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A threshold condition for soil-water transport

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The unsaturated flow equation is a robust tool for predicting water movement through fully characterized soils with well-defined sets of initial and boundary conditions. On the other hand, Beven (1989) and Germann (1990) argued that the governing equation rarely applies to field conditions, primarily due to macropore flow (e.g. Mosley, 1979, 1982; Beven and Germann, 1982; Tsuboyama *et al*., 1994). Other preferential flow processes that violate bulk-averaged soil-water flow assumptions are finger flow (e.g. Hill and Parlange, 1972; Hendrickx *et al*., 1993; Glass and Nichol, 1996) and 'mesopore' flow (e.g. Wilson and Luxmoore, 1988; Hornberger *et al*., 1991; Jackson, 1992; Luxmoore and Ferrand, 1993; Taha *et al*., 1997). These preferential flow processes, and others, can give the appearance of a 'rapid' pressure head or water content response deep in an unsaturated soil profile.

Field and laboratory data indicate that a 'pressure perturbation', 'pressure wave' or 'water content wave' may also give rise to a rapid unsaturated zone response, even when Darcy assumptions seem not to be violated (e.g. Zimmermann *et al*., 1966; Andersen and Sevel, 1974; Gilham, 1984; Kayane and Kaihotsu, 1988; Novakowski and Gilham, 1988; Marui *et al*., 1993; Jayatilaka and Gilham, 1998; Reid *et al*., 1998; Rasmussen *et al*., 2000). For example, Torres *et al*. (1998) conducted field irrigation experiments to characterize unsaturated zone influences on runoff generation and slope stability. They drove the soil profile to near-zero pressure head with corresponding soil-water contents at $\sim$0·30 (porosity $\sim$0·60). A natural storm augmented the applied rain with a ten fold spike increase in rain intensity. By comparing pressure wave velocity with approximate wetting front velocity (after Warrick *et al*. (1971)) they showed that the 1·75 h peak rainfall to peak discharge resulted from a rapid unsaturated zone response. Tracer data during a later irrigation experiment, one without a spike increase, showed that preferential flow did not occur (Anderson *et al*., 1997). Therefore, rapid pressure-wave-like responses in the unsaturated zone may be related to spike increases in rainfall.

Reid *et al*. (1998) conducted sprinkler irrigation experiments on a 'soil' prism and observed a pressure-wave-type response. Reid *et al*. (1998) applied water to an inclined soil prism at 100 mm h^{-1} for 50 min, stopped irrigating for 20 min, and then rained at 200 mm h^{-1} until the prism collapsed at 11 min. During the initial irrigation, the pressure heads increased to near-zero, and soil-water contents increased to $\sim$0·35 (porosity $\sim$0·50). These values changed

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little in response to the interruption of rainfall or the increased rain intensity, yet the soil prism failed after 11 min of the higher intensity irrigation. Reid *et al.* (1998) postulated that the latter burst of high-intensity rain produced a 'pressure perturbation' that rapidly advanced through the soil profile. The arrival of the perturbation at the soil base caused the pressure heads to 'flash' from near-zero to greater than $+0{\cdot}25$ m, similar to Gilham (1984). Taken together, these observations indicate that slight pressure head waves develop in particularly wet soil profiles. Under very specific conditions, the pressure wave advance can be approximated as a kinematic wave (Phillip, 1969). Therefore, these field studies document the occurrence of pressure waves, and we have a theory to describe pressure wave advance. But why do unsaturated zone pressure waves occur?

Field observations indicate that pressure heads can attain zero or near-zero values but remain far from saturation (e.g. McDonnell, 1990; Jackson, 1992; Torres *et al.*, 1998; Reid *et al.*, 1998; Kosugi *et al.*, 2001). In some cases, soils may develop highly non-linear water retention properties with a threshold pressure head in the near-zero range (Figure 1). The threshold is associated with a $dK/d\psi$ (or $d\theta/d\psi$ where K is the unsaturated hydraulic conductivity, ψ is the pressure head, and θ is the soil-water content) transition from approximately zero for low pressure heads, to very large values in the near-zero range (Figure 1). Hence, the threshold separates pressure head conditions where the governing equation adequately describes flow, from conditions where it may not (near-zero) (e.g. Vogel *et al.*, 2001). When pressure heads exceed the threshold value, a rapid unsaturated zone pressure head response may occur, giving rise to rapid soil-water redistribution. For example, a short high-intensity burst of rain upon a wet soil profile at the threshold pressure head may induce a slight pressure head increase, and create a short-lived but very large increase in K (Figure 1), giving rise to a release of stored soil-water (Torres and Alexander, In press). The pressure wave advance and concomitant soil-water release may account for the occurrence of near-zero pressure heads and rapid discharge responses observed in many field studies (e.g. McDonnell, 1990).

