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DEVELOPMENT AND TESTING OF A COMPUTER MODEL TO SIMULATE WATER TABLE RESPONSE TO SUBIRRIGATION

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1 ABSTRACT

A two-dimensional finite difference model (WATABLE) was developed to simulate water movement from a buried microirrigation line source, and the response of the water table to irrigation, precipitation, evapotranspiration, deep percolation, and runoff. The water uptake by plant roots was simulated by an extraction function with a root distribution term. Deep percolation was modeled with a water table-drainage flux relationship, and runoff was simulated at the surface and at the face of the water furrow. The accuracy of the model in simulating infiltration and redistribution of soil water was determined by comparison with other computer simulations and experimental observations from the literature. The comparisons were selected to test the applicability and accuracy of the model with soils that had widely varying hydraulic properties. Results from WATABLE agreed very well with other simulation models and the model was able to reproduce closely the experimental results taken for comparison. This article focuses on the development and testing of the simulation model and a further article will present the calibration and verification of the model comparing results with experimental observations on water table management research plots.

KEYWORDS: drainage, modeling, subsurface drip irrigation.

ROSA, J.A., SMAJSTRLA, A.G., CAMPBELL, K.L. DESENVOLVIMENTO E TESTE DE UM MODELO COMPUTACIONAL PARA SIMULAR A RESPOSTA DO LENÇOL FREÁTICO À SUBIRRIGAÇÃO

2 RESUMO

Um modelo computacional em duas dimensões (WATABLE) foi desenvolvido para simular o movimento de água a partir de uma linha de irrigação localizada enterrada, e a resposta do nível do lençol à irrigação, precipitação, evapotranspiração, percolação profunda e escorrimento superficial. O consumo de água pelas raízes foi simulado com uma função de extração e um termo de distribuição de raízes. A percolação profunda foi modelada através de uma relação entre profundidade do lençol e

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fluxo de drenagem na parte inferior do perfil. A precisão do modelo na simulação da infiltração e da redistribuição da água no solo foi determinada comparando-se resultados obtidos com este modelo e simulações feitas com outros modelos e dados experimentais obtidos na literatura. As comparações foram selecionadas de modo a testar a aplicabilidade e precisão do modelo em diferentes tipos de solos. Os resultados obtidos com o WATABLE foram concordantes com aqueles obtidos com outros modelos, e o modelo foi capaz de reproduzir muito bem os resultados experimentais tomados como referências. Este artigo apresenta o desenvolvimento e os testes de simulação com o modelo, e um futuro artigo apresentará os resultados da calibração e verificação do modelo usando-se dados de campo obtidos em uma área experimental em manejo de lençol freático.

UNITERMOS: drenagem, modelagem, irrigação por subsuperfície.

3 INTRODUCTION

In recent years computer models have been developed to simulate the day-by-day performance of drainage and water table control systems. They range from very complex numerical solutions of differential equations to approximate methods for conducting a water balance in the soil profile (SKAGGS, 1992). Many of these models have been field tested and provide means of describing the hydrology of shallow water table soils, including effects of drainage and related water management practices on yields.

The first computer simulation models were based on a water balance in the soil profile. An example is DRAINMOD which used functional algorithms to approximate the components of shallow water table soils (SKAGGS, 1981). Approximate methods are used to simulate infiltration, drainage, surface runoff, evapotranspiration, and seepage processes on an hour-by-hour, day-by-day basis. An important feature of the model is the ability to provide information on the influence of excess and deficit water stresses on relative crop yields.

The water balance approach has also been used to develop other models. The ADAPT (Agricultural Drainage and Pesticide Transport) model (CHUNG et al., 1992) was developed by modifying the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (LEONARD et al., 1987) and extending its use by adding drainage and subirrigation algorithms from DRAINMOD. The hydrology component of the ADAPT model includes snowmelt, surface runoff, macropore flow, evapotranspiration, infiltration, subsurface drainage, subirrigation and deep seepage.

