The Feasibility of Recharge Rate Determinations Using the Steady-State Centrifuge Method

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ABSTRACT

The establishment of steady unsaturated flow in a centrifuge permits accurate measurement of small values of hydraulic conductivity (K). This method can provide a recharge determination if it is applied to an unsaturated core sample from a depth at which gravity alone drives the flow. A K value determined at the in situ water content indicates the long-term average recharge rate at a point. Tests of this approach have been made at two sites. Unsaturated K values were measured easily for sandy core samples from a site in the San Joaquin Valley of California. The results indicate that a better knowledge of the matric pressure profiles is required before a recharge rate can be determined. Fine-textured cores from a site in southeastern Washington required new developments of apparatus and procedures, especially for making centrifuge measurements with minimal compaction of the samples. Measured K values led to preliminary recharge rate determinations that are reasonable considering the known hydrology and topography of the site.

MANY SOIL AND HYDROLOGIC APPLICATIONS require accurate knowledge of recharge rates. Past approaches to recharge estimation, many of which are summarized in Simmers (1988), mostly address the problem at large areal scales, especially of watersheds and basins. Point determinations, in contrast, permit smaller scale studies as well as the examination of variability within large-scale studies. The resulting knowledge of the spatial distribution of recharging fluxes can allow for studies of local influences on recharge and studies of hydrologic processes that would otherwise not be possible.

For measurement at a point, one approach of potentially high accuracy is to determine the recharge rate from measurements of hydraulic conductivity (K) and potential gradients below the root zone. Such a determination is possible by applying the SSCM for K measurement (Nimmo et al., 1987) to carefully selected and acquired core samples from a deep unsaturated zone. Because this approach requires an unsaturated zone of at least moderate depth and because the SSCM works well for small K values, it is of particular interest in arid and semiarid regions.

The general approach may be understood by considering the hypothetical matric pressure (ψ) profile in Fig. 1a. Changing conditions at the surface cause ψ, water content (θ), and the vertical flux density (q) to fluctuate in the upper part of the unsaturated zone. Deeper in the profile, the fluctuations are damped. If the unsaturated zone is deep enough, and if the unsaturated hydraulic characteristics of the medium are uniform, then fluctuations may be completely damped so as to create a zone of uniform ψ, θ, and q (Gardner, 1964). In a layered medium (Fig. 1b), the comparable region of a deep unsaturated zone would be uniform in q, but not in ψ or θ, though if layers are sufficiently thick a uniform-ψ zone can develop within each (Childs, 1969, p. 230–233). A uniform-ψ zone has two especially useful features. First, the flow is driven by gravity alone, so that knowledge of K leads directly to the value of q. Second, because of the damping of moisture fluctuations in the upper profile, the recharge rate (R) that q indicates can be a long-term average.

To obtain the recharge rate in a uniform-ψ zone, one needs a K measurement on a negligibly disturbed sample at the particular water content that exists in the zone. The measurement technique must be accurate in both K and θ. The recharge-rate determination can be no better than that of K, and for many applications the order-of-magnitude uncertainty typical of common unsaturated K methods is inadequate. A compounding problem is that the K range of interest is too low for measurements by the most accurate conventional methods; R values of 1 to 600 mm yr^{-1} require measurement of K values of 3×10^{-11} to 2×10^{-8} m s^{-1}.

For making K measurements that indicate R, the SSCM has several advantages. It has the accuracy of a steady-state method. For a sandy soil, for example, it can give K to within $\pm 8\%$ at a θ known to within $\pm 2\%$ (Nimmo and Akstin, 1988). The centrifugal force permits measurements at K values as low as 10^{-11} m s^{-1}. With adjustments of the centrifuge speed and the mass of apparatus contacting the surface of the core sample, this force can simulate the overburden pressure existing in the field.

The basic objective of the study described here was to assess the feasibility and practicality of using SSCM to determine recharge rates. The steps followed were: (i) to obtain core samples from a part of the unsaturated zone where ψ is known or estimated to be uniform, (ii) to measure $K(\theta)$ for the cores across a range that includes or comes as close as possible to the field water content θ_f, and (iii) to assess whether the results are reasonable with respect to other measurements and known influences.

THEORY

The SSCM establishes steady flow in a sample with a known body force in a way that permits measurement of q. The SSCM apparatus, the original version of which is shown in Fig. 2a, includes a constant-head reservoir with an overflow hole that maintains a constant level of water above the ceramic plate (B) on top of the soil. The saturated K of this ceramic plate is less than that of the soil, so the soil remains unsaturated. Under operating conditions useful for K measurement, the centrifuge angular speed (ω) and the K of the ceramic plate are the dominant influences on the value of q (see Eq. [B3] of Nimmo et al., 1987). Changes in q caused by changes in ω usually have little effect on θ and hence on K because the difference in force has essentially the same effect on the flux into and the flux out of the soil. When steady flow has been established, q is

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Abbreviations: SSCM, steady-state centrifuge method; SPOC, submersible pressure outflow cell.

known from measured changes in weight of the various reservoirs in Fig. 2a. Then if the ψ gradient is known or known to be negligible, Darcy's law gives K from the formula

$$q = -K\left(\frac{d\psi}{dr} - \rho\omega^2 r\right), \quad [1]$$

where r is the distance from the center of rotation and ρ is the density of water. After centrifugation, the sample weight gives the average θ and a tensiometer brought into contact with the sample gives the ψ value to be associated with the measured K.