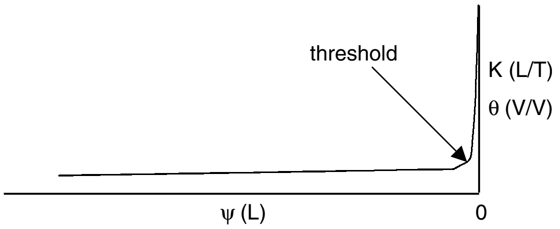

Figure 1. Wetting limb of a highly non-linear soil-water retention (characteristic) curve. The threshold point separates a region of nearly constant $dK/d\psi$ from a region where $dK/d\psi$ can be very large, as in the near-zero range. K: hydraulic conductivity; ψ: pressure head; θ: soil-water content

Pressure wave advance may result in the release of stored soil-water, leading to the redistribution of newer and older water within the soil profile, and in runoff. Horton and Hawkins (1965), however, showed that water movement through an unsaturated sand column occurred via a *displacement* process that is adequately described by the governing flow equation (Stephens, 1996). Although both processes result in flow due to a potential gradient through a continuum, the pressure-wave-release mechanism appears to contradict the current displacement view of unsaturated flow by the concomitant release of soil-water throughout the soil profile. Alternatively, the pressure-wave-release mechanism may not be a continuum process at all. I speculate that a slight soil-water pressure head increase in the near-zero pressure head range may lead to the release of stored soil-water into larger macropores, and it may help set up conditions favouring initiation of preferential flow. When macropores become hydraulically active the fluid may no longer behave as a continuum, and momentum of soil-water is no longer negligible. This important change in flow process essentially causes the governing equation to shift from parabolic to hyperbolic to account for inertia of soil-water (e.g. Liakopolous, 1965).

Germann and Di Pietro (1999) defined preferential flow as film flow 'torn' away from the bulk soil-water, and they hypothesized that preferential flow is mainly governed by momentum dissipation. They showed that momentum dissipation may dominate flow in structured soils when input rates and antecedent soil-water contents are high. I propose that preferential flow (e.g. macropore flow) is more likely to occur in soils with highly non-linear soil-water retention properties and pressure head thresholds (Figure 1) according to the pressure-wave-release mechanism described above. I speculate that the pressure-wave-release may cause parts of the soil profile to switch intermittently from 'diffusion-like' flow described by the governing equation to the dispersive flow described by Germann and Di Pietro (1999).

Such a threshold process may explain the contradictory findings reported by Mosley (1982) and by Pearce and coworkers (Pearce *et al*., 1986; Sklash *et al*., 1986); who conducted field experiments at the same study site. Essentially, Mosley (1982) showed infiltrating (new) water bypassed the bulk of the soil matrix. Pearce and coworkers (Pearce *et al*., 1986; Sklash *et al*., 1986) showed that displacement of pre-storm (old) water occurred, and they argued that old water must dominate the storm hydrograph. Taken together, these studies show that preferential flow and matrix flow may intermittently dominate runoff processes at the same location. The presence of a threshold comparable to that described above may give rise to the intermittent activity of the pressure-wave-release mechanism, and it may help reconcile their apparently contradictory observations.

The exact mechanism of unsaturated soil-water transport may ultimately dictate the shape of the probability density function for water ages in shallow groundwater seepage and runoff. Hence, soil-water release versus displacement mechanisms may yield vastly different geochemical signatures in runoff. Moreover, soil-water that is released, as opposed to displaced, may have sufficient energy to enter larger pores and lead to the initiation of preferential flow. In order to investigate the behaviour of soil-water at near-zero pressure head conditions, detailed column experiments on natural and artificial porous material are needed to document the occurrence of water content waves and pressure waves. Additional experimental and theoretical studies should focus on the mechanisms of soil-water transport when soil-water contents are far from saturation but pressure heads are near zero.

References

Andersen LJ, Sevel T. 1974. Six years' environmental tritium profiles in the unsaturated and saturated zones. In *Isotope Techniques in Groundwater Hydrology*, Vol. 1. IAEA Proceedings Series No. STI/PUB/373. IAEA: Vienna; 3–20.

Anderson SP, Dietrich WE, Montgomery DR, Torres R, Conrad M, Loague K. 1997. Subsurface flow paths in a steep unchanneled catchment. *Water Resources Research* 33(12): 2637–2649.

Beven K. 1989. Changing ideas in hydrology—the case of physically based models. *Journal of Hydrology* 105: 157–172.

Beven K, Germann P. 1982. Macropores and water flow in soils. *Water Resources Research* 18(5): 1311–1325.

Germann PF. 1990. Preferential flow and the generation of runoff, 1. Boundary layer flow theory. *Water Resources Research* 26(12): 3055–3063.

Germann PF, Di Pietro L. 1999. Scales and dimensions of momentum dissipation during preferential flow in soils. *Water Resources Research* 35(5): 1443–1454.

Gilham RW. 1984. The capillary fringe and its effect on water-table response. *Journal of Hydrology* 67: 307–324.

Glass RJ, Nichol MJ. 1996. Physics of gravity fingering of immiscible fluids with porous media: an overview of current understanding and selected complicating factors. *Geoderma* 70: 133–163.

Hendrickx JMH, Decker LW, Boersma OH. 1993. Unstable wetting fronts in water repellent soils. *Journal of Environmental Quality* 22: 109–118.

