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Rapid Measurement of Field-Saturated Hydraulic Conductivity for Areal Characterization

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To provide an improved methodology for characterizing the field-saturated hydraulic conductivity (K_{fs}) over broad areas with extreme spatial variability and ordinary limitations of time and resources, we developed and tested a simplified apparatus and procedure, correcting mathematically for the major deficiencies of the simplified implementation. The methodology includes use of a portable, falling-head, small-diameter (~20 cm) single-ring infiltrometer and an analytical formula for K_{fs} that compensates both for nonconstant falling head and for the subsurface radial spreading that unavoidably occurs with small ring size. We applied this method to alluvial fan deposits varying in degree of pedogenic maturity in the arid Mojave National Preserve, California. The measurements are consistent with a more rigorous and time-consuming K_{fs} measurement method, produce the expected systematic trends in K_{fs} when compared among soils of contrasting degrees of pedogenic development, and relate in expected ways to results of widely accepted methods.

Field-saturated hydraulic conductivity (K_{fs}) and its variation over land surfaces are important to pedologic, hydrologic, and ecologic problems that require knowledge of soil moisture or of the partitioning of precipitation into infiltration, overland flow, and evapotranspiration. The nature and variability of this partitioning affect diverse problems such as slope stability, soil erosion rates, and the ecology of water-limited landscapes.

Field-saturated hydraulic conductivity is the hydraulic conductivity of the soil when it has been brought to a near-saturated state by water applied abundantly at the land surface, typically by processes such as ponded infiltration or copious rainfall or irrigation. This type of wetting normally traps air in a significant fraction of the pores, both large and small. Because the conductance of channels with trapped air is much less than it would be if the channels were completely water-saturated, K_{fs} is less than the conductivity of a totally saturated state attainable by artificial means. Contributions to the value of K_{fs} are often dominated by the largest water-containing pores, commonly including macropores such as interaggregate cracks, wormholes, rootholes, and burrows. Though repeatability is an issue because different episodes of wetting may produce different microscale arrangements of pore water and trapped air, in this paper we assume that for practical purposes there is a repeatable K_{fs} that ideally is characteristic of the soil and independent of the measurement method.

Various types of infiltrometers are used to measure K_{fs} at the land surface (Angulo-Jaramillo et al., 2000; Reynolds et al., 2002b); they differ in attributes such as the time, effort, and specialized equipment required, the volume and degree of wetting of the soil whose average K_{fs} the measurement represents, and the measurement uncertainty in the results. One general class applies water directly to the soil surface at known positive pressure, typically by means of a single- or double-ring infiltrometer (e.g., Bouwer, 1966; Youngs, 1987). Another, implemented as various versions of tension infiltrometer, applies water at negative pressure through a membrane in contact with the soil (e.g., Ankeny et al., 1988; Perroux and White, 1988). Another type that has recently come into some use is the hood infiltrometer, which can supply water at positive or negative pressure directly to the soil surface (Schwärzel and Punzel, 2007). Other methods using instrumentation in boreholes (e.g., Bouwer, 1961; Reynolds et al., 1983), or laboratory measurement on retrieved core samples (e.g., Reeve, 1957; Klute and Dirksen, 1986), can give an indication of K_{fs} at depth. In this paper, however, our concern is surface-applied methods, which may relate most directly to infiltration capacities and runoff. Arguments have been put forward for different modes of application producing a K_{fs} value most representative of the soil-water conditions of interest, a matter which depends on the

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intended application of the data as well as on a given scientist's judgment concerning the conditions established by natural processes and by the infiltrometer.

The problem of characterizing K_{fs} over a broad area is made difficult by several factors. Besides the uncertainties and problems occurring with individual K_{fs} measurements, the extreme spatial variation of K_{fs} that is typical of both natural and modified landscapes (Mason et al., 1957; Nielsen et al., 1973; Oztekin and Ersahin, 2006), and the small area that each measurement effectively represents, make it difficult to obtain enough measurements to give a good K_{fs} characterization of any substantial area. Assessing K_{fs} across landscapes of spatially varying soils and ecology is hampered by the time and effort that traditional methods require, especially in remote areas where rough terrain and lack of roads make access difficult. Because of the great spatial variability, over a broad area it is generally better to complete measurements in as many locations as possible, even at the expense of somewhat increased uncertainty in the individual measurements. For these purposes, therefore, speed and ease of field measurement are essential.