With the apparatus of Fig. 2a, it is necessary to use different ceramic plates to measure different K and θ values of the soil. The split-function modification of Nimmo et al. (1992), a later version of which is shown in Fig. 2b, affords more flexibility through substantial adjustments of the head of water above the ceramic plate D and adjustments of the effective area of ceramic through which water flows before entering the soil. The result is that K can be measured across a wide range of θ without changing the ceramic.

In selecting the centrifuge speed, the most basic consideration is that it must be great enough that the centrifugal driving force dominates the matric pressure gradient. This criterion depends on the same hydraulic properties that are to be measured. Considering Darcy's law rearranged as

$$\frac{q}{K} = \rho\omega^2 r - \frac{d\psi}{dr}, \quad [2]$$

it is obvious that, if $q = 0$, the sample approaches hydrostatic equilibrium. The balance of forces leads directly to the profile

$$\psi(r) = \frac{\rho\omega^2}{2}(r^2 - r_0^2) \quad [3]$$

where r_0 is the r position at which $\psi = 0$, which might, for example, be established by a free water surface. With steady flow and $q << K$, the left side of Eq. [2] is essentially zero. In other words, the forces nearly balance and the profile differs little from the hydrostatic parabola of Eq. [3]. This condition makes it impossible to determine K accurately from the SSCM measurement because the total driving force is a difference of two terms, nearly equal in magnitude, with one of them, $d\psi/dr$, poorly known. To avoid this condition, the centrifuge speed must be great enough that q is nonnegligible relative to K. Then the difference between $\rho\omega^2 r$ and $d\psi/dr$ is great enough that the net force can be determined reasonably well. At even greater values of ω, $d\psi/dr$ can become negligible relative to $\rho\omega^2 r$.

Figures 3 and 4 illustrate how the properties of the medium relate to the minimum speed requirement. The SSCM $\psi(r)$ profiles have been computed by solving Darcy's law (Eq. [1]) numerically (Nimmo et al., 1987). For Oakley sand (mixed, thermic Typic Xeropsamment) and Aiken clay loam (kaolinitic, mesic Xeric Haplohumult), $K(\psi)$ characteristics are shown in Fig. 3 and $\psi(r)$ profiles in Fig. 4. Across the range of r between 170 and 200 mm, the chosen speeds of 42 and 84 s^{-1} generate accelerations of 30 and 120 $\times g$ in the middle of the sample. Fluxes in each case were chosen to correspond to a K of 5×10^{-10} m s^{-1} if $d\psi/dr$ were negligible. Oakley sand (Fig. 4a) shows poor separation (nearly canceling potentials) at 42 s^{-1} but good separation, indicating $q >> K$, at 84 s^{-1}. Aiken clay loam (Fig. 4b) shows nearly canceling potentials at both speeds. The reason that Aiken but not Oakley fails the $q >> K$ criterion is apparent in Fig. 3: at the relevant ψ values, the Aiken medium has greater values of K, requiring greater q and hence greater ω.

The second major consideration in selecting ω is compaction. In general, it is desirable to select the operating speed that, for a given apparatus and position r, simulates the field overburden. This speed is only usable, however, if it exceeds the minimum for a well-defined driving force. The effective overburden pressure at a point in a sample undergoing centrifugation is generated by the centrifugal force of the soil and apparatus, approximated at point r by

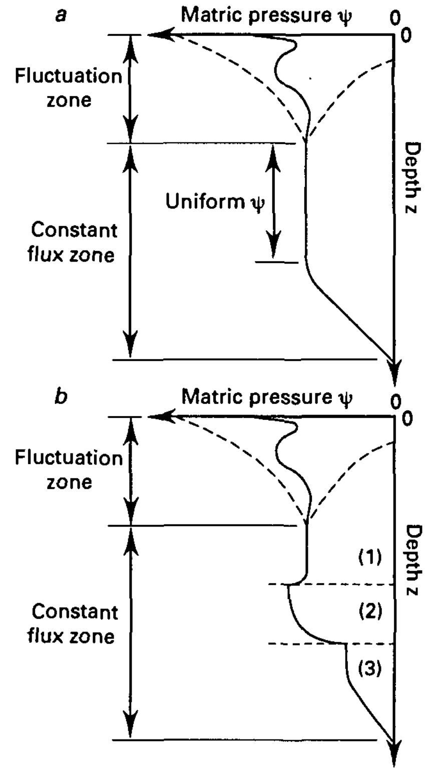

Fig. 1. Hypothetical profile of matric pressure as a function of depth in an unsaturated zone deep enough that its lower portion has a constant downward flux of water in (a) a uniform and (b) a layered profile. Dashed curves indicate possible extremes in the upper portion.

$$P_0(r) = \frac{m_a\omega^2 r_a}{A} + \frac{1}{2}\rho_{bw}\omega^2(r^2 - r_t^2) \quad [4]$$

where m_a is the mass of apparatus that rests on the soil (the constant-head reservoir in Fig. 2a, or the applicator in Fig 2b), r_a is the distance from the center of rotation to the center of mass of that apparatus, A is the cross-sectional area of the soil, ρ_{bw} is the wet bulk density of the soil, and r_t is the distance from the center of rotation to the top of the soil. For comparison, the overburden at a field site at depth z is

$$P_0(z) = \rho_{bw} g z, \quad [5]$$

where g is the gravitational acceleration.

