Enhancement of seepage and lateral preferential flow by biopores on hillslopes

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Abstract: Natural soils are generally populated with a wide variety of macropores formed from physical processes and/or biological activity. These macropores can have a large influence on the lateral flow of water in hillslope soils even when those macropores are not continuous or connected directly to ponded water. The concept of self-organization of flow paths described by Sidle et al. (2001) is analyzed through numerical simulation of variably-saturated flow in a large cylinder of soil containing a population of disconnected macropores. It is demonstrated that there is a threshold water pressure at which the macropores will become active, and above this threshold the then active network of macropores significantly increases the effective conductance of the soil volume. In the case examined here the increase exceeded 40%. The analysis presented provides a context for the explanation of soil pipe formation by the process of seepage erosion. An analogy is drawn between percolation theory in porous media and the concept of self-organization of flow pathways at the hillslope scale.

Key words: macropores, finite element modeling, flow path self-organization

Introduction

Numerous field studies have been performed in the last forty years over a variety of land and climate conditions to identify and quantify the sources of runoff from hillslopes. Recognized processes include infiltration excess, saturation excess, subsurface stormflow, and pipeflow. These studies have shown that the relative importance of a particular process at a given location depends on the characteristics of the soil, the vegetative cover, and the climate. Kirkby (1985) provided an assessment of relative importance for the first three mechanisms while Jones (1997) extended this assessment by adding information about soil pipes.

In recent years there has been some question about the importance of soil macropores, other than soil pipes, on hillslope water flow. There is the question whether macropores which generally are limited in length and are not usually directly connected, can provide an efficient pathway for moving water on a hillslope. The studies by Tsuboyama et al. (1994), Noguchi et al. (1999) and Sidle et al. (2000) at the Hitachi Ohta catchment have shown that even though macropores might not always be directly connected, they apparently become effectively connected when moisture levels are high enough to be favorable. They found this to be apparent by examining flows and dye tracings from trench walls, and also by observing at larger scale sudden changes in streamflow response at threshold moisture levels. Based on these observations Sidle et al. (2001) proposed the idea of a self-organizing network of preferential flow pathways, where the connections (e.g., loose soil, decaying organic material, fractures in bedrock, or cleavage planes at lithographic boundaries) in the network are controlled by moisture level. At low moisture the connections are closed, but with increasing moisture levels the number of open connections increases, thereby increasing the efficiency of water flow.

Analysis methodology

In what follows we will examine through numerical simulation a few examples of preferential flow related to macropores in soil. The governing equation for the flow processes is assumed to be governed by the Richards equation, which can be expressed as

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(K\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}\right) + \frac{\partial K}{\partial z} \tag{1}$$

where θ is the volumetric water content (m^3/m^3), h is the water pressure head (m), K is the unsaturated hydraulic conductivity (m/s), x, y, and z are Cartesian coordinates (m), and t is time (s). Equation (1) is subject to boundary conditions of specified pressure, $h = h_\Gamma$, and/or specified flux, $-K\dfrac{\partial h}{\partial n} - K\dfrac{\partial z}{\partial n} = q_\Gamma$, and to initial conditions on pressure $h_o = h(x, y, z, t = 0)$, where h_Γ is the pressure specified on the boundary, n is the normal to the boundary, and q_Γ is the specified flux normal to the boundary.

The solution is implemented through the Earth Science module of the commercial software COMSOL MP3.2a (COMSOL, 2006). This numerical solution is based on a Galerkin finite element procedure.

To analyze the phenomenon of self-organization of pathways, we will examine the steady-state flow of water in a column of soil matrix populated with a number of disconnected macropores. The column can be imagined to have been collected from the field, undisturbed with all macropores intact. A schematic of the column with the macropores is illustrated in Fig. 1. For the present application all the macropores are straight and cylindrical, but other shapes could have been used.

