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Hydropedology-Based Approach for Scaling Hydrological Processes

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ABSTRACT: This article presents a new paradigm in characterizing and modeling the multi-scale organized soil medium and the physical properties resulting from this organization which takes into account the hierarchical organization of the structured soil medium. The pedostructure is defined as the core of the soil medium and is the basis of the new paradigm including variables, equations, parameters, and units in soil physics. The paradigm allows for a thermodynamic characterization of the structured soil medium with respect to soil water content then bridging the gap between Pedology and Soil Physics. This approach leads to a new dimension in soil-water properties characterization that ensures a physically based modeling of processes in soil and the transfer of information from the physical scale of processes (pedostructure or laboratory measurements scale) to the application scale of the other disciplines (modeling and mapping scale).

INTRODUCTION

The last decade has brought significant contributions in soil physics, hydrology and pedology. However, due to the nature of these disciplines; these bodies of knowledge were not integrated and remained disconnected. Accordingly, the extensive knowledge of soil structure in pedology is disconnected from soil hydro-structural functionality that is studied in soil physics and hydrology. This disconnection has brought about empirical relationships between soil physics and soil structure morphology. It has also limited the progress in areas dealing with scale and soil characterization.

In soil physics, water flow has been studied in continuous porous media mechanics over a homogeneous controlled volume in which solids, water and air are considered as a mixture. Although solids belong to a structure, it is not distinguished from water and air which are mobile inside that structure. Braudeau & Mohtar (2008) showed that this is one of the principal causes of this disconnection. In fact, soil characterization consists of a permanent and unique reference to the continuous porous media mechanics which ignores or masks several important realities about soils, such as:

1. The hierarchical organization of the solids within the soil medium.
2. The physical interaction of soil water at the surface of clay particles and aggregates which explains soil water potential.
3. The reorganization of solids and aggregates under the action of hydration forces leading to swelling and shrinkage phenomena.

Over the last ten years, a new field of earth science has emerged; namely hydropedology (Lin, 2003; Lin *et al.*, 2006). Hydropedology has brought new hope in bridging these bodies of knowledge. However, bridging these disciplines requires a new paradigm in soil physics and pedology allowing for a better understanding in the following two fields: (1) the physical interactions between soil structure and soil water at the scale of the processes and (2) the characterization of this interaction and the transferability of this information across the various scales upto the external scale of the soil mapping unit.

The objective of this paper is to present an overview of the pedostructure concept as a method to scale hydrologic processes from inter-particles soil and water interactions to watershed processes. The paper will address soil characterization at all of these scales and a model that integrates these concepts with a sample application of the model to field soil water monitoring and management. The paper introduces the pedostructure concept which is the basis for the multi-scale soil water modeling approach and introduces a computer model which is built based on this concept. The paper also introduces field scale processes and scaling methodology and a sample application.

MODEL DESCRIPTION AND METHODOLOGY

Pedostructure Concept

The functionality of the pedostructure, as a Structural Representative Elementary Volume (SREV) of soil clods or peds, is quantitatively described by equations, variables and parameters that originate in the measurement and interpretation of four soil characteristic curves (Braudeau and Mohtar, 2008): (1) the shrinkage curve, i.e. the structural specific volume of a soil sample versus its water content, $\bar{V}(W)$, (Braudeau *et al.*, 2004); (2) the tensiometric curve, the soil macropore suction measured by the tensiometer as a function of the macropore water content, $h_{\mathrm{ma}}(W_{\mathrm{ma}})$, (Braudeau and Mohtar 2004); (3) the interpedal conductivity as a function of the macropore water content, $k_{ma}(W_{ma})$, (Braudeau *et al.*, 2008); and (4) the swelling of primary peds versus time, $\bar{V}_{mi}(t)$, (Braudeau and Mohtar, 2006).

