Simple predictions of maximum transport rate in unsaturated soil and rock

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[1] In contrast with the extreme variability expected for water and contaminant fluxes in the unsaturated zone, evidence from 64 field tests of preferential flow indicates that the maximum transport speed V_{max}, adjusted for episodicity of infiltration, deviates little from a geometric mean of 13 m/d. A model based on constant-speed travel during infiltration pulses of actual or estimated duration can predict V_{max} with approximate order-of-magnitude accuracy, irrespective of medium or travel distance, thereby facilitating such problems as the prediction of worst-case contaminant traveltimes. The lesser variability suggests that preferential flow is subject to rate-limiting mechanisms analogous to those that impose a terminal velocity on objects in free fall and to rate-compensating mechanisms analogous to Le Chatlier's principle. A critical feature allowing such mechanisms to dominate may be the presence of interfacial boundaries confined by neither solid material nor capillary forces.

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1. Introduction

[2] Prediction of the transport rates of water and other substances within the unsaturated zone is critical to infiltration and runoff, erosion, plant growth, microbiota, contaminant transport, aquifer recharge, and discharge to surface water. Unsaturated-zone flow is fundamentally complicated by nonlinearity and hysteresis of unsaturated hydraulic properties and extreme sensitivity to materials and hydraulic conditions. In recent decades, it has become increasingly clear that much unsaturated-zone transport of importance, especially when water is abundant, occurs through a small fraction of the medium along preferential paths such as wormholes, fractures, fingers of enhanced wetness, and regions near contacts between dissimilar portions of the medium. This flow, for which accepted theory applies less well, occurs at rates typically some orders of magnitude faster than flow through the remainder of the medium. In many applications, its importance is redoubled because preferentially transported substances are exposed to only a small fraction of the soil or rock and only for limited time, reducing opportunity for adsorption or reactions.

[3] Different modes of preferential flow have been recognized, distinguished by the mechanisms that make it physically or conceptually distinct from nonpreferential or matrix flow. Three categories, macropore, fingered, and funneled flow, are often designated for this purpose [*Jarvis*, 1998]. A given flow problem may involve any single one or any combination of these categories. Some quantitative models are derived for only one category, though one model may be used for a broader variety of cases than it was conceptualized for. Fingered flow, for example, may be treatable with a model based on macropore concepts; the mathematical formulation may be applicable even though the underlying conceptualization is intuitively less appropriate. A finger comprising many wetted micropores is not the same thing as a filled macropore, but several important characteristics (elongation, high conductance, etc.) are common to both. The model presented here treats all preferential flow modes in combination without distinguishing among them.

[4] Diverse approaches have been used to quantify and predict preferential flow [*Šimunek et al.*, 2003]. One of the most basic is simply to apply to preferential flow the diffuse continuum approach embodied in the Richards equation as typically applied to matrix flow [*Philip*, 1968b; *Othmer et al.*, 1991]. In effect, such an approach uses effective unsaturated hydraulic properties considered to represent characteristics of both the preferential and matrix domains. Mathematically, the water-retention and unsaturated hydraulic conductivity properties may be represented by a sum of functions [*Peters and Klavetter*, 1988; *Durner*, 1994; *Zurmühl and Durner*, 1996] or by formulas otherwise modified to represent the effects of preferential flow [*Liu and Bodvarsson*, 2001]. A variation is to apply the diffuse continuum approach for only that fraction of the total macroporosity that is active, that is, filled and connected in a way that allows throughflow [*Philip*, 1968a; *Liu et al.*, 1998].

[5] It is also a common practice to treat preferential flow differently from nonpreferential flow, often in combination with a standard Richards equation formulation for the matrix flow. Preferential flow may be taken to obey basic fluid dynamics relations through conduits of a particular geometry [*Childs*, 1969, pp. 194–197; *Jury and Horton*, 2004, pp. 139–141]. In general, this includes the possibility of turbulent flow [*Chen and Wagenet*, 1992; *Logsdon*, 1995], but usually, laminar flow is assumed. An example is the calculation of preferential flow by Poiseuille's law [*Ahuja et al.*, 1993] with the assumption that macropores

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behave as tubes. Another common choice is a cubic-law representation [*Wang and Narasimhan*, 1985], assuming macropores behave as parallel plates. Different conduit shapes may be applied in combination [*Beven and Germann*, 1981]. Another alternative is to assume that flow through macropores occurs with a perfectly sharp wetting front [*Philip*, 1968b], similar to the mode of flow described by *Green and Ampt* [1911]. Usually, such conduits are considered in terms of averages or effective continuum behavior, although *Pruess* [1999] has argued that discrete conduits must be considered more independently because spatial and temporal averages are inappropriate for widely spaced and erratically flowing macropores, which can cause flow to be faster even when a medium's average hydraulic conductivity is lower.

[6] Much attention has been given to "nonequilibrium" models, on the assumption that preferential flow is so fast that its water does not have time to equilibrate (in terms of pressure, chemical composition, temperature, etc.) with water in the adjacent matrix material [*Skopp*, 1981; *Jarvis*, 1998]. The relation between the preferential and matrix pore domains is a major concern mainly because it affects the distribution of solutes within the medium, though in some respects this relation also affects the basic preferential flow rate. A way of treating nonequilibrium effects on flow rate is to implement the Richards equation with the assumption that water retention relations at a point in the medium may deviate from their pressure/water content equilibration relationship for a finite time after a change in matric pressure at that point [*Ross and Smettem*, 2000]. In general, where the two domains are not assumed to be in equilibrium, there are many means of describing the transfer of water from preferential to matrix domains, for example, a radially symmetric Green-Ampt approach [*Beven and Clarke*, 1986].

