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Preferential flow occurs in unsaturated conditions[†]

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Because it commonly generates high-speed, high-volume flow with minimal exposure to solid earth materials, preferential flow in the unsaturated zone is a dominant influence in many problems of infiltration, recharge, contaminant transport, and ecohydrology. By definition, preferential flow occurs in a portion of a medium – that is, a preferred part, whether a pathway, pore, or macroscopic subvolume. There are many possible classification schemes, but usual consideration of preferential flow includes macropore or fracture flow, funneled flow determined by macroscale heterogeneities, and fingered flow determined by hydraulic instability rather than intrinsic heterogeneity.

That preferential flow is spatially concentrated associates it with other characteristics that are typical, although not defining: it tends to be unusually fast, to transport high fluxes, and to occur with hydraulic disequilibrium within the medium. It also has a tendency to occur in association with large conduits and high water content, although these are less universal than is commonly assumed.

Predictive unsaturated-zone flow models in common use employ several different criteria for when and where preferential flow occurs, almost always requiring a nearly saturated medium. A threshold to be exceeded may be specified in terms of the following (i) water content; (ii) matric potential, typically a value high enough to cause capillary filling in a macropore of minimum size; (iii) infiltration capacity or other indication of incipient surface ponding; or (iv) other conditions related to total filling of certain pores. Yet preferential flow does occur without meeting these criteria. My purpose in this commentary is to point out important exceptions and implications of ignoring them. Some of these pertain mainly to macropore flow, others to fingered or funneled flow, and others to combined or undifferentiated flow modes.

Evidence

Various observations have shown that preferential flow does not require saturation of the matrix material between the preferential flow paths, for example:

- **Booltink and Bouma (1991), using direct measurements from numerous small tensiometers, demonstrated that at depth, soil immediately adjacent to active macropores wetted quickly during infiltration from the soil surface, indicating preferential flow, whereas the peds between these macropores slowly increased in water content.**
- **Edwards *et al.* (1992) observed, for a range of water contents achieved with different intensities of artificial rainfall, that 'an increase in antecedent moisture probably allowed more of the smaller pores to contribute to infiltration and water movement. This *reduced the overall contribution of the large earthworm burrows* to total percolate'. [emphasis mine]**
- **Smettem *et al.* (1994) concluded that antecedent water content may be inconsequential compared with other influences: 'These results again**

- illustrate that the response to rainfall is quite variable between cores and that any antecedent effects tend to be overwhelmed by spatial and temporal variations in structural continuity'.
- Shipitalo and Gibbs (2000) found that water applied to individual earthworm burrows traveled preferentially to subsurface drains in a matter of minutes, although the soil was *not highly wetted* beforehand.
- Tallon *et al.* (2007) noted that drastic differences in initial soil wetness made little difference, and if anything, there was more deep downward transport of bacteria and chloride from the land surface under the driest treatment.
- The large number of similar observations led Stumpp and Maloszewski (2010) to conclude that '...preferential flow is *not restricted to saturated conditions*. It also can occur during high-intensity rainfall *even if the soil is initially dry*'.

A distinct but related fact is that preferential flow does not require saturation of the conduit that it flows through. Evidence includes:

- Bouma *et al.* (1977) with a combined hydraulic and micromorphometric analysis of dye-stained macropores concluded that 'water flow through participating larger macropores apparently occurs *only along the walls without filling the entire pore*'.
- Ghodrati *et al.* (1999) found macropore flow to constitute 38–50% of the total flow during infiltration in a soil column, although only film flow was observed in the macropore, which 'never became completely saturated'.
- Weiler (2001) observed that 'with a hydraulic head of 0.0 m at the macropore opening, the initial flow rate depends solely on the hydraulic properties of the macropore. After the macropore is completely filled, the flow rate usually suddenly *decreases* to a stable flow rate. This flow rate depends on flow from the macropore into the surrounding soil matrix'.
- Cey and Rudolph (2009) observed macropore tracer transport to 0.2-m depth in 6 min, whereas both matrix and macropores were under tension and unsaturated. They found water to flow in films, possibly generated by mechanisms demonstrated in the experiments of Su *et al.* (2003) and Phillips *et al.* (1989).
- A further observation from Cey and Rudolph (2009) is that preferential flow at depth ceased suddenly on cessation of the water application, adding to evidence that the films were thin, and the immediately adjacent matrix material was unsaturated and ready to absorb water.
- Through multiple lines of evidence, Rimon *et al.* (2011) found preferential flow to occur in different parts of individual pores while leaving other portions of the pore unwetted.