The cylinder contains a number of cylindrical macropores, most of which are of radius 0.005 m. The boundary conditions applied to the cylinder of soil are that the radial boundaries are impermeable, while the top and bottom boundaries are assigned the same value of pressure. The column is oriented vertically, so that the applied boundary pressures lead to a mean hydraulic gradient equal to unity within the column.

The soil matrix in the column was assigned a saturated hydraulic conductivity of 8.62×10^{-2} m/day, representative of a loamy matrix. For the current application we examined steady-state flow so specifying the moisture retention curve for the matrix was not important; only the unsaturated hydraulic conductivity function was needed. For the $K(h)$ the following function was employed,

$$K_\mu(h) = K_{\mathrm{s}_\mu} e^{\alpha_\mu (h - h_{\mathrm{e}_\mu})} \quad h < h_{\mathrm{e}_\mu} \tag{2a}$$

$$K_\mu(h) = K_{\mathrm{s}_\mu} \quad h \geq h_{\mathrm{e}_\mu} \tag{2b}$$

where for the soil matrix $K_\mu(h)$ is the unsaturated hydraulic conductivity, K_{s_μ} is the saturated hydraulic conductivity, α_μ is the pore-size index, and h_{e_μ} is the air-entry potential.

While the macropores could have been modeled mathematically with the Navier-Stokes equations as completely filled or partially-filled with water it was considered much easier to model them as being volumes filled with coarse-textured media. This way the same equation, the Richards equation, could be applied to modeling flow within them as well as within the soil matrix. The macropores in the column had radii of either 0.005 m or 0.01 m. According to the Darcy-Weisbach equation, flowing full with water under laminar flow conditions these macropores would have an equivalent hydraulic conductivity exceeding 1×10^5 m/day. The unsaturated hydraulic conductivity for the macropores was also represented by the exponential relation like equation (2); we just replace the matrix parameters by those with subscripts 'm' for macropore. Since the macropores would manifest little or no capillarity, the value of the α_m will be very large, while the value of the $h_{\mathrm{e_m}}$ will be very close to zero. The set of parameters were assigned to be: $K_{\mathrm{s}_\mu} = 8.62 \times 10^{-2}$ m/day, $K_{\mathrm{s_m}} = 8620$ m/day, $\alpha_\mu = 10$ m^{-1}, $\alpha_\mathrm{m} = 500$ m^{-1}, $h_{\mathrm{e}_\mu} = -0.20$ m, $h_{\mathrm{e_m}} = -0.01$ m. Plots of the hydraulic conductivity functions are shown in Figure 2.

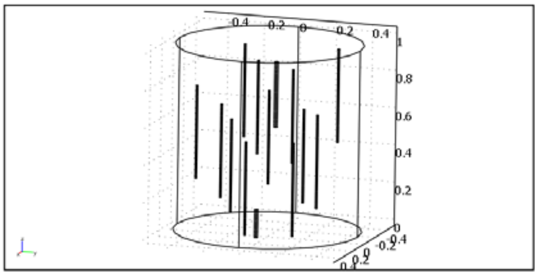


Fig. 1. Schematic of the flow region for the numerical analysis.

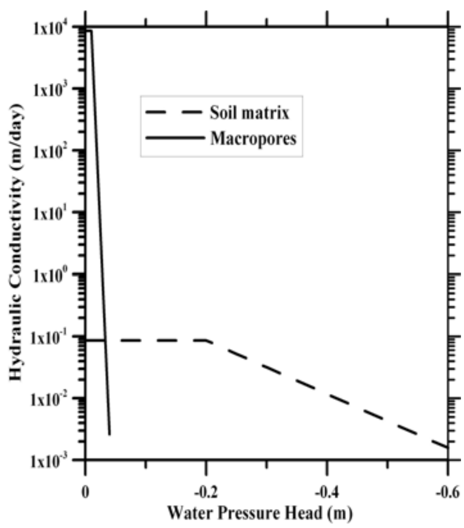
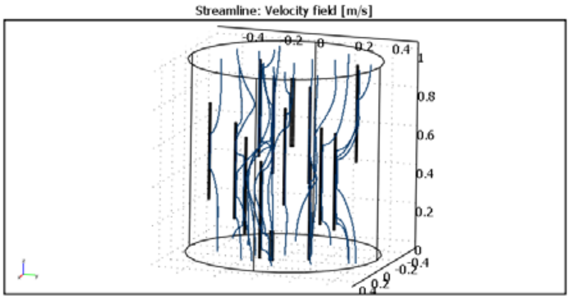