[7] Other ways of treating preferential flow apart from matrix flow do not make use of concepts of Darcian flow or laminar flow in conduits. One is to use a kinematic wave formulation [e.g., *Germann and DiPietro*, 1996], in which the flux density is taken directly to be a function of the water content, as opposed to the solution of an equation with explicit potential gradients. Another way of avoiding the Darcy-Richards formulation is to use a stochastic transfer function [*Jury*, 1982], which works with probability distributions of the transported substance and characterizes the medium with a function that implicitly incorporates all processes that affect those probability distributions. Although intended for nonequilibrium flow [*Jury and Roth*, 1990], transfer functions can be used for the effects of preferential and matrix flow together.

[8] Various approaches have been developed that involve a combination of processes to represent preferential flow, either by itself or together with matrix flow. Typically, these involve some sort of capacity or threshold that must be exceeded to cause preferential flow. The model of *Steenhuis et al.* [1994] considers preferential flow in terms of a release of water from a "mixing layer" in the uppermost part of the soil. The tipping-bucket model [*Emerman*, 1995] implicitly assumes that all of the water flows through macropores at a rate which is proportional to the water content of the macropores and that macropore flow occurs only after the micropores have been saturated. The layer-capacity model of *Weiler* [2005] takes into account the influence of the preferential-flow initiation process on the dynamic preferential/matrix flow process, incorporating the approach of *Beven and Clarke* [1986] for transfer of water from the preferential to the matrix domain.

[9] Models developed for unstable flow [e.g., *Hill and Parlange*, 1972; *Hillel and Baker*, 1988; *Selker et al.*, 1992; *Jury et al.*, 2003] have demonstrated significant successes in predicting fingered-flow characteristics such as the number, diameter, and velocity of fingers, as well as the conditions under which fingers will be generated. Evidence suggests that Darcy's law and Richards' equation may be applicable to flow within wetted fingers that are generated by instabilities. *Selker et al.* [1996] proposed a simple model in which the transport velocity in fingered flow can easily approach, but not exceed, a value given by dividing saturated hydraulic conductivity by the effective saturated water content.

[10] The general range of preferential flow rate variability for different sites and conditions has not been widely emphasized in hydrologic literature but can be estimated from typical ranges of saturated hydraulic conductivity K_{sat}. *Heath* [1983] notes a 12 order-of-magnitude range in K_{sat} for common geologic materials. Dividing K_{sat} by the effective porosity of the medium gives a transport speed V. Assuming typical K_{sat} values [*Klute and Dirksen*, 1986] and a typical effective porosity of 40%, V would range from about 10^{-6} m/s in sands to 10^{-1} m/s in coarse gravel. Alternatively considering macropore flow as gravity-driven Poiseuille flow in tubes [*Jury and Horton*, 2004] that vary in radius from 0.5 to 10 mm, transport speeds would range from 0.3 to 120 m/s. These estimates suggest the speed of preferential flow might fall within about an eight order-of-magnitude range.

[11] This study aims to identify factors most relevant to transport rates in direct field observations of preferential flow and to generalize concerning the prediction of transport rate when preferential flow occurs. The chief focus for predictions is the speed of the fastest portion of the flow, V_{max}, defined as distance traveled divided by the first arrival time of a tracer. Advantages of this choice are that V_{max} has direct practical importance (e.g., for worst-case contaminant traveltimes), is a better signifier of preferential flow than intrinsically averaged quantities, and can be determined from many published studies whether or not preferential flow was originally emphasized. This paper presents (1) published evidence from 64 diverse field tests indicating that the maximum transport speed during preferential flow varies within a smaller range than during other forms of unsaturated flow and (2) a simple episodicity-adjusting model requiring only basic infiltration data that can predict maximum flow rates when preferential flow is dominant.

2. Data From Field Observations

[12] Measured V_{max} values were compiled from the soil science and hydrologic literature. The criteria for inclusion were that the studies must be field tracer experiments in the unsaturated zone, the occurrence of preferential flow must either be obvious or adduced by the original investigators, modes of sampling must be sensitive to preferential flow, traveltime and distance must be adequately identifiable to calculate V_{max}, and it must be reasonable to assume that tracer moved the entire distance, as opposed to there being a preexisting parcel of the same substance pushed ahead to the detection point. All studies found to meet these criteria

Table 1. Studies and Data Used in Formulating Generalizations of the Maximum Speed of Preferential Transport in the Unsaturated Zone

