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THEORETICAL BACKGROUND AND APPLICATIONS OF THE HYDRUS COMPUTER SOFTWARE PACKAGES

CONTEXTE THEORIQUE ET APPLICATIONS DU LOGICIEL HYDRUS

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ABSTRACT

Hydrus-2D/3D is a numerical software to simulate water and solute movement in porous media. Currently, three different versions of the Hydrus software packages are available: Hydrus-1D, Hydrus-2D, and Hydrus (2D/3D). Similar basic processes are involved on the three models and they only differ by the dimensionality of the problems they are treating. Linear finite elements are used on Hydrus 2D to numerically solve the Richard equation for saturated-unsaturated water flow and Fickian-based advection-dispersion equations for both heat and solute transport. It is also included on the flow equation a sink term to account for root water uptake as a function of both water and salinity stress. The unsaturated soil hydraulic properties can be described using van Genuchten, Brooks and Corey, modified van Genuchten, Kosugi, and Durner analytical functions. The heat transport equation considers conduction as well as advection with flowing water. The solute transport equations assume advective-dispersive transport in the liquid phase and diffusion in the gaseous phase. The uniform variably saturated water flow in all of these models is described using the Richards. Objective of this paper is to present the theoretical background of hydrus 2D and to reviews the different application of the model on agricultural

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sciences, such as evaluating different irrigation schemes, plant water uptake and transport of particle-like substances in the subsurface.

Keywords: Hydrus, submodels, applications, Richard equation, water flow, solute dynamic

RESUME

Hydrus-2D / 3D est un logiciel numérique permettant de simuler le mouvement de l'eau et des solutés dans un milieu poreux. Actuellement, trois versions différentes des logiciels Hydrus sont disponibles : Hydrus-1D, Hydrus-2D et Hydrus (2D / 3D). Des processus de base similaires sont impliqués dans les trois modèles et ils ne diffèrent que par les dimensions des problèmes qu’ils traitent. Les éléments finis linéaires sont utilisés sur Hydrus pour résoudre numériquement l’équation de Richard afin de simuler le flux d’eau dans un système saturée-insaturée. Le logiciel utilise également les équations d’advection-dispersion à base de Fickian pour simuler le transport de chaleur et de solutés. Les propriétés hydrauliques du sol non saturé peuvent être décrites à l'aide des fonctions analytiques de Van Genuchten, Brooks et Corey, de Van Genuchten modifiée, Kosugi et Durner. Les équations de transport de soluté supposent un transport advectif-dispersif en phase liquide et une diffusion en phase gazeuse. L’objectif de cet article est de présenter le contexte théorique de Hydrus 2D et de présenter les différentes applications du modèle en sciences agricoles, telles que l’évaluation de différents systèmes d’irrigation, l’absorption d’eau par les plantes et le transport de substances dans le sous-sol.

Mots clés : Hydrus, sous-modèles, applications, équation de Richard, débit d'eau, transport de soluté

INTRODUCTION

In the recent decades, word populations have been increased. As a result, food and water demand have been raised (Douh et al., 2012). Projections for the future predict a continuous increase making it necessary the extension of cultivated lands to enhance food security (Bhouri Khila et al., 2015). In the next future it is expected a great competition to reallocate water for agricultural (Zella et al., 2007), industrial and urban needs. However, at a global scale, irrigated agriculture has been consumed rising amounts of water, with percentages up to 70-80% of the total resources in arid and semi-arid regions