Another approach used in water table management models is based on numerical solutions to the one-dimensional Richards equation for vertical flow. Lateral water movement due to drainage is evaluated using approximate equations that are imposed as boundary conditions on the solutions to the Richards equation. The SWATRE model (BELMANS et al., 1983) is an example of this approach. SWATRE is a detailed root-water unsaturated flow model that does not need modifications to deal with water tables rising to the surface, but is limited in its capability to describe saturated flow for water table management systems, due to the use of approximate methods which cannot account for field heterogeneity.

The PREFLO model (WORKMAN & SKAGGS, 1990) also uses a finite difference solution to the one-dimensional Richards equation. The model simulates soil evaporation, plant transpiration, subsurface drainage, subirrigation, infiltration, and surface runoff. The PREFLO model uses the same input data and parameters as DRAINMOD, and the main difference between the two models is the computation of the soil water movement; PREFLO considers preferential flow through large cylindrical pores and subsequent infiltration from the large pores into the mass. WORKMAN & SKAGGS (1991) reported excellent agreement between water table simulated with PREFLO and DRAINMOD, and good agreement between PREFLO and field data in a five-year period of data record.

Direct comparison of ADAPT with DRAINMOD, SWATRE, and PREFLO showed that all models were capable of predicting water table depths with similar accuracy (DESMOND et al., 1996). SWATRE and DRAINMOD are the most widely used water table management models in Europe and the United States, respectively. Several other models are listed in the literature, but generally are modifications or improvements of the models listed above.

The objective of this article is to describe the development and testing of a two-dimensional finite difference model to simulate water movement from a buried microirrigation line source, and the response of the water table to irrigation, precipitation, evapotranspiration, deep percolation, and runoff.

4 MATERIAL AND METHODS

4.1 Model development

The water pressure–based form of the Richards equation was used in this study because it is more useful for problems involving flow in layered or spatially heterogeneous soils, as well as for variably saturated flow problems. The two-dimensional form of the Richards equation for an isotropic, homogeneous, nonhysteretic, and nondeformable soil is written as:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left[K_x(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K_z(h)\left(\frac{\partial h}{\partial z} - 1\right)\right] - S(h) \qquad (1)$$

where,

h - soil moisture pressure head (cm);
C(h) - soil water capacity (cm^{-1});
K(h) - unsaturated hydraulic conductivity, $K_x = K_z$ ($cm\ h^{-1}$);
S(h) - sink or source term (h^{-1}) and
t - time (h).

A totally implicit scheme was chosen to solve the independent variable *h*, and linearization (estimation of *C(h)* and *K(h)* in time) was obtained by considering *C* and *K* constant during Δt and equal to their values calculated at the preceding time step. The linearized equation was solved by a Gaussian elimination method.

The two-dimensional flow domain was divided utilizing a block centered finite difference grid. The pressure head was evaluated at nodes located at the center of each block. The spatial increments in the *x* (horizontal) and in the *z* (vertical) directions were indicated by Δx and Δz. The index *j* (*j* = 1,2,…,JZ) was used to number the nodes in the vertical direction, and the index *i* (*i* = 1,2,…,IX) was used to number the nodes in the horizontal direction (Figure 1).

The finite difference approximation of equation 1 was obtained by discretizing the right hand side as:

$$\frac{\partial}{\partial x}\left[K_x(h)\left(\frac{\partial h}{\partial x}\right)\right] = \frac{1}{\Delta x}\left\{\left[K_{j,i+\frac{1}{2}}\left(\frac{\partial h}{\partial x}\right)_{j,i+\frac{1}{2}}\right] - \left[K_{j,i-\frac{1}{2}}\left(\frac{\partial h}{\partial x}\right)_{j,i-\frac{1}{2}}\right]\right\} \qquad (2)$$

and

$$\frac{\partial}{\partial z}\left[K_z(h)\left(\frac{\partial h}{\partial z}-1\right)\right]=\frac{1}{\Delta z}\left\{\left[K_{j+\frac{1}{2},i}\left(\frac{\partial h}{\partial z}-1\right)_{j+\frac{1}{2},i}\right]-\left[K_{j-\frac{1}{2},i}\left(\frac{\partial h}{\partial z}-1\right)_{j-\frac{1}{2},i}\right]\right\} \tag{3}$$