Reasons

Observations as described here are not inexplicable. In fact, our general understanding of flow in porous media should lead us to expect them.

Preferential flow often occurs in the absence of hydraulic equilibrium (e.g. Jarvis, 2007). It arises from a contrast in conductance between different types of flow paths, a contrast that may be heightened when matrix material between preferential flow paths is less conductive because of lower water content (Stumpp and Maloszewski, 2010). Nonequilibrium also suggests the possibility of preferential flow in the form of films on the walls of macropores bordering unsaturated matrix material, as commonly observed (e.g. Bouma and Dekker, 1978; Cey and Rudolph, 2009) and elaborated experimentally and theoretically (Tokunaga and Wan, 1997; Tokunaga *et al.*, 2000; Dragila and Wheatcraft, 2001; Hincapié and Germann, 2009).

Connectivity of flowpaths is essential to preferential flow. High water content may be evidence of a *lack* of connectivity, as filled pores may retain water *because* they are poorly connected. Common sense about water in drainpipes gives a simple illustration: a drain that flows freely generally does not fill up with water. A drain observed to be completely filled more likely is plugged than experiencing particularly fast flow. Likewise in soil and rock, a filled conduit may be evidence not of high flux but of blockage. Rosenbom *et al.* (2008) described this phenomenon in terms of unsaturated-zone preferential flow:

> Under wet conditions, biopores were stained by tracer from flowing water only if they are well connected to other large pores at depth. Under dry conditions, there was staining additionally in biopores that terminate in the matrix.... Tracers are preferentially transported in the biopores at depths of 0.45 to 1.4 m even though the matrix is only partially saturated in this depth interval during the summer season. Dead-end biopores without connection to deeper fractures will be water filled in the fall season and are therefore not readily accessible for the tracer.

Similarly, the concept of capillary water-entry value to fill large pores may not be very useful, as connectedness and other issues may matter far more than a threshold of matric potential required to fill a given macropore.

Shrinkage cracks, which commonly conduct preferential flow, are likely to be transmissive under relatively dry conditions (Hardie *et al.*, 2011). Kladivko *et al.* (2001) explained that

> ... heavy clay soils routinely have large cracks form in late summer as the soil dries, causing significant crack flow (preferential flow) to occur in fall and early winter until the soil profile becomes fully wetted again.... On these types of cracking clay soils, it appears that wetter

> conditions may decrease the prevalence of preferential flow… Kladivko *et al.* also cited the results of Bergström *et al.* (1990), who measured leaching through a heavy clay soil:
>
> Only one of the weekly tile drain samples contained detectable concentrations of the herbicide, and this occurred within 2 months of application and with very little net drainage. After more rainfall was received and the wetter soil produced more drainflow, preferential flow probably decreased, and the herbicide was not transported to the drains.

Hydrophobicity, another major cause of preferential flow, especially in fingered or funneled modes (Hendrickx *et al.*, 1993), is generally greater in drier soil. Burcar *et al.* (1994) noted that '… preferential patterns may dissipate following prolonged exposure to moisture'. This phenomenon has been confirmed by others such as Hardie *et al.* (2011).

There are striking commonalities among diverse preferential flow observations. If complete filling of macropores were essential to preferential flow, there would likely be an extremely wide range of preferential flow transport speeds in diverse media, as there is for diffuse unsaturated flow. Such variation results in part from the fourth-power-of-radius dependence of flow rate on conduit size. However, evidence points to surprisingly little variation in observed rates of preferential flow (Nimmo, 2007; Hincapié and Germann, 2009), which would not be likely if it had the expected extreme size-sensitivity of filled-conduit flow.

