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Review and Classification of Modeling Approaches of Soil Hydrology Processes***

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ABSTRACT- To use soil hydrology processe (SHP) models, which have increasingly extended during the last years, comprehensive knowledge about these models and their modeling approaches seems to be necessary. The modeling approaches can be categorized as either classical or non-classical. Classical approaches mainly model the SHP through solving the general unsaturated flow (Richards) equation, numerically or analytically. Due to a number of shortcomings of classical approaches, a trend toward the application of non-classical models has been initiated in recent years. Artificial neural networks and fuzzy logic systems are two main kinds of non-classical approaches. In this study, existing modeling approaches of SHP with an emphasis on recent trends were reviewed and compared. Also, modeling approaches of soil hydraulic functions are reviewed briefly as a main part of SHP models. Finally, classifications for SHP models from different viewpoints are presented.

Keywords: soil hydrology processes, modeling approaches, classical, artificial neural networks, fuzzy logic

INTRODUCTION

During the last four decades, computer simulation models have played an increasingly important role in the study of agricultural and environmental systems (AES). Since then, model limitations, reliability flaws, and their misuse have inspired sagacious critiques on AES modeling practices (11, 102 and 130). In fact, when used properly, models are capable tools that help researchers to expand their understanding of AES. Compared to field/laboratory experiments, modeling is quick and inexpensive (81 and 95). Of course, they cannot completely substitute physical experiments. But, models can lower the number of real-life experiments needed for a given research project. Moreover, by enabling us to perform several simulations, models provide more insight into the phenomena and the way different combinations of variables and parameters influence the results. Generally speaking, models are helpful, powerful tools for predictive and decision-making processes, if used cautiously and knowingly.

Modeling of soil hydrology processes (SHP), as a major component of an AES, has been at the center of attention of soil hydrologists for many years. Models have been continuously evolving because of the start of the computer era in SHP modeling. Use of modeling has changed our perception of soils. From a simple detachable sub-system with static parameters, we now conceive soils as an open, dynamic and heterogeneous

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system which is an integral part of a continuous environment (11, 14, 27 and 97). Its parameters are uncertain and have spatio-temporal variability originated by stochastic/deterministic causes.

In an effort to achieve a perfect model, numerous models have been developed and many of these have undergone several successive improvements. Their evolutions have proceeded through several upgrading pathways: from empirical to mechanistic formulations, from time-invariant to time-variant conceptualizations, from one- to multi-dimensional, from single- to multi-process simulations, from simple to advanced computation algorithms, and from confusing codes to more structured/modular and lucid codes. In other words, the desire to model reality as precisely as possible has motivated modelers to develop more comprehensive and complex models.

Complex (multi-process/multi-dimensional/mechanistic) models have inherent problems. One such problem is the need for large input data sets, while at the same time, physical, expense, and time limitations oblige us to use estimation of these parameters. Tedious programming efforts and high computational costs are two other problems. More importantly, complex models suffer from inherent accuracy limitations. That is, inasmuch as factual values of many parameters are not known, errors are introduced to the models via estimated values. Also, parameters spatio-temporal variations, which are not easy to capture minutely, contribute to the total input error to these complex models. It is not true to say that they are useless, but they have failed to serve us as perfect models. Yet, complex models can promote our insight into different cases and scenarios if they are used wisely. It is interesting to note that verification and validation of these models is impossible. Hence, the veracity and reliability of these models are unknown.

Infiltration, evaporation from bare soil, evapotranspiration, moisture redistribution, preferential flow, deep percolation, and root water uptake are different components of SHP. Richards Partial Differential Equation (PDE) is customarily used to model most of these components. This PDE shows high non-linearity since its coefficients, the unsaturated hydraulic conductivity and soil water retention curve, are nonlinear functions of the soil water pressure head. In far from equilibrium conditions, where flow region parameters are highly variable, spatially and/or temporally, solution of this PDE is not easy. This approach is even more complicated for multi-dimensional and for very dry cases. The aforementioned is a likely reason why most popular SHP models are still one-dimensional.

In order to resolve the problems of complex models, a shift in the modeling approaches seems to be necessary. Much needed are models with shorter execution times, to be used for optimization tasks; and models with much more lucid codes. The customary approach is to interpret SHP as deterministic phenomena. However, the recognized high non-linearity of SHP components suggests the possible chaotic behavior of these phenomena (56). Therefore, a new approach based on chaos theory may be more fruitful. In fact, the shift has already started. New modeling approaches, here called non-classical models, have arisen. These non-classical models are usually based on some new computational techniques such as artificial neural networks, fuzzy logic/mathematics, and rule bases.

