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On the use of the similar media concept for scaling soil air permeability

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ABSTRACT

Soil air permeability (k_a) is an important factor that controls subsurface gas transport and exchange of gas across the soil–atmosphere interface. It is thus crucial to evaluate the spatial distribution of k_a for both application and modeling purposes. However, relevant studies are still very limited, partly due to the fact that the dependence of k_a on soil moisture levels cannot be directly included in the methods such as geostatistical techniques for analyzing the spatial distribution of k_a. To tackle this problem, the scaling scheme based on the similar media concept, which has been widely used in soil hydrology for characterizing spatial variability of soil hydraulic properties, was employed for scaling k_a in this study. Four air permeability models, including Millington and Quirk (1960)—MQ, Hunt (2005)—HT, Brooks and Corey (1964)—BC, and Kawamoto et al. (2006)—KA, were selected to test this method using two independent datasets. For the first dataset that included k_a measured for river sediments, all of the four models were able to delineate the spatial distribution of k_a with a reference curve of k_a and a set of scaling factors. Specifically, the MQ model gave the least satisfactory results due to the less flexibility of its form; whereas, there were no significant differences in the performances for the HT, BC, and KA models. For the second dataset that contained k_a measured for agricultural soils, the overall performance of the four models for scaling k_a deteriorated, largely due to the alterations in the microscopic structures of soil samples caused by repacking and compression of soil samples. Nonetheless, as the first attempt, this study shows the viability of using the similar media concept for scaling k_a. The merit of this method resides in the fact that the spatial variations of moisture conditions and soil properties can be simultaneously included for analyzing the spatial distribution of k_a. With a reference curve of k_a and the distribution of scaling factors, this method would be particularly suitable for modeling subsurface gas transport.

1. Introduction

As one of the key factors that controls subsurface gas transport and exchange of gas across the soil–atmosphere interface, soil air permeability (k_a) describes the ability of a soil to transmit gas. The rising interest in k_a is manifested by its broad range of applications in various fields, including greenhouse gas emission (Ball et al., 1997; Conen and Smith, 1998), landfills (Jain et al., 2005; Wu et al., 2012), soil vapor extraction systems (Farhan et al., 2001; Poulsen et al., 1998), and crop growth (Barrios et al., 2005; Lipiec and Hatano, 2003). Moreover, due to easy operation and cost effectiveness, k_a measured near field capacity has been used to predict soil saturated hydraulic conductivity (Iversen et al., 2001; Loll et al., 1999).

Under natural conditions, k_a is affected by a number of soil factors (e.g., air-filled porosity and pore size distribution) and moisture conditions, all of which show various degrees of spatial variations. As such, field measured k_a exhibits significant spatial variability (Iversen et al., 2003). For application and modeling purposes, it is thus crucial to evaluate the spatial distribution of k_a and its controlling factors. However, compared to relevant researches on soil hydraulic properties, only few studies are available on the spatial distribution of k_a, which nonetheless provided valuable insights into the understanding of the spatial pattern of k_a (Iversen et al., 2003, 2004; Poulsen et al., 2001). Geostatistical techniques were mainly used in previous studies to analyze the spatial pattern of k_a. Based on the results of variograms, Iversen et al. (2003) found that the correlation range of k_a for sandy soils was larger than the one for a loamy soil, probably due to the difference in the depositional processes of those two types of soils. Although geostatistical techniques have been proven to be powerful tools for investigating naturally occurred phenomena, there are certain shortcomings for those techniques as pointed out by Henley (2001). Most notably, the underlying processes associated with studied targets cannot be explicitly considered in geostatistical techniques, which rather rely on statistical models for examining the spatial correlations of the targets.

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With respect to k_a, the main issue of using geostatistical techniques stems from the impact of soil moisture on k_a. It has been well known that k_a is highly dependent on soil moisture levels, but the spatial distribution of soil moisture cannot be directly included in the geostatistical analyses of k_a. To some degree, this is analogous to study the spatial distribution of soil unsaturated hydraulic conductivity without specifying moisture conditions. Therefore, precautions were usually taken in previous field studies on the spatial distribution of k_a. As conjectured by Iversen et al. (2003), when soil moisture contents reach field capacity, the air flow takes place in the majority of soil pores; thus, the impact of moisture on k_a can be neglected with moisture contents near and below field capacity. Although the assumption made by Iversen et al. (2003) is useful for studying the spatial distribution of k_a under dry conditions, it may fail at regions with wet climates or shallow groundwater tables. For application purposes (e.g., landfills and soil vapor extraction systems), the inclusion of moisture in analyzing the spatial distribution of k_a is also inevitable. Therefore, it is desirable to seek alternative methods to assess the spatial distribution of k_a under the influence of soil moisture.