Equating the pressures in Eq. [4] and [5] gives the depth corresponding to the equivalent centrifugally generated overburden:

$$z = \frac{m_a\omega^2 r_a}{A\rho_{bw}g} + \frac{\omega^2}{2g}(r^2 - r_t^2). \quad [6]$$

At the midpoint of a sample of length L, the depth for which overburden is simulated is

$$z_m = \frac{m_a\omega^2 r_a}{A\rho_{bw}g} + \frac{\omega^2}{2g}\left(\frac{L^2}{4} + r_t L\right). \quad [7]$$

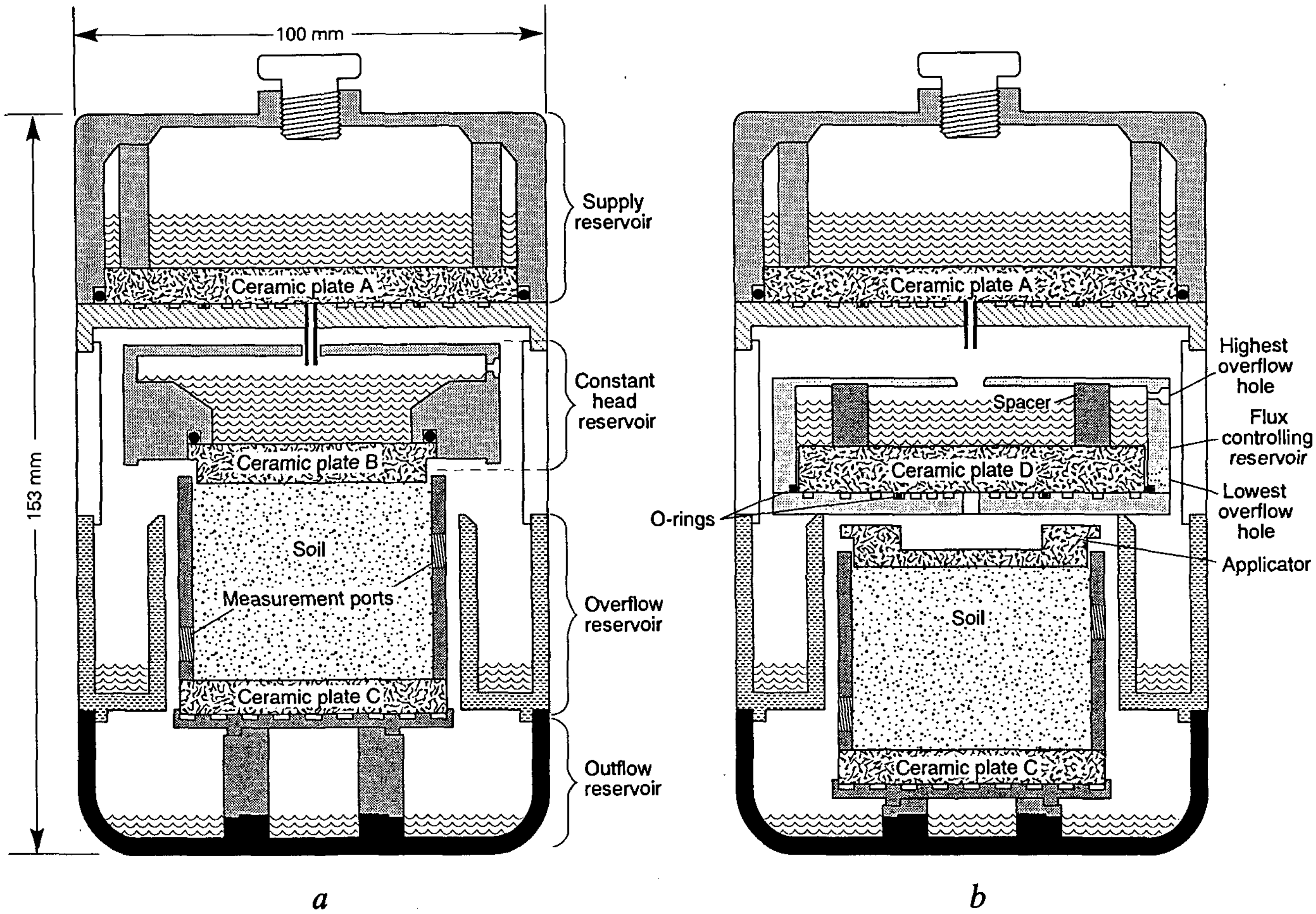

Fig. 2. Apparatus fitting into a 1-L centrifuge bucket for establishing and measuring steady-state flow through the soil: (a) the design of Nimmo et al. (1987), in which a single reservoir maintains a constant head and spreads water evenly over the soil surface; (b) a modification of the design of Nimmo et al. (1992), in which one reservoir controls flux and a separate applicator spreads water over the soil. The design here has an additional innovation in that only the relatively small mass of the applicator rests on the soil, permitting greater centrifuge speeds without exceeding the maximum tolerable compressive force on the soil.

The modified split-function apparatus in Fig. 2b was developed to permit the control of m_a for a wide range of simulated overburden pressures. It differs from the related apparatus of Nimmo et al. (1992) in that the flux-controlling reservoir is mechanically supported independently of the plate that rests on the soil. This reduces the minimum mass resting on the soil by about a factor of 10. As with any means of spreading water over the surface of the soil, the spreading must be even. For the split-function apparatus used in this study, the evenness was verified using color-indicator silica gel across a flux range that included the fluxes to be applied to the samples. This test produced wetting fronts that were flat to within about $\pm 10\%$ of the depth of infiltration. Assuming the flow in the centrifugal field to be essentially one dimensional, the flatness of the wetting front indicates uniformity of the flux over the area of the sample.

