ARTÍCULO INVITADO

HOW FAST DOES WATER FLOW IN AN UNSATURATED MACROPORE?: EVIDENCE FROM FIELD AND LAB EXPERIMENTS

¿CON QUÉ RAPIDEZ FLUYE EL AGUA EN UN MACROPORO INSATURADO?: EVIDENCIA EN EXPERIMENTOS DE CAMPO Y LABORATORIO.

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RESUMEN. Mucha evidencia disponible del campo y del laboratorio puede conducir a generalizaciones útiles sobre la velocidad de flujo en macroporos, que domina el transporte del agua y de los contaminantes. En 36 investigaciones de campo publicadas, la velocidad de transporte máxima en macroporos y otros conductos preferenciales varía sorprendentemente poco. Los estudios disponibles varían mucho en el medio, incluyendo roca fracturada y varias texturas del suelo; en la escala longitudinal, de 1 a más 1000 metros; en el tipo de trazador usado; y en la dirección del flujo. Un factor que afecta considerablemente las velocidades de transporte es el suministro de agua que genera el flujo. Un suministro esporádico de agua en la superficie del suelo, como el generado por la precipitación natural, causa un flujo preferencial marcadamente más lento que un suministro continuo, como el del riego constante. Para este segundo caso de suministro continuo, casi todas las observaciones de la velocidad máxima de transporte dan valores entre 1-100 m/d, sugiriendo que un valor medio en ese rango podría servir como una pauta para la velocidad de transporte prevista bajo condiciones comparables.

Varios experimentos de laboratorio en estudios publicados ayudan a explicar y a apoyar estos resultados de campo. Los estudios de visualización muestran que el flujo no saturado del macroporo ocurre en cuatro modos distintos. Los nombres descriptivos para éstos son: flujo en película, riachuelo continuo, riachuelo intermitente, y gota pulsante. Aunque con diferencias entre estos tipos de flujo, cambios impuestos en factores normalmente dominantes, por ejemplo la fuerza impulsora y contenido en agua, parecen causar menos cambio en el flujo del agua y solutos que lo que las teorías convencionales predicen. Por ejemplo, en un experimento en el que se aumentó en un factor de 10 el grosor de la película de agua en un macroporo, la velocidad medida del flujo aumentó en un factor de 7, mucho menos que el factor de 100 predicho por la teoría laminar del flujo. Los mecanismos compensatorios que causan este comportamiento pueden también causar que las velocidades de transporte máximas observadas en el campo varíen tan poco.

Colectivamente estos resultados sugieren que en condiciones naturales puede haber un límite de velocidad para el agua en macroporos no saturados que la ley de Darcy no puede predecir, y que depende sobre todo de características básicas de la tierra y agua. La generalización de que algunas velocidades de transporte en macroporos insaturados son casi constantes para condiciones del suministro del agua similares, aunque sea solamente aproximada, podría facilitar la predicción del transporte de contaminantes y de otras magnitudes de importancia hidrológica en las condiciones más desfavorables.

ABSTRACT. A wide range of available field and lab evidence can lead to useful generalizations about the speed of macropore flow, which often dominates the transport of water and contaminants. In 36 published field tests, the values of maximum transport speed in macropores and other preferential channels vary surprisingly little. The available tests vary widely in type of medium, including fractured rock and various soil textures; in length scale of the test, ranging from 1 to 1000 m and more; in type of tracer used; and in direction of flow. One factor that does significantly affect transport speeds is the supply of water that generates the flow. A sporadic supply of water at the land surface, as from natural rainfall, causes markedly slower preferential flow than a continuous supply, as from steady irrigation. For continuously supplied water, nearly all observations of maximum transport speed fall between 1 and 100 m/d, suggesting that an average value in that range could serve as a guideline for expected transport speed under comparable conditions.

Lab experiments in published studies help to explain and support these field results. Visualization studies show that unsaturated macropore flow occurs in four distinct modes. Descriptive names for these are film flow, continuous rivulet, snapping rivulet, and pulsating blob. To degrees that vary among these flow modes, imposed changes in normally dominant influences such as driving force and water content seem to cause less change in water and solute fluxes than conventional theories predict. In one experiment, with a factor of 10 increase in the thickness of a film, the measured flow speed increased by a factor of 7, much less than the factor of 100 predicted by laminar flow theory. Compensating mechanisms that cause this behavior may also cause the maximum transport speeds observed in the field to vary so little.