Fig. 2. The unsaturated hydraulic conductivity functions for the soil matrix and the macropores.

Results

In the following we touch upon the concept of the dynamics of the connectivity of flow paths between macropores that are not directly connected to each other. We do this by illustrating the simulation of flow within the cylindrical volume of soil at two levels of wetness, dry and saturated. For the dry condition the macropores are excluded from participating in the water flow, while under the saturated condition the macropores participate fully. There should be a threshold pressure where the macropores begin to participate in the flow but this was not identified in the present analysis for reasons to be explained later.



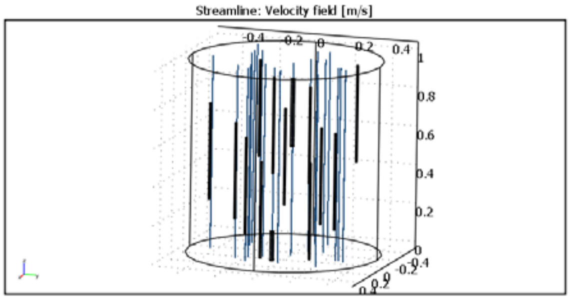


Fig. 3. Illustration of the flow pattern in the soil column for two applied boundary pressures. (a). 0.30 m, (b). –0.20 m.

The numerical simulation of flow through the cylinder was performed much like an experiment in the laboratory would be conducted. The initial state of saturation for the cylinder was made fully saturated with a sufficiently large positive pressure applied to the boundaries. Then the boundary pressure was decreased in increments and at each pressure setting the steady-state solution was acquired with the numerical simulation. The bulk flow through the column was computed from this solution.

The initial pressure setting for the column was 0.3 m. The steady-state flow for this setting is illustrated in Fig. 3a by a streamline plot. The plot illustrates that the macropores are fully participating in the flow since streamlines converge on the macropores from their pathways within the soil matrix. The flow does this because when they are saturated the macropores offer a pathway of least resistance to flow. The total flow through the cylindrical column for this condition was calculated to be 0.0968 m^3/day. To account for the contribution from the macropores to this flow, the macropore domains were made impermeable and the computation repeated for the same pressure setting. For this condition the flow was computed to be 0.06742 m^3/day. The increase in flow with the macropores present is therefore 43%.

From the initial applied pressure, the applied water pressure head was decreased incrementally by 0.01 m, and at each pressure setting the steady-state solution was derived from the numerical simulation. The solution showed that at a pressure of 0.26 m a few of the macropores located near the top of the column started to desaturate. And at each incremental decrease in the pressure, more of the macropores would partially desaturate, and the computed total discharge would decrease, but only slightly (in the sixth decimal place). At a pressure of 0.19 cm the solution did not converge so the incremental process was ended. A final pressure setting was computed at –0.20 m. At that pressure the soil matrix is still fully saturated, but the macropores are completely empty and in the flow process behave as if they are impermeable. The total flux through the column was computed to be 0.06742 m^3/day, the same result as when the macropores were treated as being impermeable objects.

The flow pattern for the solution with the water pressure setting of –0.20 m is shown in Fig. 3b. At the scale of this illustration it appears that the streamlines are perfectly straight through the column. However, a closer examination showed that when a streamline approaches a macropore, it diverts around the macropore because at this pressure the hydraulic conductivity of the macropores is essentially zero, and the macropore thereby offers a very resistant pathway to flow. This effect of streamline deflection around unsaturated highly permeable objects has been clearly demonstrated and described by Bakker & Nieber (2005).