A conceptual schematic representation of the soil-water medium dynamics is shown in Figure 1. The representation refers to a unit volume of the pedostructure at a hydraulic state (W, $\bar{V}$) defined on the shrinkage curve between W_C and total saturation W_L (see Figure 2). All the variables of this representative volume are "gravimetric" (water contents, specific volumes, and pore volumes) expressed in reference to the mass of the primary particles, which is considered constant for this unit volume. The clayey plasma of the primary peds defined as micro-porosity (Vp_{mi}) and the interped pore space defined as the macro-porosity (Vp_{ma}) are represented by two compartments which are in contact through a transitional zone at the surface of the primary peds. The parameter σ of the tensiometric curve refers to this transitional zone (Braudeau and Mohtar, 2004). Micro and macroscopic porosities are considered continuous within and between the representative volumes in all directions. The residual water, w_{re}, which does not contribute to any swelling, shrinkage, or displacement of water, is represented by the center of the microporosity (Figure 2), surrounded by the micropore swelling water, w_{bs}.

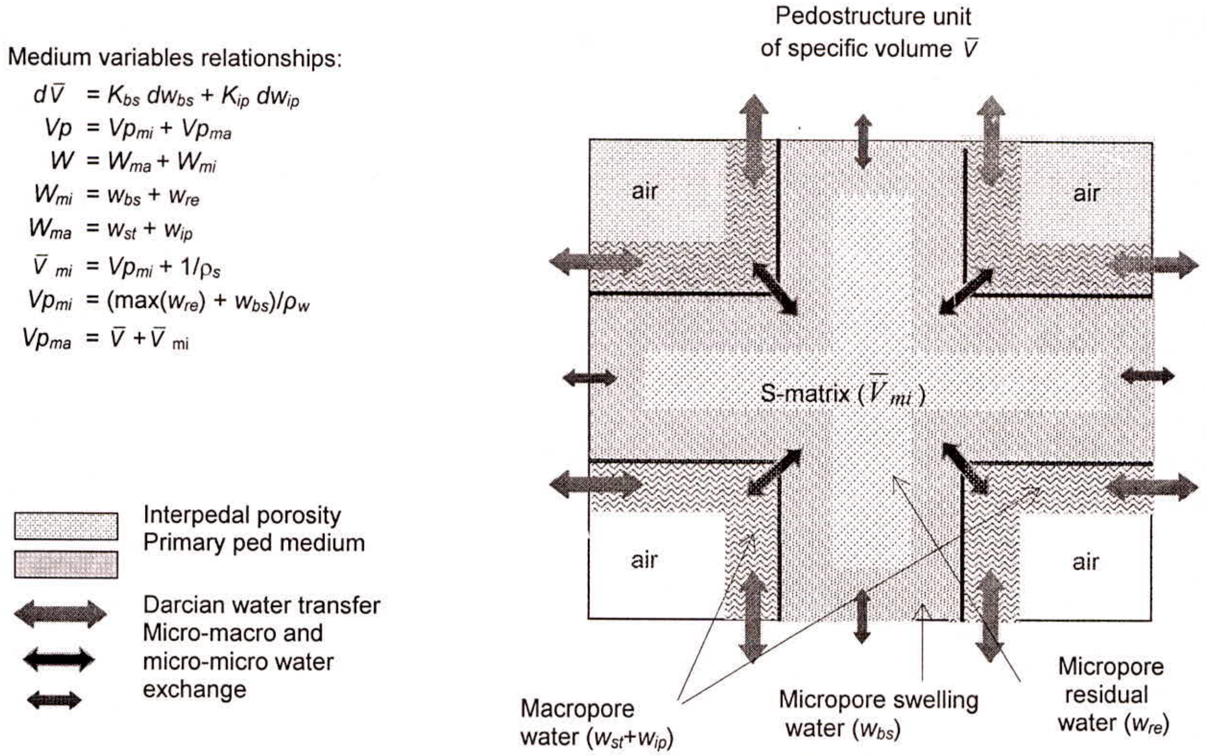

Fig. 1: Hydrostructural dynamic of the pédostructure (Braudeau & Mohtar, 2008)

