Effect of soil disturbance on recharging fluxes: case study on the Snake River Plain, Idaho National Laboratory, USA

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Abstract Soil structural disturbance influences the downward flow of water that percolates deep enough to become aquifer recharge. Data from identical experiments in an undisturbed silt-loam soil and in an adjacent simulated waste trench composed of the same soil material, but disturbed, included (1) laboratory- and field-measured unsaturated hydraulic properties and (2) field-measured transient water content profiles through 24 h of ponded infiltration and 75 d of redistribution. In undisturbed soil, wetting fronts were highly diffuse above 2 m depth, and did not go much deeper than 2 m. Darcian analysis suggests an average recharge rate less than 2 mm/year. In disturbed soil, wetting fronts were sharp and initial infiltration slower; water moved slowly below 2 m without obvious impediment. Richards' equation simulations with realistic conditions predicted sharp wetting fronts, as observed for disturbed soil. Such simulations were adequate for undisturbed soil only if started from a post-initial moisture distribution that included about 3 h of infiltration. These late-started simulations remained good, however, through the 76 d of data. Overall results suggest the net effect of soil disturbance, although it reduces preferential flow, may be to increase recharge by disrupting layer contrasts.

Résumé La perturbation de la structure du sol influence l'écoulement vers le bas de l'eau qui percole assez loin en profondeur pour recharger les aquifères. Les données d'expériences identiques menées sur un sol non-perturbé silto-limoneux et sur une tranchée à déchets adjacente et composée du même type de sol, mais perturbé, incluent (1) les propriétés hydrauliques saturées et non-saturées mesurées en laboratoire et sur le terrain (2) des profils de saturation en eau issus de tests d'infiltration de 24 h et 75 j de redistribution. Dans les sols non-perturbés, le front d'humidification ont très diffus au-dessus de 2 mètres de profondeur, et ne vont pas plus loin que 2 m en profondeur. L'analyse darcienne suggère un taux de recharge moyen inférieur à 2 mm/an. Dans les sols perturbés, les fronts d'humidification sont angulaires et l'infiltration initiale moins importante, l'eau s'écoule lentement sous 2 mètres, sans empêchements. Les simulations de l'équation de Richards suivant des conditions réalistes prédit les fronts d'humidification angulaires, tels qu'observés dans les sols perturbés. De telles simulations ont été adéquates seulement si elles commencent après une distribution initiale correspondant à environ 3 h d'infiltration. Toutefois ces simulations aux conditions initiales retardées restent correctes sur les 76 j de données. Les résultats globaux suggèrent que la perturbation du sol, bien que réduisant l'écoulement préférentiel, est à même d'augmenter la recharge en cassant les contrastes entre les différentes couches.

Resumen La alteración estructural del suelo influye en el flujo descendiente de agua que percola a suficiente profundidad para convertirse en la recarga del acuífero. Los datos de experimentos idénticos en un suelo franco-limoso sin alteración estructural, y en una trinchera adyacente con residuos simulados compuesta del mismo material de suelo, pero alterada, incluyó (1) mediciones de campo y laboratorio de propiedades hidráulicas no saturadas y (2) perfiles transitorios de contenido de agua medidos en el campo a través de infiltración estancada durante 24 h y 75 d de redistribución. En los suelos sin alteración los frentes de humedad fueron altamente difusos por encima de 2 m de profundidad, y no se extendieron a profundidades mayores de 2m. El análisis Darciano sugiere un ritmo de recarga promedio menor a 2 mm/año. En suelo alterado, los frentes de humedad fueron nítidos y la infiltración inicial más lenta; el agua se movió lentamente por debajo de 2m sin impedimento obvio. Las simulaciones en base a la Ecuación de Richards en condiciones realísticas predijeron nítidos frentes de humedad, como se observó en los suelos alterados. Tales simulaciones fueron adecuadas para suelos sin alteración solo si se comenzaron a partir de una distribución de humedad post-inicial que incluyó cerca de 3 h de infiltración. Estas simulaciones de iniciación tardía permanecieron buenas a través de los 76 d de datos. Los resultados globales

Received: 29 January 2007 / Accepted: 3 December 2007
Published online: 23 January 2008

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Electronic supplementary material The online version of this article (doi:10.1007/s10040-007-0261-2) contains supplementary material, which is available to authorized users.

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sugieren que el efecto neto de la alteración del suelo, aunque reduce flujo preferencial, puede ser el incremento en recarga mediante la perturbación de contrastes de capas.

Keywords Recharge · Unsaturated zone · USA · Waste disposal · Hydraulic properties

Introduction

Soil structure and heterogeneity are major complicating factors affecting fluxes through the unsaturated zone that may become aquifer recharge. Flow through macropores (pores larger than the intergrain pores produced by randomized packing) can be extremely rapid when they are filled with water. Layers within the soil, even when contrasting only subtly, have a basic flow-inhibiting effect, known from basic unsaturated flow theory and supported by experiments (Miller and Gardner 1962; Jury and Horton 2004). Layer contrasts also play a role in preferential flow, being a direct or indirect cause of funneled flow (where flow deflected in direction becomes spatially concentrated with a local increase in water content and therefore in hydraulic conductivity and flux) and unstable or fingered flow (caused by temporary flow-enhancing conditions of parts of the medium). Together, macropores and layers manifest both flow-inhibiting and flow-enhancing effects. To know how these complementary and opposing effects act together in controlling downward flow, and how soil disturbance by agriculture, waste disposal, or land reclamation can affect aquifer recharge rates, there is need to understand the processes of flow in heterogeneous soils of complex structure.

Effects of disturbance on fluxes in the unsaturated zone can be evaluated through the effect on the hydraulic properties that, according to accepted unsaturated flow theory, control the unsaturated flow response in a given medium. One of the properties needed to apply Darcy's law and Richards' equation (Richards 1931) to unsaturated flow is the hydraulic conductivity (K), which has a sensitive and nonlinear dependence on water content (θ). The other is the water retention, the relation between the water content and matric pressure (ψ), which depends on the pore-size distribution and other characteristics of the medium.

To assess the effect of specific structural features, much can be learned from controlled experiments on soils with and without the features of interest. In particular, the study of soil with and without modification of its natural macropore and layer structure is valuable. Many studies have considered the effect of tillage on hydraulic properties, mainly for agricultural applications (Klute 1982). Typical studies of this type (Allmaras et al. 1977, 1982; Quisenberry and Phillips 1978; Hamblin and Tennant 1981; Azooz et al. 1996) suggest that sometimes the loosening aspects of tillage dominate, while sometimes compactive aspects dominate. Bouma et al. (1975) found that cultivation of soil reduced its saturated hydraulic conductivity, as if from macropore destruction, but through effects on layers and unsaturated hydraulic conductivity, tended to increase deep percolation. Strip-mine reclamation studies are also relevant (Dunker et al. 1995; Johnson and Skousen 1995) in that reclaimed soil does not have all of the flow-affecting structural features that were present before mining. Comparing data from various studies, Gee et al. (1978) reported comparisons of water retention and hydraulic conductivity for disturbed and undisturbed soils, the most pronounced difference being markedly lower saturated and unsaturated K in disturbed material. The waste-site study of Andraski (1996) in the Amargosa Desert of Nevada, USA shows an increase in vapor transport and a reduction in flow-impeding effects of layer boundaries when the subsurface is disturbed by the emplacement of a waste trench.

Effects of disturbance have also been studied with repacked soil columns, which can involve a more drastic disturbance than typically exists in a field setting. Jayawardane and Prathapar (1992) for example repacked soil samples in a way that increased their porosity, finding this to increase K at high water contents. Another expected effect of disturbance is a more pronounced air-entry effect in the drying water retention curve, that is, the water content remains close to saturation until the matric pressure declines to a substantially negative value. This effect is consistent with an expected reduction and homogenization of the largest pores of the medium. Hayashi et al. (2006) found that disturbing and repacking samples of forest soils caused their air-entry effect to become more pronounced and to occur at lower values of matric pressure, and for the abundance of both the largest and the smallest pores to be reduced. Similarly, for silty semiconsolidated material from 45 m depth, Perkins (2003) measured soil-water retention for undisturbed cores and for samples that were disaggregated and repacked to the same porosity. The undisturbed material was macroporous with highly cemented aggregates. Retention curves of the repacked samples showed a sharper air-entry effect and a narrowing of the pore-size distribution. The net effect of such changes on recharge is not obvious; sharper air-entry may tend to keep soil near saturation for longer time, but when water content does decline, it may do so rapidly.