Collectively these results suggest that there may be a natural speed limit for water in unsaturated macropores, not predictable by Darcy's law, that depends mostly on basic earth and water properties. The generalization that certain transport speeds are nearly constant for similar water input conditions, even if true only in an approximate sense, could facilitate the prediction of worst-case contaminant travel times and other quantities of hydrologic importance.

1. Introduction

Fast flow in macropores, fractures, and other preferential flow paths is a major cause of discrepancy between measurements and unsaturated flow models. It enhances contaminant transport, not only through fast convective transport, but by reduction of contaminant adsorption in the unsaturated zone. This reduction results from the reduced amount of soil that contaminants are exposed to, as well as a reduced time of exposure.

Preferential flow is defined here as flow along pathways occupying a limited portion of the pore space, that proceeds markedly faster than flow within the rest of the medium. The diverse processes of preferential flow fall into at least the three categories of (1) macropore flow, in which the flow is within pores that are larger or more strongly interconnected than most pores of the medium; (2) funneled flow, in which layers or lenses of contrasting material divert unsaturated flow and concentrate it spatially; and (3) unstable or fingered flow, in which narrow portions of the medium become wetter than the rest and the combination of greater conductivity and wetness of those portions becomes self-perpetuating. These different processes may occur in complex combination. Most of the field studies reviewed in this paper consider their collective effect without distinguishing among them. Macropore flow, however, is likely to be the dominant type of preferential flow in most of these cases, because macropores are a pronounced feature of the soils and other media involved in these studies. Macropores may be distinguished from other pores of the medium by various definitions. One is the effective pore size, for example the criterion of Luxmoore (1981) that they are >1 mm in equivalent diameter. Another is the hydraulic behavior of the pores, for example stipulating that macropores act to channel water fast enough through the medium that it has insignificant interaction with most of the material present. A third type of distinction is based on the mode of origin of the pore, macropores being interaggregate gaps; shrink/swell cracks; holes left by roots, worms, or other biota; or fractures in rocks resulting from various geologic processes. Even where preferential flow occurs because of funneling or instability, macropores may serve as a conceptual surrogate for the other types of preferential flow path.

This paper focuses on the maximum speed of convective transport, referred to here as v_{max}, as the main quantity of interest in a variety of problems and investigations. It is critical to contaminant transport problems, e.g. predicting the arrival of contaminants at a water table or other position of concern. In many studies involving widely varying media, scales, and water input conditions, it is possible to estimate the minimum travel time of water over a particular scale length. This permits calculation of v_{max} whether or not this was originally a stated objective. A maximum has a high degree of physical relevance and sensitivity to the preferential aspects of the flow, more so than averaged quantities (Pruess, 1999). Additionally, v_{max} is of primary interest in certain practical applications, for example in contaminant transport problems where initial arrival time is important. In other applications it can serve as a first step toward predicting fluxes of water and contaminants in preferential flow.

The main purpose of this paper is to investigate how fast water flows in macropores, by compiling and reviewing previously published field and lab evidence. Field experiments collectively indicate trends and variability in transport velocity, and important features to which it is sensitive. Lab experiments elucidate the mechanisms of preferential flow that may cause the observed field behavior.

2. Field Observations

2.1. Objectives and approach

Unsaturated-zone preferential flow studies at various scales can address the question as to what the rate of travel is while preferential flow is occurring. Fast flowpaths on the order of 1 meter long, as are common in soils, have been studied in a variety of laboratory and field experiments especially over the last 30 years (Beven and Germann, 1982). More recently, fast flowpaths on the scale of 10^1 to 10^3 m have been detected within thick unsaturated zones at some locations (e.g. Bryant, 1992; Fabryka-Martin et al., 1997; Dunnivant et al., 1998; Nimmo et al., 2002).

