MODELING SPATIAL AND TEMPORAL VARIABILITY IN IRRIGATION AND DRAINAGE SYSTEMS: IMPROVEMENTS TO THE COLORADO STATE IRRIGATION AND DRAINAGE MODEL (CSUID)

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ABSTRACT

The Colorado State University irrigation and drainage model (CSUID) is a three dimensional variable saturated-unsaturated numerical model that simulates the subsurface flow and transport processes. A wide range of enhancements have been done to CSUID to fully simulate the response of agricultural fields to external stresses such as subsurface drainage systems, root extractions and irrigation activities. The model is also capable of simulating salinity transport process through the vadose zone and in the saturated zone. The partition of salinity between the soil solid phase and the water phase is included in the model to simulate the accumulation of salts in the root zone.

The strength of CSUID is in its ability to simulate irrigation-drainage activities taking into account spatially and temporal variably in water quality and quantity and under spatial heterogeneous soil properties. Soil properties such as hydraulic conductivity, porosity, Van Genutchen retention curve parameters, storativity, dispersivity, partition coefficients are all modeled as spatially variables. Having a model with these capabilities is an important step toward understanding the uncertainty in the design and management of irrigation-drainage systems. The model contains a Graphical User Interface that allows the user to visualize the input and output.

INTRODUCTION

Numerical models are essential tools in the management of water resources. The role of irrigation and drainage model models is to improve our understanding of the hydrogeological processes for the entire subsurface zone and also as predictive tools to help in making decisions. Simulating the entire subsurface zone, saturated and unsaturated zones, is of valuable significance for better management of irrigation and drainage activities. Rubin (1968) was a pioneer in the modeling of unsaturated and saturated zones as one process. Freeze (1972) used one flow continuity equation to numerically simulate the entire subsurface zones. The nonlinearity of the flow equation was the main challenge for robust and computational effective models. Small time steps and fine grid schemes are usually used to obtain acceptable numerical results from the nonlinear equations. This, in turn, normally hampers the use of such models at the field

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scale due to the expensive computational effort. Two numerical methods are usually used to solve nonlinear equation systems, there are: (1) Picard method, and (2) Newton Raphson method. The Newton Raphson method shows that it is more robust and computationally efficient but its stability depends on the initial conditions and the spatial and temporal discretization of the problem at hand. The Picard method is widely used due to its unconditional stability.

The Colorado State University Irrigation and Drainage model (CSUID) is a decision support tool that is used in the design and management of irrigation and drainage systems. It facilitates the calculation of root growth calculations, flow and transport in the unsaturated and saturated zones, drain discharge, and crop yield estimates (Garcia et al 2002). CSUID was originally designed to numerically apply the quasi-three-dimensional finite-difference scheme to solve the flow equations in the unsaturated zone using a one dimensional Richard's equation and the three dimensional equations to solve the flow in the saturated zone (Manguerra and Garcia 1995). The model was enhanced later to solve the fully three dimensional case.

The objectives of this paper are to introduce the enhancements to CSUID which include (1) the use of the modified Richard's equation to solve the entire subsurface as a single flow process, (2) enhancements to the numerical solver efficiency for flow by using the mixed form of the Richard's equation (Celia 1992) to reduce the mass balance error, (3) the use of the dispersion-advection equation with the full dispersion tensor matrix and adsorption–desorption of ions in the water soil system, (4) new solvers were added for flow and transport processes using the preconditioned conjugate gradient method, (5) the ability of the model to simulate drainage system outflow and salinity hydrographs were enhanced, (6) the model capabilities were expanded to accept three dimensional soil properties for all model inputs which include hydraulic conductivity, dispersivities, porosity, specific storativity and Van Genutchen parameters (α, n, θ_r).

Flow Equation

The modified Richard's equation (equation 1) that accounts for the unsaturated-saturated flow is used. The modified Richard's equation differs from the classical Richard's equation (1931) in that it accounts for two different storage mechanisms. In the saturated zone the specific capacity models the storage mechanism in the unsaturated zone, the specific capacity equal zero in the saturated zone and the specific storativity term will be dominant.

$$\frac{\partial}{\partial x}\left(k_{xx}(\psi)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}(\psi)\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}(\psi)\frac{\partial h}{\partial z}\right)+Q=C(\psi)\frac{\partial h}{\partial t}+S_s\frac{\theta}{n_e}\frac{\partial h}{\partial t} \qquad (1)$$

Where:

h is the hydraulic head [L] ,

$k_{xx}(\psi), k_{yy}(\psi), k_{zz}(\Psi)$ are the hydraulic conductivity in the principle direction x,y,z respectively [L/T],

ψ is the capillary pressure [L],

Q is the volumetric source or the sink per unit volume of the aquifer [T^{-1}],
$C(\psi) = \dfrac{\partial \theta}{\partial \psi}$ is the specific capacity [L^{-1}],
S_s is the specific storativity [L^{-1}],
θ is the volumetric water content [L^3/L^3],
n_e is the effective porosity [L^3/L^3].

