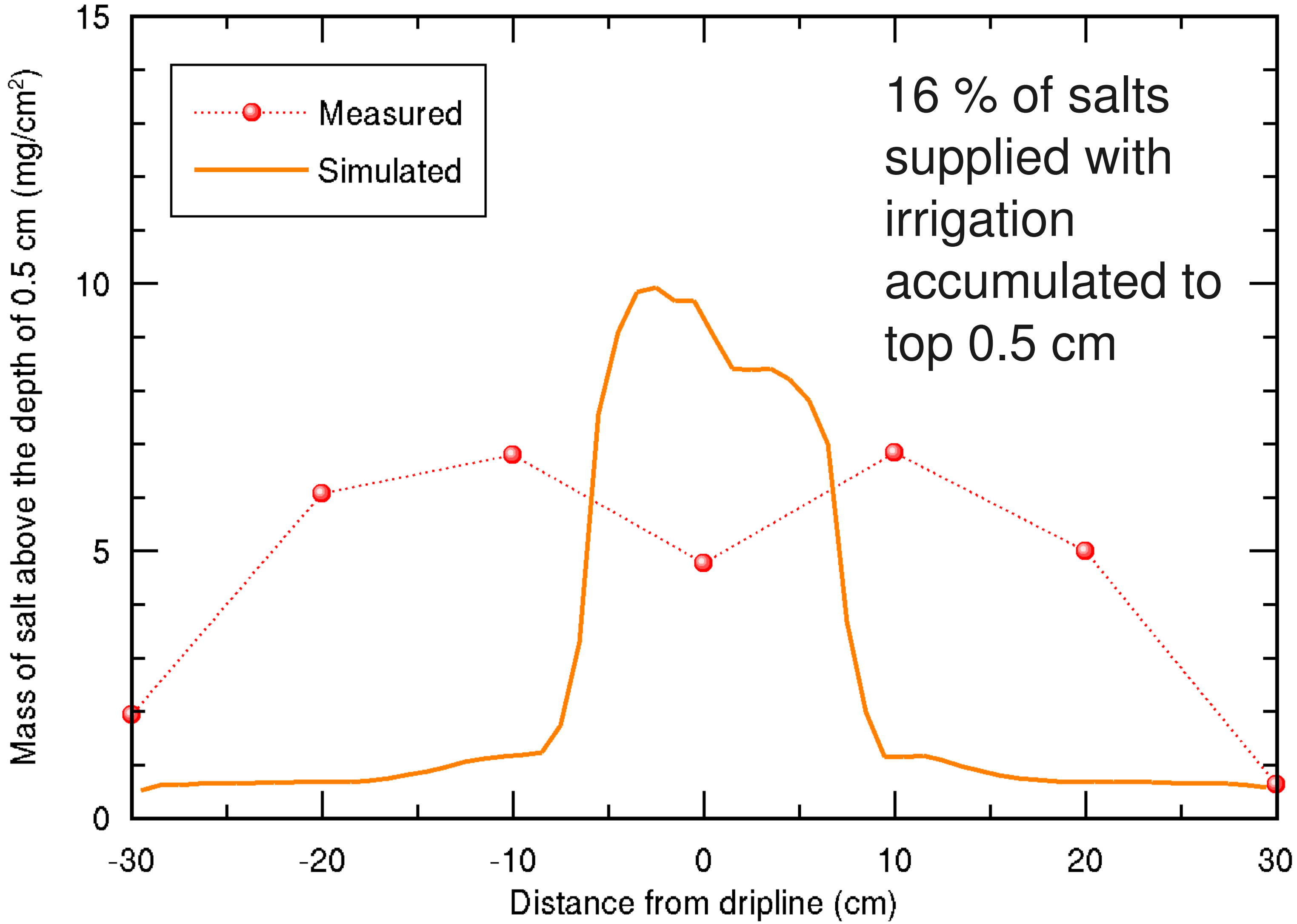
Underestimated K?

compensated root water uptake?



Comparison of measured and simulated salt concentration at the end of the experiment


t = 986.00
t = 990.00



Salt distribution along the soil surface at the end

Conlusion

- Software for predicting two dimensional movement of water and solute considering the water vapor movement has been developed.

- Simulated values were in fair agreement, but further investigation is required to improve accuracy.

- Salts in the upper root zone was transported to the soil surface and a part of them was effectively removed by scraping top 0.5 cm layer.