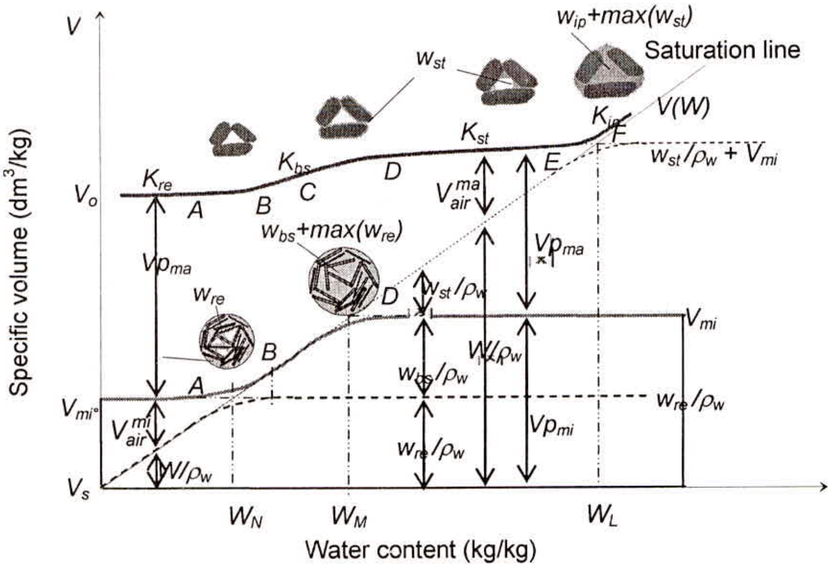

Fig. 2: Shrinkage curve. Graphical representation of the specific volumes (V_{mi} and V), the specific pore volumes (Vp_{mi} and Vp_{ma}), the air contents (air subscripted) and the water pools (W, w_{re}, w_{bs}, w_{st}, and w_{ip}) of the pedostructure starting from a measure SC. V_{mi} is the specific volume of primary peds, equal to ($Vp_{mi} + V_s$) = ($\max(w_{re})/\rho_w + w_{bs}/\rho_w + V_s$), and ρ_w is the water density. The linear and curvilinear shrinkage phases are delimited by the transition points (A, B, C, D, E and F) (Braudeau and Mohtar, 2008)

Field Scale Characterization

The pedostructure model is a new model that predicts the behavior of the soil-water media. The pedostructure model considers the hierarchical soil structure based on the functional variables and equations, as shown by Braudeau *et al.* (2004) and Braudeau and Mohtar (2004, 2006). Each soil can be uniquely characterized by 15 parameters. A computer model, Kamel® (Braudeau *et al.,* 2008), has been developed in this new soil physics paradigm, using these 15 pedostructure parameters, along with climatic data, to predict a variety of hydrostructural soil-water interactions at local scale within the soil profile, more accurately than current models. This hydrostructural modeling allows then scaling these soil-water interactions at the pedon level upto the field or watershed scale. These parameters are experimentally derived from soil cores taken from the field using four continuously measured curves: the shrinkage curve, the swelling curve, the conductivity curve and the potential curve. Kamel® can also run starting from the same soil information required by the existing soil-water models using a software, KamelSoil®, which translates the available soil information into the 15 pedostructure parameters (Braudeau *et al.,* 2008). This translation is based on the pedotransfer functions equations gathered by Saxton and Rawls (2006). These equations use soil physical properties available through many soil databases: soil texture, bulk density, organic matter content and water content at various potentials. KamelSoil® was developed using Microsoft Excel® worksheets to produce the 15 pedostructure parameters which will be as accurate as rich is the starting soil information. In this case of non measured pedostructure parameters, the soil texture is the minimum information required for running Kamel®.

Scaling Pedostructure into Field Level

The pedostructure concept and the general system theory hierarchal approach were used as a basis to define functional soil mapping units. These functional mapping units were generated using topographic maps, the existing soil survey database (SSURGO), and pedostructural parameters extracted from the soil shrinkage and water potential curves. The pedohydral homogeneity of these mapping units was tested using discriminant analysis.