For simplicity, the parameters *K(h)* were represented by *K*. The derivatives of *h* with respect to *x* and *z* were approximated by:

$$\left(\frac{\partial h}{\partial x}\right)_{j,i+\frac{1}{2}}=\frac{h_{j,i+1}-h_{j,i}}{\Delta x} \tag{4a}$$

$$\left(\frac{\partial h}{\partial x}\right)_{j,i-\frac{1}{2}}=\frac{h_{j,i}-h_{j,i-1}}{\Delta x} \tag{4b}$$

$$\left(\frac{\partial h}{\partial z}-1\right)_{j+\frac{1}{2},i}=\frac{h_{j+1,i}-h_{j,i}}{\Delta z}-1 \tag{4c}$$

$$\left(\frac{\partial h}{\partial z}-1\right)_{j-\frac{1}{2},i}=\frac{h_{j,i}-h_{j-1,i}}{\Delta z}-1 \tag{4d}$$

which when substituted back into equations 2 and 3 gave:

$$\frac{\partial}{\partial x}\left[K_x\left(\frac{\partial h}{\partial x}\right)\right]=\frac{1}{\Delta x}\left\{\left[K_{j,i+\frac{1}{2}}\left(\frac{h_{j,i+1}-h_{j,i}}{\Delta x}\right)\right]-\left[K_{j,i-\frac{1}{2}}\left(\frac{h_{j,i}-h_{j,i-1}}{\Delta x}\right)\right]\right\} \tag{5}$$

and

$$\frac{\partial}{\partial z}\left[K_z\left(\frac{\partial h}{\partial z}-1\right)\right]=\frac{1}{\Delta z}\left\{\left[K_{j+\frac{1}{2},i}\left(\frac{h_{j+1,i}-h_{j,i}}{\Delta z}-1\right)\right]-\left[K_{j-\frac{1}{2},i}\left(\frac{h_{j,i}-h_{j-1,i}}{\Delta z}-1\right)\right]\right\} \tag{6}$$

Equations 5 and 6 represent the horizontal and vertical flows, respectively. The implicit formulation of equation 1 was obtained by substituting back equations 5 and 6 into equation 1 and evaluating water pressure at the *n+1* time level. The time derivative in equation 1 was then replaced by a backward-difference approximation relative to the *n+1* time level. For simplicity, parameters *C(h)* and *S(h)* were expressed as *C* and *S*. The result is a two-dimensional finite difference equation for flow through a porous medium expressed as:

$$\begin{aligned}C^n_{j,i}\frac{h^{n+1}_{j,i}-h^n_{j,i}}{\Delta t}&=\frac{1}{\Delta x}\left\{\left[K^n_{j,i+\frac{1}{2}}\left(\frac{h^{n+1}_{j,i+1}-h^{n+1}_{j,i}}{\Delta x}\right)\right]-\left[K^n_{j,i-\frac{1}{2}}\left(\frac{h^{n+1}_{j,i}-h^{n+1}_{j,i-1}}{\Delta x}\right)\right]\right\}\\&+\frac{1}{\Delta z}\left\{\left[K^n_{j+\frac{1}{2},i}\left(\frac{h^{n+1}_{j+1,i}-h^{n+1}_{j,i}}{\Delta z}-1\right)\right]-\left[K^n_{j-\frac{1}{2},i}\left(\frac{h^{n+1}_{j,i}-h^{n+1}_{j-1,i}}{\Delta z}-1\right)\right]\right\}-S^n_{j,i}\end{aligned} \tag{7}$$

Equation 7 was then rearranged so that the unknown parameters were on the left-hand side and the known parameters were on the right-hand side. In a more useful form the equation can be expressed as:

$$A_{j,i}h_{j-1,i}^{n+1} + B_{j,i}h_{j,i-1}^{n+1} + D_{j,i}h_{j,i}^{n+1} + E_{j,i}h_{j,i+1}^{n+1} + F_{j,i}h_{j+1,i}^{n+1} = R_{j,i} \tag{8}$$

where:

$$A_{j,i} = -\frac{K^n_{j-\frac{1}{2},i}}{\Delta z^2} \tag{9}$$

$$B_{j,i} = -\frac{K^n_{j,i-\frac{1}{2}}}{\Delta x^2} \tag{10}$$

$$D_{j,i} = \frac{C^n_{j,i}}{\Delta t} - A_{j,i} - B_{j,i} - E_{j,i} - F_{j,i} \tag{11}$$