Whereas features concerning the accuracy of different methods are debatable, ease of operation can be assessed fairly objectively. The superiority of results from single- vs. double-ring infiltrometers can be argued (Bouwer, 1986), but ease and simplicity of operation are clearly greater for a single ring. Similarly, complexity of apparatus and procedures are minimized with the positive-pressure, direct-application approach. Such infiltrometers may be implemented under constant- or falling-head operation. By obviating the need for a level-control mechanism, the falling-head type minimizes the complexity of implementation. Thus the basic falling-head single-ring infiltrometer has clear advantages for the purpose of most thoroughly characterizing a broad area with a given amount of time, equipment, and personnel.

If the primary need is to characterize variability, some deficiencies in method or analysis may be unimportant so long as results have enough consistency that relative differences are real. So it sometimes may not matter if the computed result is an instrument-dependent infiltration rate rather than a true K_{fs}. But if we want to know K_{fs} for predicting infiltration or runoff, or for jointly utilizing results from different methods, then the method and analysis need to be realistic.

An issue of major concern is the various edge effects related to radial spreading, blockage of horizontal flow paths, and other phenomena. Smaller rings are clearly more vulnerable to these effects. Bouwer (1986) analyzed this question in some detail, noting that larger rings are needed for soils of smaller maximum pore size, and that typically a 0.3-m ring would cause significant edge effects affecting a calculated K_{fs} by more than a factor of 3. Shouse et al. (1994) found a zone about 0.04 m wide around the inside of the ring to be affected by blockage of horizontal flowpaths, which implies that a ring diameter needs to be much larger than 0.08 m. To neglect edge effects, Swartzendruber and Olson (1961) found that a suitable ring needs a diameter greater than about 1.2 m. Similarly, Lai and Ren (2007) found the minimum diameter to be about 0.8 m. For practical reasons, K_{fs} measurements are usually made with rings smaller than these guidelines would suggest, which underscores the importance of mathematically correcting for edge effects and flow divergence to the extent possible.

The testing of K_{fs} methods entails fundamental difficulties. Because of the extreme spatial variability of K_{fs}, a rigorous direct comparison of two methods would have to involve the same particular volume of soil. A serious obstacle is that the measurement process itself substantially wets the soil, causing temporary or permanent alteration of K_{fs} through effects such as elevated water content or structural changes. So of two methods applied sequentially at the same place, the second would not be operating under the same conditions as the first. Also, because some methods establish very different conditions, such as degree of saturation, they cannot be expected to give the same quantitative result. Another problem is the lack of a standard method to compare against, or even a scientific consensus as to which method is best. In some ways it can be reasoned that one form of implementation has a particular advantage over another, as for example a large ring or disk can be considered better than a small one, but that brings back the problem that two sizes test different volumes of soil. Consequently, K_{fs} methods are best tested in terms of basic or statistical consistency, realism of trends observed in multiple measurements, or usefulness of results. Gómez et al. (2001), for example, used this type of approach in testing four field methods. Dorsey et al. (1990) and Gupta et al. (1993) also compared four methods by statistical analysis of multiple measurements, finding significant differences between some methods.

In this paper we derive a formula for calculating K_{fs} from falling-head measurements in a finite-sized ring and describe an implementation of it using a bare-minimum apparatus. Our objectives center on the acquisition of a large number of independent K_{fs} measurements over a given area, similarly to Bagarello et al. (2004) and Loague (1990). We needed a method that was experimentally as simple and as fast as possible, with mathematical analysis correcting for experimental deficiencies to the extent possible. We tested it with the aim of characterizing K_{fs} at tens of locations across an arid-region alluvial fan with few roads. This effort is part of a larger study to explore how K_{fs} varies with pedogenic maturity and how this variation relates to ecology in Quaternary geologic map units. We used these rapidly measured K_{fs} values to select locations for the more detailed hydrologic investigations by Nimmo et al. (2009) and Mirus et al. (2009). We have also applied this method at other sites, for example agricultural lands in northwest Mississippi, but with less opportunity to compare with other methods.

Materials and Methods

Apparatus and Procedure

Typical implementation is with a bucket-sized infiltration ring, a small shovel, a stopwatch, and a few liters of water. At the Mojave Desert site (northernmost: 35.05°, southernmost: 35.01°, easternmost: −115.57°, westernmost: −115.60°), we used a steel bucket with its bottom removed, 22 cm high, that tapered from 26 cm diameter at the top to 21 cm at the bottom (Fig. 1). We placed the bucket over a test area, positioned such that no stones or other impediments were located directly under the lower rim. We then pushed the bucket into the soil, twisting gently, until the lower rim was deeper than 5 cm or until it could not be pushed further. We packed any remaining loose soil along the outside bucket edge, if necessary adding small amounts of bentonite to minimize lateral leakage. Modification of these procedures is