Controlled investigation of both undisturbed and disturbed soil is particularly useful for discerning structural effects on unsaturated flow that determine how much of it becomes recharge. A series of experiments in a silt loam soil (fine-loamy, mixed, thermic, typic calcixeroll) at the Idaho National Laboratory (INL) on the Snake River Plain in Idaho, USA, has provided data of this type (Kaminsky 1991; Shakofsky 1993, 1995; Shakofsky and Nimmo 1996; Nimmo et al. 1999). Laboratory and field measurements with identical procedures allow comparable characterizations of the hydraulic properties of both undisturbed soil and disturbed soil in a nearby simulated waste trench (Figs. 1 and 2). The field tests involved sequential measurement of water content and matric pressure profiles during ponded infiltration and subsequent redistribution (Nimmo et al. 1999). The study reported here draws on data from the several previous studies, applying them to the estimation of aquifer recharging fluxes. For convenience,

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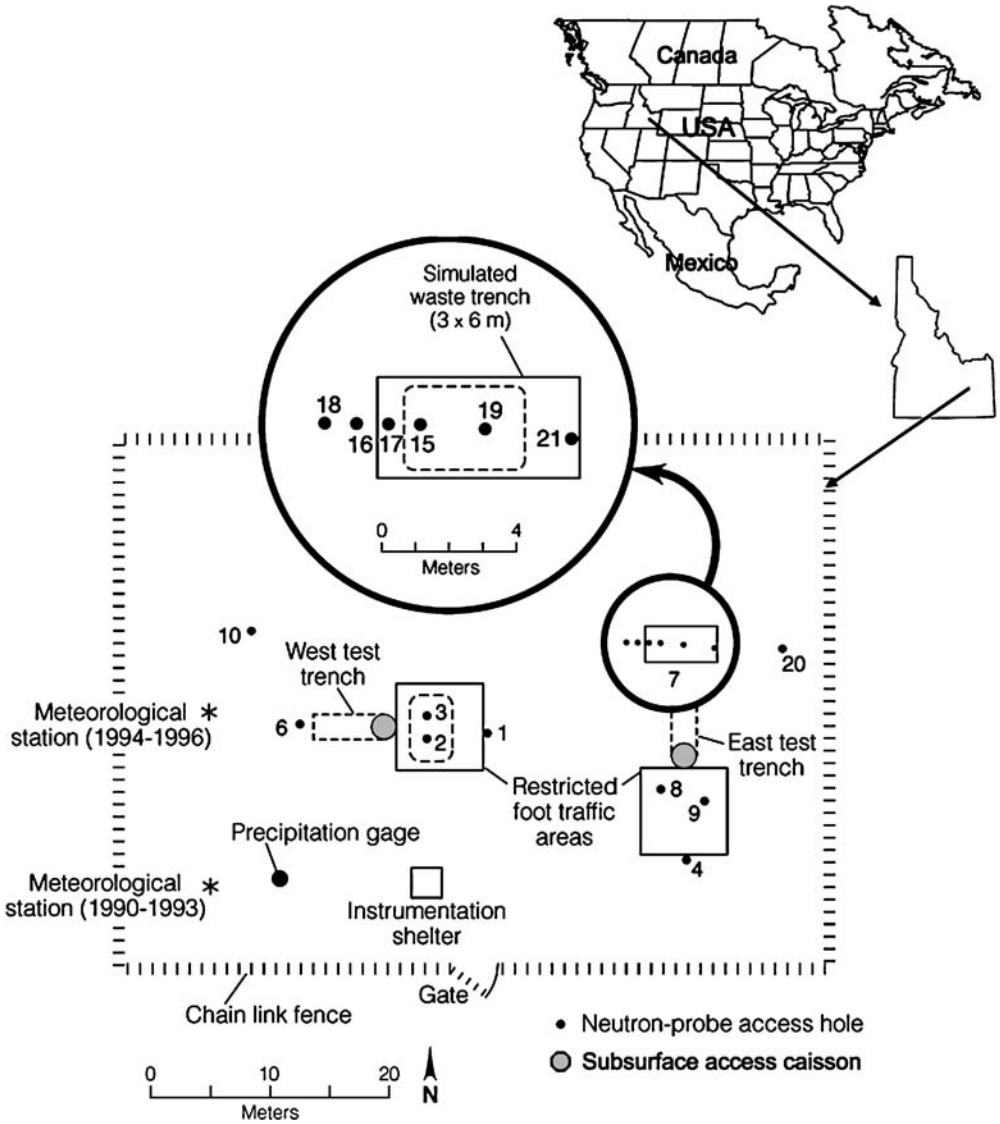

Fig. 1 The designated US Geological Survey (USGS) test area, immediately north of the Subsurface Disposal Area at the Idaho National Laboratory, showing the simulated waste trench and the location of neutron-probe access holes. The *dashed rectangles* enclosing access holes *2*, *3*, *15*, and *19* indicate the bermed areas used for the infiltration/redistribution experiments

the most important data from the earlier reports of these lab and field experiments are included in the electronic supplementary material (Electronic supplementary material). With results of these studies, application of a numerical Darcy-Richards-based unsaturated flow model shows the degree to which measured site characteristics can predict water flow. The simulations provide a link between lab-measured properties and field-measured soil water behavior.

Because mechanical disturbance affects the unsaturated hydraulic properties in various ways, and those properties have complex and nonlinear effects on unsaturated flow, the combined influences of the disturbance on a hydrologic quantity such as recharge is not straightforward to predict. This study is designed to elucidate how a disturbance that disrupts the macroporous and layered character of natural soil influences downward water flow that may become aquifer recharge. The main focus is on deep percolation, considered as downward flow of water below the root zone, where there is little except gravity to influence its further movement, such that most of it is likely to travel below the water table and thus become aquifer recharge. The approach here is to quantify the difference, at the INL site, between disturbed and undisturbed soils in affecting the transport of water through and below the root zone.

Experiments

Mapped in Fig. 1, the study site is in a designated US Geological Survey (USGS) test area adjacent to the Subsurface Disposal Area at the INL. This location is semi-arid; mean annual precipitation is about 220 mm, 30% of which falls as snow. Depth to the Snake River Plain Aquifer beneath the study area is about 200 m. In the disposal area, radioactive and mixed hazardous wastes have been buried in shallow pits and trenches since 1952 (Davis and Pittman 1990). The disposal area is in a shallow topographic depression of wind- and water-deposited sediments, underlain by basaltic lava flows. The surficial soil is about 3–6 m thick and is primarily of silt loam texture with

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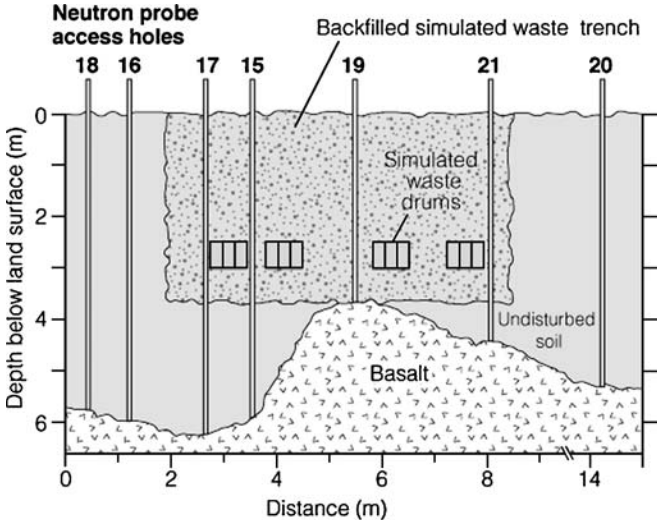

Fig. 2 Cross-section of the simulated waste trench within the USGS test area. The number and location of waste drums is approximate. The shape of the soil-basalt interface is sketched on the basis of observations made during the construction of the simulated waste trench and the neutron access holes. Note that the horizontal distance scale is contracted between 9 and 14 m

small amounts of gravel (Rightmire and Lewis 1987). There is a thin sandy-silt A horizon (zone of organic matter accumulation) from the surface to about 20 cm, underlain by a Bk horizon (zone of accumulation of carbonate, finer textured material, and development of soil structure) with variable properties, described later, to about 300 cm depth. Below that depth, the C horizon (zone relatively unaffected by biological activity and pedogenesis) extends to the basalt contact. Bartholomay et al. (1989) describe the soil's mineralogical composition. The site is vegetated primarily by cheatgrass (*Bromus tectorum*) and big sagebrush (*Artemisia tridentata*), which have rooting depths of about 0.5 and 2 m, respectively.

There are two focus areas of this study. One is the simulated waste trench constructed by the USGS in 1986 by excavating and replacing the soil to a depth of about 4 m (Fig. 2). The other is a nearby portion of the USGS test area that has not been used agriculturally or artificially altered. The undisturbed locations used in these experiments are west of the simulated waste trench near access hole 18, for core sampling, and in the west restricted foot traffic area, for the infiltration/redistribution experiment (Fig. 1). Shakofsky (1995) and Nimmo et al. (1999) reported measurements by identical procedures on the simulated waste trench and on nearby undisturbed soil. Methods for determining hydraulic and other soil properties included field observational and measurement techniques, bulk-sample techniques, and laboratory techniques using core samples obtained with a minimally disrupting, hand-operated hydraulic sampling device.