The studies examined involve a tracer applied at one location, usually the land surface, and detected at another, in the saturated or unsaturated zone. The tracers include both conservative and nonconservative solutes, and, broadly interpreted, also include pulses of liquid water in cases where evidence indicates some amount of water travels the entire distance.

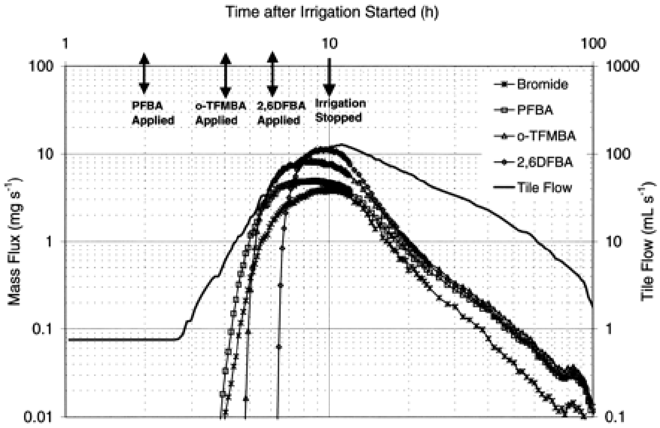

Fig. 1. Results from the experiment of Kung et al. (2000b, *Figure 2*) showing breakthrough curves of four conservative tracers and flow rate from a tile drain. Tracers were applied at the land surface and their concentrations were measured in the tile drain effluent.

2.2. Small- and large-scale examples

Kung et al., (2000a) give a good example of a small-scale study. They used tile drains, porous pipes buried horizontally at a chosen depth in an agricultural field, as sampling devices. The drains intercept infiltrated water and convey it to where it can be measured and analyzed. The tile drains were 0.9 m below the land surface, establishing the water table at about this depth. Tracers were applied to the surface, with continuous irrigation until after the time they were detected in the water extracted with the tile drains. It is assumed that tracer flows downward in preferential paths to the water table, where it almost immediately becomes present in water in the drains, and that it is sampled with negligible time delay. Figure 1 shows the breakthrough curves Kung et al. measured in this effluent. The time between tracer application and its first detection, for example 1.9 hr for tracer PFBA in Figure 1, is assumed to represent the travel time from the surface to 0.9 m depth. Thus v_{max} for PFBA in this example is 11 m/d.

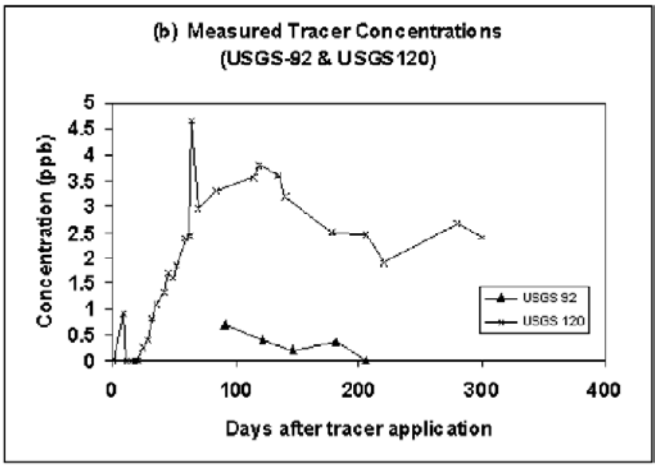

Fig. 2. Results from the km-scale tracer experiment of Nimmo et al. (2002). These data are measured concentrations for an aquifer well 200 m below and almost directly under the source of tracer (USGS 120), and a well in perched water in the unsaturated zone more than 1 km from the source of tracer (USGS 92).

An example of a large-scale experiment is that of Nimmo et al. (2002), on the Snake River Plain in southeastern Idaho within the Idaho National Engineering and Environmental Laboratory. The unsaturated zone comprises thick layers of fractured basalt interbedded with thinner sedimentary layers of various textures. Perched water is common and was sampled at a number of wells within the unsaturated zone. Aquifer wells were also sampled. A conservative tracer (1,5-naphthalene disulfonate) was applied to a large body of ephemeral surface water and later detected in the subsurface. Figure 2 shows two breakthrough curves, measured using samples from well USGS 120, in the saturated zone at 200 m depth near a point of tracer application, and from well USGS 92 in perched water 1.3 km away from the nearest point of tracer application. The USGS 120 data indicate a v_{max} of 30 m/d. The first sampling of USGS 92 was already after the time of first arrival of tracer, but the results indicate that v_{max} was greater than 15 m/d.