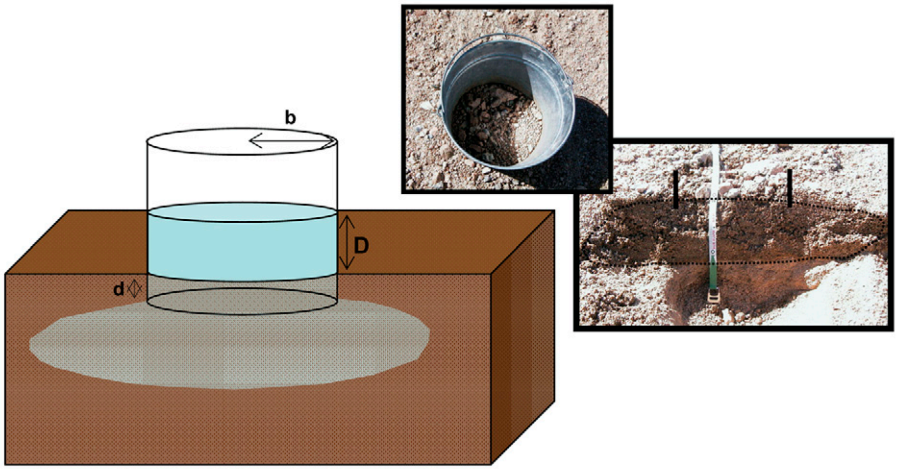

FIG. 1. The method for measurement of field-saturated hydraulic conductivity (K_{fs}): diagram of the apparatus during a measurement, photograph of the "bottomless bucket" placed on an undisturbed soil surface, and photograph of the wetted soil after excavation beneath a just-completed measurement. Definitions of the labeled dimensions are given following Eq. [1]. The darkest areas in the excavation photograph (outlined by dotted line) show wetted soil; some areas of dry soil below these are somewhat darkened by shadow. Vertical black bars indicate the placement of the ring during the infiltration test.

likely to be necessary for different soils and conditions. After laying a rubber mat within the bucket to minimize surface disturbance, we poured in a preselected amount of water, typically for initial ponding depths of 0.03 to 0.1 m, then removed the mat. We timed this operation from the start of pouring until the last patch of bulk liquid water within the bucket infiltrated below the soil surface. After the infiltration test we would typically excavate the area to view the subsurface water pathways and measure the depth and breadth of wetting front migration (Fig. 1). Application of the method in Mississippi was with a larger bottomless bucket, made of plastic, pressed by hand into soil to a few centimeters depth.

The use of commonly available buckets has the advantages of cheap and easy acquisition and makes it possible to obtain additional ones even near remote field sites. A disadvantage is that a tapered bucket has nonuniform diameter, but for a given test, use of the average diameter of the initially filled portion causes error that is negligible, being dwarfed by the imperfect correction for the departure from one-dimensionality of flow and other factors.

Theory and Calculations

The mathematical methods applied to the raw data can correct or compensate to some degree for shortcomings of the experimental method. Unlike physical improvements of apparatus or procedure, these do not usually require significant additional effort that entails a sacrifice in the number of measurements obtainable. Consequently it is important to employ mathematical corrections or compensations to the extent they are practical and effective.

With a measured infiltration flux density (i) during ponded infiltration at constant head or at an instant of time during falling-head measurement, Darcy's law with the concept of ideal one-dimensional downward flow suggests, as a first approximation, to take K_{fs} equal to i. In fact, i will normally exceed K_{fs} for various reasons, some of the main ones being: (1) sorption acts in addition to gravity to pull water downward into the soil, (2) infiltrated water in the subsurface will spread through the soil radially as well as vertically, and (3) because of ponding at positive head, water typically enters the subsurface at a positive pressure, which also adds to the effective driving force.

We consider the systematic deviation of K_{fs} from i in terms of a factor F by which i exceeds K_{fs}:

$$K_{fs} = \frac{i}{F} \qquad [1]$$

In general, F would be a function of the sorptive character of the soil and infiltrometer geometry. Applying Darcy's law with certain assumptions, various investigators have proposed K_{fs} formulas that imply a particular expression for F in terms of such parameters as the macroscopic capillary length λ of the soil (White and Sully, 1987), the ring radius b, the ring insertion depth d, and the depth of ponding D. The parameter λ is the same as or closely related to the reciprocal of the Gardner (1958) α parameter and also closely related to the Green and Ampt (1911) concept of a wetting-front potential. Wooding (1968) accounted for sorption and radial-divergence effects with the factor

