WATER RESOURCES RESEARCH, VOL. 48, W09602, doi:10.1029/2012WR012053, 2012

Practical estimates of field-saturated hydraulic conductivity of bedrock outcrops using a modified bottomless bucket method

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Received 27 February 2012; revised 9 July 2012; accepted 21 July 2012; published 14 September 2012.

[1] The bottomless bucket (BB) approach (Nimmo et al., 2009a) is a cost-effective method for rapidly characterizing field-saturated hydraulic conductivity K_{fs} of soils and alluvial deposits. This practical approach is of particular value for quantifying infiltration rates in remote areas with limited accessibility. A similar approach for bedrock outcrops is also of great value for improving quantitative understanding of infiltration and recharge in rugged terrain. We develop a simple modification to the BB method for application to bedrock outcrops, which uses a nontoxic, quick-drying silicone gel to seal the BB to the bedrock. These modifications to the field method require only minor changes to the analytical solution for calculating K_{fs} on soils. We investigate the reproducibility of the method with laboratory experiments on a previously studied calcarenite rock and conduct a sensitivity analysis to quantify uncertainty in our predictions. We apply the BB method on both bedrock and soil for sites on Pahute Mesa, which is located in a remote area of the Nevada National Security Site. The bedrock BB tests may require monitoring over several hours to days, depending on infiltration rates, which necessitates a cover to prevent evaporative losses. Our field and laboratory results compare well to K_{fs} values inferred from independent reports, which suggests the modified BB method can provide useful estimates and facilitate simple hypothesis testing. The ease with which the bedrock BB method can be deployed should facilitate more rapid in situ data collection than is possible with alternative methods for quantitative characterization of infiltration into bedrock.

Citation: Mirus, B. B., and K. S. Perkins (2012), Practical estimates of field-saturated hydraulic conductivity of bedrock outcrops using a modified bottomless bucket method, *Water Resour. Res.*, *48*, W09602, doi:10.1029/2012WR012053.

1. Introduction

[2] Direct measurements of field-saturated hydraulic conductivity K_{fs} (L/T) provide invaluable insights to inform hydrologic models or management decisions for a given site of interest. Because field experiments are expensive, the most cost-effective method for allocating resources toward characterizing K_{fs} depends on the objectives of the given study. There is a wide array of documented methods for field characterization of K_{fs} on soils, which typically involve some form of a ponded infiltration test. However, there is a lack of convenient methods for characterizing surface K_{fs} on bedrock outcrops. Thus, quantitative characterization of bedrock infiltration often relies on slug tests in the subsurface, laboratory experiments on intact core samples, or hydraulic conductivity values reported in the literature for lithologies similar to the site of interest. Our objective is to develop and test a method for practical field estimates of K_{fs} on bedrock outcrops.

[3] The value of double-ring versus single-ring ponded infiltration tests on soils is debatable [e.g., *Bouwer*, 1986] and the nuances of the falling-head test are not trivial [e.g., *Phillip*, 1992]. However, for practical applications in the field, the simplicity of the single-ring, falling-head infiltration test often considerably outweighs the possible advantages of more complex experiments. In this spirit, the bottomless bucket (BB) method [*Nimmo et al.*, 2009a] was developed as a parsimonious formulation of the standard single-ring ponded infiltration method of soils analysis [*Reynolds et al.*, 2002]. The BB method involves a falling-head test and employs an analytical solution to account for the effects of lateral subsurface spreading. Because it favors simplicity over precision, its rapid deployment allows numerous measurements in a short time that are extremely useful for performing statistical analyses or hypothesis testing.