(Bouksila, 2011), where irrigation is a key factor to intensify agricultural productivity and to fulfil sustainable agricultural development. For that purpose, agro-hydrological models, after calibration and validation related to the specific context in which they are applied, can be considered a powerful tool for irrigation scheduling aimed to optimize water use efficiency. Agro-hydrological models are simplified and conceptual descriptions of the water cycle in the Soil plant atmosphere system and can be used for understanding or predicting the processes occurring in the system. These models are based on empirical or physically based approaches to link a certain input (for instance precipitation or irrigation) to the model output (for instance crop transpiration). The firsts are black-box systems using regression techniques or transfer functions to evaluate the model output, whereas the seconds tend to represent each single process by means of more complicated deterministic models. For instance, when studying the dynamic of crop water stress to quantify actual transpiration, it is possible to schematize the plant system by means of a global crop indicator, like the water stress index depending on soil water status. During dry periods therefore, once known the evolution of soil water status and the crop water stress function, it is possible to determine the actual transpiration. Of course, this macroscopic and empirical approach requires to accept some simplifying assumptions, such as the one related to the neglected plant capacitance. On the other hand, by using a deterministic model, crop water stress can be modelled by schematizing the plant as an electrical circuit in which however a high number of parameters related to soil and plant, such as root geometry, resistance to water flow along the soil-root path, root capacitance, not easy to be evaluated. Simplified agro-hydrological water balance models using a black-box approach include, for example, FAO-56 model (Allen et al., 1998) or AQUACROP, whereas physically based models includes, between others, Hydrus-2D/3D (Šimůnek and van Genuchten, 2008) and SWAP (van Dam et al., 2008).

Hydrus-2D/3D is numerical software to simulate water and solute movement in porous media. Currently, three different versions of the Hydrus software packages are available: Hydrus-1D, Hydrus-2D £, and Hydrus (2D/3D). Similar basic processes are involved on the three models and they only differ by the dimensionality of the problems they are treating. HYDRUS-1D treats one-dimensional problems associated with soil columns, lysimeters, soil profiles and plots. However, Hydrus-2D solves two-dimensional or axisymmetrical dimensional problems as subsurface drip irrigation, and Hydrus (2D/3D) calculates both two- and three-dimensional problems. All these versions may be used to simulate the movement of water, heat, and multiple solutes in variably saturated porous media.

Recently, numerous studies have confirmed the suitability of the model to simulate water infiltration and solute transport from buried emitters (Lazarovitch et al., 2007).

This paper explains the theoretical background of hydrus 2D and reviews the different application of the model on agricultural sciences. We strongly believe that such a review would be crucial for the HYDRUS community being in a continuous growth.

THEORITICAL BACKGROUND

Linear finite elements are used on Hydrus 2D to numerically solve the Richard equation for saturated-unsaturated water flow and Fickian-based advection-dispersion equations for both heat and solute transport. It is also included on the flow equation a sink term to account for root water uptake as a function of both water and salinity stress. The unsaturated soil hydraulic properties can be described using van Genuchten, Brooks and Corey, modified van Genuchten, Kosugi, and Durner analytical functions. The heat transport equation considers conduction as well as advection with flowing water. The solute transport equations assume advective-dispersive transport in the liquid phase and diffusion in the gaseous phase.

The uniform variably saturated water flow in all of these models is described using the Richards equation

$$\frac{\partial \theta}{\partial t} = \frac{\partial y}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial y}{\partial z} + K(h)\right] - S(x,z,t) \qquad (1)$$

where θ [cm^3 cm^{-3}] is the volumetric soil water content, t [s] is the time, x [cm] and z [cm] are the horizontal and vertical space coordinates, h [cm] is the soil water pressure head, K [cm s^{-1}] is the unsaturated hydraulic conductivity and finally, S(x,z,t) [cm s^{-1}] is a sink term expressing the rate of root water uptake (Šimůnek et al., 2011).

The most difficult aspect related to the Richard equation is the strong nonlinear based equation, only a relatively few simplified analytical solutions can be derived. Most practical applications of Richard equation require a numerical solution, which can be obtained using a variety of methods such as finite differences or finite elements. The equation of Richards is generally related to two dependent variables (the water content and the pressure head). Solutions of this equation require the identification of soil hydraulic functions describing the soil water retention and hydraulic conductivity properties. The soil water retention curve (also called the soil water characteristic curve, the capillary pressure-saturation relationship, or the pF curve) describes the relationship between the water content and the pressure head. Water retention curve and the saturated soil hydraulic conductivity are characterized using several models among which is possible to cite the Van Genuchten-Mualem (Van Genuchten, 1980), described as following:

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

θ_s[cm^3 cm^{-3}]is saturated volumetric water content; ***θ_r[cm^3 cm^{-3}]***is residual volumetric water content; ***α*** is the inverse of the air-entry value; ***n [-]*** is the pore size distribution index; ***m [-]*** is1-1/n;