Site and Investigation	Medium	Surface Conditions	Tracer	Means of Sampling	Total Infiltration Since Application of Tracer, m	Ratio of Input Duration to Travel Duration	Transport Distance, m	V_{max}, m/d
Idaho National Laboratory (INL) (Horizontal) [*Nimmo et al.*, 2002]	Basalts, sediments	Ponded	Naphthalene disulfonate	Piezometer in perched water		1.00	1300	26
INL (Horizontal) ([*Robertson et al.*, 1974, p. 99], cited by [*Orr*, 1999, p. 17])	Basalts, sediments	Ponded	Water pulse	Piezometer in perched water		1.00	670	9.6
Yucca Mountain [*Fabryka-Martin et al.*, 1997]	Welded and nonwelded tuff	Arid climate, 170 mm/yr	^{36}C1	Extracted from rock samples	4.2		300	0.03
INL (Vertical) [*Nimmo et al.*, 2002]	Basalts, sediments	Ponded	Naphthalene disulfonate	Piezometer in aquifer		1.00	200	25
Apache Leap, AZ [*Davidson et al.*, 1998]	Partially welded tuff	Semiarid climate, 370 mm/yr	^{14}C	Extracted from core samples	9.2		130	0.01
Los Alamos Canyon, NM [*Levitt et al.*, 2005]	Variously fractured basalts	Ponded, probably for about 4 d		Sampling port in well in perched water		0.36	78.4	7.1
Los Alamos Canyon, NM [*Levitt et al.*, 2005]	Variously fractured basalts	Ponded, probably for about 4 d		Sampling port in well in perched water		0.36	55.5	5.0
INL (solute) [*Dunnivant et al.*, 1998]	Basalts, sediments	Ponded	^{75}Se	Piezometer in perched water		1.00	55	3.7
INL (wetting front) [*Dunnivant et al.*, 1998]	Basalts, sediments	Ponded	Wetting front	Neutron detection of water		1.00	55	5
Yucca Mountain [*Yang*, 1992]	Fractured tuff	Arid climate, 170 mm/yr	^{3}H	Core	3.6		47	0.006
Los Alamos Canyon, NM [*Levitt et al.*, 2005]	Variously fractured basalts	Ponded, probably for about 4 d		Sampling port in well in perched water		0.57	46.4	6.6
Hanford Site, WA [*Pruess and Yabusaki*, 2002]	Sandy alluvium	Leaking tank	Uranium	Well		1.00	37	1.8
Yucca Mountain [*Yang*, 1992]	Welded and nonwelded tuff	Arid climate, 170 mm/yr	^{3}H	Core	3.6		32	0.004
Nevada Test Site [*Bryant*, 1992]	Sandy alluvium	Ponded in ditch	Bromide	Suction sampler		1.00	30	0.3
Los Alamos Canyon, NM [*Levitt et al.*, 2005]	Variously fractured basalts	Ponded, probably for about 4 d		Sampling port in well in perched water		0.50	23.5	2.9
Yucca Mountain [*Salve*, 2005]	Fractured welded tuff	Ponded on floor of test bed	Wetting front	Electrical resistance sensors		1.00	22	1.7
Yucca Mountain [*Salve et al.*, 2005]	Fractured welded tuff	Ponded along fault	Pentafluorobenzoic acid (PFBA) and Bromide	Collection sampler		1.00	20	2.0
Yucca Mountain [*Salve et al.*, 2005]	Fractured welded tuff	Ponded along fault	Wetting front	Electrical resistance sensors		1.00	19	0.6
Darling Range, Australia [*Johnston*, 1987]	Coarse soil	Rain, 102 mm over about 12 hr	Water pulse	Piezometer	0.102	1.00	15	30
Box Canyon, ID [*Faybishenko et al.*, 2000]	Fractured basalt	Ponded	Water pulse	Suction sampler		1.00	12	6
Box Canyon, ID [*Faybishenko et al.*, 2000]	Fractured basalt	Ponded 46% of the time	Bromide	Suction sampler		0.46	10.1	1.1
Box Canyon, ID [*Faybishenko et al.*, 2000]	Fractured basalt	Ponded	Water pulse	Suction sampler		1.00	7	7
Princeton, MN [*Komor and Emerson*, 1994]	Loamy fine sand	Sprinkler irrigation, about 30 mm	Atrazine; bromide	Piezometer	0.03		4.6	38
Etiwanda, CA [*Butters et al.*, 1989]	Loamy sand	Sprinkler irrigation, 9.1 mm/d	Bromide	Suction samplers	0.26		4.5	0.16

Table 1. (continued)