Figure 3 shows a basic characterization of properties of the disturbed and undisturbed soil profiles. This evidence indicates distinct horizon development in the undisturbed profile. The disturbed soil of the simulated waste trench is much more homogeneous; the absence of natural layers is evident in the relatively smooth profiles of the carbonate

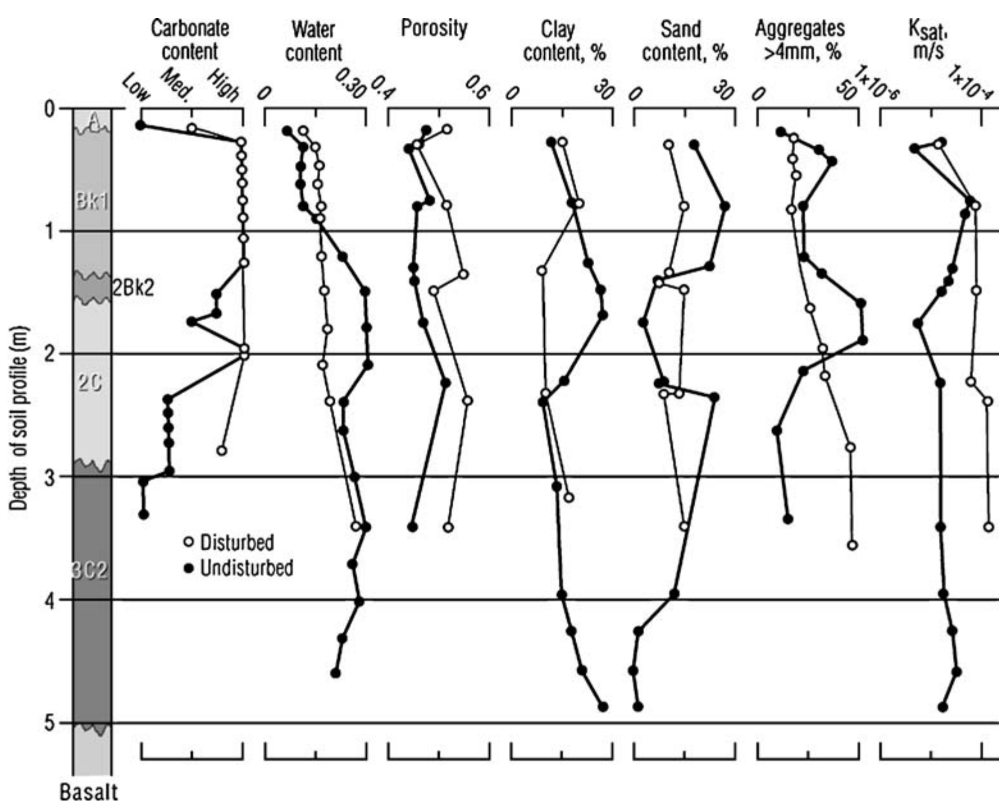

Fig. 3 Selected properties with depth in the undisturbed and disturbed soil (Shakofsky 1993; Nimmo et al. 1999). *Point symbols* represent single measurements. Water content and porosity are in dimensionless volumetric units. K_{sat} is the saturated hydraulic conductivity

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content, clay content, and aggregate distribution. The carbonate content drops off sharply below about 2 m in the undisturbed profile, about the same as the rooting depth for big sagebrush. Baker and Ahern (1989) found that carbonate depth could serve as a proxy for rooting depth in some soils and several studies have shown relationships between carbonate depth and climate (Jenny and Leonard 1939; Jenny 1941; Arkley 1963). In the 1.4 to 2.2-m interval of the undisturbed profile, the greater clay content may cause the greater moisture content as well as the greater interparticle cohesion that increases aggregate size. Similarly, an inverse relationship appears between saturated hydraulic conductivity (K_{sat}) and aggregation. An exception to the trend in homogeneity is the porosity, which varies with depth about equally in the two profiles, and is about 5% greater in the disturbed area, a likely result of loosening of the soil. Construction of the simulated waste trench created an essentially unlayered, homogenized soil with increased porosity.

Pittman (1989) describes the installation of neutron access holes at the site and presents water-content data obtained over time with a neutron-scattering probe. The neutron probe used in both routine monitoring and the infiltration/redistribution experiments was calibrated by correlating neutron measurements at the time of access hole installation with gravimetrically measured water contents of the soil removed in making the holes. The standard error for these neutron measurements was ±2.8%. Additional long-term soil moisture and meteorological data for the site are given in later reports (Davis and Pittman 1990; Pittman 1995; Perkins et al. 1998; Perkins 2000).

Lab experiments: hydraulic property measurements on core samples

Measurements were made on minimally disrupted soil core samples, including at least two each of disturbed and undisturbed from nine depths between 18 and 340 cm. Water retention was measured with a modified pressure-cell assembly, the submersible pressure outflow cell (SPOC) (Constantz and Herkelrath 1984). Pressure increments were applied to an initially saturated soil. A strict criterion for equilibration at each point (Nimmo et al. 1999) and close spacing of points, especially in the wettest portion of the curves, provided for high resolution data for evaluation of structural effects. The curves without point symbols in Fig. 4 illustrate a portion of the data set, the drying retention curves. The data for both wetting and drying curves are in the section Electronic supplementary material in tabular form. The main shape features of the lab-measured drying curves—the air entry very near zero matric pressure, the abrupt drop to a bend between −10 and −30 kPa, and the nearly flat tail beyond the bend-differ little between the undisturbed and disturbed media. The shapes are typical of naturally structured surface soils, not repacked samples. The most obvious disturbance—related distinction is that there is more spread among the undisturbed curves, indicative of greater heterogeneity and more pronounced layer contrasts as evident also in Fig. 3.

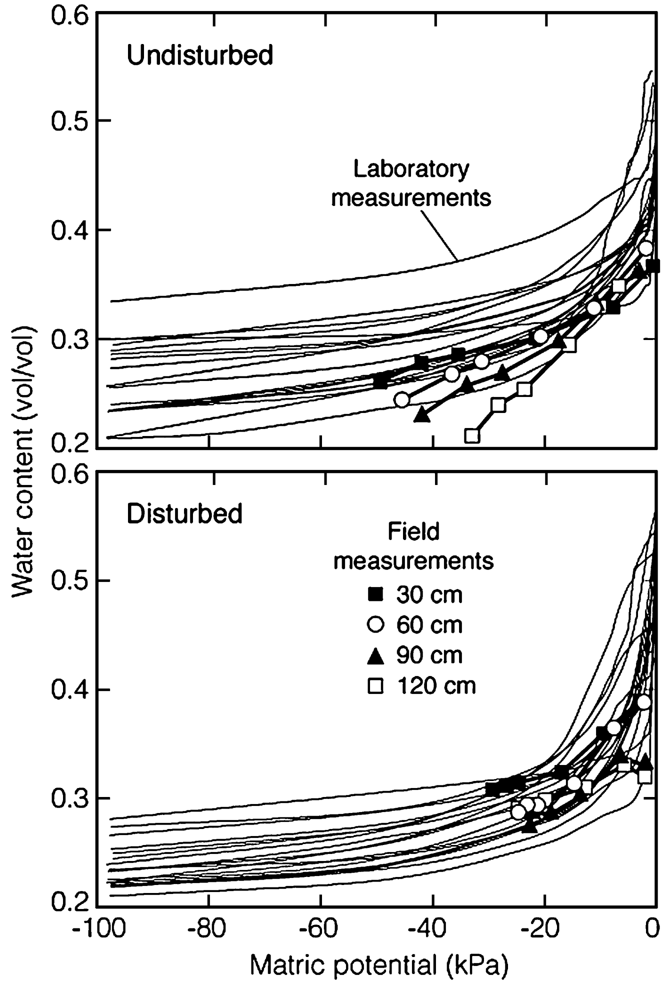

Fig. 4 Soil water retention curves measured by the SPOC (submersible pressure outflow cell) method and the field method for sediment samples in the undisturbed area and simulated waste trench. Only drying curves are shown. *Connected point symbols* show the field-measured data from the four tensiometer depths, and *curves without point symbols* show laboratory measurements on two replicate core samples at each of nine depths. Porosity appears as the endpoint of lab curves

Measured wetting curves (see section Electronic supplementary material) suggest essentially the same disturbance-related generalizations as the drying curves.

The K(θ) values used in numerical simulations were generated using the one-step outflow method (Gardner 1956), carried out at the end of the water-retention experiment. Data were reduced by the method of Passioura (1977) and, as a check, also by an inverse method. In addition to the one-step outflow results, steady-state centrifuge (SSC) measurements of K(θ) and retention (Nimmo et al. 2002) were carried out on four disturbed and four undisturbed core samples. Saturated hydraulic conductivity was measured by a falling-head method (Klute and Dirksen 1986). Figure 5 and two figures from Nimmo et al. (1999, pp 16–17) show the range of the unsaturated K results measured by the laboratory one-step outflow method. Figure 6 gives the SSC-measured water retention and K(θ). On the semilog plot the lab-measured K(θ) curves tend to be concave-down. The K magnitudes are

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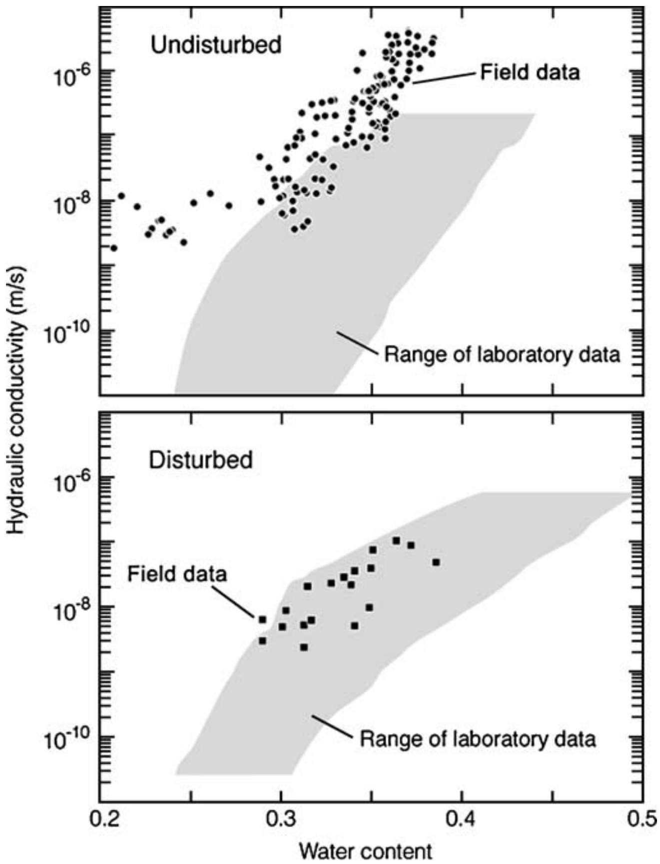

Fig. 5 Field measurements of unsaturated hydraulic conductivity for undisturbed and disturbed soil, shown as *point symbols*. *Gray shading* indicates the range of one-step-outflow-method laboratory measurements from approximately the same depths

about as expected for these media. As with the retention results, there is greater spread, indicative of greater heterogeneity, in the undisturbed medium. Apart from this spread, the greatest disturbance-related difference is a lesser sensitivity to θ of the field-measured K in the disturbed medium (Fig. 5). This tendency is an expected effect of mechanical disturbance, as it implies a narrower pore-size distribution. The trends in K_{sat} measurements (Nimmo et al. 1999, p. 13) include considerable scatter, a general tendency for K_{sat} to increase with porosity, and otherwise no evidence of a significant difference between disturbed and undisturbed soil.