The saturation pressure relationship is simulated by using the Van Genutchen relationship (Van Genutchen 1980). This model is usually preferred by modelers due to the continuity of the equation. The Van Genutchen equation is

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + (\alpha h)^n\right)^m} \tag{2}$$

Where:
θ_s is the saturated water content,
θ_r is the residual water content,
α, n, m are Van Genutchen model fitting parameters.
The α, n, θ_r, porosity, storativity, hydraulic conductivity and mechanical dispersion are assigned to the model as three dimensional variables to account for the spatial variability and uncertainty in soil parameters.

Transport Equation

The transport process is modeled mathematically by the advection dispersion equation (equation 3). The transport equation simulates the partitioning of salinity between the solid phase and the water phase. The solution supports also the full dispersion tensor matrix.

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij} \frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(\theta v_i C) + q_s C_s + R \tag{3}$$

Where:
C is the concentration [M/L^3],
i, j represent the x,y,z direction,
D is the hydrodynamic dispersion coefficient [L^2/T],
v is the seepage velocity [L/T] ,
q_s is the sink-source term and defined as the volumetric flux of per unit volume of aquifer [T^{-1}],
C_s is the source or the sink concentration [M/L^3],
R is the sorption term [ML^3/T].

The salinity sources could be the irrigation water salinity and boundary condition salinities. The sink sources could be outflow salinity from the drain.

Boundary Conditions

The model allows different types of boundary conditions. First type boundary conditions can be used such as constant head or constant concentrations. Second type boundary conditions include a specified flux with specified boundary conditions. These boundaries allow the modeler to simulate a wide range of problems. Currently, the CSUID model is modified to account for the third type boundary condition or general boundary condition as is called in MODFLOW documentation (McDonaldand Harbaugh 1988). This boundary condition imposes a linear relationship between an external constant head and the lateral flow into the model domain. The general boundary condition allows the change in lateral flow into the model as the difference between an external head and an internal head change.

Irrigation

The modeler can divide the simulated area into several basins. Each basin can be assigned a different irrigation schedule. The model allows the user to assign different irrigation application depths with different salinity concentration for each irrigation. This capability will enhance the flexibility and applicability of the model. CSUID can be used as a design tool for irrigation schedules based on the response of a water soil system to the evapotranspiration stress. The importance of CSUID is that it takes into account the impact of soil properties and the contribution of shallow water to the root uptake.

Root Extraction and Crop Yield Functions

The general equation to model root extraction can be described in equation (4). Where $\alpha(h, h_\phi, x)$ is the root zone response function, and b(x) represents the root growth function. CSUID gives the user the option to choose different combinations of these two functions. Another family of crop yield functions are used in CSUID to approximate the response of the crop to stress resulted from water content shortage and osmotic pressures induced by saline water. The reference evapotranspiration is an input parameter which could be obtained from other sources such as ET estimation models, remote sensing, etc. Other parameters modelers need to obtain are the crop coefficients that represent the impact of crop conditions on water uptake.

$$S(h, h_\phi, x) = \alpha(h, h_\phi, x) b(x) T_p \tag{4}$$

Where

$S(h, h_\phi, x)$ is the volumetric root water uptake per unit volume of the aquifer [1/T],

$\alpha(h, h_\phi, x)$ is the water stress and osmotic stress response function[-],

h is water head [L] ,

h_ϕ is the osmotic head [L],

$b(x)$ is the root growth function [L^{-1}],

T_p is the potential transpiration [L/T],

Subsurface Drainage

The drain flow can be simulated using the conductance equation such as equation 5 where the flow into the drain is a function of the elevation of water table above the drain and the conductance of the drain. The conductance of the drain represents the ease of water movement from the soil to the drain.

$$Q_d = C_d (h - D) \tag{5}$$

Where
Q_d [L^3/T],
C_d is the drain conductance [L^2/T],
h is the water table above the drain [L],
And D is the elevation of the drainage [L].