Discussion

The phenomenon of the moisture dependence of the interaction between the soil matrix and the macropores presented by Tsuboyama et al. (1994) and Sidle et al. (2001) is only partially demonstrated by the results presented in Figs 3a,b. In these figures two extreme end conditions were considered; one extreme is where the macropores do not participate at all, while the other extreme is where they participate fully. Based on the form of the hydraulic conductivity functions shown in Fig. 2, the threshold for participation by the macropores should occur near a water pressure of –0.02 m. To examine the transition from one extreme to the other will require improvement in the numerical simulation procedure. As mentioned in the Results section, the numerical simulation failed to converge when boundary pressures were set in the range where the macropores would desaturate. Examining the hydraulic conductivity function for the macropores illustrated in Fig. 2 it is easy to understand the problem. The hydraulic conductivity for the macropores changes by 10 orders of magnitude over a pressure range of about 0.04 m, indicating a very nonlinear problem. Possibly a variable transformation procedure could be employed to resolve this problem.

The application presented was for vertical flow in a soil column containing macropores. In hillslope soils the flow will be both vertical and lateral, and the macropores will have a diversity of orientation, shape, size, and length, where the degree of diversity will depend on the origin of the macropores. A conceptual diagram

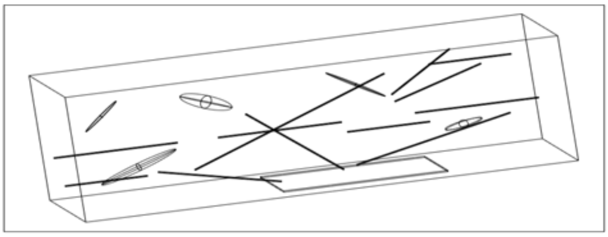


Fig. 4. Illustration of a segment of hillslope soil containing various shaped and oriented macropores.

of a portion of a hillslope segment representing such a situation is illustrated in Fig. 4. This represents a shallow soil overlying an impervious barrier such as bedrock or fragipan. In this flow domain gravity will tend to make the saturation be highest toward the bottom of the domain, and this is the area where the macropores will be activated first. As a perched water table rises the number of macropores activated in the flow process will increase.

The self-organization concept proposed by SIDLE et al. (2001) based on the experimental work of TSUBOYAMA et al. (1994) and NOGUCHI et al. (1999) is in some ways analogous to the concept of percolation at the pore scale in porous media (HUNT, 2005). In that concept the porous medium is represented by pores (nodes) and pore throats (bonds). For two immiscible fluids, let's say water and air, some of the pores will be filled with water and others with air; the proportion being dependent on the size of pores and pore throats, and the capillary pressure. Starting with a high capillary pressure the porous medium will be completely filled with air. As the capillary pressure decreases water will move into some of the pore throats and pores, and at some threshold pressure there will be a continuous path of pore/pore throats filled with water such that water flow will be possible. This process of increasing water saturation leading to eventual water flow is a process of self-organization. It is intriguing that perhaps a model similar to percolation models could be used to describe the self-organization that appears to occur in hillslope soils.

Finally we want to mention that the flow through soils containing embedded macropores produces conditions that could potentially lead to seepage erosion. In effect, because the flow converges on the macropores under saturated conditions, the hydraulic gradient in the soil matrix near the entry point to the macropore can be quite large. In the simulation result shown in Fig. 3a, the largest hydraulic gradient calculated exceeded 25. This compares to the background mean hydraulic gradient of 1.0 set up by the equally applied pressures on the two boundaries of the column. Hydraulic gradients elevated above 1.0 have the potential to cause seepage erosion, as described by SAMANI & WILLLARDSON (1981). A macropore that discharges to the open could easily cause seepage erosion, and this could lead to a migration of the erosion point to join with other macropores. In this way a continuous open path could be created, and thereby the formation of a continuous macropore, or a soil pipe.

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