$$F = 1 + \frac{4\lambda}{\pi b} \qquad [2]$$

Reynolds and Elrick (1990) accounted for the sorption, positive-head, and radial-divergence effects by

$$F = 1 + \frac{\lambda + D}{C_1 d + C_2 b} \qquad [3]$$

where C_1 and C_2 are empirically determined constants for which Reynolds and Elrick recommended the values 0.993 and 0.578, respectively. These particular values for C_1 and C_2 include a factor of π, as is clear from the restatement of the Reynolds and Elrick formula by Reynolds et al. (2002a, p. 819). For the case of infiltration into wet soil, in which the sorptive effect would be negligible, Youngs et al. (1995) accounted for the radial-divergence and positive-head effects with

$$F = 1 + \frac{D}{C_1 d + C_2 b} \qquad [4]$$

and C_1 and C_2 being the same Reynolds and Elrick (1990) constants. Philip (1992), following Green and Ampt (1911), accounted for sorption and positive head, but not radial divergence, with the factor

$$F = 1 + \frac{D + \lambda}{z_w} \qquad [5]$$

where z_w is the depth of the wetting front, i.e., the product of cumulative infiltration and the change in water content due to infiltration. Bagarello et al. (2004) tested this formula directly. Zeleke et al. (2004) and Zeleke and Si (2005) applied it with an inverse approach utilizing a set of head-vs.-time measurements.

For use with any ring whose diameter is significantly less than the likely extent of lateral spreading of infiltrated water, the formula needs to account for the radial divergence. The analysis that does this and most closely approximates our design and procedure is Reynolds and Elrick's (1990) formula for gravity- and suction-driven angularly symmetric radial spreading below a finite insertion depth during constant-head ponding:

$$K_{fs} = \frac{i}{\left[1 + \frac{\lambda + D}{L_G}\right]} \quad [6]$$

where the ring-installation scaling length

$$L_G = C_1 d + C_2 b \quad [7]$$

is defined for convenience. Use of this equation requires that the infiltration occur in soil initially dry enough that its hydraulic conductivity is much smaller than K_{fs}. It includes all of the most important complicating factors except for the falling head.

The value of λ, an index of how strongly water is driven by capillary forces in a particular soil, is most strictly determined by computing an integral of the soil's unsaturated hydraulic conductivity over the range of matric pressure experienced by the soil during the wetting process (Philip, 1985). In general this direct calculation cannot be done because the unsaturated hydraulic conductivity is not known. Developing a practical approach to such cases, Elrick et al. (1989) pointed out that the sensitivity of conductivity calculations to the value of λ is slight and that it would normally be adequate to choose a value from one of four broad soil categories based on textural and structural considerations. They proposed that for most soils with significant structural development, a λ value of about 0.08 m would be suitable. For extremely coarse and gravelly soils, a value of 0.03 m may be better, and for fine-textured soil without macropores, 0.25 m. As an example of the sensitivity of the factor F (Eq. [3]) to λ, with a typical bucket-sized infiltrometer giving L_G a value of about 0.1 m and D also about 0.1 m, the calculated K_{fs} would vary by about 15% for λ variation from 0.08 to 0.03 m.

Considering the Reynolds and Elrick formula applied instantaneously during a falling-head test, the infiltration rate equals the rate of change of pond depth, so that

$$K_{fs} = \left(-\frac{dD}{dt}\right) \Big/ \left[\frac{1}{L_G}\left(L_G + \lambda + D\right)\right] \quad [8]$$

Rearranging, and integrating over time t, during which the ponded depth falls from its initial value D_o to $D(t)$,

$$\int_0^t K_{fs} dt = \int_D^{D_o} \frac{L_G}{\left[L_G + \lambda + D\right]} dD \quad [9]$$

Thus the formula accounting for matric suction, lateral spreading, and falling head is

$$K_{fs} = \frac{L_G}{t} \ln\left(\frac{L_G + \lambda + D_o}{L_G + \lambda + D}\right) \quad [10]$$

With a set of $D(t)$ data, one can consider

$$L_G \ln\left(\frac{L_G + \lambda + D_o}{L_G + \lambda + D}\right) = K_{fs} t \quad [11]$$

from which it is clear that the slope of a plot of the effective infiltration length (left-hand side of Eq. [11]) vs. t should equal K_{fs}. This formula can be applied whether or not the test is continued until no water remains in the ring, as long as both D_o and $D(t)$ have been measured. If the falling head is allowed to fall to zero, and does so at time t_f, the proposed formula Eq. [10] simplifies to

$$K_{fs} = \frac{L_G}{t_f} \ln\left(1 + \frac{D_o}{L_G + \lambda}\right) \quad [12]$$

Results and Discussion

Field Tests

In the absence of absolute standards of K_{fs}, we tested this methodology by assessing whether appropriate systematic trends in measured results are observed when comparing among measurements by other methods and with measurements on various soils. We applied it to alluvial fan deposits of the Providence Mountains in the Mojave National Preserve, California. We conducted the tests using 1 to 4 L of water, and calculated K_{fs} using Eq. [12] with λ equal to 0.08 m.