For typical values of $\rho_{bw} = 2$ Mg m^{-3}, $A = 2 \times 10^{-3}$ m^2, $r_a = 150$ mm, $r_t = 160$ mm, $L = 40$ mm, m_a ranging from 20 to 300 g, and ω from 10 to 540 s^{-1}, the range of depths that can be simulated is 0.04 to 400 m. For shallow depths, however, the minimum speed requirement entails an application of force that exceeds the field overburden. The resulting compaction may significantly affect $K(\theta)$. For a sandy soil at low θ, however, Nimmo and Akstin (1988) obtained substantial evidence that the effect of centrifugal compression at least up to 1910 $\times$ g is essentially negligible. At or near saturation, with the largest pores conducting most of the water, the effect is greater because compression preferentially reduces large pores. Fine-textured media are potentially more susceptible to changes in $K(\theta)$ because they are more compressible. This problem is compounded by the fact that fine-textured media, like the Aiken clay loam of Fig. 4b, typically would have a greater minimum speed requirement.

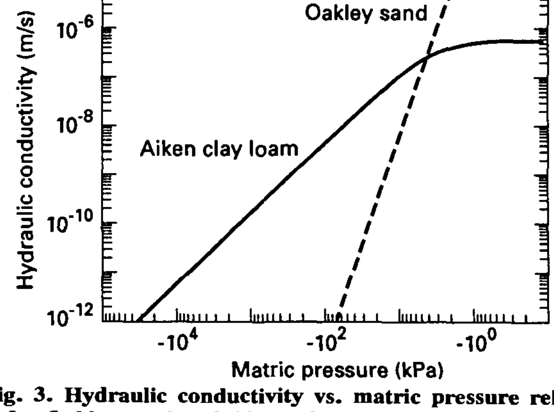

Fig. 3. Hydraulic conductivity vs. matric pressure relations for Oakley sand and Aiken clay loam, used for computing hypothetical matric pressure profiles within a sample during steady-state centrifuge measurements.

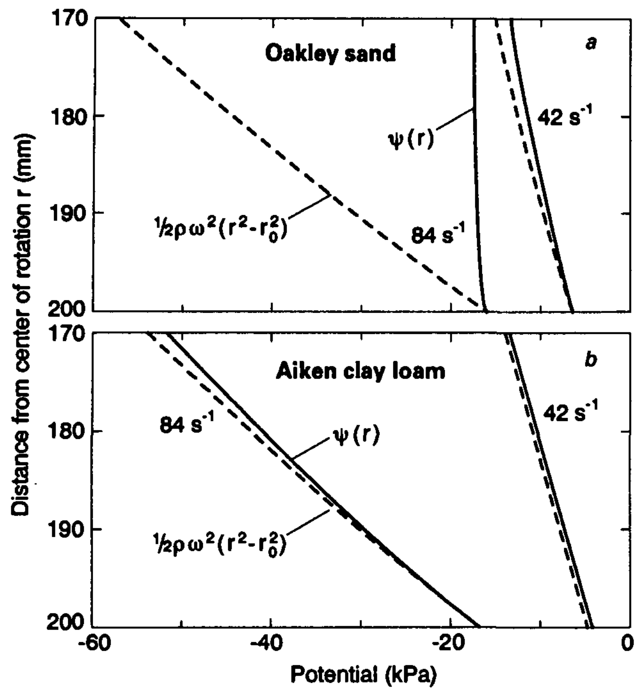

Fig. 4. Steady-state centrifuge profiles of matric pressure (solid curves) and negative centrifugal potential (dashed curves) at centrifuge speeds of 42 and 84 s^{-1} for (a) Oakley sand and (b) Aiken clay loam.

Once the operating speed has been selected, one can use Darcy's law (Eq. [1]) to estimate what K value will be measured for a given value of q. The q values to be applied should be selected so as to cause the resulting K values to bracket any reasonably estimated recharge rates, without exceeding the saturated hydraulic conductivity (K_{sat}). It is of value to make SSCM measurements at three or more different q values. Then the initially calculated K, θ, and ψ values may provide adequate $K(\psi)$ data to calculate the steady-state centrifuge $\psi(r)$ profiles more accurately than before. The revised $\psi(r)$ values then yield improved $d\psi/dr$ for a more accurate $K(\psi)$. This sequence can be iterated using a Newton–Raphson scheme to produce the K values that best characterize the SSCM data. With knowledge of the field θ, the recharge rate can be read from the final $K(\theta)$ curve.

MATERIALS AND METHODS

The proposed methods were tested in two distinct hydrogeologic settings, one an alluvial fan in California and the other a loess deposit in Washington. The California site, studied first, turned out to be less suitable for recharge rate determinations. Results from that site are included here because they provide data for an entirely different medium and they illustrate certain problems and considerations that are important in the field application of our methods. Table 1 gives bulk densities and textural properties of the samples used for SSCM tests.

The California site is in western Fresno County at 36°38′12″N and 120°38′22″W on a feature known locally as the Panoche Fan. This fan is part of the complex of Pleistocene and recent alluvial fans that form the western margin of the San Joaquin Valley (Bull, 1964; Miller et al., 1971; Schoellhamer and Kinney, 1953). Down to a depth of 15 m, core sampling was possible only in a few gravel-free layers. Panoche samples were collected from sand layers at depths of 7 to 11 m below the streambed of Panoche Creek in early November 1986, at which time the creek had been dry for several months.

The Washington samples were collected from two locations

Table 1. Bulk density and particle size data for samples used in steady-state centrifuge method measurements.