The governing convection–dispersion solute transport equation for a non-reactive solute in homogenous medium is described as:

$$\frac{\partial \theta c}{\partial t} = \theta D_{ij}\frac{\partial^2 c}{\partial x^2} - q\frac{\partial c}{\partial x} \tag{3}$$

Where ***C[g cm^{-3}]*** is solute concentration in the liquid phase, subscripts ***i*** and ***j*** denote either horizontal coordinate ***(x)*** or vertical coordinate ***(z)***; the first term on the right-hand side of the equation represents the solute flux due to dispersion, and the second term the solute term due convection with flowing water. ***q [cm s^{-1}]*** is the water flow density and ***D_{ij}*** [cm^{2}s^{-1}] is the horizontal and vertical hydrodynamic dispersion coefficient. The details information about the models can be obtained from technical manual (Šimůnek et al., 2009).

As it was indicated above, the flow equation 1 incorporates a sink term to account for water uptake by plant roots as a function of water and salinity stress. The model of (Feddes et al., 1978) which is shown in the equation 5, allows defining the water uptake rate in any generic point of the root zone according to its pressure head, determining by the way the reduction in the transpiration rate when the soil can no longer provide for the plant the required amount to reach potential transpiration.

$$S(h) = \alpha(h)S_{max} \tag{4}$$

where ***S_{max} [cm s^{-1}]*** is the maximum water uptake and ***α (h)*** is a dimensionless water response function for water uptake. Feddes et al., (1978) proposed a linear model for water stress response function ***α(h)*** which involves five threshold variables: pressure head below which root water uptake occurs, P_0, pressure head below which rate for root extraction is maximum P_{opt}, thresholds of pressure head below which the rate of roots extraction is lower than the maximum P_{2H} and P_{2L}, evaluated according to the high **(r_{2H})** or low **(r_{2L})** potential transpiration rates and finally, pressure head below which root water uptake ceases, P_3.

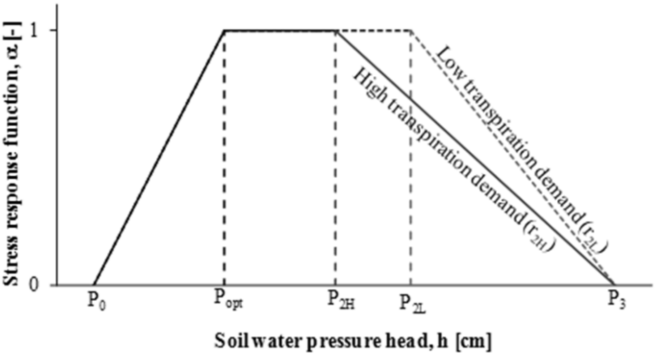

Figure 1: Stress response function Van Genuchten (1987) expanded the formulation of Feddes by including osmotic stress as follows

$$S(h, h_\phi) = \alpha(h, h_\phi) S_{max} \tag{5}$$

When the maximum water uptake rate is equally distributed over a two-dimensional rectangular root domain, S_{max} becomes

$$S_{max} = \frac{1}{L_x * L_z} L_t T_{max} \tag{6}$$

in which T_m ***[cm s^{-1}]*** is the maximum transpiration, L_x and L_z***[cm]*** represent the width and the depth of root system, while L_t ***[cm]*** is the width of the soil surface associated with the transpiration process . In cases in which it is $L_x=L_t$, the term S_m is equal to T_m/L_z. The equation 1.4.7 can be generalized by introducing a non-uniform distribution of maximum water ladling into a root zone of arbitrary shape (Vogel, 1987):

$$S_m = b(x, z) L_t T_m \tag{7}$$

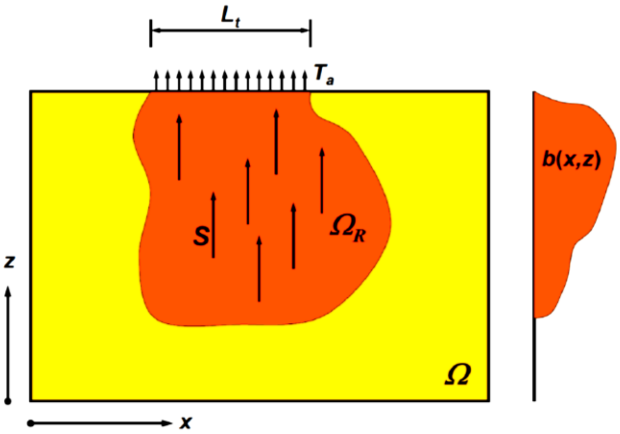

Figure 2: Schematic Distribution of maximum root water uptake, b (x, z) in the root zone (Šimůnek et al., 2009).