Site and Investigation	Medium	Surface Conditions	Tracer	Means of Sampling	Total Infiltration Since Application of Tracer, m	Ratio of Input Duration to Travel Duration	Transport Distance, m	V_{max}, m/d
Fran Ridge, NV [*Glass et al.*, 2002]	Fractured welded tuff	Ponded ~4 cm deep, 23 cm of water in 36 min	Water pulse	Electrical resistance tomography	0.07	1.00	3.5	390
Etiwanda, CA [*Butters et al.*, 1989]	Loamy sand	Sprinkler irrigation, 9.1 mm/d	Bromide	Suction samplers	0.26		3	0.10
Hauerseter Delta, Norway (18-O) [*Swensen*, 1997]	Sandy soil with gravel	Rain + melting snow, ~11 mm/d	^{18}O	Suction samplers	0.19		2.2	0.13
Hauerseter Delta, Norway (Cl-) [*Swensen*, 1997]	Sandy soil with gravel	Rain + melting snow, ~11 mm/d	Chloride	Suction samplers	0.29		2.2	0.08
Lanna, Sweden [*Larsson and Jarvis*, 1999]	No-till soil	Combination, ~2 mm/d	Bromide	Piezometer	0.04		2	0.10
Etiwanda, CA [*Jury et al.*, 1982]	Loamy sand	Rain, 210 mm	Bromide	Suction samplers	0.21		1.8	0.05
Etiwanda, CA [*Butters et al.*, 1989]	Loamy sand	Sprinkler irrigation, 9.1 mm/d	Bromide	Suction samplers	0.11		1.8	0.16
Great Bend Prairie, KS [*Sophocleous et al.*, 1990]	Sandy soil	Ponded for ~.8 d	Bromide	Suction sampler		0.60	1.8	1.4
Yucca Mountain [*Hu et al.*, 2001]	Fractured welded tuff (Alcove 6)	One-dimensional horizontal borehole injection	Water pulse	Observation of wetting front arrival		1.00	1.6	480
Box Canyon, ID [*Faybishenko et al.*, 2000]	Fractured basalt	Ponded	Bromide	Suction sampler		1.00	1.5	1.9
Great Bend Prairie, KS [*Sophocleous et al.*, 1990]	Silt and clay loam	Ponded for ~1 d	Bromide	Suction sampler		0.40	1.5	0.60
Woodburn, IN [*Bottcher et al.*, 1981]	Silty clay	Semihumid climate, 60 mm rain in the 4 d	Ammonia and phosphorus	Tile drain	0.06		1.5	0.43
Etiwanda, CA [*Jury et al.*, 1982]	Loamy sand	Rain, 150 mm	Bromide	Suction samplers	0.15		1.2	0.04
Etiwanda, CA [*Butters et al.*, 1989]	Loamy sand	Sprinkler irrigation, 9.1 mm/d	Bromide	Suction samplers	0.09		1.2	0.13
INL [*Nimmo et al.*, 1999]	Undisturbed soil	Ponded	Water pulse	Neutron detection of water		1.00	1.2	31
Ames, IA [*Jaynes et al.*, 2001]	No-till loam	Sprinkler irrigation, 4 mm/hr	Bromide	Tile drain	0.0064	1.00	1.2	18
Ames, IA [*Jaynes et al.*, 2001]	No-till loam	Sprinkler irrigation, 4 mm/hr	Benzoic acids	Tile drain	0.0018	1.00	1.2	60
Syv Creek Catchment, Denmark (Plot 2) [*Villholth et al.*, 1998]	Tilled silty to sandy loam	Irrigation, 9.4 mm in the 134 min until solute breakthrough	Chloride	Tile drain	0.0094	1.00	1.2	13
Syv Creek Catchment, Denmark (Plot 3) [*Villholth et al.*, 1998]	Tilled silty to sandy loam	Rain, 3.3 mm in the 26 min until solute breakthrough	Chloride	Tile drain	0.0033	1.00	1.2	66
Ames, IA [*Everts and Kanwar*, 1990]	Tilled loam	Sprinkler irrigation, 8 mm/hr avg	Bromide, nitrate	Tile drain	0.0037	1.00	1.1	56
Yucca Mountain [*Salve and Oldenburg*, 2001]	Fractured nonwelded tuff	One-dimensional horizontal borehole injection, constant head	Water pulse	Electrical resistance sensor		1.00	1.07	9.2

Table 1. (continued)

Site and Investigation	Medium	Surface Conditions	Tracer	Means of Sampling	Total Infiltration Since Application of Tracer, m	Ratio of Input Duration to Travel Duration	Transport Distance, m	V_{max}, m/d
Hupselse Beek, Netherlands [*van Ommen et al.*, 1989]	Tilled soil	Humid climate, ~50 mm tracer travel	Bromide	Tile drain	0.05		1	0.07
Negev Desert, Israel (water pulse) [*Dahan et al.*, 1999]	Fracture in chalk	Ponded	Water pulse	In situ drainage samplers		1.00	1	50
Negev Desert, Israel (benzoic acid) [*Dahan et al.*, 1999]	Fracture in chalk	Ponded	Benzoic acids	In situ drainage samplers		1.00	1	22
Elkhorn, WI (4.4 mm/hr) [*Gish et al.*, 2004]	No-till silt loam	Sprinkler irrigation, 4.4 mm/hr	Bromide	Tile drain	0.0012	1.00	0.95	3.52
Elkhorn, WI (2.4 mm/hr) [*Kung et al.*, 2005]	No-till silt loam	Sprinkler irrigation, 2.4 mm/hr	PFBA	Tile drain	0.019	0.60	0.95	0.12
Elkhorn, WI (1.2 mm/hr) [*Kung et al.*, 2005]	No-till silt loam	Sprinkler irrigation, 1.2 mm/hr	PFBA	Tile drain	0.0168	0.30	0.95	0.07
Etiwanda, CA [*Butters et al.*, 1989]	Loamy sand	Sprinkler irrigation, 9.1 mm/d	Bromide	Suction samplers	0.07		0.9	0.12
Willsboro, NY ("First Pulse") [*Kung et al.*, 2000b]	No-till loam	Sprinkler irrigation, 7.5 mm/hr	Various solutes (second pulse)	Tile drain	0.0031	1.00	0.9	53
Willsboro, NY ("First Pulse") [*Kung et al.*, 2000b]	Tilled loam	Sprinkler irrigation, 5 mm/hr	Various solutes (second pulse)	Tile drain	0.0076	1.00	0.9	14
Willsboro, NY ("Second Pulse") [*Kung et al.*, 2000b]	No-till loam	Sprinkler irrigation, 7.5 mm/hr	Various solutes (first pulse)	Tile drain	0.0016	1.00	0.9	100
Willsboro, NY ("Second Pulse") [*Kung et al.*, 2000b]	Tilled loam	Sprinkler irrigation, 5 mm/hr	Various solutes (first pulse)	Tile drain	0.0011	1.00	0.9	100
Butlerville, IN [*Kung et al.*, 2000a]	No-till silt loam	Sprinkler irrigation, 2.9 mm/hr	Various solutes	Tile drain	0.0047	1.00	0.8	12
Willsboro, NY [*Richard and Steenhuis*, 1988]	No-till fine sandy loam	Precipitation, 2 mm/d avg.	Various agrichemicals	Tile drain	0.04		0.8	5.3
Willsboro, NY [*Steenhuis et al.*, 1997]	No-till fine sandy loam	Rain, 2.5 mm/hr avg.	Chloride	Tile drain	0.009	1.00	0.8	10
Butlerville, IN [*Kladivko et al.*, 1991]	No-till silt loam	Sprinkler irrigation, 7.1 mm/hr	Chloride	Tile drain	0.014	1.00	0.75	0.04
Hauerseter Delta, Norway (Cl-) [*Swensen*, 1997]	Sandy soil with gravel	Rain + melting snow, ~11 mm/d	Chloride	Suction samplers	0.143		0.7	0.05
Etiwanda, CA [*Butters et al.*, 1989]	Loamy sand	Sprinkler irrigation, 9.1 mm/d	Bromide	Suction samplers	0.055		0.6	0.10
North Wyke, Devon, UK [*Williams et al.*, 2003]	Stony loam	Sprinkler irrigation (5 mm/hr)	Chloride	Suction samplers	0.0073	1.00	0.5	8.3
Etiwanda, CA [*Butters et al.*, 1989]	Loamy sand	Sprinkler irrigation, 9.1 mm/d	Bromide	Suction samplers	0.022		0.3	0.13