The scaling of pedostructure concept was demonstrated at the Haggerty-Cox farm located in West Lafayette, Indiana. Three soil map units were selected to encompass the maximum soil variation at the site. The SwA map unit consists of a Starks-Fincastle complex on 0–2% slopes. The Fincastle series is classified as a fine-silty, mixed, superactive, mesic Aeric Epiaqualf. The Starks series is classified as a fine-silty, mixed, superactive, mesic Aeric Endoaqualf and is very similar to the Fincastle series except for the presence of water-worked, stratified material at the base of the profile. These two soil series often occur so closely associated that it is impractical to separate them during mapping. Hence, they are mapped as a complex of two similar soils. The MsC2 map unit consists primarily of Miami silt loam on 6–12% slopes. The Miami series, classified as fine-loamy, mixed, active, mesic Oxyaquic Hapludalfs, consists of moderately well-drained soils formed in upto 18 inches of loess overlying dense, loamy glacial till. The HoA map unit consists primarily of Hononegah fine sandy loam on 0–2% slopes. The Hononegah series, classified as sandy, mixed, mesic Entic Hapludolls. Sampling location was selected to include the three soil types under investigation. A representative sample was obtained from the Ap horizon and the mid-point of the Bt horizon based on the existing soil survey. The measurements were conducted for 21 Ap and 21 Bt horizon samples distributed as follows: 7 samples from Hononegah, 7 samples from Miami (MsC2), and 7 samples from Starks (SwA).

For the sandy loam soils in the area of study, the shrinkage curve measured was found to be flat. The shrinkage curve does not distinguish the different water pools and inflection points as shown by the typical curve discussed by Braudeau *et al.* (2004). Accordingly, the methodology developed by Braudeau *et al.* (2004) was extended to obtain the PS parameters of the soil water medium. The potential curve (the soil water suction, h_{ma}, measured using a tensiometer against the water content W) was integrated with the shrinkage curve in the procedure used to extract the PS parameters. The link between the shrinkage and potential curves could be feasible through using the physical equation describing the potential curve given by Braudeau and Mohtar (2004). These equations relate the macropore water content, W_{ma}, to the macropore parameters of the shrinkage curve: k_M, W_M and W_L.

Discriminant analysis was performed on results using SAS® 9.1 software. The analysis for Ap was separated from Bt horizons. Only the shrinkage curve parameters (k_{bs}, V_O and W_L), potential curve parameters (σ, E_{ma}, W_L, W_C and W_D), and the combination of the two curves parameters (k_{bs}, V_O, σ, E_{ma}, W_L, W_C and W_D) were used to investigate for discriminating soil mapping units. For each soil group the within-samples matrix of sums of squares and products (SSP matrix), W, and the analogous between-samples SSP matrix, B, were formed. The latent roots and vectors of the matrix $W^{-1}B$ was then found and the discriminant scores obtained by multiplying the vectors by the original variates (the parameter values). The compilation of the scores in a table allowed an investigation of the uniqueness of the parameters.

Cracks and Preferential Flow Paths

Cracks generate disconnects between the soil matrix as the result of the dynamics of the soil shrinkage and swelling properties in response to weather and time. Movement of water inside those discontinuities is much faster than moving through the soil matrix, thus resulting in what is referred to as preferential flow paths. Understanding the cracking behavior of soils is fundamental to characterize and model preferential flow in soils.

Our efforts to understand the cracking behavior of soils have led to the development of the Restrained Ring Method (Abou Najm *et al.*, 2008a), to assess and measure the evolution of the internal stress in soil as it dries. Coupled with digital imagery analysis to quantify the strain generated by the soil as it dries, the results of the Restrained Ring Method were used to generate stress-strain relationships for drying soils (Abou Najm *et al.*, 2008b). Such new tools developed at the laboratory scale will be extended to the field scale to characterize the cracking behavior of soils. Those tools are expected to be of key value to the understanding of the cracking behavior of soils especially for deep cracks. Shallow surface cracks are under current evaluation at the field scale using the shrinkage and swelling properties of soils. Shallow cracks are currently evaluated using digital imagery analysis through research collaboration with the USDA's NPARL in Sidney, Montana. Soil surface images are automatically collected every one hour along with water content and soil temperature data at multiple depths. Current investigation is directed towards relating the area of cracks to the water content at the field. Moreover, understanding the connectivity between the crack network as well as its depth is under current investigations.

A physically based model is being developed to predict the evolution of crack area, volume, and network, and improved understanding of the preferential flow.

Kamel Description

The Kamel® model was developed according the pedostructure concepts and using exclusively the physically based pedostructure functions and parameters (Braudeau *et al.*, 2008).