Surficial mapping classified deposits on the southern side of the selected alluvial fan in broad categories on the basis of inset relations and pedogenesis (D. M. Miller, unpublished maps; Miller et al., 2009), using the same classifications published by Bedford (2003) for an adjacent area. The lower part of Fig. 2 diagrams these classifications. The active washes (Qya1) represent deposition at decadal or shorter time scales. Inset terraces above them (Qya2) have been active on a decadal scale. The older deposits show increasing degrees of pedogenic development and stratification, generally with overall clay content increasing with age. The oldest of the young category of deposits (Qya4) have noticeable desert pavements with incipient interlocking of surface clasts. Underlying Av and Bw horizons are persistent features, with a calcic horizon (Btk) below. Intermediate-age (Qia) deposits include desert pavement with interlocking, varnished surface clasts overlying a platy-structured silt-rich Av horizon underlain by a Bt argillic horizon and calcic Btk horizon. Most deposits with desert pavements have been dated as late Pleistocene, with some falling in the range of late-middle Pleistocene (Young et al., 2004).

Comparison with Other Studies and Other Methods

On average, our measured K_{fs} values vary systematically with the Qy and Qi categories (Fig. 2). Some variation results from temperature differences between tests, though the known dependence of viscosity on temperature (a factor of 1.5 over the range 9 to 25°C) suggests this effect probably distorts the K_{fs} values negligibly in comparison to uncertainties arising from other causes

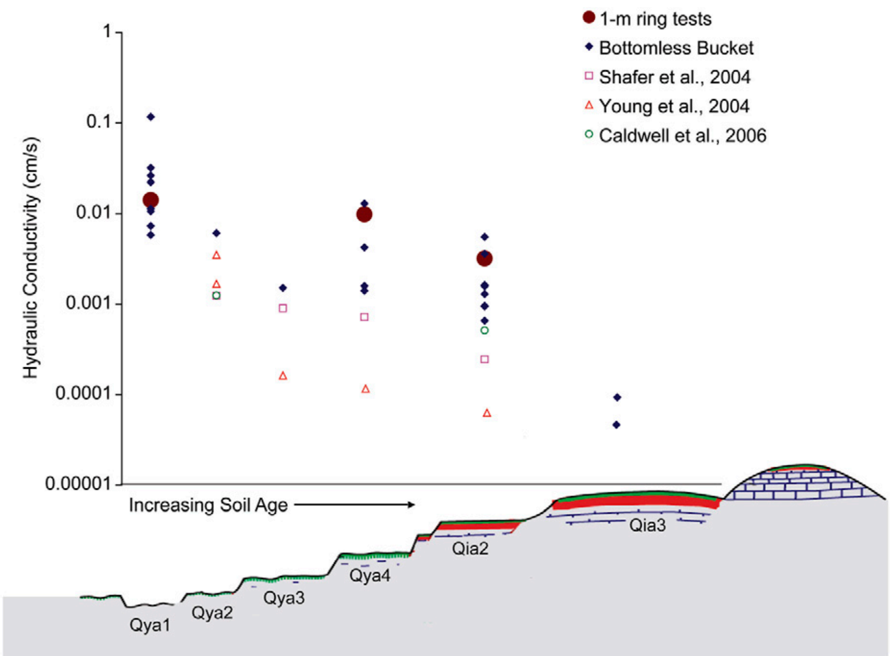

FIG. 2. Measurements indicating field-saturated hydraulic conductivity (K_{fs}) as a function of soil age from several studies, including ours using Eq. [12], in the Mojave National Preserve and vicinity. The diagram below the graph illustrates the different-aged alluvial deposits tested. (Adapted from Miller et al., 2009.)

such as extreme spatial variability. Progressive development of surface and near-surface features such as desert pavement and Av horizons correlates with a measured decline of K_{fs} with soil age. Other studies, also shown in Fig. 2 and discussed below, have shown this general trend with soil age.