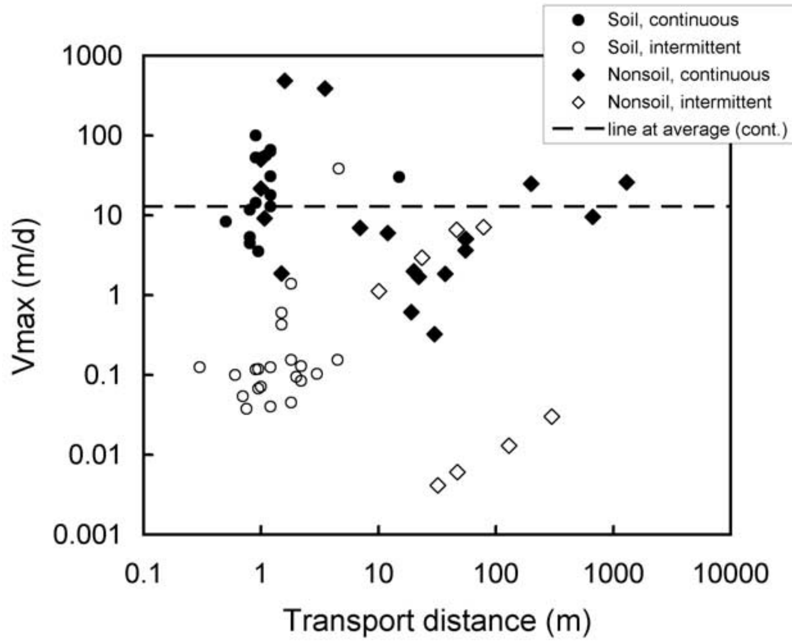

Figure 1. Observed maximum speed of transport in the case studies of unsaturated-zone preferential flow from Table 1. The continuous/intermittent distinction refers to whether or not water at land surface was supplied during the entire time of travel to the sampling point. The dashed line is at the V_{max} value of 13 m/d, the geometric mean for continuous-input cases.

were included. These studies were sought from the published literature with the conscious objective of finding a wide variety of media, scales, and other relevant features. I do not claim to have found all the relevant cases, a more exhaustive search would doubtless discover more studies meeting these criteria, but rather that the cases found constitute a reasonable basis on which to formulate generalizations that can be formally proposed for wider consideration and testing.

[13] Additional rules applied in determining traveltimes are (1) if there are replicates, as from repeated experiments in the same place, take the average first-arrival traveltime from the set of replicates; except that if the replicates are from a set of laterally spread out point samplers at the same depth, take the earliest, to simulate the result of a method that senses tracer over an area broader than the effective sampling area of a single sampler. (2) Where data indicate a time interval, rather than a point in time, of first arrival, use the midpoint of that interval. If the beginning time of the interval is unknown, take it to be 0 for purposes of averaging. (3) Use multiple cases from a single study if they differ in a significant way, for example in porous material or infiltration rate.

[14] Table 1 lists 64 V_{max} values compiled from 38 studies. The data span about five orders of magnitude, a range that is modest given the diversity of media and conditions. Figure 1 makes clear that certain factors show little or no trend, including spatial scale from 0.3 to 1300 m, and medium, categorized here as either soil or nonsoil porous material. Sampling method, including unsaturated-zone sampling using suction samplers, extracted cores, or excavation, as well as shallow saturated-zone sampling using wells, piezometers, or agriculturally functional tile drains, also showed no significant trend. Tracers included various solutes, radioisotopes, and wetting fronts; variation in the adsorptive character of tracers can often be negligible in preferential flow [*Kung et al.*, 2000b] and is not likely to significantly affect V_{max}.

[15] One factor that does make a significant difference is the temporal distribution of water input. Where input was continuously substantial in terms of volume flow rate per unit area, as from ponded conditions or continuous irrigation, V_{max} is distinctly greater and somewhat less variable than where it was intermittent, as from natural rainfall. The greater significance of the temporal distribution of water input, compared to other factors normally expected to influence V_{max}, is consistent with the pattern observed by *Nimmo* [2003] for a smaller data set. The values of geometric mean μ_g and geometric standard deviation σ_g in Table 2 also illustrate this observation. The interpretive significance of σ_g is that dividing or multiplying μ_g by σ_g designates confidence limits analogous to the additive confidence limits defined by an arithmetic standard deviation. Thus the range of one standard deviation from the mean would be 0.1 to 31 m/d (2.5 orders of magnitude) for the entire set of 64 V_{max} values, compared to 2.5 to 68 m/d (1.4 orders of magnitude) for the 34 continuous-input cases.