$$E_{j,i} = -\frac{K^n_{j,i+\frac{1}{2}}}{\Delta x^2} \tag{12}$$

$$F_{j,i} = -\frac{K^n_{j+\frac{1}{2},i}}{\Delta z^2} \tag{13}$$

$$R_{j,i} = \frac{C^n_{j,i}}{\Delta t}h^n_{j,i} + \frac{K^n_{j-\frac{1}{2},i} - K^n_{j+\frac{1}{2},i}}{\Delta z} - S^n_{j,i} \tag{14}$$

Equation 8 was written for each of the interior nodes in the soil profile. The grids bordering the boundaries required equation 8 to be modified so that the equation would describe the boundary conditions.

4.2 Boundary Conditions

A flux boundary condition was employed for the surface grids to represent infiltration by precipitation. To describe the bottom boundary condition, vertical drainage across the lower boundary of the soil profile was approximated by a flux that depended on the position of the water table level. The bottom boundary condition consisted of a prescribed drainage flux-water table relationship, *QB(h)*, as given by Hopmans & Stricker (1989):

$$QB(h) = ae^{b|h|} \tag{15}$$

where *a* and *b* are parameters determined from calibration of *QB* and *h*. This type of boundary condition suggests that there is at all times some downward flux leaving the soil water system at the bottom, although its magnitude can be very small as compared to the upward flux.

The left boundary of the grid was defined as a plane of symmetry that passed through the center of the field (Figure 1). Usually, in this situation there is no flux across a plane of symmetry, so this boundary was simulated with a no-flux boundary condition. At the right side of the last column of cells also there was no flux because of another plane of symmetry that passed by at the center of the water furrow. The last column of cells at the right boundary of the grid (i = IX) represented the center of the water furrow and was simulated as a pressure head boundary condition. More details on the handling of the boundary conditions are presented by Rosa (2000).

4.3 Irrigation

The subirrigation with buried microirrigation line sources was simulated by considering two irrigation lines at the depth corresponding to the depth in the field (Figure 1). One of the irrigation lines was placed at the line of symmetry (i = 1), so that only half of the flux from the line was considered to enter in the simulated soil profile. The irrigation flux was included as source at the nodes where the lines were placed, as suggested by Jnad et al. (1998).

4.4 Water uptake by plant roots

This model considers a root distribution term to determine the fraction of the total water use extracted from each node in the finite difference grid. A macroscopic extraction function developed by Smajstrla (1982) and modified by Stone (1987) was used. The extraction function was:

$$S_{j,i} = ET_r * A_t * RDT_{j,i} * R_{j,i}^{(ET_r / C / R_{j,i})} \qquad (16)$$

where:
$S_{j,i}$ - soil water extraction rate ($cm^3\ h^{-1}$);
ET_r - evapotranspiration rate ($cm\ h^{-1}$);
$RDT_{j,i}$ - root distribution term or the percentage of water extraction for the soil cell;
A_t - total surface area of the grid (cm^2);
$R_{j,i}$ - relative available soil water content, and
C - calibration constant.

The evapotranspiration rate, ET_r, in equation 16 was calculated by distributing the daily crop evapotranspiration over a 24-h period. A sinusoidal type distribution, as used with success by Vellidis (1992), was selected and given by:

$$ET_r = \frac{ET}{T_{cycle}} \left[1 + \sin\left(\frac{2\pi T_{day}}{T_{cycle}} - \frac{\pi}{2} \right) \right] \qquad (17)$$

where:
ET_r - predicted evapotranspiration rate ($cm\ h^{-1}$);
ET - daily crop evapotranspiration ($cm\ day^{-1}$);
T_{cycle} - the period of the cycle (hr), in this case 24 h;
T_{day} - the current time on the 24-h clock minus the beginning time of the cycle (h).