Numerical Solution

Richard's equation (equation 1) is a nonlinear equation that has a limited number of analytical solutions for simplified cases. This explains the popularity of the numerical solutions that are based on finite difference or finite element approximations of the Richard's equation. Head based Richard's equation usually produce large mass balance errors (Celia 1990), while water content based equations usually produce acceptable mass balance errors. However, the water content based equation will not be able to solve the flow equation in the saturated zone since the change in the water pressure does not produce a change in the water content. Celia suggested using the mixed Richard's equation 6. This equation is used in SWAP (van Dam et al., 1997) and HYDRUS (Simunek et al., 1998, 1999a). The precondition conjugate gradient method is used to solve the system of nonlinear equations in an iterative way.

$$C\frac{\partial h}{\partial t} + \frac{\theta}{n_e} S_s \frac{\partial h}{\partial t} \cong \frac{\theta^{n,m-1} + C^{n,m-1}\left(h^{n,m} - h^{n,m-1}\right)}{\Delta t} + \left(\frac{\theta}{n_e}\right)^{n-1/2} S_s \frac{h^{n,m} - h^{n-1}}{\Delta t} \tag{6}$$

Where
n represents the time level,
m iteration level,
Δt time step.

The advection dispersion transport equation (equation 2) can be linear or nonlinear depending on the adsorption term. If the linear isotherm is used to calculate the sorped phase then the transport equation will be linear and nonlinear if the Freundlich or Langmuir isotherms are used.

The Eulerian approach is used to solve the transport equation so the concentration will be approximated at fix grid nodes as opposed to Lagrangian method where the grid is moving or deforming with the flow. The use of Eulerian approach is impacted by the problem of artificial oscillation and numerical dispersion. This problem can be overcome by using small time steps and small spatial grid size. A Courant number (vt/x) of less than 2 will eliminate the oscillation, where v is the seepage velocity, t is the time step and x is grid size.

Sorption Desorption Process

The partitioning of chemical ions between the water phase and soil phase are approximated by a linear relationship. The nonlinear Freundlich and Langmuir sorption isotherms are avoided in this model in order to reduce the nonlinearity of the simulation that already exists in the flow equation. The adopted approximation of the absorption-desorption process is a linear relation with a maximum salinity capacity that the water can hold, after which the ions will be concentrated on the soil grains or as separate salt solid phase.

Model Limitations

CSUID only simulates the liquid phase of water. The impact of the entrapped air on infiltration and swelling of the soil are not simulated in the model. Near dry conditions where water transmits to the atmosphere as vapor phase are not simulated. In order to simulate the evaporation process at the soil surface the liquid phase flow, the vapor phase flow and heat transfer equations should be solve simultaneously.

The model does not simulate the hysteretic phenomena in water flow and also ignores the potential gradients resulting from the different chemical concentrations, temperature and osmosis pressures. These limitations are not restrictive to the numerical simulation of the saturated-unsaturated flow.

ONE-DIMENSIONAL ILLUSTRATIVE EXAMPLES

Infiltration Example

The model was run to simulate the infiltration in a column of soil with a hydraulic conductivity of 5 m/day. An irrigation event of 8 cm/day and of salinity concentration of 10 g/L is applied for two days. The changes in water content and salinity profiles were plotted in Figures 1a, 1b.