2.3. Compiled studies

The observations compiled here come from field experiments in which the observed transport can be indicative of convective liquid transport. No known studies of relevance have been excluded, though the list is not exhaustive.

The mode of sampling varies among studies. Most of the smaller-scale studies were in agricultural fields with solution sampling at depth using tile drains, wells, or suction samplers (Komor and Emerson, 1994; Kladivko et al., 1991; Richard and Steenhuis, 1988; Sophocleous et al., 1990). Other studies involved agricultural fields with core sampling (Jury et al., 1986), undisturbed soil with neutron detection of infiltrating water (Nimmo et al., 1999), and infiltration into a fracture in chalk with collection of water at 1 m depth (Dahan et al., 1999).

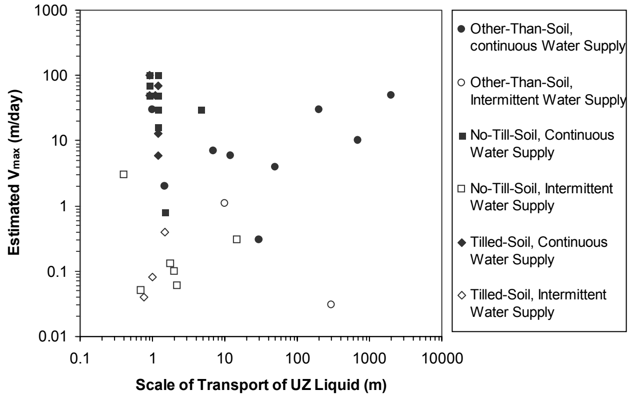

Fig. 3. Estimated maximum rate of preferential flow over various distances, for field experiments. The distinction between continuous and intermittent supply of water is highlighted with solid and open symbols.

Table 1. Means and standard deviations of v_{max} from compiled studies.

		n	Geometric mean	Arithmetic mean	Arithmetic Standard Deviation
	Scale (m)	36	3.5	90.8	346.4
	All v_{max}	36	4.6	26.9	33.3
Media	Other-than-soil	11	3.6	12.8	16.5
	No-till soil	18	4.7	33.4	37.9
	Tilled soil	8	5.8	31.8	37.3
Surface conditions	Ponded	12	5.9	15.2	16.9
	Sprinkled	15	41.3	54.7	34.4
	Intermittent	11	0.2	0.9	1.9
Means of sampling	Tile drain	18	13.5	44.1	38.7
	Saturated-zone point	7	4.7	17.8	19.2
	Unsaturated-zone point	10	1.5	7.7	12.0
	Core	2	0.1	0.1	0.1

For 36 studies that meet the selection criteria, Figure 3 compares v_{max} as a function of scale length. The range of v_{max} is 0.03 m/day to 100 m/day, that is, about 3.5 orders of magnitude. The scale length in these experiments also spans a 3.5-order-of-magnitude range, from 0.4 to 2000 m. Table 1 gives means and standard deviations for certain categories of investigation.

2.4. Factors with relatively little influence on v_{max}

The scatter of the points in Figure 3 appears to have no trend with scale length. If valid in general, this observation would suggest that essentially equivalent phenomena act at all scales, and it suggests a simple scalability of preferential flow, for example using Miller similarity (Miller, 1980).

It is of much interest how preferential flow varies with surface and subsurface characteristics. Media include both rock and soil with textures ranging from gravel to clay. The sites differ also in vegetation, and in some cases tillage practices. To have categories with a reasonable number of points for averaging, the media were lumped together in three broad categories: no-till soil, tilled soil, and media other than soil. The averages in Table 1 suggest little or no dependence of v_{max} on these categorizations.