Field experiments

Simulated floods allowed assessments of the behavior of water in the unsaturated zone. Ponding for the field experiment in the undisturbed area began on 16 August 1990, and in the disturbed area on 19 August 1994. The transient water-content profiles measured in these field tests with a neutron soil-moisture probe were the standard of comparison for numerical simulations. The measurements also permitted calculation of hydraulic properties by the instantaneous profile method as reported by Kaminsky (1991) and Nimmo et al. (1999).

These experiments involved 24 h of flood infiltration followed by redistribution with the surface covered to prevent evaporation. This was done in two bermed areas that were cleared of surface vegetation, one in undisturbed soil and the other within the simulated waste trench (Fig. 1). Each rectangular 2.0×4.4-m bermed area (dashed lines in Fig. 1) enclosed two neutron access holes (nos. 2 and 3 in the undisturbed soil and nos. 15 and 19 in the disturbed, Fig. 1) and eight field tensiometers, two at each depth of 30, 60, 90, and 120 cm. The tensiometers and the tubes for neutron probe access were driven into slightly undersized boreholes in order to make a tight fit and minimize the possibility of artificially creating vertical fast flowpaths. Tensiometers were installed several weeks before the ponding experiments. They were read using electronic transducers and a datalogger. Water was applied to the two bermed areas and ponded 8 cm deep. The chosen duration and depth of ponding were to facilitate hydraulic property measurement by the instantaneous profile method and to be comparable to an unusually large but physically plausible flood. The total amount of water applied in 24 h was 1.08 m, or 9.5 m^3 over the bermed area, in the undisturbed soil. The total amount of water was unfortunately not measured in the disturbed soil. In both locations, water content and matric pressure profiles were measured for 11 weeks.

Figure 7 shows water-content profiles at selected neutron access holes over 76 d of measurement. The full data set is in the section Electronic supplementary material. The apparent cumulative infiltration, averaged for the two sets of measurements in each experiment, as indicated by the 6, 12, 18, and 24-h data, is 0.30, 0.39, 0.40, and 0.43 m for undisturbed soil, and 0.10, 0.16, 0.23, and 0.28 m for disturbed soil. In Fig. 8, the successive increments of apparent added water during the four 6-h intervals of infiltration highlight the markedly steadier infiltration in the disturbed soil. The maximum water contents (θ_{max}) during ponded infiltration are less than the porosity of the media, indicative of trapped air. In the undisturbed soil, the wetting fronts were diffuse and ill-defined, as found also, for example, in a cracked soil by Mitchell and van Genuchten (1993); a portion of the water goes to 2 m depth in less than 6 h. During redistribution, the main effect in undisturbed soil is loss of water from the upper 2.5 m. The water lost may spread laterally beyond the range of neutron-probe sensitivity, or flow steadily downward through a zone of effectively uniform ψ. In the disturbed soil, the wetting fronts were sharp with high and fairly uniform θ behind, resembling those commonly observed in repacked soil samples. As would be expected for homogeneous soils when evaporation is negligible, redistribution closely follows a constant-area rectangular pattern. Water appears to move easily and uniformly downwards. It reaches 3 m depth in about 32 d and shows no evidence of having stopped, even after 76 d.

The shape and behavior of these θ profiles suggests that both layering and preferential flow paths are more significant in the undisturbed than the disturbed medium. In the disturbed soil, the infiltrated water appears to remain within the volume sensed by the neutron probe,

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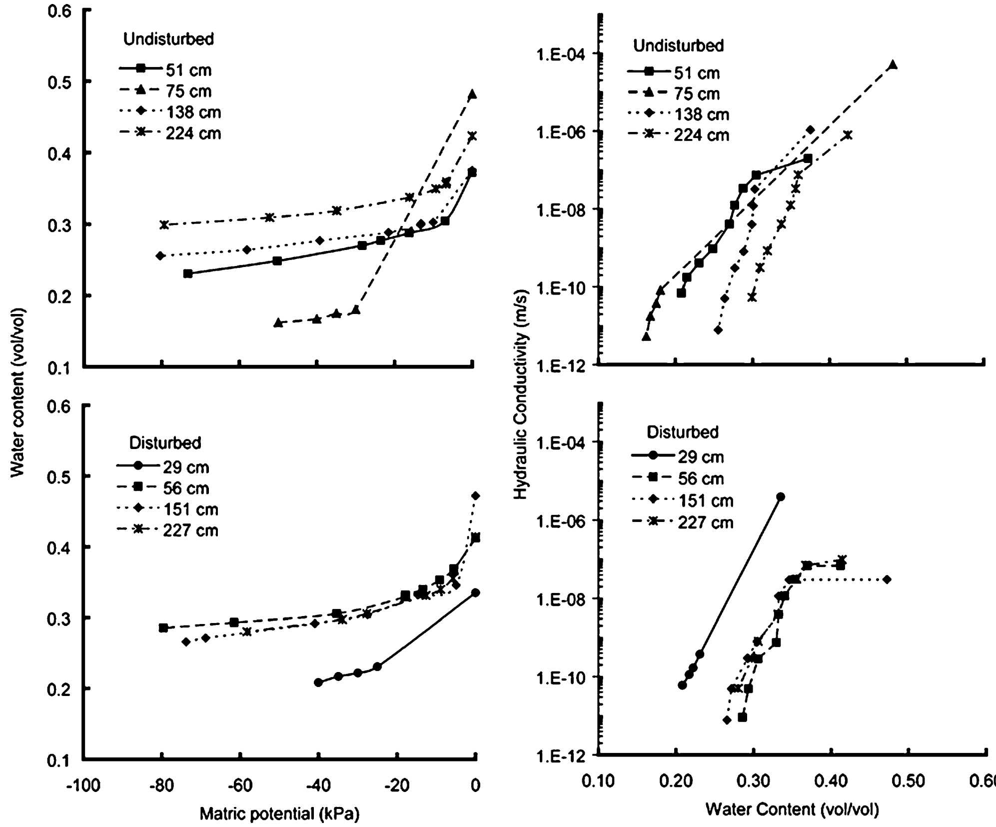

Fig. 6 Water retention (relation between water content and matric potential) and unsaturated hydraulic conductivity measured by the steady-state centrifuge method for undisturbed and disturbed soil samples taken at four depths

perhaps because in the absence of a significant impeding layer, there is less lateral flow.

Field-measured soil water retention curves created by pairing θ measurements with simultaneous ψ measurements from the tensiometers are in Fig. 4. Except for the driest undisturbed measurements at 120-cm depth, there is good consistency between the lab and field results. The undisturbed soil shows less retentivity at greater depth.

The field instantaneous-profile measurements of K, based on fluxes computed from the neutron-measurements of water content and gradients computed from the tensiometer measurements, are in Fig. 5. Many of the lab and field results agree, especially those for disturbed soil, within about an order of magnitude, fairly good agreement for the methods used. Basile et al. (2003) also compared field instantaneous profile measurements with

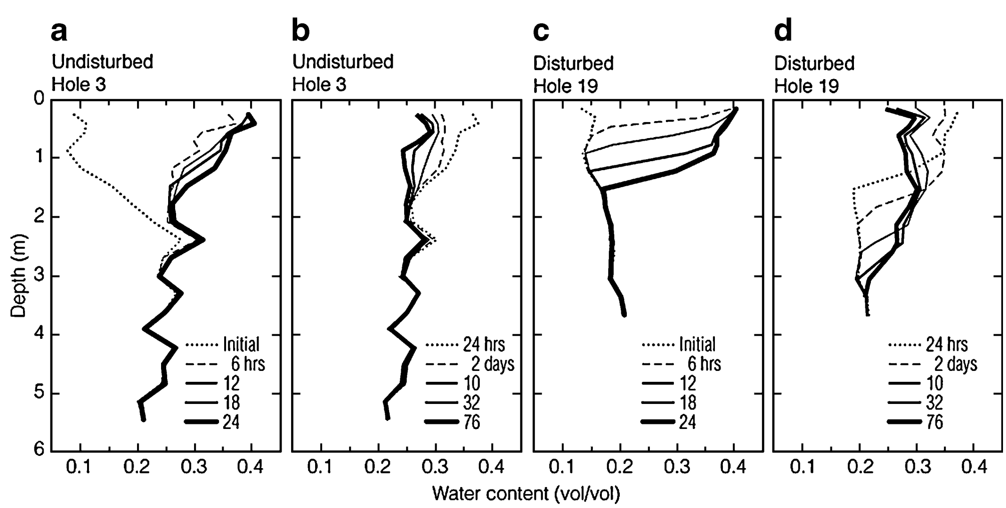

Fig. 7 Measured water content in undisturbed (**a**,**b**) and disturbed (**c**,**d**) soil as a function of depth during 24 h of infiltration and 75 d of redistribution. The initial profiles were measured a few minutes before infiltration started. Elapsed times indicated in the legend are taken from the beginning of infiltration