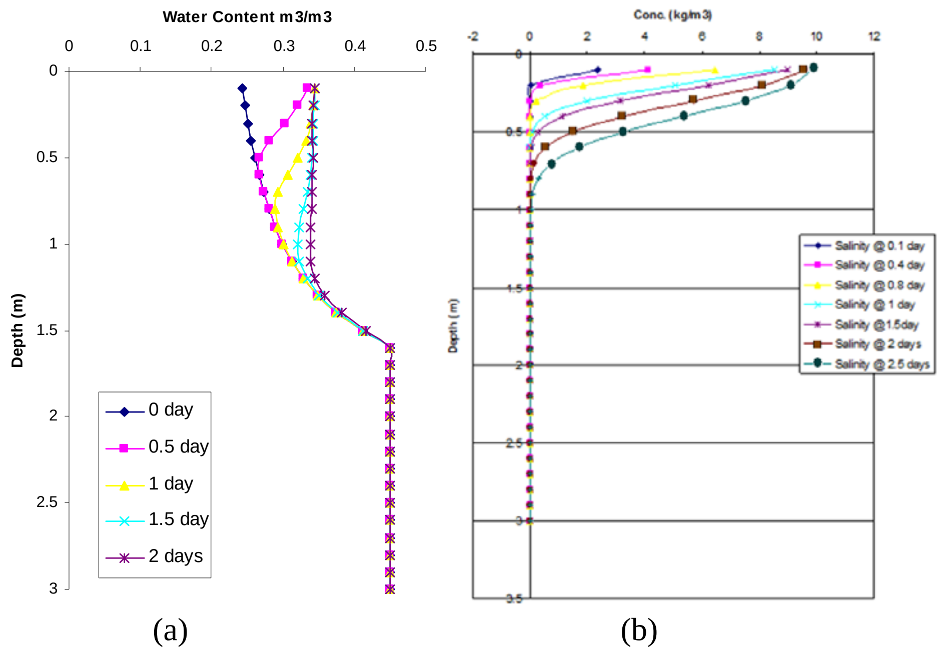


Figure 1. (a) Water Content profile with time, (b) Salinity profile with time after saline irrigation event.

Leaching Example

In this example the initial salinity of the soil water profile was assumed to be zero and it was irrigated using saline water (5 g/L) for one day, then a fresh water (rainfall event) was assumed. The output results (Figure 2) show the salination and desalination of root zone following each of the events. This example is for homogenous soils and explains the leaching of salinity from the root zone. If heterogeneous soils are used, then more flow will occur in the high conductivities zones and salinity will remain in low conductivity zones.

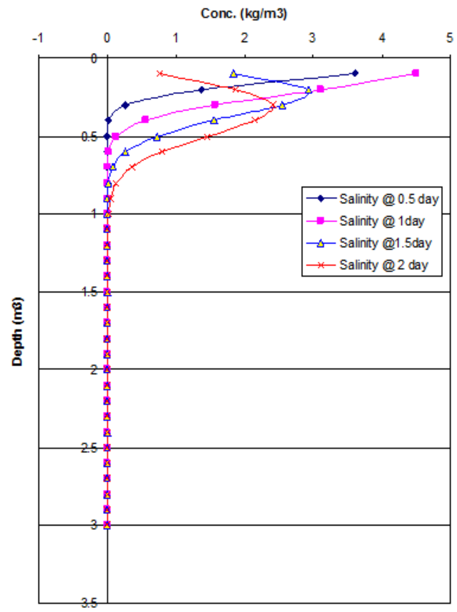


Figure 2. Salinization of the root zone due to saline water irrigation event followed by a rainfall event with zero salinity

Three Dimensional Water Table Control Problem

In this example, an irrigation event is applied on part of the field to simulate the impact of irrigation on a shallow water table. Waterlogging problem can be flagged if the water table reaches the root zone or if the water content of the root zone reaches saturation. Figures 3 and 4 show a cross section of the field with the change of water content distribution and salinity concentrations with time.