This paper focuses on different approaches of modeling the SHP, both classical and non-classical, with an emphasis on the most recent ones. A classification of the approaches is then presented, which is done through consideration of differences among models on the basis of conceptualization, formulation and the algorithm used.

Review of SHP Modeling Approaches

Generally, two main categories of the modeling approaches of SHP can be distinguished: classical and non-classical. Those which are called classical approaches use various methods to solve the governing PDE, Richards equation. On the other hand, non-classical approaches are those which try to model SHP through other heuristic approaches. These two categories are reviewed in the following sections.

Classical Approaches

Numerical Modeling

Computer simulations via numerical solutions of Richards PDE were the most popular among the classical approaches. The first SHP models were developed during the early sixties which were based on the Finite Difference (FD) method (4). They were followed, one decade later, by the Finite Element (FE) method (2). The most notable advantage of FE over FD is the capability to accurately map irregular system boundaries in multi-dimensional simulations as well as to more easily include non-homogeneous medium properties (19). Yet, in terms of numerical stability and accuracy of the solutions, Celia et al. (40) showed that for one-dimensional (1D) unsaturated flows, FD methods are preferred over FE methods. They also showed that a mixed form of the Richards' is a general mass conservative numerical solution for variably saturated soil moisture (VSSM) flow.

Faced with numerical problems to solve Richards' via an FD scheme, Dane and Mathis (9) developed a "space step size adaptive" scheme. Meaning that, a fixed number of nodes were automatically distributed to establish fine grids where large soil moisture pressure head gradient occurs. Moldrup et al. (18) promoted a rapid and numerically stable method that had been first proposed by Wind and van Doorne (5). The model was labeled "moving mean slope", because it uses the average slope of the natural log of the unsaturated hydraulic conductivity function. Despite its promising features, the model had two shortcomings: it was developed for 1D cases only and it was not rapid any more enough for coarse soils.

Ammentorp et al. (7) reported their work on the unsaturated zone component of the SHE (Système Hydrologique Européen) watershed scale model. The VSSM flow component, based on the 1D numerical solution of Richards equation, deals with heterogeneity through separate model runs for each typical soil profile. Another watershed model with a pioneer 3D VSSM component in its time, based on FD solution of the Richards equation, was developed by Al-Soufi (6). Inasmuch as the model was 3D, soil heterogeneities, were directly taken care of. Both models did not consider any measures for data uncertainty. To express soil data uncertainties, Chung and Austin (8) used stochastic inputs for their 1D model. The model considers a heterogeneous layered soil profile, and uses Monte Carlo simulation to produce stochastic input parameters for each soil layer. A comprehensive review of soil water dynamics modeling in the unsaturated zone was presented by Feddes et al. (60). For more on modeling practices before 1988, refer to this article.

During the last decade, many modelers have developed their own versions of numerical computer simulation models each with its pros and cons. They have dealt with

SHP modeling complications in different ways. Innovative numerical models use approaches that have never been used earlier in SHP modeling. An example is the model developed by Rieder and Prunty (105). The model, based on a simple coupled differential equation set, solves heat and mass transfer simultaneously. Another example is the model based on the "Lie group" method of differential equations' classification (32). In recent years, as the parallel processing becomes more available, the number of SHP models that make use of this advantage has increased. The model developed by Thomas and Li (123 and 124) is an example of such models. To attenuate the numerical difficulties, Prevedello et al. (103) introduced gravitational and global soil moisture diffusivities that substitute the Richards' with a diffusivity type equation for which many solutions are available. However, their model is not applicable to positive pressure (i.e. saturation) which is a commonly occurring situation (e.g. during ponded-infiltration or ground water dynamic). Also, in the same direction, to lessen the nonlinearity of the VSSM flow, Amokrane and Villeneuve (29) used a variable transformation which had reduced the Richards' into a diffusion format. But, inasmuch as this model is a diffusion type, as well as the other model just mentioned above, it is not applicable to saturated cases. To speed up computations, a number of modelers have tried to establish more accurate explicit numerical methods, usually using a kind of predictor-corrector scheme.