3. Quantitative Predictive Model

[16] For cases of continuous water input, these observations suggest use of a constant V_o as a simple prediction of the fastest traveltime:

$$V_{max-pred} = V_o \tag{1}$$

where V_o takes the value of μ_g for the continuous-input V_{max} values, 13 m/d based on the 34 relevant data in Table 1. If

Table 2. Summary Statistics for Maximum Transport Speed[a]

Quantity	Cases Considered	Number of Cases	Geometric Mean, m/d	Geometric Standard Deviation
V_{max}	All	64	1.8	17.3
V_{max}	Continuous input	34	12.9	5.3
V_{max}	Intermittent, I_{total} known	23	0.08	5.5
V_{max}	Intermittent, I_{total} not known	7	2.5	2.6
$V_{max\text{-}adj}$	Intermittent, I_{total} known	23	12.9	2.3

[a]The quantity $V_{max\text{-}adj}$ in the last row is computed using a value of $i_o = 30$ mm/hr, as explained in connection with equation (2).

V_{max} for this case is lognormally distributed, the geometric standard deviation of 5.3 for those 34 data suggests a 90% probability that a V_{max} measured under comparable conditions would fall between 0.8 and 200 m/d.

[17] For cases of intermittent water input, a pulsed-transport concept can extend this generalization. Assumptions are that input occurs in hypothetical pulses during which the tracer's speed is constant and between which it is negligible, and that input during the pulses occurs at a universal effective rate i_o that produces the tracer speed V_o. Input here is quantified as all the water put onto the land surface, equivalent to total infiltration if runoff is negligible; this permits direct use of precipitation or irrigation data given as volume per unit area. If, for a given case, the total amount of water input I_{total} during the transport process from time 0 to t_f is known, the total effective duration t_p of pulses during that time equals I_{total}/i_o. The predicted V_{max} for that case is

$$V_{max-pred} = V_o \frac{t_p}{t_f} = V_o \frac{i_{avg}}{i_o} \qquad (2)$$

where i_{avg} is the actual average input rate, I_{total}/t_f.

[18] The value of i_o, like V_o, is to be inferred from data. Because the ratio i_{avg}/i_o scales V_o to give a predicted V_{max}, its inverse i_o/i_{avg} can scale a measured V_{max} to give an adjusted value V_{adj} which would equal V_o if the value chosen for i_o is right for that case. Using the 23 cases from Table 1 in which the water input is intermittent and I_{total} known, an optimized i_o value of 0.73 m/d (30 mm/hr) predicts V_{adj} values such that their geometric mean equals the 13 m/d value of V_o for the continuous-input cases. These V_{adj} values cluster more tightly ($\sigma_g = 2.3$) than the original V_{max} values ($\sigma_g = 5.5$), supporting the usefulness of this pulsed-transport concept.

[19] In some intermittent cases, I_{total} is not known, but the total duration t_{in} of input is known, for example when ponding persists for a known time. Assuming then that input proceeds at rate i_o during t_{in}, the pulsed-transport model indicates

$$V_{max-pred} = V_o \left[\frac{t_{in}}{t_f}\right]. \qquad (3)$$

Equations (1), (2), and (3) together represent a predictive model for V_{max} for continuous input and for intermittent input if either I_{total} or t_{in} is known.

4. Discussion

4.1. Evaluation of Results and Testing

[20] Figure 2 shows that for the full set of 64 cases in Table 1, about 85% of the V_{max} values predicted using equations (1), (2), and (3) fall within one order of magnitude of the measurements. This comparison suggests that this model, which requires elementary data about water input conditions but no information about the medium or its moisture state, might approach order-of-magnitude accuracy in predicting minimum traveltimes.

[21] Because in many applications order-of-magnitude accuracy would be a loose criterion for a quantitative scientific model, it is worth considering what uncertainty is tolerable or achievable for the specific task of unsaturated-zone traveltime prediction. This issue has been too seldom addressed; *Corwin et al.* [1999] note that a field confirmation is attempted for only about half of published models of unsaturated zone solute transport, and most such attempts are not done at the scale of relevance to the practical prediction problem. In applications that require predictions over times as long as thousands of years, if such predictions are based on a deterministic quantitative model, it is impossible to directly test that model within the duration of a practical scientific study. Comparisons of model predictions among themselves sometimes show a large range of variation. One example is the range of 3.5 orders of magnitude in traveltime-to-aquifer predictions among models developed for the Idaho National Laboratory between 1966 and 1998 [*National Research Council*, 2000, p. 30]. Given this general situation for predictive applications, a prediction made with order-of-magnitude confidence can be of value.

[22] The particular values that the Table 1 data suggest for the predictive model parameters are consistent with their physical interpretation. The V_o value of 13 m/d is within a range typical of preferential flow. The i_o value of 30 mm/hr is comparable to heavy rainfall or irrigation. Note that i_o is based on data for water input at the surface; if the model had been developed based on data for infiltration less evapotranspiration or for estimated downward percolation fluxes, a smaller i_o would result. The total water input rate has the advantage of being known in more cases and with greater accuracy.