Especially important for confirmation of the method's adequacy are three measurements we made using the constant-head single ring method with 1-m diameter (Nimmo et al., 2009). K_{fs} was calculated using the Reynolds and Elrick (1990) formula (Eq. [3]). These more rigorous measurements are an important standard for comparison because they were conducted using widely accepted procedures for the single-ring method (Reynolds et al., 2002a). They were made with constant head, much larger ring size, and closely monitored infiltration, which afforded confirmation of the effectively constant infiltration rate. These three measurements also show declining K_{fs} with soil age, and in each case fall within the range of bottomless bucket measurements for the same classification of soil surface.

Figure 2 also includes results of Shafer et al. (2004), Young et al. (2004), and Caldwell et al. (2006), which were obtained on comparable units in the Mojave Desert, though varying in parent material and other characteristics. These results show essentially the same trend of decreasing K_{fs} with deposit age and are systematically smaller than our K_{fs} measurements by about one order of magnitude. This sort of deviation is expected, since the tension infiltrometer tests were conducted under a slight negative head (between −3 and 0 cm water) at the soil surface, as opposed to the slight positive head in our ponded experiments. The small tension applied to the soil prevents some of the largest macropores from filling with water. With a greater number of large pores empty, it is expected that such measurements yield smaller values than obtained in ponded tests like ours. As to whether it is more useful to have a K_{fs} value that does or does not reflect major macropore effects, the answer depends on the purpose the measurements serve, as well as on the physical processes active during the measurement procedure. In an active wash, ponded water application is appropriate for simulating the effects of surface water in the wash during a major storm. On the older, elevated surfaces, natural ponded conditions may be rare, and it is not clear what method most closely approximates events that would typically cause substantial infiltration. The generally low near-surface permeability of these older soils, and their greater heterogeneity, may mean that it is not unusual for localized runoff to generate substantial macropore flow during major storms. Without any local runoff or other bulk water at the surface, infiltration would mainly be from individual raindrops, the water of which goes from a slight positive pressure to negative between the pre-impact and soil-absorbed condition. It is not clear whether artificial application at positive or negative pressure is more closely analogous to this natural process. Further hydropedologic research is needed for confronting this issue.

Progressive Falling-Head

Because our primary test location for this method was dominated by coarse soils and relatively high infiltration capacities, for which the full-to-empty implementation of Eq. [12] is more appropriate, we additionally include here some time-dependent results of the method applied using Eq. [10] to two locations of swelling, silt-loam-textured soil in northwestern Mississippi. Figure 3 shows measured effective infiltration vs. time from a field of soybeans (Test 4) and a field of cotton (Test 16). After deviations early in each test, the data fall reasonably close to a straight line through the origin. The slope of this regression line is a convenient calculation of K_{fs} from a set of D vs. t data, here giving 2.9×10^{-7} m/s for Test 4 and 1.3×10^{-6} m/s for Test 16.

A related consideration is whether K_{fs} changes as infiltrated water accumulates in the soil. To investigate this issue, we repeated some of our measurements at the Mojave site with the ring in the same place. The soil-water behavior during the measuring process of the young and intermediate-age soils made this sort of test practical: water movement into the initially dry soil was sufficiently limited that the first few falling-head tests yielded different K_{fs}, but was rapid enough to make it practical to conduct a number of repetitions. For soils of five locations and three degrees of development, Fig. 4 shows the succession of K_{fs} values as a function of the cumulative amount of water applied in the series of tests. In all of these cases, the measured K_{fs} was fairly steady after about 5 to 10 cm of water had been applied. Although the desire for standardization motivates a preference for use of the later, steadier values of K_{fs}, for a given application the early values may be most relevant, such as in regions where soil water generally infiltrates during small or moderate-sized storms preceded by long dry intervals.

Significant Features of the Method

This simplified method has advantages shared with other single-ring falling-head methods for K_{fs}, and differs from previous designs in having cheaper, simpler apparatus and a mathematical formula that goes further in compensating for inherent shortcomings of the physical implementation. It is quick and easy, requiring very little and inexpensive equipment, and not requiring vehicular access. It also is minimally disturbing, requiring no removal of soil or vegetation, and leaving no residual material except water. The method gives K_{fs} values that include the effects of macropore flow, which can be important to soil–water–plant relations and various other hydrologic and geologic processes. A tradeoff with more elaborate methods is that the effectively sampled volume is less than for larger diameter rings and larger volumes of applied water. This method is appropriate for application to near-surface processes, as opposed to those dependent on phenomena at greater depths; as with any ring-infiltration technique the measured value of K_{fs} is most representative of the soil immediately under the circular area of infiltration.