Some well-known SHP 1D models based on FD methods are GLEAMS (15), OPUS (116), SWAP (128), HYDRUS-1D (158), RZWQM (87) and LEACHM (76). Each of these models has a long history of improvement. For instance, SWAP, a new version of SWACROP and SWATRE, has been improved by a change of Richards' equation solution scheme from head-based to mixed-based due to the recommendations of Celia et al. (40). Also, it has been improved by the addition of new components such as adsorption-decomposition of solutes and heat transfer as well as by attachment of hysteresis to the water retention curve. The GLEAMS model is another example which has recently been modified for flow through cracking clay soils by Morari and Knisel (94). Also, the ADAPT model (48) was developed by combining algorithms of GLEAMS and DRAINMOD (21 and 22). This hybrid water table management model considers macropore flow as a component of VSSM flow.

On the other hand, an example of models based on the FE scheme is the one developed by Antonopoulos and Papazafiriou (30). They used the Galerkin FE method, the most common FE scheme used in SHP, to solve 1D, vertical transient flow of water, and mass transport of conservative solutes in unsaturated media. Another example is the SAWAH model (133), which simulates simultaneously saturated and unsaturated flows in a soil profile, including the case where moving saturated horizons exist above the water-table level. SAWAH operates with variable time-steps and uses implicit and explicit schemes for unsaturated and saturated flows respectively. Another FE method is the boundary integral equation, also known as the boundary element (BE) that lessens the dimensionality of the problem by initially solving the problem only on its domain boundary. An interior solution can then be sought from the boundary solution. Taigbenu (119) and Montas et al. (93) have applied this method to solute transport and preferential flow problems respectively. Ju and Kung (78) have compared lumped mass with consistent mass and linear elements with quadratic/cubic elements in FE SHP models. For a time-dependent problem with a large and complex domain, they suggest the use of a lumped mass scheme with linear elements. They also concluded that the time step should not be constant in such a case. Popa et al. (156) considered mixed FE discretization for a class of degenerate parabolic problems including the Richards equation. In this work, after regularization, time discretization was achieved by an Euler implicit scheme, while mixed FE were employed for the discretization in space. Based on the results obtained in this work, a simple iterative scheme was considered to solve the emerging nonlinear elliptic problems. A stochastic FE method, which is based on the perturbation technique, was developed by Chaudhuri et al. (147). In this method, an alternate approach was used for obtaining improved computational efficiency. A multi-scale FE linearization scheme was presented by He et al. (150) for effectively simulating unsaturated flow in heterogeneous porous media spanning over many scales. The central goal of this method was to obtain the large-scale solution of Richards' with heterogeneous coefficients accurately and efficiently on a coarse grid without resolving all the small-scale details.

In any case, both FD and FE methods face some general problems. Difficulty in estimation of the effective values of unsaturated hydraulic conductivity, which significantly controls the model outputs, is one example of such general problems. Moreover, knowing the rightful spatio-temporal average values of unsaturated hydraulic conductivity in the descretized domain is important; especially, when soil-moisture differs sharply between two adjacent nodes or when rapid temporal changes happen. Recognizing the importance of inter-node hydraulic conductivity calculation methods on numerical models, Li (85) recommended the use of a composite integration formula, where each increment is subdivided into a number of intervals, to gain the best results. Another general problem is the high computational cost, especially in 3D VSSM flow simulations. To reduce the computational cost, Huang et al. (74) established a new convergence criterion for the numerical solution of the mixed based Richards equation. They compared this with standard and mixed conversion criteria and found a considerable decrease in the computational cost; especially, when the initial soil conditions are very dry or when soil hydraulic functions were extremely nonlinear. In fact, these are conditions where numerical solutions with standard or mixed conversion criteria fail to converge, become unstable, or only slowly converge. Another advantage of FE over FD schemes may be conceived as flexibility of the FE grid that can be adapted to irregularities of the external and internal boundaries of the flow domain. However, FD schemes may be preferred due to their better stability for VSSM flow problems, as found by Celia et al (40). A hybrid approach, crossed from FE and integrated FD, in SHP modeling is "control volume FE" as described by Patankar (20) and employed by Di-Giammarco et al. (55). Hence, the model is conservative at local scales and capable of dealing with irregular and complex geometries.