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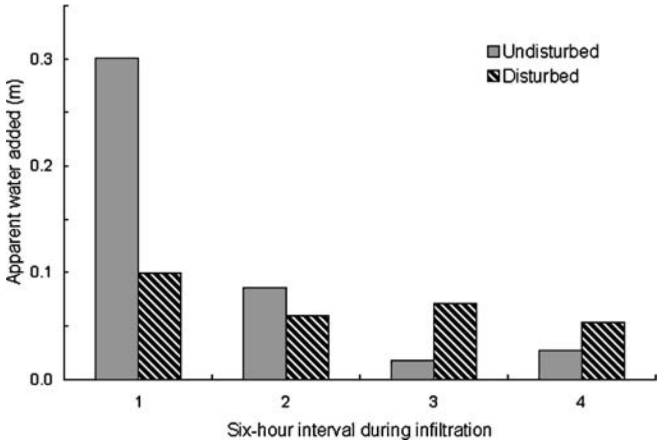

Fig. 8 Water added during each of the four 6-h intervals of the 24-h infiltration period, computed from the measured water content profiles

estimates based on lab measurements, finding the field-measured K values to be greater. The same trend appears in results for the undisturbed soil, but to a much lesser degree in the disturbed soil. The poorer field-lab agreement for undisturbed soil may result from a scale effect that is greater in this more heterogeneous medium.

Numerical simulations

A modified version of VS2DT (variably saturated two-dimensional transport; Lappala et al. 1987; Healy 1990) quantitatively related the water flow observed in the field to the laboratory-measured properties. This code is a finite difference approximation to the solution of Richards' (1931) equation, thus embodying generally accepted Darcy-Richards unsaturated flow theory, i.e. the combination of Darcy's law with the continuity equation. For use in the numerical simulations, the laboratory measurements of water retention were fit with van Genuchten (1980) curves. The measurements of unsaturated hydraulic conductivity were independently fit with the formula derived by substituting the van Genuchten (1980) formula into the model of Mualem (1976). Modifications of VS2DT for this study accommodated 36,000 nodes, 99 component media, and soil-water hysteresis.

The sequence of simulations progressed from simple to complex. The first used a basic one-dimensional model. Successive simulations incorporated various enhancements such as hysteresis, two-dimensionality, and increased detail of layered structure. This sequence of simulations allowed evaluation of the general adequacy and importance of individual enhancements.

Basic model

The basic one-dimensional simulation used lab-measured properties averaged over each observed soil horizon (five layers with boundaries at 21, 141, 171, and 301 cm as shown in Fig. 3) of the undisturbed medium and averaged over the entire profile of the disturbed medium (Nimmo et al. 1999). The initial condition in each case was a water content of 0.16, approximating the average initial water content in the field profiles. The boundary condition at the top of the profile was 8 cm of ponded water for the first 24 h, and zero flux thereafter.

During both infiltration and redistribution the basic one-dimensional simulations (Fig. 9) give essentially rectangular profiles with sharp wetting fronts, resembling measurements for the disturbed but not the undisturbed soil. The predicted downward movement is fairly steady, as would be expected if there were no macropores or significantly contrasting layers. Quantitative differences in unsaturated hydraulic properties of the individual soil horizons of the undisturbed medium (Figs. 4 and 5) seem to affect results chiefly as (1) variation in the maximum attained water content under ponding (θ_{max}), stemming in part from the variation in porosity, and (2) variation in rate of drainage, most obviously in the rapid loss of water from the 0.2 to 1.3 m layer. Downward flow is faster than observed (Fig. 7) for nearly all cases, the main exception being for undisturbed soil during the infiltration period. The simulations show consistently faster movement in the disturbed soil, in disagreement with observations except late in the redistribution period. Except for a qualitative agreement with the general shape of profiles in the disturbed soil, the basic one-dimensional model inadequately simulates the major features of the measured profiles: (1) diffuseness of the wetting front and (2) inhibition of flow below 2 m in the undisturbed soil, and (3) the rate of water movement in both soils.

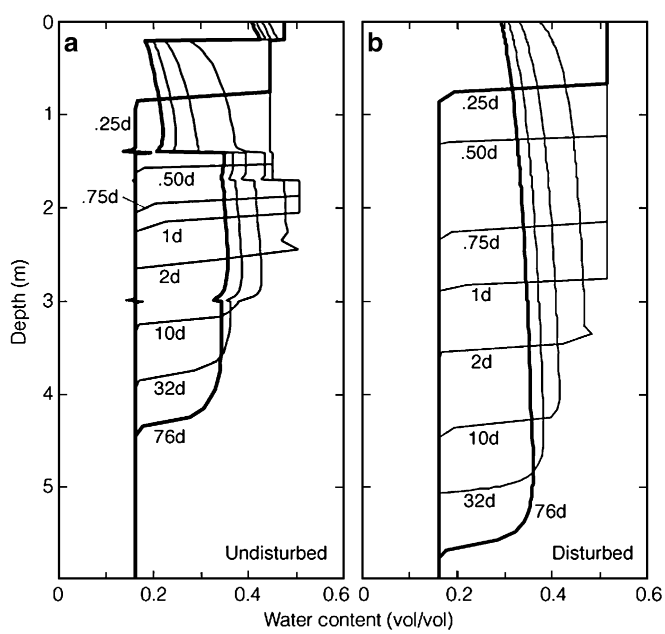

Fig. 9 Infiltration and redistribution predicted by the basic one-dimensional model for **a** undisturbed and **b** disturbed soil at selected times

DOI 10.1007/s10040-007-0261-2

Basic model with adjusted parameter values

Air trapping and other phenomena are likely to cause the actual field values of θ_{max} and K_{sat} to differ from the lab-measured values of porosity and K_{sat} used in the initial simulations. In effect, the values of these two parameters control the dimensions of the rectangle that approximates the infiltration-influenced part of the predicted profile. For more realistic θ_{max} values, the data used were the water contents measured in the laboratory after preparatory wetting of the core samples under ponded water (Table 1).

For the undisturbed soil, PEST software (Doherty et al. 1994) in combination with VS2DT revealed the optimum K_{sat} value for the closest simulation of field-measured θ. Fit quality remained poor and showed only weak sensitivity to the value of K_{sat}. This suggests that for undisturbed soil, the K_{sat} and θ_{max} parameters do not contain the information necessary to represent effects of layers, macropores, or other features of the medium not well handled by the basic model.

For the disturbed soil, the combination of a realistic θ_{max} and a K_{sat} adjusted to about one-half of the measured average resolved the major quantitative discrepancies between measured and simulated θ profiles.

Model with realistic enhancements

The numerical simulations were enhanced by incorporating more realistic representations of key features of unsaturated flow, with the goal of seeing which if any of these features might enable a qualitatively adequate prediction of the undisturbed-soil profiles. The main enhancements included:

1. Two-dimensionality. This permits lateral diversion of water as expected because of the finite dimensions of the infiltration area.
2. Hysteresis. The modified version of the VS2DT code with explicit treatment of hysteresis accounted for the fact that wetting occurs in the advancing front of the profile while drying occurs in the trailing region as it is depleted of water. The measurements of Shakofsky (1995) and Nimmo et al. (1999) include both drying and wetting water retention data. The wetting data were extended using the hysteresis model of Nimmo (1992) to cover the same ψ-range as the drying data. All hydraulic-property hysteresis was assumed to be represented in the water retention, i.e. that K(ψ), but not K(θ) was hysteretic.
3. Finer resolution of layers. Using the full data set reported by Nimmo et al. (1999), nine layers were modeled in both the undisturbed and disturbed soils using an average of two replicate core-sample measurements to characterize each layer. Layer boundaries were taken to be midway between the nine sampling depths, at 24, 47, 72,110, 143, 153, 193, and 283 cm. These layers were chosen based on the availability of hydraulic property data at nine depths rather than on the soil horizon designations as in the basic model.
4. Measured initial conditions. The θ values measured immediately before infiltration established the initial condition (IC) for the water content profile.

Table 1 Average effective lab-measured θ_{max} for each of nine layers

Layer (cm)	θ_{max} undisturbed	θ_{max} disturbed
0–24	0.432	0.470
24–47	0.413	0.427
47–72	0.373	0.433
72–110	0.424	0.485
110–143	0.429	0.417
143–153	0.418	0.473
153–193	0.420	0.427
193–283	0.444	0.448
283–500	0.395	0.434

Although these enhancements improve the realism of the numerical simulations, none of them significantly improved the simulated profile shape for undisturbed soil. Figure 10 shows their combined effect as curves with the thickest line (labeled ‘natural IC’).