Where K_{fs} is particularly small or decreases strongly at shallow depths, water may leak out laterally near the edge of the ring, causing overestimation of K_{fs}. Before we began the practice of packing the outside contact areas of the ring with bentonite when working with such soils, significant leakage occurred in some measurements, whose K_{fs} are omitted from Fig. 2. Another issue during ring installation is that a near-surface layer of low permeability, such as an Av horizon, is vulnerable to disruption, especially if its thickness is not large relative to the ring penetration depth.

Based on their influence on K_{fs} through Eq. [3], and their dependence on the geometrical dimensions calculated by Reynolds and Elrick (1990), the optimized empirical values of C_1 and C_2 have only modest sensitivity to dimensions substantially outside the tested ranges. For example the calculated results in Reynolds and Elrick's Fig. 3 for a fine-textured medium show no significant change in L_G for D values down to 0, and for a sandy medium show about a factor-of-two increase of L_G as D declines to 0.005 m. Thus the use of rings somewhat larger than 0.2 m and ponded depths less than 0.05 m are not likely to require different C_1 and C_2 values, especially since a K_{fs} measurement would seldom have an uncertainty better than ±10% and the justifiable precision is likely closer to one than three significant figures. For coarse media, however, it may be desirable to base K_{fs} on data limited to D greater than about 0.01 m.

As with any method of K_{fs} measurement, problems may arise from deviations of the actual system from the ideal assumed in the design of the method. Most methods, for example, assume the medium to be homogeneous and isotropic, whereas natural deposits and soils are heterogeneous and anisotropic, often to extreme degrees. One idealization requiring attention is the assumption that infiltrating water moves through the soil without increasing the amount of water stored in the soil. Our method, like that of Reynolds and Elrick (1990), assumes water content is unchanging throughout a semi-infinite domain, so that the water flux at any point is unaffected by the increase in stored water that occurs at the fringes of the wetted region. With a constant-head method D is held fixed until the rate of change of the water

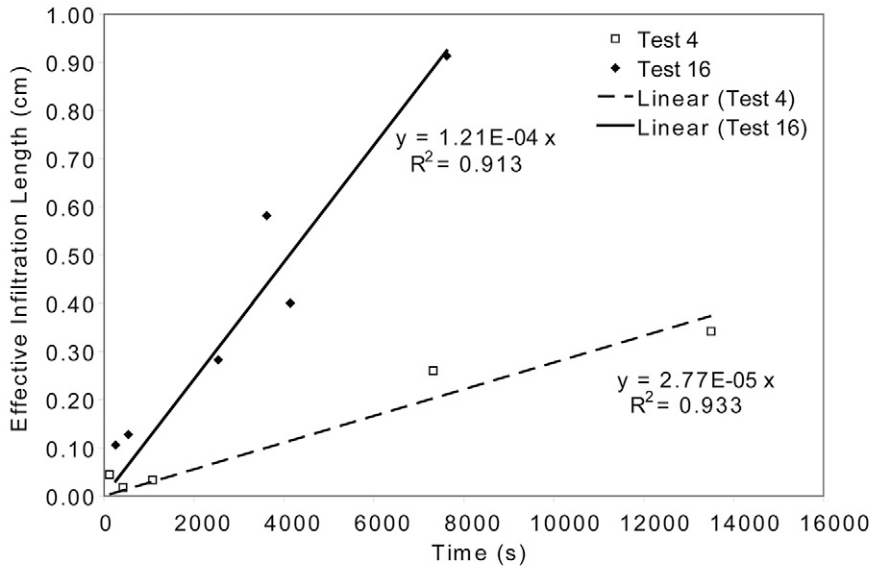

FIG. 3. Examples of falling-head measurements as a function of time, for two locations of fine-textured soil in Mississippi, plotted in terms of the effective infiltration length (the left-hand side of Eq. [11]).