Concurrent to modeling practices on SHP, many researchers have tried to simulate SHP components in separate models or with an emphasis on a single component. Some instances of such components and research works are listed here: infiltration (36, 39, 46 and 47); actual evaporation from bare soil and/or actual transpiration (57, 136 and 138); preferential flow (54, 64 and 134); soil deformation and/or swelling (45, 63 and 122); redistribution (91 and 96); and hysteresis (73 and 127). Effective parameters and data uncertainty were two important issues in SHP research works during these years. Both issues aimed to provide more realistic estimates of VSSM flow parameters that explain the real world situations to the model in a better way. Among researches, those who used so called "inverse methods" (75, 82 and 120) and statistical and stochastic measures (17 and 145) were dominant. Wildenschild and

Jensen (131) have studied and compared different effective parameter estimation methods for soil hydraulic characteristics. They concluded that none of the practical methods performed well, but among other field feasible methods, stochastic methods were found to be more reliable.

Knowledge of soil-plant relationships is essential in many SHP simulation cases; therefore, some modelers have considered plants' interactions with soil in their models. For example, the effect of root distribution on soil-water flow, plant water uptake pattern (42 and 79), mechanisms of root growth and soil-water uptake have become modeling subjects. Jonse et al. (77) have proposed a conceptual approach to model main root growth properties. They have taken into account different soil factors affecting rooting. Clausnitzer and Hopmans (49) have developed a transient 3D model of root growth and soil water flow, where root elongation of a single plant is simulated via translocation of the root apices in individual growth events as a function of current local soil conditions.

The surrounding environment is detached from the simulation domain and replaced by boundary conditions (BC). Therefore, the proper setup of the BC has key importance in the modeling process. The soil surface, usually selected as the upper boundary, is the interface between soil and atmosphere; where infiltration and evaporation or evapotranspiration take place. From models that have been developed for the upper boundary interface processes, few examples are mentioned here. A conceptual infiltration model with redistribution, which was developed first by Smith et al. (117), was improved by Corradini et al. (50) to become faster and simpler. The model is an analytical approximation of a single ordinary differential equation and is claimed to be fast and accurate enough for most hydrological applications. Wilson (132) has proposed a model for surface flux boundary which is based on a system of equations for heat and mass transfer in the soil-atmosphere continuum. In contrast to Wilson's approach, most other models totally discretize the soil from the atmosphere even though it is not the case in reality.

Generally, 1D models have been evolved via two paths: first, expanding by embracement of more processes, and second, reinforcing by inclusion of more details of SHP. However, their application is logically restricted to the pedon scale.

Examples of multi-dimensional (2D/3D) models, generally not as popular as 1D models, are discussed hereafter. More FE based models may be seen among these models. FLAMINCO, a 3D model developed by Huyakorn et al. (12), is based on the Galerkin FE scheme that simulates water flow and migration of non-conservative contaminants in a variably saturated and anisotropic porous media. A second example is LINKFLOW (69, 70), a quasi-3D model based on FD which was developed to simulate the movement of soil water under a cropped field during various water table management practices. It comprises two main components: a 1D unsaturated flow module and MODFLOW (16) that functions as a 3D saturated flow module. Almost the same approach has been pursued by Yakirevich et al. (137) to develop the quasi-3D model. In their first paper, implementation of the quasi-2D model, they have reported their 2D model as being several times faster than two well-known 2D models: the SUTRA model (26 and 24) and the 2DSOIL model (98). The model developed by Wu (135) is a complex numerical model to simulate 1D, 2D and 3D simultaneous transport of water, heat, and multi-component reactive chemicals in saturated-unsaturated soils. The model is based on the Galerkin FE method. Gregersen (67) developed the SIM2D model, a 2D SHP model that is based on Galerkin FE scheme for the time-independent part of the Richards equation, while employing a fully implicit FD scheme to estimate time derivatives. The VS2DT model, a 2D-FD model, was developed to simulate the interactions between surface water and ground water. The model may be used to simulate river and groundwater interactions as well as transports between the root zone and groundwater (41 and 71). Russo et al. (106) developed a 3D-FD model intending to improve the knowledge of flow transport through a 3D heterogeneous porous media at real field scale. The model is based on a 3D mixed form of Richards' solved by a modified Picard method. Flow field hydraulic properties, assumed as statistically anisotropic random space functions, were generated stochastically. Today, HYDRUS 2D and 3D developed by Simunek et al. (159 and 160) are known as two dominant multi-dimensional as well as multi-process models.