Thank you for your attention

Atmospheric Boundary Condition

$$E = \frac{\rho^*_{vs} h_{rs} - \rho^*_{va} h_{ra}}{r_a + r_{sc}}$$

$$h_{rs} \approx h_{re} = \exp\left(\frac{\psi_w}{R_v T}\right)$$

$\rho_v{}^*$: saturated water vapor density (g/cm³)

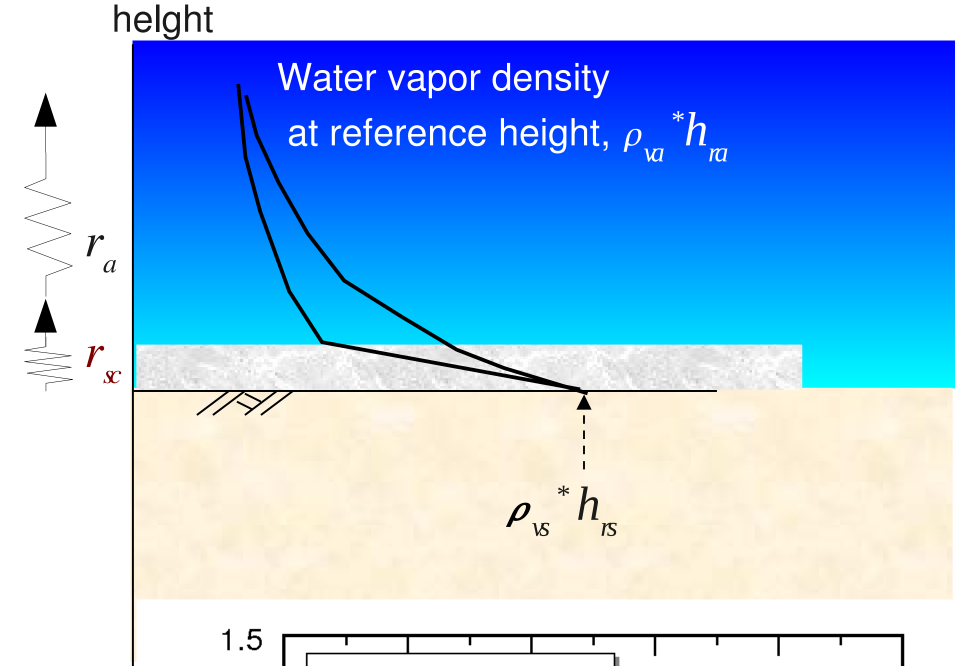
h_r : relative humidity

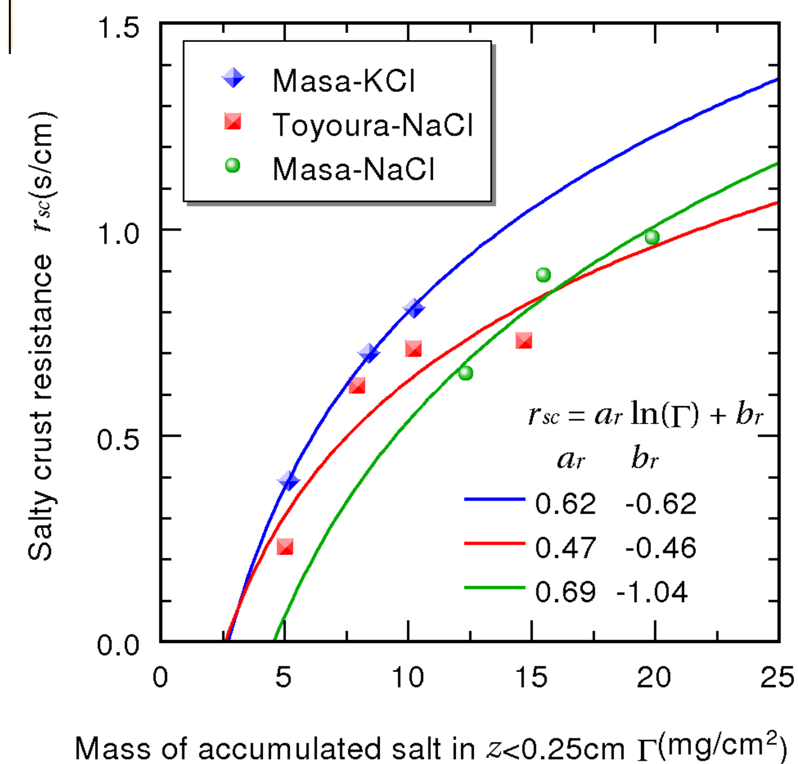
r_a : aerodynamic resistance (s/cm)

r_{sc}: salty crust resistance (s/cm)

ϕ_w: water potential(cm)

R_v : the gas constant for water vapor (4697 cm/K)





Salty crust resistance as a function of accumulated salt