Hill DE, Parlange J-Y. 1972. Wetting front instability in layered soils. *Soil Science Society of America Proceedings* 36: 697–702.

Hornberger G, Germann P, Beven K. 1991. Throughflow and solute transport in an isolated sloping soil block in a forested catchment. *Journal of Hydrology* 124: 81–99.

Horton JH, Hawkins RH. 1965. Flow path of rain from the soil surface to the water table. *Soil Science* 100(6): 377–383.

Jackson CR. 1992. *Characterization of subsurface flow in shallow soiled hillslopes*. PhD Thesis, University of Washington.

Jayatilaka CJ, Gilham RW. 1998. A deterministic-empirical model of the effect of the capillary-fringe on near-stream area runoff. 1. Description of the model. *Journal of Hydrology* 204(1–4): 180.

Kayane I, Kaihotsu I. 1988. Some experimental results concerning rapid water table response to surface phenomena. *Journal of Hydrology* 102: 215–234.

Kosugi K, Mori K, Yasuda H. 2001. An inverse modeling approach for the characterization of unsaturated water flow in an organic forest floor. *Journal of Hydrology* 246: 96–108.

Liakopoulos AC. 1965. Retention and distribution of moisture in soils after infiltration has ceased. *IAHS Bulletin* 10(2): 58–85.

Luxmoore RJ, Ferrand LA. 1993. Towards pore scale analyses of preferential flow and chemical transport. In *Water Flow and Solute Transport in Soils*, Russo D, Dagan G (eds). Springer Verlag: New York; 45–60.

Marui A, Yasuhara M, Kuroda K, Takayama S. 1993. Subsurface water movement and transmission of rainwater pressure through a clay layer. In *Hydrology of Warm Humid Regions*, Gladwell JS (ed.). IAHS Publication no. 216. IAHS: Wallingford; 463–470.

McDonnell JJ. 1990. A rationale for old water discharge through macropores in a steep, humid catchment. *Water Resources Research* 26(11): 2821–2832.

Mosley MP. 1979. Streamflow generation in a forested watershed, New Zealand. *Water Resources Research* 15(4): 795–806.

Mosley MP. 1982. Subsurface flow velocities through selected forest soils, South Island, New Zealand. *Journal of Hydrology* 55: 65–92.

Novakowski KS, Gilham RW. 1988. Field investigations of the nature of water-table response to precipitation in shallow water-table environments. *Journal of Hydrology* 97: 23–32.

Pearce AJ, Stewart M, Sklash M. 1986. Storm runoff in humid headwater catchments. *Water Resources Research* 22(8): 1263–1272.

Phillip JR. 1969. The theory of infiltration. *Advances in Hydrosciences* 5: 215–296.

Rasmussen TC, Baldwin RH, Dowd JF, Williams AG. 2000. Tracers vs. pressure wave velocities through unsaturated saprolite. *Soil Science Society of America Journal* 64: 75–85.

Reid ME, LaHusen RG, Iverson RM. 1998. Debris flow initiation experiments using diverse hydrologic triggers. In *Debris Flow Hazards Mitigation: Mechanics, Prediction, and Assessment*, Chen CL (ed.). ASCE: 1–11.

Sklash M, Stewart M, Pearce A. 1986. Storm runoff generation in humid headwater catchments. *Water Resources Research* 22(8): 1273–1282.

Stephens DB. 1996. *Vadose Zone Hydrology*. CRC Press: Boca Raton, FL.

Taha A, Gresillon JM, Clothier BE. 1997. Modeling the link between hillslope water movement and stream flow: application to a small Mediterranean forest watershed. *Journal of Hydrology* 203: 11–20.

Torres R, Alexander LJ. In press. Intensity–duration effects on drainage: column experiments at near-zero pressure head. *Water Resources Research*.

Torres R, Dietrich WE, Montgomery DR, Anderson SP, Loague KM. 1998. Unsaturated zone processes and the hydrologic response of a steep, unchanneled catchment. *Water Resources Research* 34(8): 1865–1879.

Tsuboyama Y, Sidle RC, Noguchi S, Hosoda I. 1994. Flow and solute transport through the soil matrix and macropores of a hillslope segment. *Water Resources Research* 30(4): 879–880.

Vogel T, vanGenuchten MT, Cislerova M. 2001. Effect of the shape of the soil hydraulic functions near saturation on variably saturated flow predictions. *Advances in Water Resources* 24: 133–144.

Warrick A, Biggar JW, Nielsen DR. 1971. Simultaneous solute and water transfer for an unsaturated soil. *Water Resources Research* 7(5): 1216–1225.

Wilson GV, Luxmoore RJ. 1988. Infiltration, macroporosity, and mesoporosity distributions in two forested watersheds. *Soil Science Society of America Journal* 52: 329–335.

Zimmermann U, Munnich KO, Roether W, Kruetz W, Schubach K, Siegel O. 1966. Tracers determine movement of soil moisture and evapotranspiration. *Science* 152(3720): 346–347.