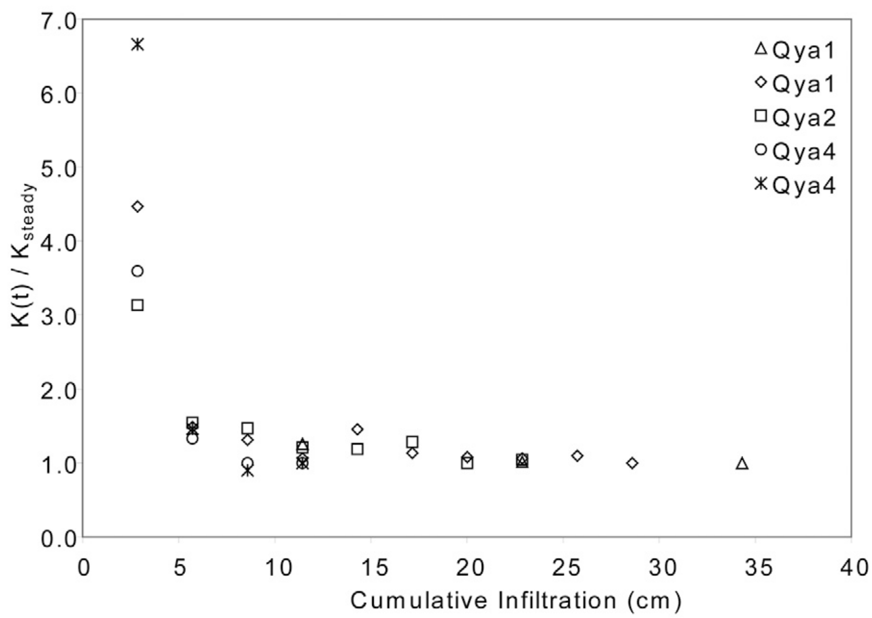

FIG. 4. Successive values of field-saturated hydraulic conductivity *(K_{fs})*, normalized to the steady-state value approximated as K_{fs} of the last completed measurement, in consecutive falling-head tests for Mojave Desert soils of five locations and three degrees of development, as a function of the cumulative amount of water applied in the series of tests.

input to the soil is considered negligible; i.e., steady flow has been established in a practical sense. It is normally assumed that by that time the influence on water fluxes of the ongoing change in stored water also is negligible. This influence may be nonnegligible at early times, which otherwise could provide data usable in a constant- or falling-head measurement. With a series of D values at various times, data can be plotted as in Fig. 3 to ascertain which early data should be excluded. If the earliest calculated K_{fs} values change significantly from one measured interval to the next, they may be discarded just as early data from a constant-head measurement may be discarded. In our tests we found negligible time-dependence of calculated K_{fs} for all but the very earliest times, consistent with the observation that when we did constant-head tests in the same soils, effective steadiness was established quickly (Nimmo et al., 2009).

A shortcoming of this K_{fs} measurement method is that even though it corrects for subsurface lateral flow, the correction is done for the standardized degree of lateral spreading that is implicit in the empirically determined value of L_G. The same is true for essentially every method that corrects for this inherent deficiency of the field measurement. In reality the spreading, as seen in Fig. 1, for example, can be more or less pronounced than what L_G is empirically based on. When no observations from installed soil moisture probes or from excavation are made of the subsurface spreading, there is little or no basis for further refinement. Where pertinent observations such as the height and width of the subsurface wetted area have been made, however, the analysis could be modified to incorporate such data for a truer correction. Future research might profitably develop a means of utilizing such data in the calculation of K_{fs}.

This method is suitable for a wide variety of soils and settings. It is less appropriate for areas with significant slope or with extremely high K_{fs} that would require much more than a few liters of water. Its measurements would have greater uncertainty in areas where biotic crusts or other absorptive materials take up much of the applied water. The method does not rely on an assumption of one-dimensional flow, as symmetric radial spreading is treated in the formula for calculating K_{fs}, but like all methods that assume such symmetry, it does not account for heterogeneity. Thus its result should be interpreted as an effective value of K_{fs} that the tested volume of soil would have if it were homogeneous and obeyed Darcy's law.

Conclusions

We developed and applied a methodology for K_{fs} measurement that combines a simple falling-head small-diameter (~20 cm) single-ring infiltrometer with analytical formulas for calculating K_{fs} that compensate both for the nonconstant head and for the subsurface radial spreading that unavoidably occurs with small ring size. It produces an actual K_{fs} estimate for fundamental use, which can be directly compared with results of other methods, rather than an apparatus- or procedure-dependent operational property.

This methodology permits individual field measurements to be obtained in a short time, sometimes much less than an hour including setup and removal of apparatus. The field implementation is minimally disturbing, highly portable, and can be constructed of widely available components, making it especially advantageous for characterizing remote and sensitive areas. These attributes make it an important research tool for investigation of habitat quality for land-use management decisions, ecosystem response to climate change, watershed and hillslope hydrology, soil hydraulic properties, erosion and landslide susceptibility, geomorphologic development, and other applications involving soil–water interactions at the earth's surface. The case study in which we tested this method shows that its results are consistent with those of other methods, and that it is sufficiently precise to detect variations in K_{fs} with degree of pedogenic development and to illustrate systematic decreases in K_{fs} with soil age.

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