The type of tracer is noted in compiling results but not considered independently here. Evidence suggests that there is little difference in the behavior of conservative and nonconservative tracers when the flow is preferential. In many studies (e.g. Kung, 2000b; Kladivko, 1991) the intrinsic conservatism of the tracer has little effect on initial tracer travel times by preferential flow, consistent with the understanding that, being concentrated in space and time, preferential flow severely limits both the time and intensity of the tracer's exposure to subsurface media with which it would react.

In most cases the dominant direction of preferential flow is vertical, but in some large-scale studies it is horizontal or nearly horizontal, with a much smaller component of gravitational force. There are too few horizontal-flow data here to draw conclusions on this matter.

2.5. The influence of surface conditions on v_{max}

Where water is supplied by a pond or by continuous irrigation, v_{max} tends to be markedly greater than if the supply is intermittent. More surprisingly, the data suggest that within the category of water continuously and copiously supplied, v_{max} varies little. For studies with intermittent water supply, the mean is markedly less. In different locations and over various scales, there tends to be a surprisingly uniform v_{max}, suggesting that preferential flow depends more on hydraulics than on the characteristics of the media. An implication of this is that v_{max} may not be inferable from Darcy's law, specifically that it cannot be interpreted in terms of a characteristic hydraulic conductivity (K), the proportionality factor between flux and force, which depends on the medium.

The v_{max} values compiled in Figure 3 and Table 1 suggest that for a wide range of media and conditions, compensating (i.e. flow-rate stabilizing) mechanisms might be routinely active, and that the v_{max} values are nearly constant for similar water input conditions. The following sections further explore this idea.

3. Lab Experiments

3.1. Flow modes in an unsaturated macropore

The visualizations and measurements by Su et al. (1999) show what modes of unsaturated flow are possible for continuously supplied water that flows through a fracture that is not fully saturated. These experiments used an artificial fracture constructed with parallel plates, transparent so that the form adopted by water flowing between them could be seen and photographed. In response to a variations in imposed flow conditions, for example driving force adjustments by changing the angle of tilt with respect to gravity, the flowing water varied in terms of intermittency and shape of the water-occupied space. The observed phenomenal may be divided into four categories, or flow modes, based on: (a) whether or not water bridges across the fracture aperture; and (b) if water does bridge the aperture, what is the temporal continuity of its path between inlet and outlet. For water that bridges the aperture, the essential subdistinction is whether, across the domain of interest, it is (i) consistently connected, (ii) sometimes but not always connected, or (iii) never completely connected. Table 2 summarizes and Figure 4 illustrates the flow modes that arise from these criteria, referred to here as film flow, continuous rivulet, snapping rivulet, and pulsating blob.