In Hydrus - 2D model, the spatial distribution of the root system described by the model of Vrugt et al. (2001):

$$(x,z) = \left(1 - \frac{z}{Z_{max}}\right)\left(1 - \frac{x}{X_{max}}\right) exp\left(-\left(\frac{P_z}{Z_{max|Z^*-Z|}} + \frac{P_x}{R_{max|x^*-x|}}\right)\right) \quad (8)$$

Where $\mathbf{Z_{max}}$***[cm]***is the maximum rooting depth; $\boldsymbol{X_{max}}$ ***[cm]***is the maximum rooting length in the radial direction; $\boldsymbol{x}$ ***[cm]***radial distance from the origin of the plant; $\boldsymbol{z^*}$***[cm]***,$\boldsymbol{p_z}$***[cm]***, $\boldsymbol{x^*}$***[cm]***and $\boldsymbol{p_x}$ ***[cm]***: Additional empirical parameters.

APPLICATION OF HYDRUS 2D IN AGRICULTURAL SCIENCES

Thanks to its ability for simulating both water and solute transport, Hydrus have been involved in a wide spectrum of agricultural applications referenced in peer-reviewed journal articles and many technical reports. These studies aimed to simulate the flow and transport of entities involved in agricultural applications for testing different forms of irrigation management such as drip and furrow irrigation, the transport of salt under irrigation with saline water and the water and nutriment uptake to provide guidelines for plant design. All these applications have been developed for optimizing irrigation water use. However, due to the simplifying assumption in their theoretical development as well as the high number of required variables, related to soil, plant and external environment, such models need to be validated, before any other successive use.

A number of 100 manuscripts and even more, where Hydrus (2D/3D) was used to simulate irrigation, was been identified. The major number of these manuscripts studied irrigation under arboricultural crops (Almond, vineyards, orchids, mandarin, citrus) (eg. Yao et al., 2012, Deb et al., 2013), and only a number of 20% of the manuscripts studied the irrigation under horticultural crops. The investigated crop was mainly corn crop but it can be also found some other horticultural crops like tomato, pepper, eggplant and potatoes.

In the section below, it is briefly reviewed applications of the Hydrus models to drip and furrow irrigation practices, irrigation and soil salinization problems and water and nutriment uptake. Modeling surface or subsurface drip irrigation has been a pioneer application of Hydrus (2D/3D). Skaggs et al.(2004) successfully validated the Hydrus-2D model by a comparison between simulated and measured soil water content under drip irrigation and concluded that the model can be used as a helpful tool for evaluating soil water content patterns around drip emitters. More than 80 manuscripts where in Hydrus (2D/3D) was used for simulating drip irrigation. The representation of the emitter in the soil profile changed in these studies. Some authors like Skaggs et al. (2004) considered the emitter as a line source, others like Lazarovitch et al. (2009) and Kandelous and Šimůnek (2009) considered the emitter as a point source. Kandelous et al. (2011) discussed under which conditions it is preferable to present the drip emitters as a punctual or line source in an axisymmetrical 2D domain. They concluded that an axisymmetric 2D representation is preferableonly before the overlap of the wetting patterns and a planar 2D model is used when wetting fronts from each two consecutive emitters fully overlapped. They reported that the 3D model is the only model that could entirely describe subsurface drip irrigation.