	Depth	Bulk density	Sand	Silt	Clay	Median grain size
	m	Mg m^{-3}		%		μm
Panoche	7.7	1.62	90	10	0	219
Panoche	8.1	1.62	80	20	0	83
Palouse ridge	18.2	1.71	13	64	23	16
Palouse swale	4.3	1.48	12	61	27	14

on a hill at 46°45′46″N and 117°12′1″W in eastern Whitman County. The area is part of an extensive loess deposit that forms rolling topography known as the Palouse Hills (Lotspeich and Smith, 1953; Baker et al., 1988). Samples at depths from 3 to 20 m were obtained in September 1988 and October 1989 from one location on a ridge and another 238 m to the north–northeast and 34 m lower in a swale that marks the headwaters of an unnamed tributary to the South Fork of the Palouse River.

Core samples were obtained through hollow-stem augers using 61-mm i.d., ring-lined, split-barrel samplers. The sampler was hydraulically pushed where possible (Palouse samples) and hammer driven where necessary (Panoche samples). Samples were sealed in plastic immediately after collection and were stored before use in a humidified chamber at a controlled temperature of 22 °C. Before measurements were made in the centrifuge, samples were trimmed to 50 mm in diameter and 40 mm in length. This was accomplished by means of a screw-driven piston that pushed the sample out of the field retainer, through a cylindrical blade, and into the retainer used for centrifuge measurements.

The SSCM measurements for the Panoche samples were completed using techniques and operating parameters developed previously for other sandy soils, so no extensive preliminary characterizations were done. Figure 5 shows the $K(\theta)$ results and $\theta(\psi)$ measurements made in connection with the SSCM. For each sample, some extrapolation is necessary to estimate K at the measured field water content. Results for the two samples are widely different: about 4×10^{-10} m s^{-1} at 7.7-m depth, and about 7×10^{-8} m s^{-1} at 8.1 m. Interpretation in terms of recharge rates depends on the matric pressure gradient. When the samples were taken, no means were available for in situ ψ measurements, but later tensiometer measurements on these and other core samples within the same gravel-free layer indicated ψ values of -24.9, -23.1, -17.5, and -15.7 kPa at depths of 7.1, 7.7, 8.0, and 8.1 m, respectively. These measurements indicate a ψ profile in this layer similar to that of Region 2 in Fig. 1b. The recharge rate at 7.7 m derived from the K measurement would be about 4 mm yr^{-1} taking the measured ψ values into account, compared with 13 mm yr^{-1} if there were no ψ gradient. At 8.1 m, ψ is changing more sharply with depth and the gradient is too uncertain for computations of recharge rate. There also may be other complications besides the nonuniform ψ profile, such as the possibility that depth was insufficient for steady downward flow. An accurate recharge rate determination would thus require more detailed field ψ measurements to establish the steadiness and dimensionality of flow. Although this site is not wholly unsuitable for SSCM recharge determinations, the implementation would be difficult.

Because little was initially known about the characteristics of the Palouse samples, we made several types of measurements before using the SSCM. We measured K_{sat} to establish an upper limit for the selection of q values to be applied and to investigate the potential seriousness of compaction effects. The value of K_{sat} was measured both with the falling-head centrifuge method (Nimmo and Mello, 1991) and the benchtop falling-head method (Klute and Dirksen, 1986). The data, graphed in Fig. 6a, clearly show the importance of centrifugal

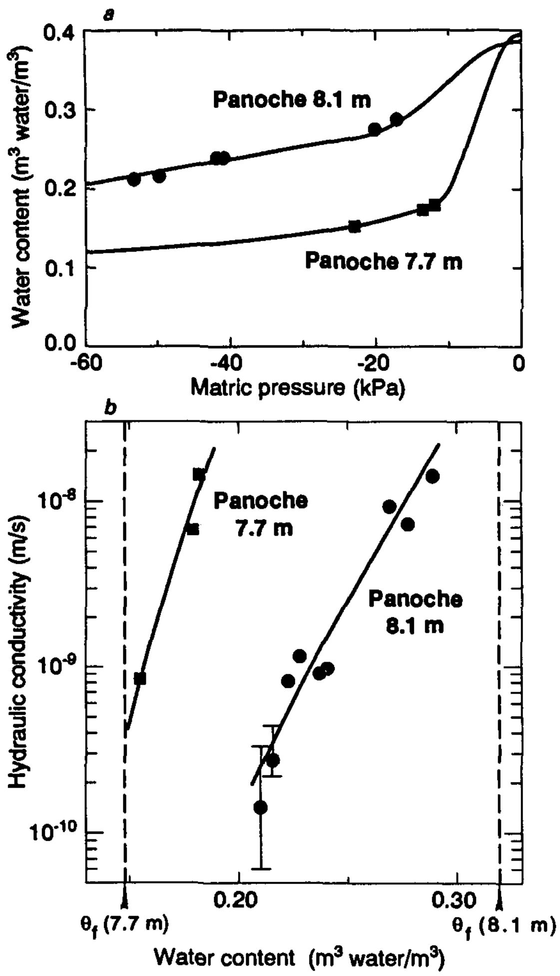

Fig. 5. Measurements of (a) water retention and (b) unsaturated hydraulic conductivity for Panoche core samples, made using the steady-state centrifuge method (SSCM). After each SSCM run, the sample weight indicated the average water content, a tensiometer gave the measured matric potential, and a solution of the centrifugal form of Darcy's Law yielded hydraulic conductivity.