There are more multi-dimensional models not listed here, but none of them are as popular as most 1D models. Theoretically, unsteady multi-dimensional numerical models have the ultimate capability of dealing with real world temporal and spatial variability; however, some problems are practically encountered. In addition to laborious work needed to develop such models, the lengthy execution time for these models is a matter of concern for practical applications, especially whenever several runs are required. Moreover, 3D models require a great deal of input data. This means that the quality of the model results is greatly dependent on the quality of input data. In other words, if the input data carries a small error then the accumulated error might discredit the model results.

Most important factors affecting the input data quality may be addressed as follows. The first factor is the extension of point values to the surrounding areas. Not only is the assumption associated with this extension (i.e. homogeneous field) not true for most cases, it is practically unfeasible to measure the characteristics of a field at any point. Secondly, temporal variability makes point measurements even less factual. Finally, measured data are intrinsically associated with errors to a degree and some input data are only estimated values assessed upon point-measured data. The first and second factors are due to the heterogeneity/complexity of natural systems which neither can be captured minutely nor removed. In fact, comprehensive simulation of SHP and satisfactory result interpretation requires that heterogeneities of these systems to be taken into account. Therefore, highly accurate results could not be expected when deterministic models are used to simulate non-deterministic systems, as is the case for most of the numerical models discussed.

Analytical Modeling

Due to the disadvantages of numerical approaches as discussed above, to solve the problems associated with SHP modeling, many researchers have tried to model SHP, analytically. Portraying VSSM flow as a diffusion-convection wave process and simplifying vertical soil-water flow, Smith (23) approximated the VSSM flow via an analytical model based on kinematic waves. The idea has tempted some other researches to pursue this path to SHP modeling. Some examples are Germann (10) on macropore flow; Mdaghrialaoui and Germann (90) on macropore and diffusive flow; and Singh and Joseph (115) on VSSM flow with crop-roots uptake.

Broadbridge et al. (38) analytically solved a versatile nonlinear convection-diffusion model for non-hysteretic redistribution of liquid in a finite vertical unsaturated porous column. With zero-flux boundary conditions, they transformed the nonlinear boundary-value problem to a linear problem which was exactly solvable by the method of Laplace transforms. They claimed that this technique can be applied to arbitrary initial conditions. Philip (101) gave an analytical solution to the redistribution of water in a horizontal column of infinite dimension. He used the Boltzmann transformation and assumed power law flux-concentration relations to solve the problem. Philip's solution is an implicit integral that requires iterative numerical integrations to have a sorptivity equal to desorptivity. Shao and Horton (161), too, presented an exact solution to horizontal water redistribution by using general similarity theory. In this work a power function of soil water diffusivity was used to derive the exact solution. Zhu and Mohanty (167) presented some analytical solutions for steady state vertical infiltration. They claimed that their work complemente Warricks solutions for evaporation. Menziani et al. (153) have presented analytical solutions for the linerized 1D Richards' for discrete arbitrary initial and boundary conditions. The result was the soil water content at any required time and depth in a semi-infinite unsaturated porous medium domain.

Tracy (163) derived clean analytical solutions from Richards' for 3D unsaturated groundwater flow. Clean means that the boundary conditions and steady state solutions are closed form expressions and the transient solutions have relatively simple additional Fourier series terms. Two-dimensional versions of these solutions were also given. The primary purpose for the solutions was to test linear and nonlinear solvers in finite difference/volume/element computer programs for accuracy and scalability. Another analytical solution from Richards' for 3D unsaturated flow was derived by Tracy (164) for a box-shaped soil sample. He concluded that both solutions are very valuable in testing numerical models using the finite element/volume/difference computational techniques. Zlotnik et al. (168) presented a technique, referred to as the launch pad technique, which was based on the traveling wave solution to generate an exact solution of the boundary value problem for the Richards equation. This technique that was applicable to any descriptor of unsaturated hydraulic properties was illustrated on an application involving the infiltration of water into soils with properties described by Brooks-Corey (1) and van Genuchten (25) models. In spite of the simplicity of the analytical solutions, it is a fact that analytical models are only applicable to simplified cases that may be accepted as rough estimates of real situations.

Yet, having not achieved the perfect model, some researchers have started to look in totally different directions. They have been seeking for some other approximate methods, that need less or simpler input data and/or have less computational cost, to be employed instead of 3D numerical models, provided that the accuracy of the results remains the same. A brief review of their attempts is given in the next two parts.