[23] The proposition that a 13 m/d V_o value is somehow representative of continuous-infiltration preferential flow requires explication. The deviation of a measured V_{max} from 13 m/d does not imply a degree of error in that measurement. The implication rather is that, assuming a lognormal distribution, V_{max} for different sites would tend to fall within a range centered logarithmically on 13 m/d. As noted above, for the data assembled here, the 90% probability range would be 0.8 to 200 m/d. The quantification of such a range is empirical, but the range itself may be hypothesized to relate to basic properties of the unsaturated zone system such as fluid viscosity and density, surface

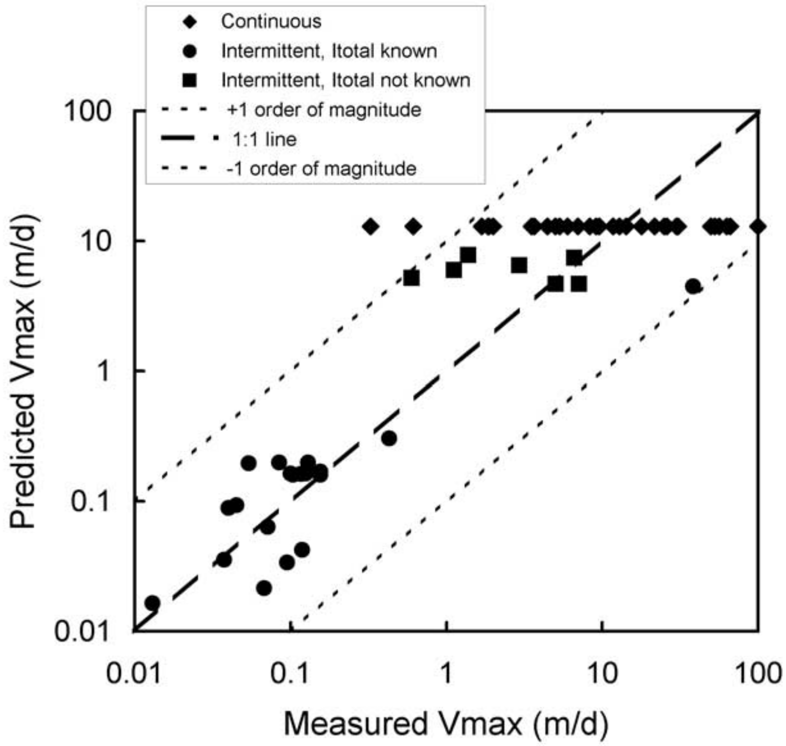

Figure 2. For the 64 listings in Table 1, predicted versus measured maximum transport speed of preferential flow in the unsaturated zone based on the model of uniform speed during periods of water input. Dotted lines mark the bounds of order-of-magnitude agreement.

tension, and the acceleration of gravity. The value of V_o could perhaps be scaled with some properties of this sort, though probably not in a linear way.

[24] Applied to a site where transport data are not available, this model should not be interpreted as predicting in all situations the arrival of transported substance at depth L in time $L/V_{max\text{-}pred}$, where $V_{max\text{-}pred}$ is computed by the appropriate choice of equations (1), (2), and (3). Rather, it indicates that if conditions the model is based on apply, in particular that between the points of tracer injection and sampling are one or more preferential flow paths through unsaturated material, $L/V_{max\text{-}pred}$ predicts an approximate first arrival time of the tracer. The fact of tracer arrival does not guarantee that its concentration will exceed any specific threshold, especially because the model says nothing about the amount of water (or tracer in it) that is preferentially transported in the given time; if some small amount of tracer has traveled the full distance through preferential flow paths, there might not be enough of it present to register above the detection threshold. This situation might commonly occur with samples taken from below the water table, as there can be substantial dilution of the tracer once it is mixed into the water resident in the saturated zone. These considerations also suggest that nondetections must be interpreted cautiously with respect to this model and are not necessarily appropriate for tests of its general applicability.

[25] Because relatively few data are available, all were used to optimize the values of V_o and i_o, precluding independent testing until there are additional data. Further testing is essential for this reason and also because the data set with which the model was developed likely has significant biases. Owing to motivations to investigate extreme or clear-cut situations, published studies may overrepresent cases with greater than average rates or prevalence of preferential flow. Yet the 38 studies represented cover diverse investigator objectives as well as sites and conditions, so it is likely that within at least some category of preferential flow problems, a relatively uniform maximum speed dominates over a diversity of other factors.

4.2. Implications for Unsaturated Flow Theory

[26] The minimal observed variability in V_{max} counters the conventional paradigms of unsaturated-zone hydrology. Because preferential flow entails many diverse processes, a universal explanation is elusive, though some relevant flow behaviors may be illustrated by considering hypothetical perturbations that would be expected to alter V_{max}: (1) For processes of fingered flow, i.e., preferential flow through a narrow contiguous network of essentially saturated micropores, increased flow rate can change the number or diameter of fingers without changing the transport speed through the fingers themselves. (2) For a system of preferential pathways operating at less than its full flow capacity, an increase in flow can be accommodated by using a larger fraction of the system's capacity, e.g., filling some of the macropores that were unfilled at lower flow rates, without significantly increasing the speed of travel through any active pathway. (3) For a preferential flow process that dynamically generates detached mobile blobs [*Su et al.*, 1999], increased flow rate may create blobs more frequently but without changing the speed at which each travels once it has been created. (4) Alternatively, with unchanged flow

rate but increased driving force, say from changing the tilt of a fracture, a likely response would be the creation of smaller blobs with greater frequency. The smaller blobs would likely have a lower ratio of mass to viscous friction, slowing their travel and thus partially compensating for the increased force. (5) For thick-film (sheet) flow in macropores with constant inflow rate, increased driving force is likely to decrease the film thickness, increasing viscous friction per unit mass and again partially compensating for the greater force. Similar compensating mechanisms can be hypothesized for many other preferential flow processes, in general operating analogously to Lenz's law in electromagnetism or Le Chatlier's principle in chemistry: The response of a system to a perturbation acts in opposition to the perturbation's primary effect.