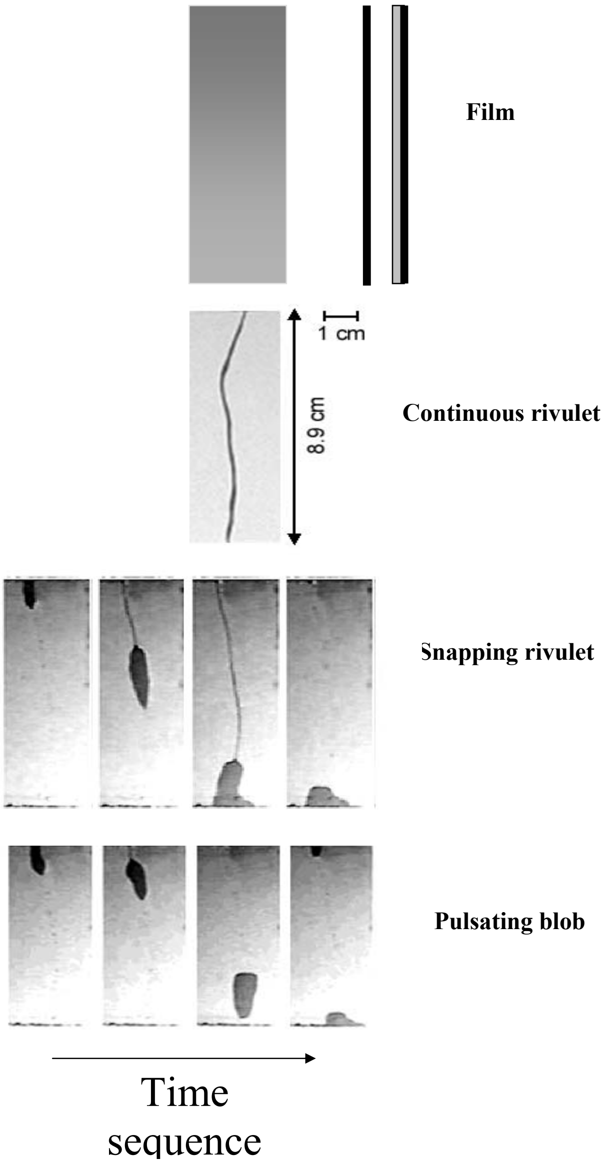

Fig. 4. Illustration of four modes of flow in a parallel-plate macropore. Adapted from Su et al. (1999).

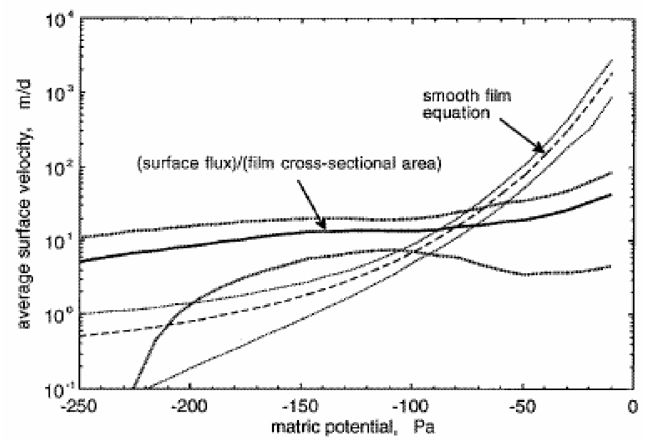

Fig. 5. Average film velocities on the face of a block of tuff, calculated from measurements and from laminar flow theory, as a function of matric potential of the medium. The four curves in addition to the two principal curves indicate the range of uncertainty. From Tokunaga and Wan (1997).

3.2 Response of flow rate to hydraulic perturbation

Distinction among these four flow modes is useful in understanding rates of macropore flow; the different processes respond differently to flow rate influences. Of most interest is how they behave in response to perturbations that would affect flow rate, the main issue being whether the magnitude of change in flow rate is greater or less than would be predicted by traditionally applied concepts such as Darcy's law. A straightforward example is the issue of what happens to flux when driving force changes.

Su et al. (2003) showed with experiments in artificial fractures in a sandstone that, even in isolated fractures, film flow on the inside walls of fractures can be a significant fraction of total flow through the medium. Because for all fracture apertures greater than a certain size film flow is independent of the aperture, the aperture size distribution of the medium is not very important to this flow mode. This is one way in which flow in macropores can depend less on the particular medium than is expected for unsaturated flow in general.

Tokunaga and Wan (1997) investigated the behavior and flow rates of water in films, 2 to 70 µm thick, on the surface of an unsaturated block of porous tuff. Reduction of the matric potential reduced the estimated film thickness and its flow rate. Figure 5 shows some of their measured flow rates, compared with predictions from laminar flow theory based on the estimated film thickness as a function of matric potential. The measured flow rates vary with film thickness much less than the theory predicts, another way in which water flowing in macropores can be relatively insensitive to hydraulic perturbations.

Su et al. (2001) measured solute transport for the flow modes identified by Su et al. (1999), at constant imposed flow rate but various driving forces. Figure 6 shows some results. Given that the imposed water flow rate was the same for each curve in a single graph, an initial expectation for convective solute transport would be for little or no variation in solute travel time with the different amounts of force.

Table 2. Categorization of possible flow modes in an unsaturated fracture

	Continuity	**Name**	**Characteristic behavior**
Non-bridged	Any	Film flow	Flowing liquid clings to a wall.
Bridged	Always	Continuous Rivulet	Stream of liquid clings to both walls.
	Sometimes	Snapping Rivulet	Cyclic; connected during part of cycle.
	Never	Pulsating Blob	Cyclic; bridged water never connects.