Simulation with alterative initial conditions

Another test assessed whether the process that causes the substantial discrepancy between measured and simulated water contents in the undisturbed soil might be active primarily during the early parts of the field experiment, when conditions were changing most rapidly. For a short time after application of ponded water to initially dry soil, some flow-related processes are likely to occur that do not occur or are much diminished at later times. Examples are the trapping and release of air beneath the applied water, and the particularly rapid flow that may occur into large macropores or cavities within the heterogeneous soil. If these processes are poorly described by Richards’ equation, the computed solution might have deviations at early times that distort the computed solution. If so, simulated results at later times might be improved by skipping some of the early portion of the infiltration period. This hypothesis was tested by computing the numerical simulation starting not from the pre-infiltration water content distribution, but from the water content $\theta(z, \tau)$ measured at a selected time τ after the start of infiltration. Using this IC means abandoning the attempt to predict the early data for possibly improved predictions otherwise. Figure 10a shows predictions at the end of the 24-h infiltration, for three different values of τ. With early times bypassed, the simulations exhibit a more diffuse wetting front, in better agreement with the shape of the measured profile. A similar comparison at the end of 75 d of redistribution (Fig. 10b) also shows simulations that are significantly more realistic in shape, especially for the 3 and 6 h values of τ. Thus by ignoring certain processes occurring in the first few hours of infiltration, and not attempting to predict the water content changes directly caused by those processes, the water content profiles between about 0.2 and 76 d into the experiment appear to be much more reasonably predicted by the numerical

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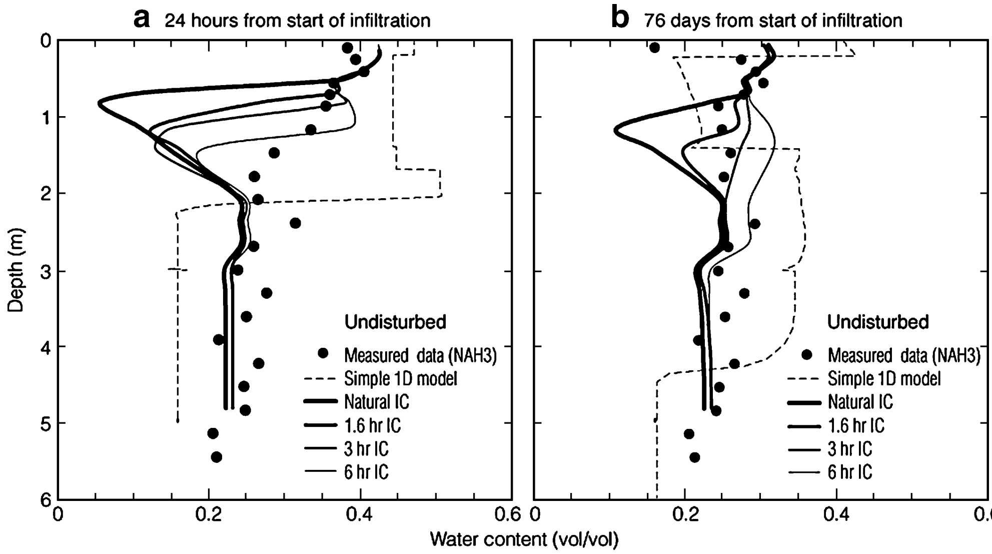

Fig. 10 Predicted and measured water content profiles for undisturbed soil at neutron access hole 3 **a** at the end of the 24-h infiltration period and **b** after 76 d of redistribution. Predictions shown include the basic one-dimensional model, the enhanced model with natural initial condition (IC), and with time-delay IC and three different values of the delay time τ. NAH 3 refers to neutron access hole 3 as shown in Fig. 1

model. This result suggests that in reality the processes occurring between 0 and about 0.2 d cannot readily be modeled with a Darcy-Richards approach, and that the actual effect of those processes persists for at least 76 d, as is clear from the obvious differences in the simulated curves in Fig. 10b.

Discussion

Hydraulic properties

The general character of the hydraulic properties is similar between the undisturbed and disturbed soil. The effect of preferential paths is not obvious in the measurements either on core samples or in the instantaneous-profile-method field results. Differences in measured properties among soil layers are apparent, though more subtle than would be expected from observed soil–water behavior in the field.

The property measurements show slight disturbance-related differences in water retention and unsaturated K, greater vertical and horizontal heterogeneity in the undisturbed medium, reasonable agreement of lab and field measurement techniques, and reasonable basic agreement between steady-state centrifuge measurements and those of other methods. Tendencies in the slopes of hydraulic conductivity and water retention curves are consistent with a reduction in breadth of the pore-size distribution caused by waste-trench construction. For example, K tends to be less sensitive to θ in the disturbed soil. This implies that in the disturbance of waste-trench construction, some of the largest pores are made smaller (as by reducing interaggregate gaps) and some of the smallest pores are made larger (as by crushing aggregates).

It is conceivable that better knowledge of K at high water content might help in the incorporation of macropore influences into predictive models (e.g. Leummens et al. 1995), though various factors limit the improvement that is likely to be made, for example the nature of trapped air, and the uncertainty with which the actual field θ values are known. For a given θ near saturation, the intrapore air content (for these INL soils just after infiltration, about 20% of pore volume) may represent unfilled macropores, or trapped air in small pores. These distinct possibilities have drastic implications for K, as they determine whether water does or does not fill the largest pores.

Response to simulated flood

Field water-flow behavior differs between the undisturbed and disturbed locations much more than do the individually measured properties. Thus, the recharge rates may be affected more than is apparent from measurements of hydraulic properties of core samples. During artificial flood infiltration, there is rapid wetting throughout a 2-m thickness in the undisturbed soil, but a sharp, slower moving wetting front in the simulated waste trench. Preferential flow, possibly conducted through macropores, is substantial in the undisturbed soil, permitting rapid downward flow in the shallowest layers. The 2-m depth rapid wetting is coincident with the rooting depth of big sagebrush.

In the undisturbed medium, the measured change in water content during the 24 h of ponding accounts for about 0.4 m of infiltration, suggesting that half or more of the applied water spread beyond the bermed area or at least to positions outside the range of the neutron probe. This behavior overall suggests a strong influence of preferential paths in the top 2 m, and flow-impeding layering below 2 m depth. A conceivable alternative to there being an effective flow impediment below 2 m, is for

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water below this depth to have moved quickly down through preferential paths without entering the soil matrix as needed for it to be sensed by the neutron measurements. This explanation seems unlikely given that no significant change in θ was measured down to the fractured basalt bedrock at 5.5 m depth. Natural layering, absence of root channels, and decreased soil aggregation below 2-m depth appear to be an effective retarding influence on downward flow. Major macropore-forming influences such as biological activity and aggregation generally are present mainly at shallow depths, typically a few meters or less. The concept of a maximum crack depth (Chertkov and Ravina 1998), though developed for vertisols, is consistent with the observation here of a depth below which preferential flow is insignificant.

In the disturbed soil, there are few pathways of fast preferential flow, but also no barriers, so water moves freely and uniformly to deeper depths. The destruction of impeding layers, the absence of roots, and higher K_{sat} at such depths may be particularly effective for increasing aquifer recharge, because at the deeper depths reached in the disturbed soil, water may largely evade the opportunity for removal by evapotranspiration. Seyfried and Wilcox (2006) found that the removal of a plant community, primarily big sagebrush, led to increased infiltration at a site in southwest Idaho.

Interpretation with respect to unsaturated flow theory

For disturbed soil, measured and simulated results agree qualitatively, in the shape of the water-content profile (Figs. 7c,d and 9b). With adjustment of soil-water property parameters, there is reasonably good quantitative agreement as well. Water behavior in the disturbed soil may resemble that of repacked soil columns, or possibly that of cultivated agricultural fields. This would suggest the Darcy-Richards formulation can work well for these types of media, which were commonly studied during the decades of the twentieth century when this unsaturated-flow theory was developed and became accepted.

For undisturbed soil, the basic Darcy-Richards approach did not accurately predict the unsaturated-zone response to a small-scale flood. Only the direct observation of water flow in the field indicates the full range of unsaturated-flow behavior at the undisturbed-soil location. The disagreement was qualitative in that significant features of water-content profile shape were absent from the predictions of both the simplest and the most enhanced models (Fig. 10), namely (1) the rapid wetting throughout a 2-m thickness of profile in the undisturbed soil, and (2) the apparent impediment to water flow at 2 m depth.

Several factors may cause the numerical simulation to be inadequate. Input hydraulic property values may be insufficiently accurate or detailed. This study, however, used measurements of greater rigor, resolution, spatial detail, and multiple-method corroboration than would normally be available. These measured values create a consistent and reasonable picture of unsaturated flow in a medium altered by disturbance. Preferential flow may be inadequately represented by these properties; in the numerical simulations, preferential flow should already be implicitly included through the measured properties of the media, but the simulated results indicate that it is underestimated. One possible reason is that there are no direct measurements for ψ between 0 and about -10 cm-water, the range where macropore effects are likely to be manifested. New modifications of water retention measurement techniques for application in the range near saturation, like that of Tokunaga et al. (2002), may reveal more and permit better application of the Darcy-Richards approach, but detailed treatment of wet-end unsaturated properties is rare. If such data were available, it is unclear whether they would significantly improve the simulated results. A second consideration is whether the core sample size was adequate. With preferential flow and layer effects appearing to be important at scales of 1 m and more, however, it does not seem likely that one could be confident of capturing such effects in samples small enough to permit practical laboratory measurements. A third issue is whether layering effects are adequately represented by the properties used in modeling. It is clear that the simulations underestimated effects of layers on flow and that layer effects captured in direct measurements of properties do not explain the apparent flow impediment in the undisturbed soil. A relatively impermeable layer at about 2 m depth could account for the minimal alteration of θ below that depth in the undisturbed medium. If it were thin enough, such a layer could have gone undetected in these experiments because the core sampling was not continuous. This would not explain the observed evidence for preferential flow, however. A straightforward adjustment of parameter values, though adequate for simulating the disturbed profile, did not lead to substantial improvement in simulating the undisturbed profile. This suggests that the measurements of the basic unsaturated hydraulic properties do not adequately represent soil structure for hydraulic evaluations.