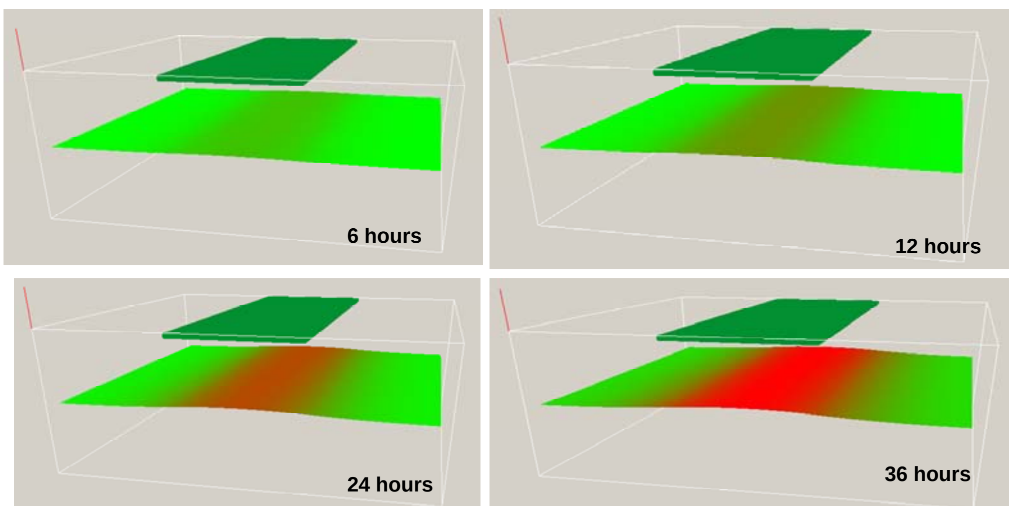
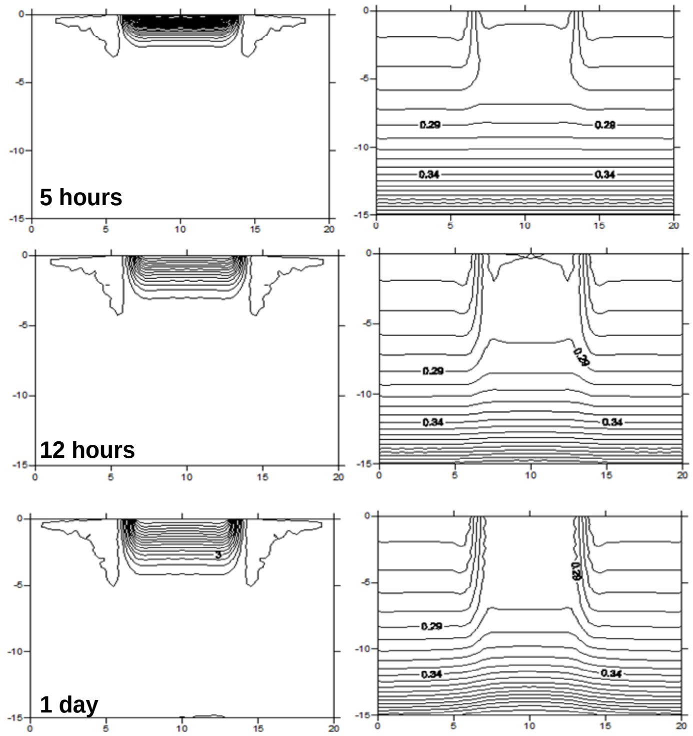


Figure 3. Response of water table to irrigation event on part of the field.



(a) (b)

Figure 4. Cross sections of a field under irrigation using saline water. (a) is the salinity distribution with time, (b) water content distribution with time.

Drainage Example

In this example, drainage is used in the input to simulate the response of the water table to a subsurface drainage pipe. Figure 5 shows the change in water table with time. CSUID will also generate a flow and salinity hydrograph for each drain. The drain hydrograph shown in Figure 6a and 6b shows that the outflow rate is higher at the start of the simulation and it decreases until it reaches a steady state flow rate. This is because at the start of the simulation the water table is high above the drain and the hydraulic gradient is at its maximum. As the water table decreases, the hydraulic gradient decrease and the flow rate, in turn, will decrease.

Figure 6a shows the hydrographs for two cases, the first case is a hydrograph without irrigation and the second case is a hydrograph with irrigation. Figure 6b shows the hydrograph for a field that was irrigated for 5 days. The response of the hydrograph to irrigation can be clearly noticed. The hydrograph in Figure 6c shows the salinity of the drain for a case when a saline pulse of irrigation is applied followed by irrigation with water of very low salinity.