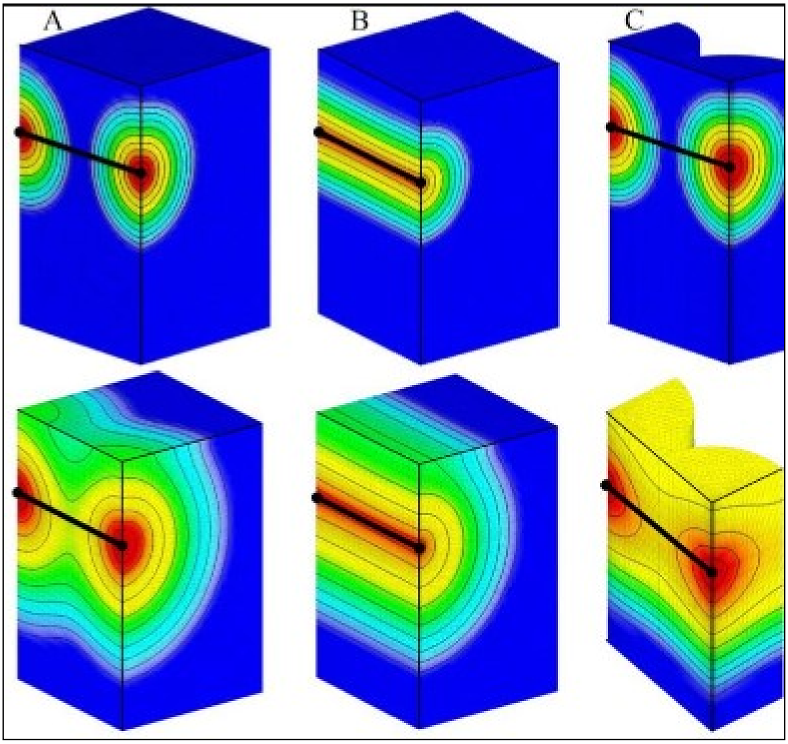

Figure 3: Water content distribution in a surface, drip-irrigated soil profile simulated as (A) a three-dimensional system with two point sources, (B) a two-dimensional system with a line source and (C) axysmmetrical with a point source. The first row shows a notoverlapped front and the second row a fully merged front (from Kandelous et al., 2011)

Estimating the position of the evolution of wetting irrigation bulb in the time for irrigation system design was successfully determined using Hydrus model (Cook et al., 2006, Warrick and Lazarovitch, 2007, Lazarovitch et al., 2009; and Kandelous and Šimůnek, 2010). Dabach et al. (2015) studied the optimal tensiometer placement for high-frequency subsurface drip irrigation management in heterogeneous soils. A similar pattern was also studied by Assouline et al. (2006) and Mubarak et al. (2009). The effect of different drip irrigation treatment in soil water and salinity distributions were simulated by Hanson et al. (2008, 2009),Shan and Wang (2012), Selim et al.(2012, 2013), and Phogat et al. (2014). Others investigations used Hydrus to study N leaching under different irrigation management (Li et al., 2004, 2005; Gärdenäs et al., 2005; Hanson et al., 2006; Ajdary et al., 2007).

More than 20 papers treating the furrow irrigation by Hydrus model. A first application was developed by Benjamin et al. (1994) in which he usedHydrus-2D to simulate fertilizer distributions under furrow irrigation. Later on, Abbasi et al. (2003a,b, 2004) conducted a study to compare between measured and simulated soil water contents and solute concentrations along a blocked-end furrow irrigation system using HYDRUS-2D. Similarly, Mailhol et al. (2007) and Crevoisier et al. (2008) found good agreement between measured and simulated data with Hydrus-2D in terms of pressure heads, nitrate concentrations, and N leaching in seasonal studies of conventional- and alternate -furrow irrigated systems while considering both root water and nutrient uptake. Ebrahimian et al. (2012) used the Hydrus-1D and Hydrus-2D models for simulating waterflow and nitrate transport under different fertigation systems following conventional furrow irrigation, fixed alternate-furrow irrigation, and variable alternate-furrow irrigation. Ebrahimian et al. (2013 a,b) similarly used the 1D surface and 2Dsubsurface models to develop scenario analysis aiming to reduce nitrate losses.