Equation 17 was used to calculate the water extraction rate from each cell at every time step. To make sure that the total water extraction calculated matched the actual ET_r, a comparison between the two values was done, and if necessary, the calculated water extraction for each cell was adjusted by:

$$S_{j,i} = S_{j,i} \frac{ET_r * A_t}{\sum S_{j,i}} \qquad (18)$$

Finally, to be consistent with the units in equation 11, $S_{j,i}$ was converted in units of h^{-1}, by:

$$S_{j,i} = \frac{S_{j,i}}{dz * dx * dy} \qquad (19)$$

where *dz, dx, and dy* are the dimensions of the node (L), with dy = 1 cm.

4.5 Evaluation of the soil hydraulic properties

The soil hydraulic properties water content, $\theta(h)$, unsaturated conductivity, $K(h)$, and soil water capacity, $C(h)$ were evaluated at the end of each time step. Genuchten (1980) closed-form equation for the soil water retention curve and Mualem (1976) unsaturated hydraulic conductivity function were used to describe the soil hydraulic properties.

The internodal hydraulic conductivity was estimated by the geometric weighting method because it was found preferable in terms of flexibility, precision, and feasibility for simulating water flow in partially saturated soil (HAVERKAMP & VAUCLIN, 1979).

4.6 Initial conditions

The solution to equation 11 requires that initial values of *h* be specified everywhere in the solution domain:

$$h(x,z,t) = h_0(x,z) \qquad \text{for } t=t_0 \qquad (22)$$

where h_0 is a prescribed function of (x,z) and t_0 is the time when the simulation begins. In this work, the initial condition was represented by equilibrium between the depth of the water table at the beginning of the simulation and the position of the cell in the soil profile.

5 RESULTS AND DISCUSSION

The accuracy of the model in simulating infiltration and redistribution of soil water was determined by comparison with other computer simulations and experimental data from the literature. The comparisons were selected to test the applicability and accuracy of the model with soils that had widely varying hydraulic properties.

The first example was taken from the one-dimensional HYDRUS code (VOGEL et al., 1996). The example considers transient infiltration of water in a large caisson. The soil was assumed to be at a uniform initial water content of 10% volume. In the simulation, the caisson was wetted by applying water by ponding. The bottom boundary consisted of free drainage with a unit hydraulic gradient. For the flow simulation, the 6 m deep caisson was discretized into 120 cells of uniform size, leading to a cell size of 5 cm. As shown in Figure 2, results for the two simulations agreed very well.

The second example considers water movement in a cropped field profile in the Hupselse Beek watershed of the Netherlands. Atmospheric data and observed ground water levels provided the required boundary conditions for the numerical model. Calculations were performed for the period of April 1 to September 30 of the relatively dry year 1982. Parts of this problem were previously simulated using the SWATRE (BELMANS et al., 1983), SWMS_2D (ŠIMUNEK et al., 1994) and HYDRUS (VOGEL et al., 1996) computer programs.

The soil profile consisted of two layers: a 40-cm thick A-horizon, and a B/C-horizon that extended to a depth of about 300 cm. The depth of the root zone was 30 cm. The soil surface boundary conditions involved actual precipitation and potential transpiration rates for a grass cover. The surface fluxes were incorporated by using average daily rates distributed uniformly over each day. The bottom boundary consisted of a prescribed drainage flux-groundwater level relationship as used in this work.

The groundwater level was initially set at 55 cm below the soil surface. The initial moisture profile was taken to be in equilibrium with the initial ground water level. Figure 3 shows the variations in the calculated groundwater level with time. In this example, simulations with the WATABLE and HYDRUS computer models agreed very well.

The third example was selected to verify the performance of the numerical model for a two-dimensional, transient, variably saturated flow condition. The experiment has been presented in detail by Vauclin et al. (1979). The same example was used by Clement et al. (1994) to verify their two-dimensional variably saturated model and by Dogan (1999) to verify his three-dimensional variably saturated model.

The flow domain consisted of a rectangular slab of soil, 300 cm long x 200 cm deep. The vertical right-hand side of the slab was connected to a constant head reservoir to maintain the water level constant at a depth of 135 cm at this side. At the soil surface a constant flux of 14.8 cm/hr was applied over the left 50 cm of the top of the modeled domain. The remaining soil surface at the top, the left-hand side and the bottom of the slab were no-flow boundaries. A water table was imposed at the depth of 135 cm and the experiment began when hydrostatic equilibrium was obtained throughout the flow domain.