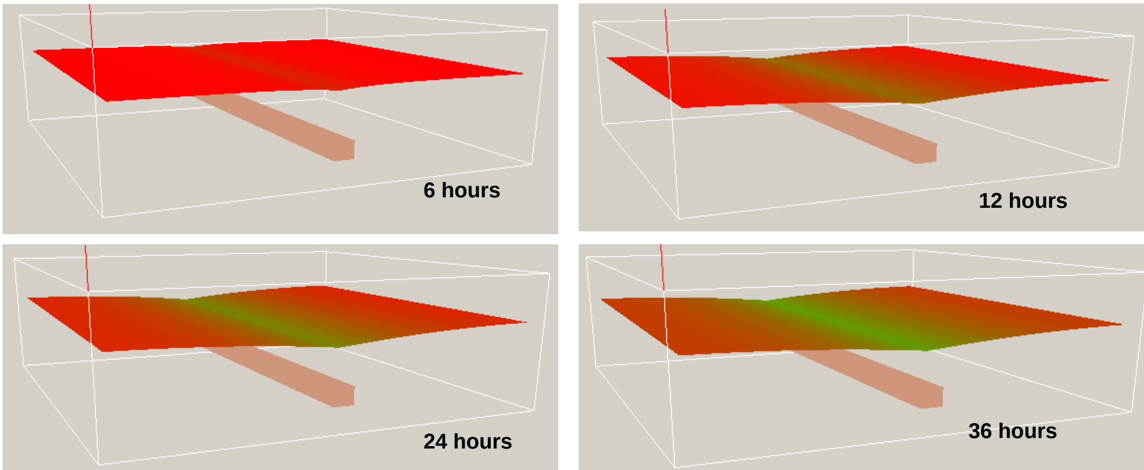
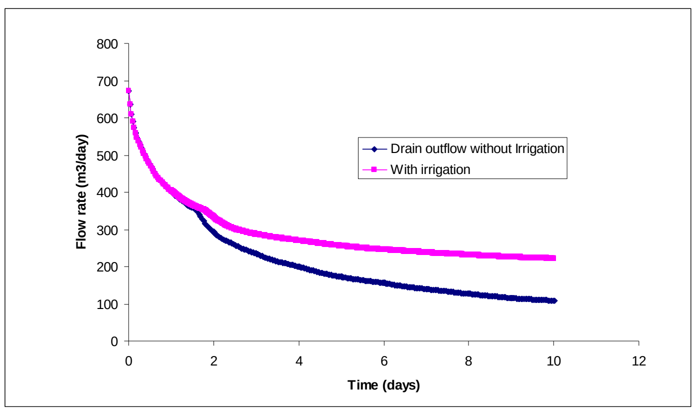
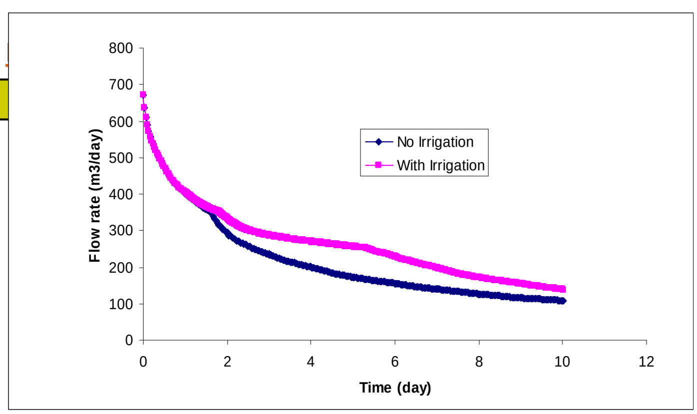


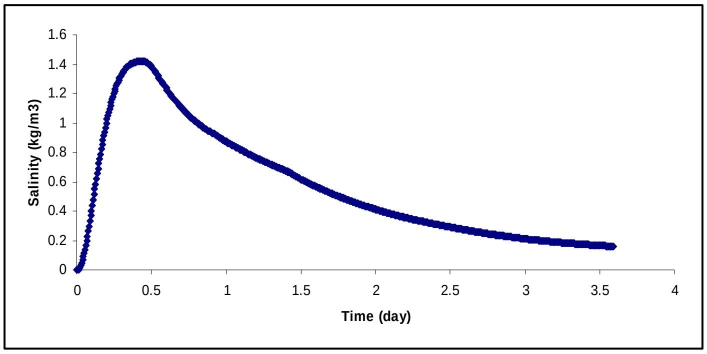
Figure 5. Water table response with time to drainage system.



(a)



(b)



(c)

Figure 6. Drain hydrographs for different cases, (a) Drain outflow hydrograph for the field with irrigation and without irrigation, (b) Outflow hydrograph for irrigation of 5 days then the irrigation stopped, (c) Salinity hydrograph of irrigation using a pulse of saline water then continue the irrigation using water with no salinity.

CONCLUSION

This paper describes the enhancements to the Colorado State University Irrigation and Drainage (CSUID) model. CSUID is an effective tool that can be used to simulate the shallow groundwater systems and simulate irrigation and drainage activities. The ability of the model to consider the variability in the soil properties in all three dimensions is a unique feature that provides a unique modeling capability. The numerical solvers were modified to minimize the mass balance error by using the mixed head and water content based Richard’s equation introduced by Celia (1990). The preconditioned conjugate gradient method is used to solve the flow equation and the transport equation. CSUID has a graphical user interface that helps the modeler to build the dataset and assign input parameters and visualize the output. Illustrative examples show that the model is able to response as predicted under certain stresses.

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