Non-classical Approaches

Progress in computer science, applied mathematics, and numerical computation methods have helped promote the SHP modeling practices. Most of the non-classical models are inspired from those impressions such as fuzzy logic, artificial neural networks, expert systems, and parallel computing. Tim (125) discussed some such computer technologies in relation to hydrology and water quality modeling; and has foreseen the impact of these technologies on those models. The technologies examined were: user interfaces, virtual reality, animation, remote sensing, geographical information systems, global positioning system, knowledge base systems, and object oriented programming. In his opinion, scale problems in models and data collection techniques need more considerations and improvements. He also recommended the incorporation of all, or at least most of the above-mentioned components in a comprehensive decision support system. This is a definite challenge to researchers.

As discussed earlier, stochastic approaches can be suitable tools for accounting soil heterogeneity in real conditions. As a pioneer researcher in modeling of SHP through stochastic approaches, Ewen (59) developed a novel model named SAMP (Subsystems And Moving Packets). The model was approximate and stochastic due to random movements of soil-water packets within and between the flow-field cells. He claimed that his model is capable of improving the realism of simulations especially for non-equilibrium conditions. Vollmayr et al. (129) employed stochastic modeling via application of a 2D Monte Carlo technique, where particles hop between the sites of a square lattice that represents the soil matrix. The model suites parallel computing purposes and its results are acceptable for a simple 2D problem. Future practices will reveal capabilities of both models.

Harter and Yeh (68) proposed a numerical-stochastic model with high-resolution Monte Carlo simulations. They concluded that the stochastic unsaturated flow theory, despite its simplifications, captures many fundamental principles of VSSM flow. The hybrid stochastic model developed by Loll and Moldrup (86) is based on two steps; first, a deterministic model using stratified data to produce a deterministic response surface, and second, a stochastic model through a Monte Carlo method using the deterministic response surface to provide the total model response. The model was tested for a 1D case successfully. A major contribution is claimed to be the ability to provide a fast and time efficient way to analyze the sensitivity of the stochastic model response to different inputs. Zhang and Lu (166) and Lu and Zhang (152) also developed a stochastic model for transient unsaturated-saturated flow in randomly heterogeneous media using the method of moment equations. They first derived partial differential equations governing the statistical moments of the flow quantities by perturbation expansions and then implemented these equations under general conditions using the method of finite differences. Pan et al. (155) proposed a simple analytical method for estimating surface soil moisture directly from rainfall data. In this method, soil moisture dynamics were represented by a linear stochastic partial differential equation. Ye et al. (165) considered a numerical prediction of transient flow in randomly bounded heterogeneous porous media driven by random sources, initial heads and boundary conditions without resorting to the Monte Carlo simulation.

Another set of promising non-classical methods in SHP modeling is the application of artificial neural networks (ANN) and fuzzy logic (FL) systems. Need for a better modeling approach to imitate the real world with its complexity, dynamism and non-linearity, has motivated SHP modelers to investigate any novel simulation technique. ANN and FL Systems, two new computational intelligence technologies, have received increased attention from SHP modelers. Utilization of ANN and FL technologies is new in SHP modeling . Reported applications are yet few but increasing and promising. One of the first studies of this kind was reported by Altendorf et al. (28) who used ANN to predict soil moisture from soil temperature data. They preferred the use of ANN because of its black-box (or regression type) nature, which leads to a minimum number of input parameters, in contrast to the mechanistic approach.

Bardossy and Disse (35) developed two fuzzy rule-based models for infiltration. The models which are based on Green-Ampt and Richards equations are mechanistic but non-numerical. The authors concluded that their model needs less input parameters and runs much faster in comparison to classical models, however, the model was very sensitive to rule consequences which where not easy to be tuned/calibrated. Later, Bardossy and Duckstein (33) and Bardossy et al. (35) extended the idea to model VSSM 3D flow via fuzzy rules. The model was much faster than classical models and the resulting accuracy was acceptable, besides less input parameters were needed. However, still the same problem persists: difficulty in establishing proper rule consequences. Moreover, the model is sensitive to the number and definition of the fuzzy sets.