Transient positions of the water table predicted by WATABLE were compared with the experimental results presented by Vauclin et al. (1979) in Figure 4, which illustrates that there was a very good agreement between the two sets of data.

The fourth example was chosen to verify the performance of the numerical model in modeling transient, unconfined drainage problems with seepage-face boundaries. The experimental data were taken from VAUCLIN et al. (1975). A saturated slab of soil, similar to that used in the previous example, was allowed to drain after a sudden drop in the external water table. Before drainage, the water table was maintained at the depth of 55 cm. At the time t= 0, the external water table was dropped instantaneously to the depth of 125 cm at the right-hand side, and was maintained there subsequently. No-flow boundaries were imposed at the left-hand side, on the bottom, and on the top of the flow domain. Hence, on the right side, the seepage face boundary was transiently determined between the depth of 125 and 55 cm. Below the external water table level of 125 cm, a constant head boundary was applied.

The transient simulation was continued until steady state was approached. Numerically simulated water table positions were compared with experimental results (VAUCLIN et al., 1975) in Figure 5, in which WATABLE was able to reproduce closely the experimental results.

6 CONCLUSIONS

The model developed in this work is able to simulate different water flow problems, including problems of infiltration, drainage and evapotranspiration.

The results of the model are in very good agreement with other simulation models and experimental data, which confirms that the model is suitable for application.

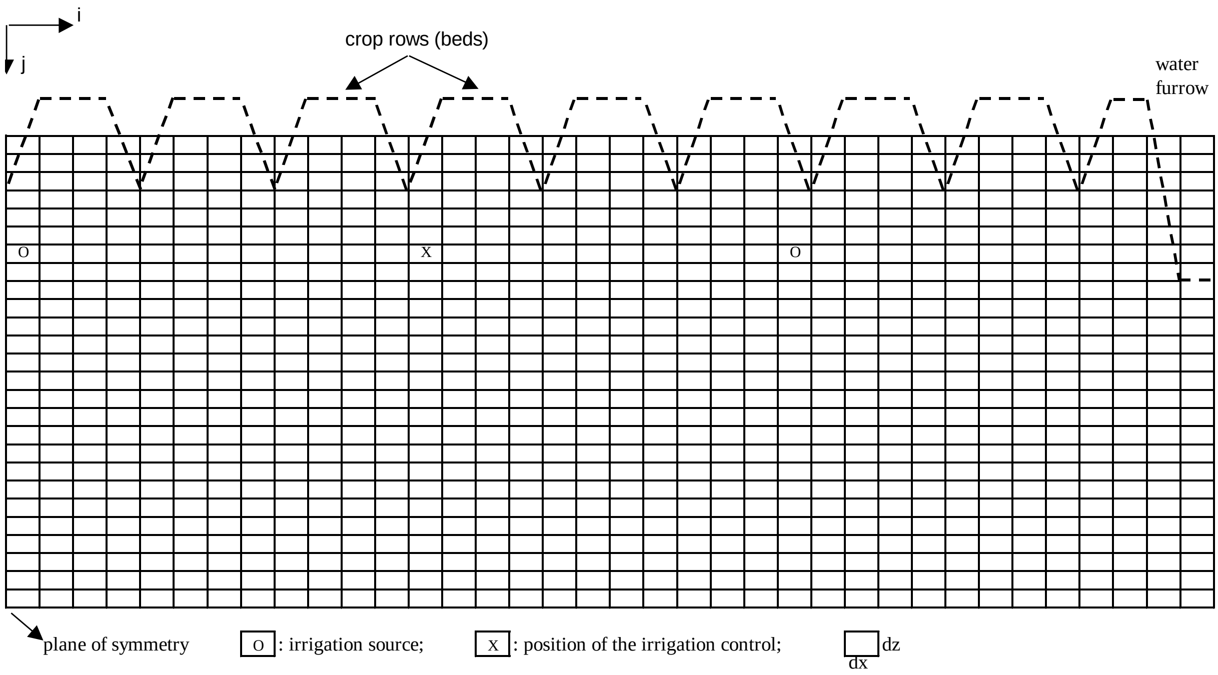

Figure 1. Grid system for the finite difference two-dimensional model.