Implications

Published case studies and observations of preferential flow make clear that preferential flow sometimes occurs in media much drier than saturation; can occur in pores incompletely filled; can occur in macropores before the onset of ponding, and even delay or prevent ponding; and can, in several ways, be *inhibited* by higher water content. These possibilities are not always allowed for by the criteria written into models to predict preferential flow, which usually accord with a traditional unsaturated-zone assumption that wetter conditions produce greater and faster flow. This should not be taken to imply that preferential flow cannot become greater with increasing wetness; indeed, observations suggest that many processes of preferential flow are enhanced by greater wetness. However, evidence as cited in this commentary shows there are important situations where preferential flow is enhanced by relative dryness.

Because unsaturated flow involves extreme complexity of process, medium, and state, usually compounded with severe scarcity of characterizing information, we use many drastic simplifications. Typical modelling efforts assume that processes are not hysteretic, that large volumes of geologic media have little or no heterogeneity, that one site's measured properties apply at another, etc. A requirement of a saturated or nearly saturated medium for preferential flow can be considered as this sort of simplification and justified if it makes no significant difference in the conclusions. Although attractive on the grounds that it often is the case, the wetter-implies-faster assumption entails particular vulnerabilities because the consequence of being wrong is that one could predict not only the wrong *degree* but also the wrong *direction* of a trend that bears directly on hazard, water-supply, and ecosystem assessments. Preferential flow in some cases is more effective in dry than wet soil. Thus, the justification is precarious because this simplification may produce conclusions opposite to the actual physical trends.

Various practical problems can result from erroneous prediction of trend with dryness. The hazard expected from unsaturated-zone spread of contamination could be underestimated in relatively dry conditions and overestimated in wetter conditions. Similarly, aquifer recharge estimates may be erroneously low if low-saturation preferential flow is neglected, or erroneously high if a model exaggerates the role of preferential flow in very wet conditions.

The growing diversity of applications of preferential flow models also heightens the importance. Ecohydrology is a prominent example. Preferential flow, far from being considered a nuisance as it frequently is in agricultural and engineering applications, is critical to the plant–soil–water relations that determine the health and evolution of ecosystems, for example, through plant survival and competitive strategies. Well beyond the common pursuits of minimizing or avoiding preferential flow, there is need for genuinely understanding its role in system properties and processes.

To create alternative models with greater realism and applicability, we need more ways of formulating unsaturated flow that are not strongly wedded to the wetter-implies-faster concept. There is limited usefulness to the concept of an on/off status of macropores according to standard capillary diameter/pressure relations controlling their filled or unfilled state, which can prevent the representation of actual preferential flow occurring under far-from-saturated conditions. In addition to the concept of filled large pores, we need to incorporate additional processes or possibilities such as reconceptualization of macropores smaller than traditionally assumed. Recent efforts include the water-content wave model of Germann *et al.* (2007), the active area concept of Nimmo (2010), and the flow net concept (a sort of sub-pore-scale dual domain) of Rimon *et al.* (2011).

Considering that preferential flow often is regarded in a hydraulic sense as nonequilibrium flow, that is, that 'infiltrating water does not have sufficient time to equilibrate with slowly moving "resident" water in the bulk of the soil matrix' (Jarvis, 1998), the types of measurements relevant to preferential flow prediction also need reevaluation. Standard TDR (time-domain reflectometry) or neutron-probe measurements of water content, for example, are sensitive primarily to the typically large fraction of water that has limited mobility. Matric potential measurements likewise have questionable relevance because of nonequilibrium conditions. Possibly more useful would be measurement techniques that isolate the abundance or energy of that portion of water that is within preferential flow paths, although such methods are not readily available and their ability to alleviate this problem is unclear. A currently achievable water content or matric potential measurement, sensitive to water in the nonpreferential as well as the preferential domain, is not suitable to serve alone as a predictor of preferential flow.

We need practical models of unsaturated-zone water flow and contaminant transport that realistically treat all major types and processes of preferential flow, not just those that accord with the wetter-implies-faster concept. Because the stakes are high for water resources and other issues, this is a critical component of the ongoing development of models and measurement techniques for preferential flow in the unsaturated zone.

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