The numerical simulations incorporating hysteresis, layer contrasts, and directly measured soil water properties failed even to qualitatively agree with the profiles observed, which suggests that the Darcy-Richards formulation as implemented with widely used measurement and computational methodology may be unsuitable for modeling soil–water behavior in this undisturbed soil. Such unsuitability could result from the main controlling factor of the flow being something other than a Darcian direct proportionality between flow rates and potential gradients. An alternative explanation could be that preferential flow paths are underrepresented in the core samples relative to the actual soil in the field; this might be consistent with the measured properties in Fig. 5, but the numerical experiments suggest that increased hydraulic conductivity resulting from fuller representation of macropores in samples would not substantially improve the simulated profile shape. Inadequacy of Darcy's law in this case may stem from the combination of ponded conditions and highly developed preferential paths. In many natural or

DOI 10.1007/s10040-007-0261-2

artificially modified settings, however, the conditions generated in this experiment are not unusual.

Time-delayed initial condition

The use of a water-content profile measured at a time τ after the start of infiltration entails (1) for part of the data set, an abandonment of Darcy-Richards modeling, and (2) the selection of a new IC. Focusing on the second of these effects, the substitution improves numerical simulations for both the remainder of the infiltration period and the 76-d redistribution period. Another way to look at this situation is to say that if one simply does not try to simulate the first few hours during infiltration, but only the period after that time, a Darcy-Richards model can give reasonable predictions. The improvement in simulated results with a time-delay IC is evidence of the short-comings of accepted theory, or at least its typical implementation, for processes occurring early in the infiltration period.

To evaluate the possible ideal value of τ, simulated results for a range of τ were computed and compared with measurements. Goodness of fit, computed as the sum of squared residuals between simulated and measured results, is graphed in Fig. 11 as a function of τ. Fit quality improves with increasing τ up to about 2 h. Beyond τ= 3 h, there is no significant further improvement. For this soil under these conditions, 3 h appears to be the optimum interval by which to delay the IC. The optimum may vary with soil type, mechanical treatment, texture, and other factors not tested here.

These results suggest that preferential paths may have essentially all their influence during the first few hours of ponded infiltration. This concept is qualitatively the same as the two-stage water movement described by Quisenberry and Phillips (1976), who mentioned 1 h as the time interval during which macropore flow takes place.

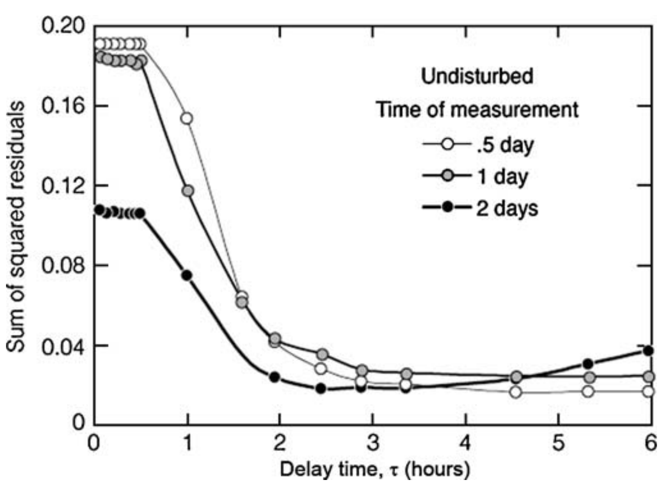

Fig. 11 Goodness of fit to water content profiles measured 0.5, 1.0, and 2.0 d after the start of infiltration in undisturbed soil, as a function of the time τ by which the initial condition was delayed in the simulation. Each of the three curves is based on 16 numerical simulations with different τ values

Mathematically, the change in the θ profile during such an initial interval appears to contain the information needed to quantify effective properties of a medium with preferential flow paths, and to account for preferential flow, even 11 weeks later. Thus the difference in θ profiles between 0 and τ could be used as an index of the relative total effect of preferential pathways throughout the soil profile. Figure 12 shows this index plotted with depth for the disturbed and undisturbed profiles. In both cases it strongly declines with depth. These results are consistent with the expectation that abundance of macropores or other preferential flow paths would decline with depth. Other investigators, for example Perillo et al. (1999), for similar reasons charted such quantities as the number and effective cross-sectional area of preferential flow paths as a function of depth. In Fig. 12, down to about 2.7 m depth, this Δθ-based index is greater for undisturbed soil, again consistent with the expected abundance of macropores and with the greater deviation between measured results and Darcy-Richards model predictions. Even in the disturbed soil the index has a large magnitude near the land surface, where it is likely that weathering and biological influences significantly altered the soil structure during the first 8 years after construction of the simulated waste trench.

Recharging fluxes

Because moisture conditions in the undisturbed soil below 2 m appear unperturbed by the artificial flood, it is possible on the basis of available data to estimate long-term average fluxes, which likely represent aquifer recharge, below this depth (Nimmo et al. 1994). Given the average annual precipitation of 0.22 m, and the fact that the topographic

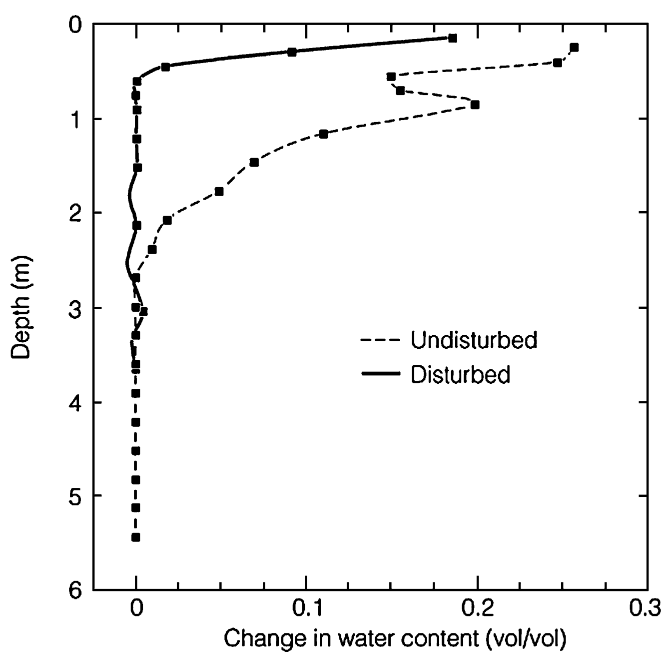

Fig. 12 Measured change in field water content during the first 3 h of infiltration. This quantity may serve as an index of the hydraulic effect of preferential paths as a function of depth

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setting of these experiments would not normally accumulate significant runoff, natural episodes of infiltration greater than the 1.08 m of the undisturbed field experiment are probably rare. Even if, because of layering or other features, only 0.3 m of the applied water would go as deep as 2 m, the recurrence interval for natural events that exceed this would be many years. It is reasonable to assume, then, that the unchanging character of the θ profile below 2 m persists over significant time, and that therefore the matric pressure gradient is negligible so that flow here is driven by gravity alone. These inferences are supported also by water contents measured in neutron-probe access holes 2 (undisturbed) and 19 (disturbed) several years later, when the influences on water content were natural. Examples using data from 1999 are in Fig. 13 (Perkins 2000). That year had 160 mm of precipitation. The undisturbed data show a pattern similar to that of the water contents measured in the infiltration/redistribution experiment 9 years earlier, though fitting within a slightly smaller envelope. As before, significant variations of water content occurred only down to about 2 m depth. The disturbed data likewise show a pattern similar to that observed in the field experiment 5 years earlier. With the longer time interval of measurements, however, the 1999 data indicate significant water content change all the way down to the fractured basalt bedrock at 3.3 m depth. These trends suggest that over the course of a year there is a significant transient pulse of deep percolation, likely to become recharge, in the disturbed but not the undisturbed medium.

Below 2 m in the undisturbed soil, the known unsaturated hydraulic conductivity at the steady water-content value of about 0.28 (volumetric, dimensionless), can give a direct estimate of the long-term average recharge rate by the steady-state Darcian method (Nimmo et al. 1994). SSC measurements on the sample from 224 cm depth suggest a K at this water content of about 1×10^{-11} m/s or 0.3 mm/year. Lab-measured K values by the one-step outflow method at 3.4 m depth range from 2×10^{-12} to 7×10^{-11} m/s for the range of water content present below 2 m. The extremes of this range suggest the amount of long-term average gravity-driven flow is between 0.06 and 2 mm/year. The geometric average of about 0.3 mm/year agrees with the estimate from the more accurate SSC method. The great sensitivity of K to θ at these low θ values means that the uncertainty of this estimate is greater than the 0.06 to 2-mm/year range suggests. As a whole, this evidence suggests the long-term average flow at 2–4 m depth is downward and probably less than 2 mm/year. This estimate might be indicative of natural recharge because the undisturbed profile has not been exposed to major artificial deviations from the natural semi-arid climatic and hydrologic conditions. Of course the rare events that would contribute more infiltration in a short period than the infiltration experiment may augment this estimated continuous component of deep percolation, but such events are still not likely to contribute a major fraction of the recharge over the long term.