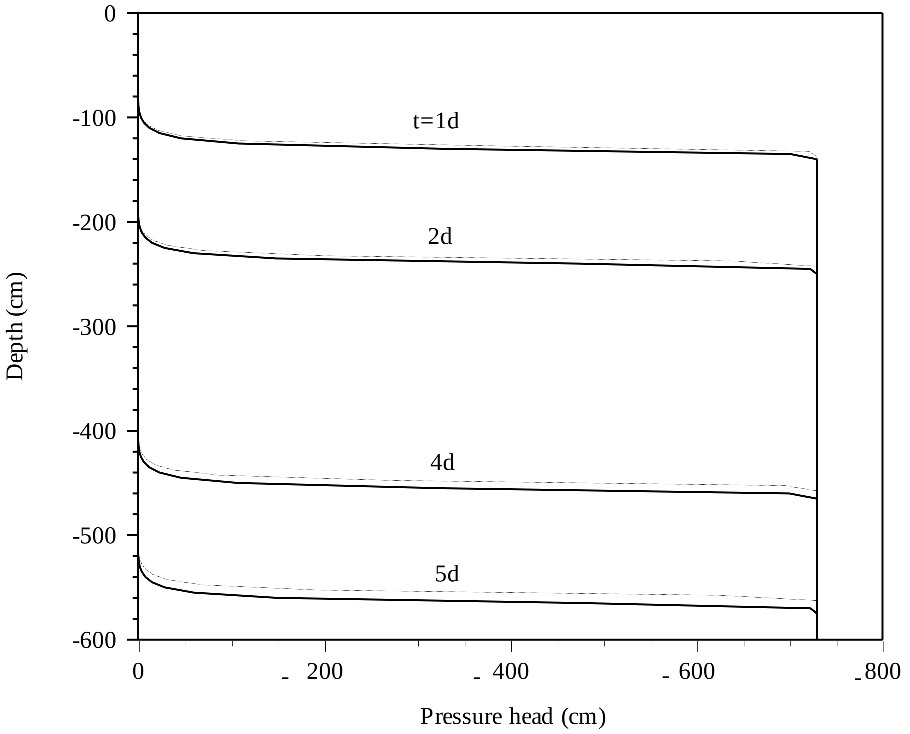

Figure 2. Predicted water pressure head during transient infiltration in Bandelier Tuff by the HYDRUS (—) and WATABLE (-------) models.

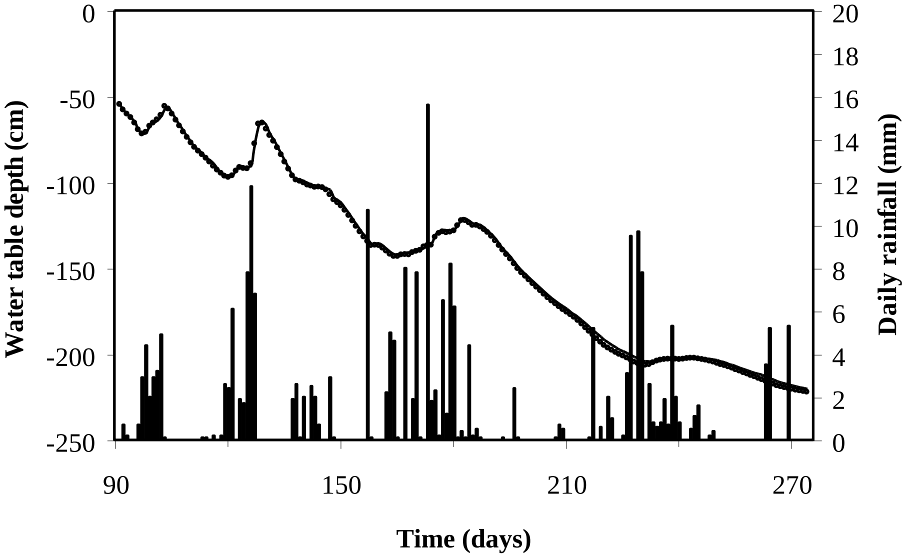

Figure 3. Precipitation and location of the water table level for the second example, as simulated with HYDRUS (—) and WATABLE (°).