Shukla et al. (111) trained an ANN to mimic the Boussinesq equation for the prediction of water table level. In comparison to the numerical Boussinesq model the ANN model was much faster. This trail was pursued by Yang et al. [139-144] who developed several ANN models for the prediction of water table depths and/or drainage outflow. Yang et al. (143) also applied ANN to simulate soil temperature and pesticide concentrations in soil. Sreekanth et al. (118) reviewed anumber of articles on ANN modeling of water table depth and investigated the importance of input parameters in such models. A general conclusion from ANNs fast execution and their generalization abilities is that they can be employed as ideal models/tools for many AES real-time problems such as automated water table management systems and precision farming (58).

A novel approach suggested by Davary et al. (52 and 53) applies ANN and the fuzzy inference system (FIS) to SHP modeling. The method helps speed-up model execution as well as facilitate input data preparation in two ways: via usage of soft data (i.e. qualitative information) along with hard data (i.e. quantitative information); and via minimization of the number of input variables. The approach seems promising in speeding-up 2D and 3D SHP models. Schutze et al. (157) presented an alternative methodology based on self-organizing maps (SOM) which was further developed in order to include multiple input-output (MIO) relationships. Authors have claimed that Richards' and its inverse solution were approximated via application of the resulting SOM-MIO network, with an outstanding accuracy. Jiang et al. (151) implemented and tested an ANN-based algorithm for soil moisture estimation. The ANN model was calibrated (trained) and validated (tested) with data including National Centers for Environmental Protection's (NCEP) daily precipitation. Strong correlation was demonstrated between the ANN estimations and measured values for spatially averaged data. Sy (162) employed an ANN multilayer perceptron to model infiltration. When the results of the model were compared with the traditional Philip and Green-Ampt models, ANN provided the highest accuracy in terms of cumulative infiltration.

Acknowledging uncertainty of soil/aquifer parameters and trying to avoid expensive yet inadequate field parameter evaluations, Chen and Kao (43) adopted fuzzy variables within a geographical information system (GIS) to generate parameter needs for groundwater pollution potentiality assessments. The same approach may be adopted to provide parameters needed for 2D/3D VSSM flow modeling based on easily measurable soil physical characteristics (soft/hard). Perret et al. (100) defined input variables as fuzzy variables to incorporate the uncertainty of these variables (namely, saturated hydraulic conductivity, drainage coefficient, and depth to an impermeable layer) into the drainage design process to find the mid-span water-table depth. The authors claimed that their model is considerably simpler than fully stochastic methods. Following a similar logic, Schulz and Huwe (109), assumed VSSM flow parameters as fuzzy variables and solved the 1D steady state VSSM flow. They compared fuzzy with stochastic approaches and found FL as a very flexible tool for expression of model parameter vagueness or for the introduction of soft data to the model. Almost in the same direction, Freissinet et al. (62) explained a FL-based approach to assess imprecision. Their method was to compute the output of a deterministic SHP model as the mean response and then to estimate the imprecision range of the mean value via fuzzy computations using fuzzy variables. They described their method as a simple and flexible tool for risk analysis studies. Overall, employing fuzzy variables and fuzzy mathematics has brought up the opportunity to use soft data and has facilitated the inclusion of uncertainty for SHP components.

Since soil hydraulic functions (SHF), mostly those including soil water retention curves and unsaturated hydraulic conductivity functions, are a main part of SHP modeling, a brief review of SHF and their modeling approaches is presented in the next part.

Soil Hydraulic Functions

Analytical equations for SHF have improved to become more accurate and/or general. After Brooks and Corey (1), Campbell (3) and van Genuchten (25) who introduced their historic models, work by Green et al. (66), Tzimopoulos and Sakellariou-Makrantonaki (126), Mallants et al. (89), Mohanty et al. (92), Assouline et al. (31) and Mace et al. (88) are examples in this research category. Leong and Rahardjo (84) reviewed and compared most popular soil-water retention equations and found Fredlund-Xing equations (61) to be more favorable. Leij et al. (83) also reviewed SHF; however, they did not assume a single method as the best. Other noteworthy research on SHF has been done by Rawls et al. (104), Shao and Horton (110), Sidiropoulos and Yannopoulos (112), and Simunek et al. (114).

Chen (44) developed a conceptual capillary model based on fractals that generated conductivity curves close to the measured values. Fuentes et al (148) replaced the exponent of Campbell (3) formulation of soil hydraulic properties with a function of fractal dimension. More recently, Ghanbarian and Liaghat (149) too have developed a model for estimating the SHF based on fractals.