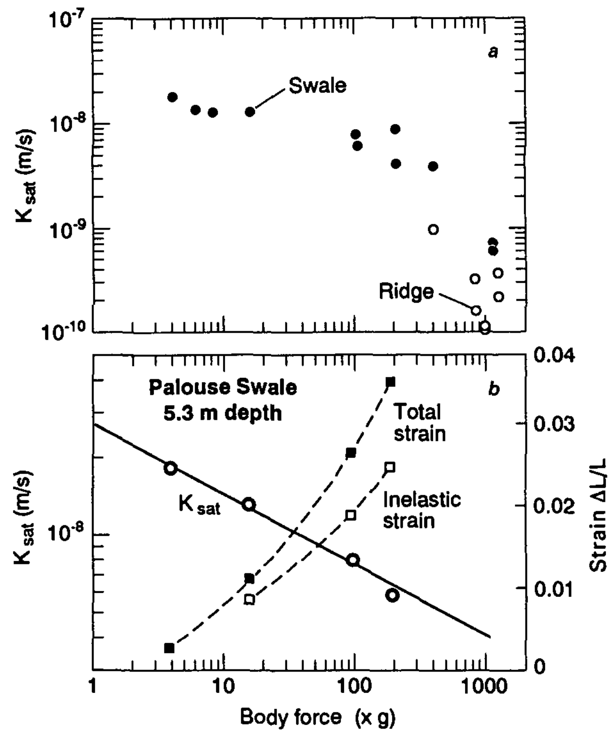

Fig. 6. (a) Saturated hydraulic conductivity (K_{sat}) vs. maximum applied body force for several Palouse samples and (b) K_{sat} and compressive strain ($\Delta L/L$, where L is the height of the sample) vs. applied body force for a Palouse swale sample. The K_{sat} and total strain were measured during centrifugation, and the inelastic strain was measured after centrifugation stopped.

compaction. For some of the falling-head centrifuge measurements, total strain was measured simultaneously by a linear displacement transducer. A specially modified centrifuge (Nimmo, 1990) permitted the electrical measurements during centrifugation. The relation between K_{sat} and compaction, measured simultaneously, is shown in detail in Fig. 6b for a swale sample from 5.3-m depth. In going from 1 to 200 × g, K_{sat} declines by about a factor of 4. This might be a reasonable upper limit for the effect of centrifugation on unsaturated K. Measurements on the same sample after centrifugation show that about one-third of the strain was elastic.

For the purpose of predicting $\psi(r)$ profiles during centrifugation, $\theta(\psi)$ curves were measured in a SPOC (Constantz and Herkelrath, 1984), and approximate $K(\theta)$ values were obtained with the one-step outflow method (Gardner, 1956; Passioura, 1976). Detailed SPOC measurements, including drying and wetting $\theta(\psi)$ curves and one-step outflow measurements, were made for two samples from each sampling location. The $\theta(\psi)$ measurements enabled the conversion of one-step outflow diffusivity data to $K(\theta)$. Although these results could produce recharge rate estimates, such estimates would have questionable accuracy. The four samples were chosen to span the range of hydraulic characteristics covered by the entire set of Palouse samples. On the basis of the resulting measurements for four samples, the two representing the extremes of curve steepness, the ridge sample from 18.0-m depth and the swale sample from 4.1 m, were selected for illustration (Fig. 7 and 8) and for SSCM measurements. The extremes were selected to best represent, for testing the methods, the range of characteristics of the Palouse site. The ridge sample shows great variation of K with θ and little variation of θ with ψ, probably because it is a fine-textured sample at greater bulk density than is common in surface soils. Because the SPOC samples were unsuitable for further use, core samples from the same boreholes at 0.2 m greater depth were used for SSCM measurements.

Darcy's law (Eq. [1]) was solved for $\psi(r)$ using the one-step outflow data in Fig. 8 and with q values corresponding to a K range of 3×10^{-11} to 7×10^{-9} m s^{-1}. The results show that, at speeds of about 146 s^{-1} (400 × g) and greater, centrifugal force overwhelms $d\psi/dr$ for both samples. This speed was chosen for the SSCM measurements. For these compressible, fine-textured samples, all measurements were made at the same speed, so that differences in K could be related to θ alone. Used with the apparatus of Fig. 2b, the chosen speed applied compressive forces equivalent to about 9.7 m of overburden, thus exceeding that of the swale sample (4.3 m) and not reaching that of the ridge sample (18.2 m). The centrifugal force compacted the swale sample to 97.3% of its original volume while having no measurable effect on the ridge sample. The first fluxes applied to each sample were chosen to produce a K slightly less than K_{sat}. Succeeding values of q were progressively smaller, until there was too little flow for accurate measurement.

The SSCM $K(\theta)$ measurements for the two selected Palouse samples are shown in Fig. 8. Comparison with the one-step outflow results in the same figure suggests good agreement for the swale samples, the outflow data appearing much like an

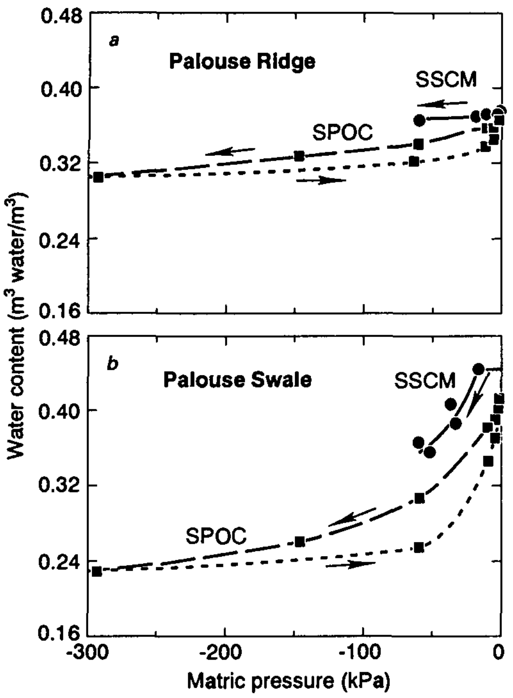

Fig. 7. Water retention data, measured using the submersible pressure outflow cell (SPOC) method and the steady-state centrifuge method (SSCM) for (a) Palouse ridge and (b) Palouse swale samples. The ridge samples came from depths of 18.0 m for the SPOC and 18.2 m for the SSCM, the swale samples from 4.1 m for the SPOC and 4.3 m for the SSCM.