The results, however, differ markedly in travel time, showing that the three flow modes examined here do not behave as expected from the most basic conceptualizations. Especially noteworthy is the case of snapping rivulet flow, in which transport rates are actually greater for smaller driving forces. This is probably related to the observation of Su et al. (1999, *Figure 11*) that during the fastest-movement phase of snapping rivulet flow, travel velocities are as great or greater for the case of smaller driving force. In an unsaturated zone where some or all of these flow modes are occurring, it is hard to predict the effect of a perturbation in driving force, but it is clear that the net result can be dominated by phenomena outside the framework of Darcian flow.

4. Discussion

4.1. Compensating mechanisms

Considerable field and lab evidence suggests that flow in unsaturated macropores does not show the conventional dependences on characteristics and conditions of the medium or on driving force. Much of the evidence suggests that the variability of fluxes in unsaturated macropores may be considerably less than accepted unsaturated flow theory predicts. Thus there is evidence that certain mechanisms, not necessarily evident in micropore flow or in saturated macropore flow, are active in unsaturated macropore flow that compensate for the effects of such influences as fracture aperture or magnitude of driving force.

It is possible that mechanisms of this sort depend much on the character of air-water interfaces in the unsaturated macropore. One feature of likely importance is the degree to which these interfaces are pliant, that is how much they are free to change shape or position in response to a change in force or flow rate. This contrasts with rigid interfaces constrained to a particular shape and position, typically by capillary or adsorptive forces. Where interfaces are rigid, the fixed geometry of the effective flow conduits can lead to Darcian flow.

For film flow, specifically thick (> 2 μm) film flow (Tokunaga et al., 2000), pliant interfaces should be expected. The film has a thickness sufficient that preferential flow occurs in response to gravity (Tokunaga and Wan, 2001); conductance and flow rate increase with film thickness. If there were an increase in the effective force of gravity, water would be drawn faster down the wall of the macropore, and the film would become thinner. The film, then being a thinner flow channel, would be less conductive. This reduction in conductance would partially compensate for the increase in applied force, causing the variation in flow to be less than proportionate to the variation in force. The resulting behavior might be as seen in Fig. 5, where the measured speed of transport varies less than predicted by theory.