[27] The minimal variability can also be considered in terms of natural speed limits on preferential flow. The constant V_o may approximately indicate an upper speed limit that depends, as suggested above, on properties of water and the earth itself, such as viscosity and the acceleration of gravity. Various illustrative analogs support this idea. As an object falling through earth's atmosphere reaches a terminal velocity dictated by the balance of a velocity-dependent frictional force with the force of gravity, so might a parcel of water driven by gravity within a uniform macropore reach a maximum speed dependent on viscous friction. Because water has greater viscosity than air, this subsurface terminal velocity would be slower and more quickly approached than for the object in air. The rate of laminar flow in filled tubes varies much with tube diameter because within a large tube more of the fluid is at a greater distance from solid walls, thereby experiencing less friction; whereas in the movement of drops, rivulets, or sheets down the inner face of a fracture, all of the liquid may be within a small distance of the solid surface. The maximal thickness, perpendicular to the fracture face, of such a traveling water parcel would be largely determined by the properties of water and the nature of the solid surface, which vary less among media than does pore geometry. Processes that distinguish preferential from diffuse flow may create an effective lower limit to the speed of preferential flow. For example, where the soil matrix is absorbing water out of preferential flow in a macropore, if the preferential flow rate is below a certain speed, the water will be lost from the preferential channel before it travels significantly. Thus the speed of preferential flow may be limited on the lower end by processes that take the slower conceivable speeds out of the preferential category, while an upper limitation may result from processes analogous to the terminal velocity of an object falling in a fluid.

[28] Similar observations concerning limitations on the variability of transport speeds in preferential flow have been made before, especially for the case of fingered flow. *Kim et al.* [2005] found the solute velocity in fingered flow to be computable from the quotient of hydraulic conductivity and water content within a finger and thus to be "almost independent of the flow rate." Similarly, *Darnault et al.* [2004] found in fingered flow that flux increases caused the generation of more fingers without affecting the finger velocity, which depended only on soil properties.

[29] As to why a minimally variable V_{max} might be evidenced in preferential but not saturated or diffuse unsaturated flow, a likely critical distinction is the issue of a confined versus unconfined flow conduit. Considering in macropore flow the intrapore conduit to be the water-filled space bounded by solid or air, then unless the macropore is totally filled with water, preferential flow is free to adjust the dimensions of its conduit at the air-water interfaces, whereas saturated flow has its conduit constrained by solid boundaries, and unsaturated micropore flow has its conduit constrained by either solid boundaries or fixed-geometry capillary interfaces. This reasoning also suggests what might be an important distinguishing characteristic between micro- and macropores: A macropore could be defined as one in which at certain water contents there are air-water interfaces not geometrically constrained by capillarity. Also, worth noting is that whereas diffuse unsaturated flow may depend strongly on the connectedness and tortuosity of a sequence of filled micropores whose individual lengths in the direction of flow are not much greater than their effective diameters, preferential flow paths are composed of extended linear features and so may be less affected by these factors.

4.3. Practical use

[30] The model represented by equations (1), (2), and (3) potentially has great value in practical applications. For example, this model suggests the ratio V_o/i_o (empirically estimated to equal about 18) as an essentially universal constant that needs only to be multiplied by the infiltration or precipitation rate to give an estimate of maximum transport rate. The time of first arrival at the water table from a disposal or spill site at the land surface could be simply predicted as $L/V_{max\text{-}pred}$, where L is the distance of travel and $V_{max\text{-}pred}$ is from the appropriate choice of equations (1), (2), and (3).

[31] The data needed to predict V_{max} are essentially just the total amount of water applied during the time interval of interest or the fraction of that time that copious input is occurring. In the form of precipitation rates, irrigation schedules, or similar information, these are available for perhaps the great majority of cases of potential interest.

[32] In contaminant-transport and other applications, knowledge of V_{max} is useful even though it is not the only transport characteristic needed. It provides some answers directly, such as the earliest arrival time of a contaminant at a water table of known depth. In applications that require instead some type of average transport rate or the arrival time of a certain amount of transported substance, an estimate of V_{max} can be useful in other ways, especially in combination with other known facts or estimated quantities. For example, if the transport speed of the center of mass of a contaminant plume is known, the additional knowledge of V_{max} can help quantify large-scale dispersion as well.

5. Conclusions

[33] Evidence assembled here indicates that for certain types of rapid-transport situations, flow within the unsaturated zone is less variable and more easily predicted than previously thought. Preferential flow in the unsaturated zone is not as closely analogous to either saturated flow or diffuse unsaturated flow as implied in widespread approaches to it, for example the modeling of fractured rock as an equivalent granular medium. Having one or more boundaries confined by neither solid material nor capillary

forces, the streams, blobs, and fingers of preferential flow undergo transport by processes unique among subsurface flow phenomena, affording new and simplified approaches to hydrogeologic problems and requiring new theoretical treatments that are not currently active in hydrogeologic or porous-media research.

[34] The maximum speed of transport by preferential flow in the unsaturated zone, critical to contaminant transport and other problems, appears to vary far less with location and subsurface medium than do typical subsurface transport rates, such that it might be roughly predicted from easily determined infiltration conditions.

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