A good review on SHF fractal models is done by Gimenez et al. (65). This novel approach leaves several unanswered questions that need to be addressed. How to merge saturated and unsaturated fractal models is one such question. In fact, the total model (saturated-unsaturated) may require more than one fractal dimension for different scaling regions. In other words, the geometrical interpretation for different soil moisture conditions may vary, as in dry soils SHF could be mainly determined by surface area, whereas near saturation SHF is primarily a function of pore structure (51). Kravchenko and Zhang (80) pursued such an idea using two fractal dimensions for wet and dry parts of SHF. How to parameterize a soil pores system is another question in this domain. A study of this kind was the fractal model of soil-water retention function with a randomly connected network developed by Bird and Dexter (37) that revealed the pore connectivity importance in addition to the importance of the pore size distribution.

Fractal approaches for SHF estimation are still recruiting and need more explorations and improvements in different ways.

Simons (113) tried to describe the soil matrix as a permeable pore structure via the pore tree model. The model simulates the pore structure via tree-shaped porous sub-systems that are randomly interconnected through common branches. The model may be seen as an alternative mathematical explanation of soil matrix in comparison with fractals. Simons has expressed his future plan to improve the model to couple convective and small scale diffusive transport.

Pachepsky et al. (99) developed an ANN model for soil-water retention relationships from easily measurable data. Tamari et al. (121) and Schaap and Bouten (108) worked on the same subject concurrently. All three studied compared ANN with regression models and found the ANN models to be superior and more favorable. In fact ANN models have been replacing regression pedo-transfer functions due to their flexibility. For example, Schaap et al. (107) developed alternative ANN models, each with a different number of independent variables, to estimate the soil-water retention curve and unsaturated hydraulic conductivity. They found ANN-based functions' performance superior to existing pseudo-transfer functions in two ways: enhanced accuracy and availability of alternative functions for cases with different numbers of independent input parameters.

Estimation of SHF via ANN has been increasingly extended during some last years. For instance using ANN Minasny et al. (154) developed a pedotransfer function to estimate soil hydraulic functions. Agyare (146) too developed their ANN-based models for soil unsaturated hydraulic conductivity, respectively. However, compared to regression equations, one disadvantage of ANN models is that the mathematical formulation does not symbolize any meaningful/physical relationship between inputs and outputs.

In order to reach a wide spectrum of SHP models, a classification for these models seems to be necessary. This facilitates the comparison of models and helps readers to drive an inclusive conclusion. Hence, a brief classification of SHP modeling approaches is presented in the next part.

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مرور و طبقه‌بندی نگرش‌های مدل‌سازی فرآیندهای هیدرولوژی خاک

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چکیده- برای استفاده از فرآیندهای هیدرولوژی خاک (SHP)، که در سال‌های اخیر شدیداً کسترش یافته‌اند، درک جامعی از این مدل‌ها و نگرش‌های مدل‌سازی آن‌ها ضروری به‌نظر می‌رسد. نگرش‌های مدل‌سازی را می‌توان به دو دسته‌ی کلی کلاسیک و غیر کلاسیک تقسیم‌بندی کرد. روش‌های کلاسیک عمدتاً SHP را از طریق حل عددی و یا تحلیلی معادله‌ی عمومی جریان غیراشباع (معادله‌ی ریچاردز) مدل می‌کنند. به‌دلیل محدودیت‌های روش‌های کلاسیک، در سال‌های اخیر تمایلی به استفاده از روش‌های غیر کلاسیک شکل گرفته است. شبکه‌های عصبی مصنوعی و سیستم‌های منطق فازی دو دسته‌ی عمده از روش‌های غیر کلاسیک به شمار می‌آیند. در این مقاله روش‌های رایج مدل‌سازی SHP با تاکیدی بر کارهای فعلی مرور و مقایسه شده‌اند. هم‌چنین روش‌های مدل‌سازی توابع هیدرولیکی خاک به عنوان یک بخش عمده از مدل‌های SHP به‌طور مختصر مرور شده‌اند. در نهایت تقسیم‌بندی‌هایی برای مدل‌های SHP از دیدگاه‌های مختلف ارائه شده است.

واژه های کلیدی: فرآیندهای هیدرولوژی خاک، روش‌های مدل‌سازی، کلاسیک، شبکه‌های عصبی مصنوعی، سیستم‌های منطق فازی

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