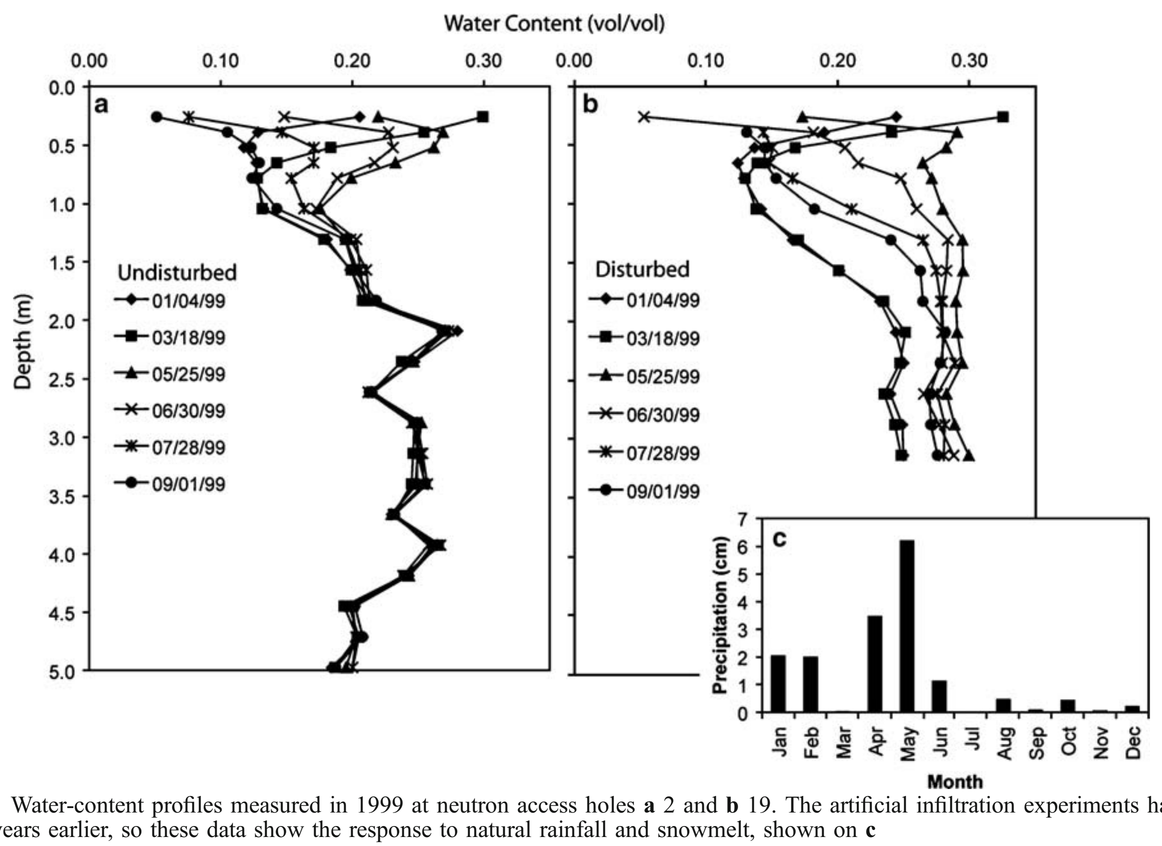

Fig. 13 Water-content profiles measured in 1999 at neutron access holes **a** 2 and **b** 19. The artificial infiltration experiments had ended several years earlier, so these data show the response to natural rainfall and snowmelt, shown on **c**

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Even at 2 mm/year, this estimate is less than the recharge range of 3.6–11 mm/year estimated for this site by Cecil et al. (1992) using the depth of the peak concentration of bomb-test fallout tracers. The estimates of Cecil et al. (1992), however, use the assumption that the tracers moved from the land surface to the depths of measured peak concentration, 1.3–1.65 m, at a constant rate over the three decades since the bomb tests. A problem inherent in this tracer-method assumption is that the tracer probably moved downward faster at first, likely covering a large fraction of the total travel distance, perhaps the entire root zone, during the first few years. A tracer method applied in this way is therefore likely to overestimate the average deep-unsaturated zone flux, and it is not surprising that an estimate based on measured K would suggest a lower flux. More recent flux estimates (LD Cecil, US Geological Survey, personal communication, 2004) by the chloride mass-balance method suggest recharge rates about an order of magnitude lower than the bomb-tracer estimates, in closer agreement with results of this study.

The measured loss of water during redistribution from the 0–2-m interval of the undisturbed soil can be compared with this downward flux estimate. If the water lost from the profile for the period between 1 and 32 d flowed downward, it would represent an average flux density of 5×10^{-8} m/s, and for the period between 32 and 76 d, it would represent 5×10^{-9} m/s. Because either of these estimates greatly exceeds the actual estimated flow rate of about 10^{-11} m/s below 2 m, a different mechanism must be causing this water loss, probably lateral flow.

A comparable situation is not apparent in the disturbed soil, where moisture conditions seem to be transient throughout the 0–3.5-m zone of neutron measurements. For example, at 2 m depth, for the period between 10 and 32 d, neutron measurements indicate a transient flux density of 1×10^{-8} m/s (300 mm/year). With the lack of flow steadiness here, this result is not a long-term recharge rate, though it may be representative of water flow in response to snowmelt or local flooding. Considering not the actual flux but the saturated hydraulic conductivity of the simulated waste trench, it exceeds that of the undisturbed soil by an order of magnitude or less (Fig. 3). This modest difference, with the minimal apparent preferential flow in the simulated waste trench (Fig. 7) suggests that there was little development of macropores during the 8 years of weathering of the waste-trench material. This result contrasts with the substantial macropore development that Albright et al. (2006a and b) observed in 4 years of weathering of compacted clay landfill covers. Albright et al. (2006a) noted K_{sat} increases of more than three orders of magnitude. This comparison suggests that macropore development in landfill covers is extremely sensitive to the particular materials involved and possibly other conditions. The backfilled silt loam soil at this Idaho site may be less susceptible to macropore formation than the clay-rich materials frequently chosen for landfill covers.

Conclusions

Landfill construction by excavating and replacing soil destroys preferential paths and homogenizes layers, with great effect on unsaturated flow. During infiltration and redistribution from an artificial flood, there is essentially simultaneous wetting throughout a 2-m thickness of undisturbed soil, but a sharp wetting front in the disturbed soil of a simulated waste trench. It also appears that some feature of the soil impedes downward movement of water at about 2 m depth in the undisturbed soil, but not in the disturbed soil. Numerical simulation with a Darcy-Richards-based code such as VS2DT can work reasonably well for the disturbed (though not the undisturbed) soil, especially if K_{sat} and θ_{max} are determined by inverse calculations using field profile data. These distinctions suggest that, in the undisturbed medium, the retarding effects of layers are effective even though preferential flow is strongly evidenced. In the disturbed material of a landfill, with respect to deep unsaturated zone fluxes, reduced preferential flow may be more than compensated for by the loss of natural layering. For the site and conditions tested, the preferential paths exert their influence on redistribution of water mainly during the first 3 h of infiltration. The change in θ during this time interval, as a function of depth, has value for predicting unsaturated flow for several weeks after infiltration ceases. It effectively represents a quantification of macropores (or of a general propensity for preferential flow) that may be useful as a practical index, and may permit more realistic simulating of long-term flow behavior.

The influence of mechanical disturbance is not so apparent, however, in measured hydraulic properties. Field and laboratory measurements by standard techniques give a consistent picture of pronounced layering of the undisturbed medium that is absent in the simulated waste trench, but do not reflect the effects of preferential paths in the sense that predictions based on them could adequately represent preferential flow. Hydraulic-property measurements typically lack good data at water contents between about 85 and 100% of saturation, a range of likely importance in quantifying downward flow at the surface. Standard measurements of $K(\theta)$ and $\theta(\psi)$ do not contain the information needed to understand all significant behavior of infiltrated water.

For aquifer-recharging fluxes through this undisturbed soil profile, the treatment of preferential flow and impeding layers is more important than the degree of realism in the elements of routine soil characterization such as knowledge of water retention and hydraulic conductivity, resolution of layers, and the modeling of more than one dimension. In layered soil, the downward flux of water becomes steady at relatively shallow depths, and consequently the estimation of long-term average recharging fluxes by the Darcian method, using unsaturated hydraulic conductivity measurements below the depth of the fluctuation, can be done more reliably in undisturbed than in disturbed soil. In response to substantial infiltration over a short time, the observed behavior of water below 2 m depth indicates that transient fluxes likely to become recharge are greater in disturbed than in undisturbed soil. For conditions like those tested here, this result suggests that the recharge-increasing effect of layer-contrast destruction dominates the recharge-reducing effect of macropore destruction.

Acknowledgements This research would not have been possible without the work of several scientists who contributed especially to the early stages. J. R. Pittman and J. F. Kaminsky conducted the undisturbed-soil field experiment. S. M. Shakofsky conducted most of the lab measurements, the disturbed-soil field experiment and the one-dimensional numerical simulations. G. S. Lords made critical contributions in sample collection and field experiments. M. A. Denton did most of the two-dimensional and hysteretic numerical simulation. Much gratitude is owed to R. W. Healy, who modified the VS2DT code for this study to account for hysteresis.

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