Along the line of the above thinking, the scaling scheme based on the similar media concept may provide a promising approach to investigating the spatial distribution of k_a with the consideration of moisture conditions. First introduced by Miller and Miller (1956), the similar media concept is based on the assumption that the internal geometry of similar media only differs by microscopic length scales that can be characterized by scaling factors. The purpose of this scaling approach is to coalesce a range of functional relationships into a single curve through scaling factors that depict the spatial distribution of those functional relationships. More specifically, scaling factors are used to relate soil properties at a given location to the mean properties at a reference location, which are invariant of moisture conditions. This scaling method has been widely used in soil hydrology to characterize spatial variability of soil hydraulic properties and soil hydraulic functions with associated model parameters (Hendrayanto et al., 2000; Hopmans, 1987; Shouse and Mohanty, 1998; Tuli et al., 2001; Warrick et al., 1977; Zavattaro et al., 1999). With a reference functional relationship and the distribution of scaling factors, this method is particularly suitable for modeling purposes (Kabat et al., 1997; Oliveira et al., 2006; Peck et al., 1977; Salvucci, 1998). Given the similarities between water flow and gas transport in soils, one can expect the viability of applying this scaling approach for investigating the spatial distribution of k_a under the influence of soil moisture.

To our knowledge, this research was the first attempt to extend the use of the similar media concept for scaling k_a. The main objective of this study was to examine the feasibility of this approach using two datasets collected from the USA and France. Four air permeability models were selected to delineate the functional relationship between k_a and saturation degree of air. The results of this study demonstrated the feasibility of using the similar media concept for scaling k_a, which also opened the door for utilizing this method for simulating gas transport in soils.

2. Materials and methods

2.1. Similar media concept in soil hydrology

The use of the similar media concept for scaling soil water retention and hydraulic conductivity curves is well documented in the literature (see the review by Vereecken et al., 2007). So, only a brief overview is given here. Based on the similar media concept, it is assumed that the microscopic structures (e.g., tortuosity, and relative particle size and pore size distributions) of similar soils are identical and only differ by microscopic length scales that can be characterized by scaling factors (Peck et al., 1977; Warrick et al., 1977). The scaling factor (α) is thus defined by the ratio of the microscopic characteristic length of a soil (λ) to the characteristic length of a reference soil (λ_m):

$$\alpha_i = \frac{\lambda_i}{\lambda_m} \tag{1}$$

where $i = 1, 2, \ldots, L$ is the location of the soil and the subscript m denotes the reference soil. By its definition, α is invariant of soil moisture conditions and only dependent upon the location of the soil. As such, the soil water retention curve at any location can be scaled to the reference water retention curve through α:

$$h_i(\theta) = \frac{h_m(\theta)}{\alpha_{w,i}} \tag{2}$$

where h is the soil matric potential, θ is the volumetric moisture content, and the subscript w denotes water. The scaling relationship of the soil hydraulic conductivity curve can be written as:

$$K_{w,i}(\theta) = K_{w,m}(\theta)\alpha_{w,i}^2 \tag{3}$$

where K_w is the hydraulic conductivity. Due to the fact that soil porosity may vary across locations, instead of θ, the saturation degree of moisture (S_w) is usually used (Warrick et al., 1977):

$$S_w = \frac{\theta}{\phi} \tag{4}$$

where ϕ is the soil porosity.

To describe the reference curves of h_m and $K_{w,m}$, soil water retention and hydraulic conductivity models (e.g., Brooks–Corey model and van Genuchten model) have been used, although polynomial functions of $h_m(S_w)$ and $K_{w,m}(S_w)$ were also adopted (Warrick et al., 1977). By optimizing the differences between measured and calculated $h(S_w)$ and $K_w(S_w)$ across all the locations, the model parameters for the reference curves of h_m and $K_{w,m}$, and the scaling factor $\alpha_{a,i}$ at each location can be obtained (Hopmans, 1987; Tuli et al., 2001).

2.2. Extension of the similar media concept for scaling soil air permeability

Although the scaling theory based on the similar media concept has been widely used in soil hydrology, there is a surprising lack of studies on its application for assessing the spatial distribution of k_a. Strictly speaking, soil water permeability (k_w) should be used in the scaling procedure (Eq. (3)), as regardless of fluid properties, soil permeability, whether it is k_w or k_a, represents the intrinsic properties of soils to transmit fluids and thus reflects the microscopic structures of soils. However, given that the fluid of interest remains under the same conditions (e.g., temperature), the fluid properties do not change across locations and conductivities (e.g., K_w) can be used in Eq. (3). Therefore, one can write a similar scaling relationship for k_a based on Eq. (3):

$$k_{a,i}(S_a) = k_{a,m}(S_a)a_{a,i}^2 \tag{5}$$

where $S_a = (1 - S_w)$ is the saturation degree of air and the subscript a denotes air. For the same reason for using S_w in scaling $h(S_w)$ and $K_w(S_w)$, S_a was used in this study instead of the volumetric soil–air content. Note that α_a is also invariant of soil moisture conditions and only dependent upon the location of the soil.

To delineate the reference relationship of $k_{a,m}$, four air permeability models were selected (Ghanbarian-Alavijeh and Hunt, 2012). The first model was proposed by Millington and Quirk (1960) (denoted as MQ hereafter):

$$k_a(S_a) = k_o \times S_a^2 \tag{6}$$

where k_o is the air permeability at the porosity ϕ.