(a) Input: Four kinds of input are required to run Kamel®:

1. *Pedostructure parameters* comprising the depths of the four soil horizons, the thickness of the soil layers (choice of the discretization), the root

distribution (% of the total roots mass) by horizon, and the pedostructure parameters for each horizon.

2. *Initial soil moisture* which consists of initial saturation level of the available water in each soil layer along the profile.
3. *Rain and/or evapotranspiration* for entering the potential evapotranspiration and rain intensity during simulation.
4. *Surface properties and end-of-profile drainage conditions* giving the conditions at the surface and the end of the profile. Some properties of the surface layer (for example, conductivity at saturation, bulk density, thickness of the surface layer and surface water storage) can be changed during a simulation taking into account the impact of tillage, irrigation, etc. The condition at the end of the profile concerns the drainage, which can be either free or sealed drainage.

(b) Output: The different kinds of output are:

1. State variables at user specified depth increments from the surface.
2. Volumetric contents of water pools, pore space, air, available water storage, available macropore water storage, etc. per group of 10 cm of soil layers over the entire soil profile.
3. All state variables of the surface referenced to the structural mass of the surface layer. These variables can also be displayed in *xy* graphs.
4. All variables of the soil profile water budget, such as infiltration (cumulative flux through the first layer), drainage (through the last layer), run-off, water storage in the profile, water storage in the surface layer and on the surface, and rain.

Following to the definition of the pedostructure concept in a physically based modeling, all the processes within the defined soil layer or pedostructure were calculated in reference to the structural mass, in such a way that the contents of any material is calculated at the scale of the considered SREV and expressed in kg or dm^3 per kg of solids (dry soil). However, the outputs of the model (results of internal processes) can be converted to units based on depth of soil, horizon in terms of m^3/m^3 of soil or m/m, kg/ha, etc. In the model, both types of output are provided:

1. The structural state variables, which are local, at the scale of the process, and address the soil-layer delimited by the discretization. These variables are defined in reference to the structural mass of the SREV, which can be either the organizational variables and parameters like W, Vp_{ma}, etc. in kg or dm^3 per kg of dry soil or functional variables such as h_{ma}, k_{ma}, Ps_{mi} that are expressed in terms of these organizational variables and parameters.
2. The volume average variables, which are macroscopic variables averaged over a REV (depth of soil or a pedon). These variables such as height of water per height of soil or available water are generally used by agronomists, are not physically located at a given scale and are in units of m/m or m^3 per m^3 of soil. In fact, the use of these units allow for local results to be easily extended to larger scales (1 ha for example). The conversion is made using the following relationship: $\theta = (1/\rho_w)W/\overline{V}_{hor}$ where θ is the volumetric water content in m^{3}m^{-3} and ρ_w is the water bulk density in dm^{3}kg^{-1}.

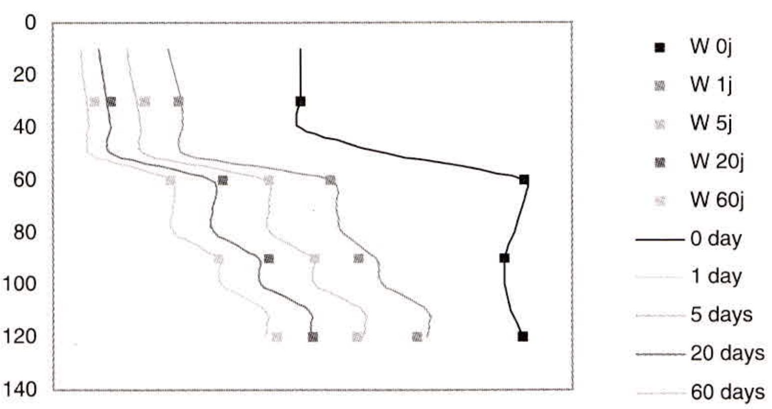

Fig. 3: Showing soil moisture profiles from Kamel® output as compared to Davidson experimental data: drainage from saturation without any evaporation or water uptake by roots. *W* 0 j is the initial moisture experimental data from Davidson, *W* 1 j is the measured moisture profile after 1 day, and *W* 60 j is the measured moisture profile after 60 days. Lines represent computed profile using Kamel® (Braudeau *et al.*, 2008)

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