With the increase of the use of saline water for irrigation of several arboricultural and horticultural crops, awareness about soil salinization and sodification have been increased. Hydrus models have been considered in several research papers for evaluating sustainable irrigation strategies when using saline water, assessing reclamation of saline or sodic soils, and evaluating the movement of salts after irrigation with saline water saline waters or caused by a shallow saline groundwater table. For Hydrus model, the transport of solute can be predicted either assuming that salinity behave like an inert component (Hanson et al., 2008; Dudley et al., 2008; Robertset al., 2009) either by considering that saline ion could chemically react together or with major ions in the soil (Ramos et al., 2011). With the earlier approach, it was not possible to investigate on the cation exchange, the dissolution of mineral amendments, or precipitation of these minerals in case of an oversaturation while the newest version allows considering those geochemical processes and the effects of salts and soil water quality on soil properties. Ramos et al. (2011, 2012) demonstrated the applicability of these models for simulating multicomponent major ion transport in soil lysimeters irrigated with waters of different quality. Ramos et al. (2011) compared results obtained when considering the solute as an inert component or when considering it as a reactive component and discussed their respective advantages and disadvantages. He concluded that in a case of considering possible reactions of the solute with the majors ions in the medium, more input information is required (the solution composition of irrigation waters and Gapon exchange constants for all soil horizons) and simulation runs will be longer (~20 times) than when considering it as an inert solute. Ramos et al. (2011) studied the salinity by describing field data of the water content and overall salinity in terms of electrical conductivity (ECe) and the concentrations of individual soluble cations as well as of the Na adsorption ratio and the exchangeable Na percentage. He found that the main differences between the two approaches were found when soil water contents decreased significantly below field capacity, in such case the first approach simply increased ECe linearly as the soil dried out, while the second approach produced a nonlinear increase in ECe as a result of cation exchange. Hanson et al. (2008) reported that Hydrus modeling showed considerable leaching around the drip lines caused by the spatially varying soil wetting patterns that occur during drip irrigation.

Hydrus 2D have been also recently been used for simulating root and nutriment uptake. In 2009, Šimůnek reported that Hydrus models are now available with a relatively comprehensive macroscopic root and solute water and solute uptake taking into account both saline and water stress. Comparing the ability of Hydrus-1D and Hydrus-2D to simulate water and Nutrient uptake, it reveals that the advantage of Hydrus-1D is in the fact of the possibility to prescribe a time variable rooting depth either using the logistic growth function or in a tabulated form, feature which is not possible by Hydrus-2D who assumes a constant root distribution during the simulation. However, both models do not allow the spatial extent of the rooting zone as a result of environmental stresses. Since several investigations have been developed to overcome these deficiencies by modifying the Hydrus model or by coupling other models for simulating various root growth. Zhou et al. (2012) joined HYDRUS-1D to WOFOST (Boogaard et al., 1998) crop-growth model for developing a resulting model allowing to simulate the growth and yield of irrigated wheat and maize. For the same purpose, Han et al. (2015) coupled Hydrus-1D with a simplified crop-growth model used in the Soil and Water Assessment Tool (SWAT) to simulate the effect of groundwater table on cotton growth and root zone water balance. Recently, Šimůnek (2016) also developed in both Hydrus-1D and Hydrus (2D/3D) the root-growth model of Jones et al. (1991) for involving the influence of various environmental factors on root development under stress conditions.

CONCLUSION

Hydrus-2D/3D is a numerical software to simulate water and solute movement in porous media. In that paper, it was reviewed the theoretical background of hydrus 2D. Linear finite elements are used on Hydrus 2D to numerically solve the Richard equation for saturated-unsaturated water flow and Fickian-based advection-dispersion equations for both heat and solute transport. It is also included on the flow equation a sink term to account for root water uptake as a function of both water and salinity stress. The unsaturated soil hydraulic properties can be described using van Genuchten, Brooks and Corey, modified van Genuchten, Kosugi, and Durner analytical functions. The uniform variably saturated water flow in all of these models is described using the Richards equation. The governing convection–dispersion solute transport equation is used for a non-reactive solute in homogenous medium. The sink term could be ascribed according to the model of Feddes or Feddes and Van Genuchten. In a second part of the manuscript, it was also discussed the different application of the model on agricultural sciences, such as evaluating different irrigation schemes, plant water uptake and transport of particle-like substances in the subsurface.

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