extension of the SSCM data. The ridge results compare less favorably, but the two data sets differ in θ by only about 0.03 m^3 water m^{-3} and have a similarly steep $K(\theta)$ slope. These $K(\theta)$ values are at and slightly below the low-K extreme of $K(\theta)$ measurements for a Palouse soil at 24- to 43-m depth by Conca and Wright (1992a,b). Because of the great distance (about 100 km) between their field site and ours, it is not surprising that our measurements do not fall in the midst of theirs.

The $\theta(\psi)$ data obtained in connection with the SSCM measurements appear in Fig. 7 with the SPOC data. Agreement is good with respect to the shape of the curves. There is a θ-direction offset in each pair of curves, but this is not surprising because the samples in each pair were not identical and had different porosities before and during the measurements. The SSCM data for the swale sample show considerable scatter, possibly because the relatively low density of the sample makes it sensitive to the mechanical influence of tensiometer contact.

For the conditions of each of the five swale measurements of Fig. 8, the SSCM $K(\psi)$ results led to the computed $\psi(r)$ profiles in Fig. 9. These profiles indicate that the three wettest measurements were done with $d\psi/dr$ essentially equal to zero in most of the sample. For the other two measurements,

Table 2. Measurements of saturated hydraulic conductivity (K_{sat}) for Palouse samples.

Depth	Force†	K_{sat}
m	$\times g$	m s^{-1}
	Ridge sampling location	
4.7	1	5.7×10^{-7}
5.9	1	4.8×10^{-9}
8.9	1000	1.1×10^{-10}
9.0	1000	1.0×10^{-10}
13.6	800	1.6×10^{-10}
15.0	1200	2.1×10^{-10}
18.0	1200	3.5×10^{-10}
18.1	800	3.1×10^{-10}
18.2	400	9.3×10^{-10}
	Swale sampling location	
4.3	400	3.9×10^{-9}
4.5	1	6×10^{-8}
5.3	1	2.5×10^{-8}
5.3	4	1.8×10^{-8}
5.3	6	1.4×10^{-8}
5.3	8	1.3×10^{-8}
5.3	16	1.3×10^{-8}
5.3	100	7.9×10^{-9}
5.3	200	6.9×10^{-9}
5.4	1	5×10^{-8}
5.9	1	7.1×10^{-9}
17.0	1100	6×10^{-10}
19.4	1100	7×10^{-10}

† Maximum compressive force (expressed as a multiple of gravitational force at earth's surface) to which the sample was exposed before or during the measurement. All the measurements at 5.3-m depth in the swale were made with the same sample.

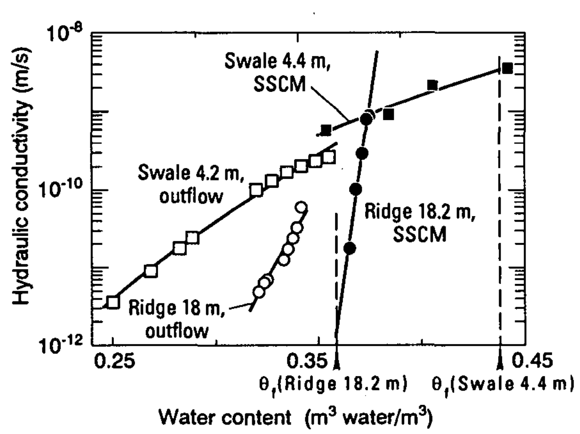

Fig. 8. Hydraulic conductivity vs. water content for the same Palouse samples as in Fig. 7, measured using the steady-state centrifuge method (SSCM), and also computed from one-step outflow data. The smooth curves are least squares power law fits. The SSCM hydraulic conductivity corresponding to the field water content (θ_f) is taken as an indication of recharge rate.

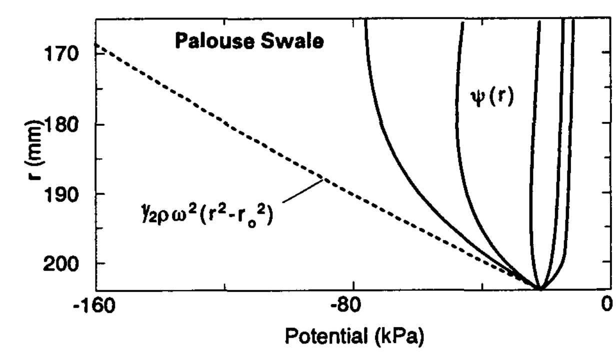

Fig. 9. Steady-state centrifuge profiles of matric pressure (ψ) as a function of distance from the center of rotation (r) for the properties and conditions of the five steady-state centrifuge method (SSCM) Palouse swale measurements of Fig. 8. The dashed line shows the equilibrium profile of the centrifugal potential (Eq. [3]). In each case the net driving force, determined by the difference between $\psi(r)$ and the centrifugal potential, is significantly different from zero. This confirms one of the necessary conditions for a valid SSCM measurement.