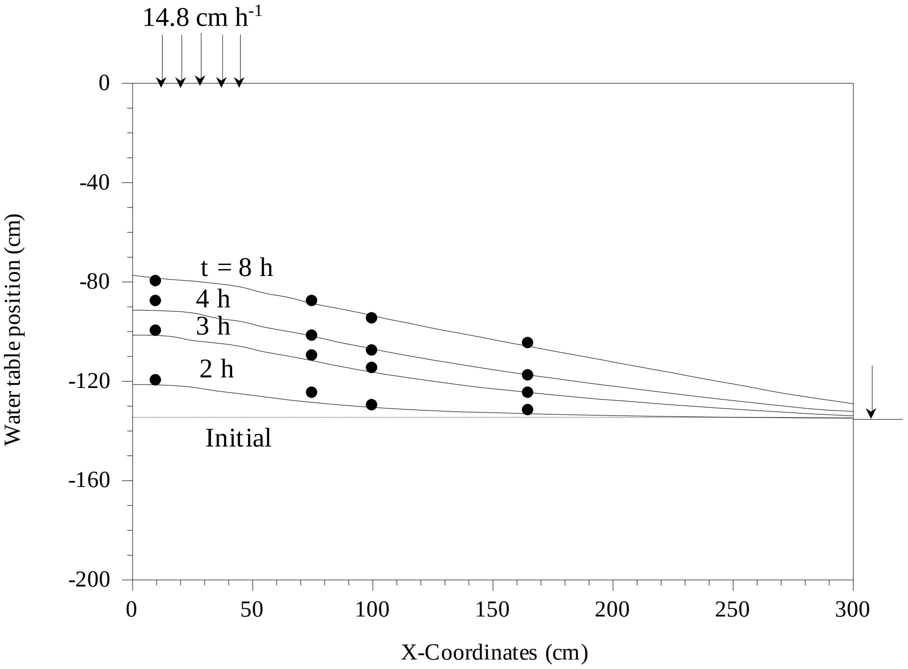

Figure 4. Simulation of transient water table mounding, comparing results of the WATABLE model (lines) and experimental data (•) collected by Vauclin et al. (1979).

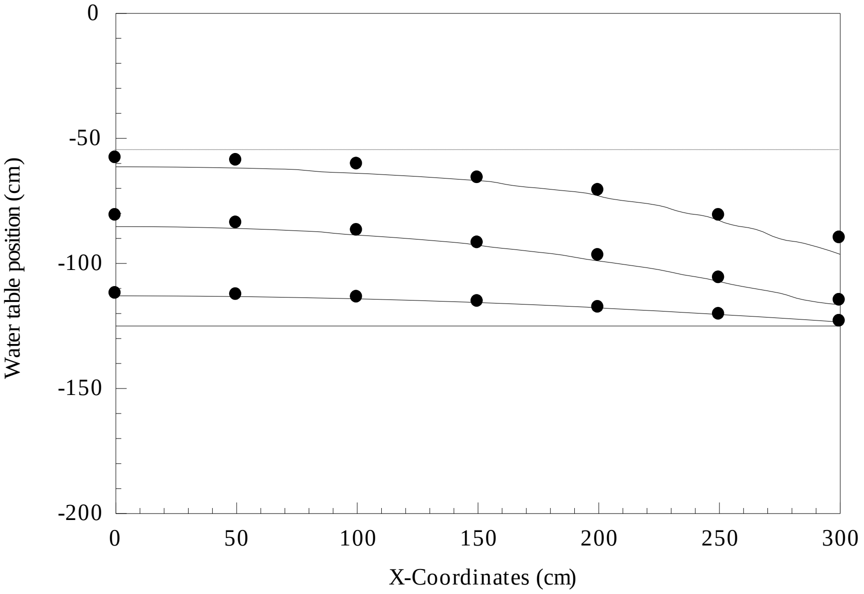

Figure 5. Simulation of transient drainage, comparing results of the WATABLE model (lines) and experimental data (•) collected by VAUCLIN et al. (1975).

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