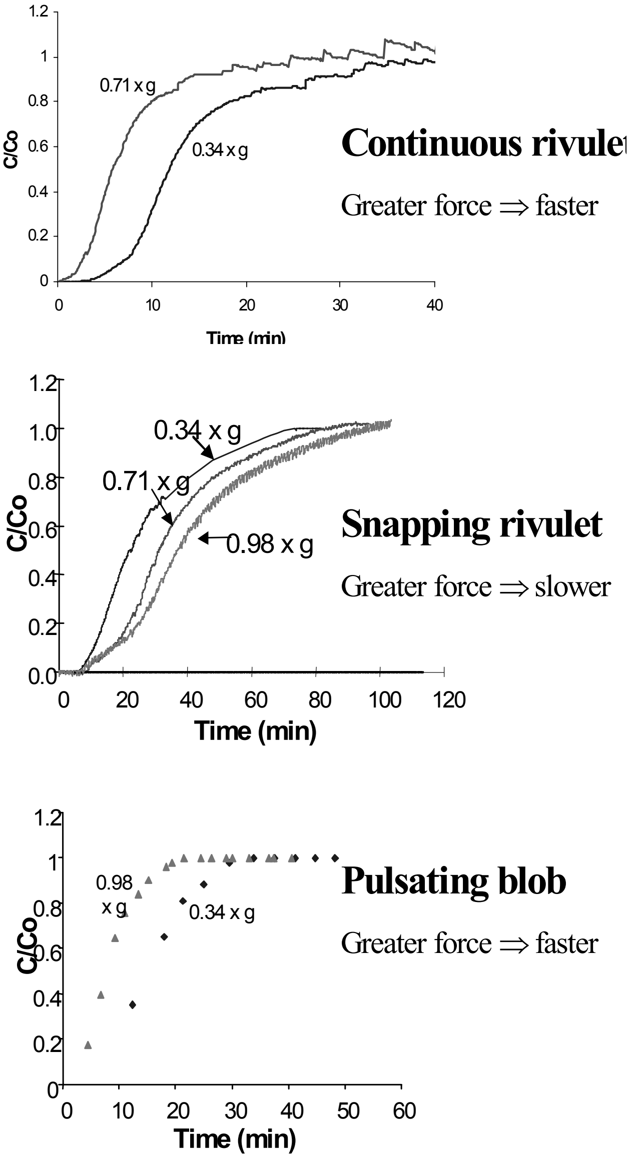

Fig. 6. Breakthrough curves for solute transport during various modes of unsaturated flow through an artificial parallel-plate macropore. Driving forces, indicated as a fraction of normal earth gravity, were varied by adjusting the tilt of the parallel-plate apparatus. The imposed flow rate was the same for each tilt angle, 5 ml/hr for the experiments with continuous rivulet and pulsating blob flow, and 3 ml/hr for those with snapping rivulet flow. Adapted from Su et al. (2001).

In the other flow modes described above, some of the air-water interfaces are likely to be pliant. Each flow mode should have its own characteristic relation between force and flow rate. In general, a pliant interface, being free to change, would be likely to respond in ways that oppose an applied change, leading to a less-than-proportional increase in flux for an increase in force. In continuous rivulet flow, the width of the rivulet could change like a thick film, with similar effect. Another example is that in snapping rivulet or pulsating blob flow, smaller blobs that might result from greater force would likely experience more friction per volume of water.

Other phenomena may also limit the variation of macropore flow rate. One example is that fracture intersections or other features of macropore connectedness may have effects that are independent of aperture size. Another is that macropores with greater flow rate may have more sedimentary material transported into them, with a limiting effect on flow rate.

The net effect of active compensating mechanisms would be to cause the effective unsaturated hydraulic conductivity of the medium to decrease with increasing force, and thus to make the flux more constant. For the field experiments summarized in Figure 3, this might explain why measured speeds of transport vary less than would the traditional hydraulic properties of the diverse media.

4.1 Practical application

If there are flow mechanisms that in some degree counteract the effect of a variation in conditions, this is potentially a very useful result for the prediction of contaminant first-arrival times. It may also indicate an effective speed limit on water travel time, dependent mostly on properties of water and the earth itself. Under common conditions that favor preferential flow with a continuous supply of water, a useful rule of thumb might be to assume that v_{max} falls between about 1 and 100 m/day. In the field experiments with such conditions, with water applied in effect continuously over a two-dimensional space (that is, considering in Figure 3 the solid point symbols except for the v_{max} of 0.3 m/d measured with a one-dimensional line source), if one had assumed a constant maximum transport speed of 10 m/d, the error would have been at most a factor of 10. Whether or not such a rule of thumb can be successfully applied, the net effect on unsaturated flow in a macroporous medium is that flow behavior is probably less sensitive to unknown conditions than is Darcian flow, thus making it easier to predict.

5. Conclusions

Field evidence shows a significant dependence of preferential flow on water input conditions, particularly whether the supply is continuous or intermittent. On the other hand, soil type, pore size (apart from the fact that there must be pores that permit preferential flow), grain size, and other medium-dependent properties may be less important than is usually thought. Diverse media, for example surface soils and thick layers of fractured rock, clearly have pores of different character but these differences may not be strongly relevant to the travel time of initial convective transport. Experiments show no clear trend of maximum flow rate with distance spanned by the test, evidence which favors a simple scalability of preferential flow.

There is experimental support for the occurrence during macropore flow of compensating mechanisms that may be responsible for the small degree of variation observed in the field. Some of these flow modes involve air-water interfaces that are pliant, meaning their shape and position can adjust in ways that tend to compensate for imposed changes that by themselves would increase flux. This may explain the field and lab observations of unsaturated-zone flow velocities that seem to be independent of scale and minimally dependent on medium. These results are encouraging for the development of models that may represent preferential flow more realistically, and that may be effective at all scales. Such models would likely require a framework that goes beyond the Darcy-Richards formulation, perhaps with a characteristic rate of travel that does not depend on the medium, for at least some of the flow.

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