$d\psi/dr$ was not zero, but was sufficiently different from the centrifugal force that the net force could be determined. The ridge results (not shown) deviated even more from the equilibrium profile. Thus in both cases the SSCM profiles are suitable for determining K.

Estimating recharge rates at the Palouse site is easier than at the Panoche site because it has a much greater degree of uniformity with depth, as known from textural observations made at the site and confirmed with laboratory measurements. Water content measurements also showed a high degree of uniformity at and near the depths sampled. The combination of uniform water content and texture suggests that the assumption of negligible ψ gradient should be adequate for our feasibility test. Reading off the K values corresponding to the θ values indicates a recharge rate of 110 mm yr^{-1} in the swale and <1 mm yr^{-1} on the ridge. The uncertainty here is larger for the ridge because of the steepness of the $K(\theta)$ curve. The greater recharge rate in the swale, where water can accumulate, was expected. For comparison, Bauer and Vaccaro (1990) computed a value of 63 mm yr^{-1} averaged across a 2.6-km^2 area, 3.2 km away from our site. Although quantitative conclusions cannot be based on our results from only two samples, the fact that for the ridge we find less recharge than the areally averaged value of Bauer and Vaccaro (1990) and for the swale more recharge suggests that the results are reasonable and supports the feasibility of using the SSCM in recharge studies.

DISCUSSION

A critical feature of any recharge rate determination is whether it is sufficiently accurate and reliable for its intended application. For our method, the readily quantifiable factors contributing to uncertainty may be considered in two categories. First, there is the uncertainty of the measured $K(\theta)$ results, determined by combining estimated uncertainties on all the quantities used in the computation. The uncertainty in K ranged from ±6% for the wettest points to ±20% for the driest. The uncertainty in θ was about ±0.002 m^3 water m^{-3}. Except for the driest K values, these uncertainties for the Palouse and Panoche media are about the same as for earlier measurements on Oakley sand (Nimmo and Akstin, 1988). Second, there is uncertainty in θ_f that translates into uncertainty in recharge rate when the value $K(\theta_f)$ is read off the curve. This becomes large when K has a strong θ dependence. The ±0.002 m^3 water m^{-3} uncertainty in θ_f leads to uncertainties in $K(\theta_f)$ of about ±5% for the Palouse swale and ±90% for the Palouse ridge sample, and ±22 and ±9% for the 7.7- and 8.1-m Panoche samples. The steep $K(\theta)$ curve of the Palouse ridge sample shows how the characteristics of the medium, rather than the SSCM, can limit the accuracy of the recharge determination. If, as an alternative to the θ targeting procedure we have used so far, the recharge rate were determined using a field ψ measurement and a $K(\psi)$ curve, it would be subject to an additional uncertainty due to $\theta(\psi)$ hysteresis. The hysteretic SPOC measurements suggest that this uncertainty would be about ±50%. Where the $K(\theta)$ dependence is unusually strong, as for the ridge sample, the $K(\psi)$ approach may be superior even with the uncertainty of hysteresis. All of these estimates of uncertainty must be considered along with the deviations of field conditions from the assumed gravity-driven ideal. At the Panoche site, for example, there is more uncertainty from the incomplete knowledge of the ψ profile than from the $K(\theta_f)$ measurements.

An important limitation of the SSCM is that some media and conditions require a great centrifugal force in order that the net driving force can be known accurately. The medium may have to be compressed to a greater extent than it would be in the field. While for sandy media at low θ this is not a serious problem, in other circumstances it may alter the hydraulic characteristics to a significant but unknown degree. For the Palouse swale, the results shown on Fig. 6b suggest that a centrifugal strain of about 4% may change K_{sat} by roughly a factor of 4. Because at θ_f the swale sample is nearly saturated, the effect on $K(\theta_f)$ may also be nearly a factor of 4, indicating an underestimation of recharge. Besides being nearly saturated, this fine-textured sample was particularly vulnerable to compaction and was subjected to an equivalent overburden nearly twice as great as existed in the field. It may be nearly a worst case for effects of centrifugal compaction. Making all measurements with the same centrifugal force assures that compaction effects will not confuse the dependence of K on θ, but it limits the range of K that can be measured. A fuller understanding of the relation between compaction and unsaturated hydraulic properties is desirable to extend the range of media and conditions that the SSCM can accommodate.

Some developments are needed in the general approach to recharge rate measurement using core samples, whether SSCM is the chosen method or not. Most important is the need for negligibly disturbed samples. All available core-sampling techniques involve some structural disruption that can affect $K(\theta)$. Better apparatus and procedures are desirable, as well as an understanding of sampler-induced disturbances that might permit corrections of measured results. A second need concerns applications that require an areally averaged recharge rate, for which it is desirable to have an optimized scheme for choosing sample locations and for computing an appropriate average of measured results.

The SSCM has several demonstrated advantages for the determination of recharge rates. It can measure $K(\theta)$ for core samples of various textures across a K range that includes values of particular importance in recharge applications. It permits a determination of both $K(\theta)$ and $K(\psi)$, affording flexibility in targeting field conditions. The ability to make measurements quickly, to adjust the K to be measured, and to know the approximate values of K, θ, and ψ while a series of measurements is in progress, facilitates the approach to a target θ or ψ value. The method produces measurements of good accuracy, at least with respect to the characteristics of the samples. Finally, it permits measurements with an overburden pressure that approximates field conditions.

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