[4] The original motivation for developing the simple BB method was to provide reconnaissance information with limited resources to support the planning of more involved experiments. For example, *Nimmo et al.* [2009a] employed results from 28 BB tests in the Mojave National Preserve (California, USA) to gain insights on spatial variability before designing detailed experiments to quantitatively evaluate the influence of pedogenesis on soil-hydraulic properties [*Nimmo et al.*, 2009b; *Mirus et al.*, 2009]. Similarly, *Perkins et al.* [2011] used 42 BB tests to assess spatial variability in soil-hydraulic properties and land-use impacts

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Published in 2012 by the American Geophysical Union.

to select a site for a larger-scale tracer application. The BB method has also proven a particularly useful approach for rapid characterization of K_{fs} in settings where more involved and robust techniques are highly impractical. For example, *Perkins et al.* [2012] conducted 55 BB tests in a remote, densely forested site on the island of Maui (Hawai'i, USA) to demonstrate the effectiveness of reforestation and native plant restoration on the recovery of soil-hydraulic properties and ecologic functioning. Similarly, *Ebel and Nimmo* [2010] used 8 BB tests to characterize infiltration capacity in remote areas on Rainier Mesa within the Nevada National Security Site (NNSS) (Nevada, USA), where site access and sample collection are highly regulated.

[5] This work was motivated by the need to quantify infiltration in remote areas of Pahute Mesa (PM), also within the NNSS. Snowmelt and flooding on bedrock outcrops are particularly important for quantifying infiltration and recharge in arid environments like PM. Established methods for estimating K_{fs} of exposed bedrock were not practical for our investigation at PM. For example, slug tests [e.g., *Hvorslev*, 1951] require an existing borehole or well and a sufficiently shallow water table. Laboratory measurements [e.g., *Caputo and Nimmo*, 2005] would require intact core samples that are difficult and costly to obtain. Large-scale ponded infiltration tests [e.g., *Caputo et al.*, 2010] are challenging in rugged terrain and would require unreasonably large quantities of water for a single test in a remote, arid environment.

[6] Here, we present a modification of the BB method for practical estimates of K_{fs} on bedrock outcrops. Like the original BB method for soils, the bedrock BB method was also developed to favor simplicity, cost-effectiveness, ease of use, and durability over precision. First, we describe the original BB method for soils and the minor modification of the apparatus and protocol for adaptation to bedrock infiltration. Then we evaluate the reproducibility of K_{fs} estimates using both repeated laboratory experiments and a sensitivity analysis. Finally, we present results from the modified and original BB method on both bedrock and soils at PM to further illustrate the methods' potential utility for hypothesis testing and informing models.

2. Review of the Bottomless Bucket Method for Soils

[7] A detailed description of the BB method and supporting theoretical developments are provided by *Nimmo et al.* [2009a], but we repeat the salient points here. Typical BB tests employ a bucket-sized infiltration ring (i.e., a bottomless bucket), a stopwatch, a ruler, and a few liters of water. The BB is placed over a test area, positioned such that no impediments (e.g., stones, roots, or surface litter) are located below the rim, and then gently twisted until refusal (ideally about 5 cm below the surface). For dry, sand/stone-rich soils such as those on PM it is also necessary to seal the outer bucket edges with bentonite to eliminate lateral leakage. The depth from the upper rim of the BB to the ground surface is measured in four locations around the rim, and their average subtracted from the total height of the bucket to calculate the average depth of insertion. Following this step it is useful to fix the ruler to the inside of the bucket. Water is added into the BB as quickly as possible without disturbing the soil surface (note: a piece of paper or plastic can be placed on the soil surface as water is added, then removed following application of water). Once a sufficient volume of water is ponded in the ring, the water level is measured with the ruler and the stopwatch is started; falling head is monitored through time until the water level approaches zero, but before ponding ceases. At this point, the time and water level are noted and more water is added to the BB again. These falling-head tests are repeated until the rate of head decline is of sufficient regularity to support an assumption that field-saturated conditions are reached. Using results from the final (or multiple) field-saturated experiment(s) the K_{fs} value is calculated for each measurement interval with the following equation:

$$K_{fs} = \frac{L_G}{t} \ln\left(\frac{L_G + \lambda + D_o}{L_G + \lambda + D}\right) \tag{1}$$

where D_o is the initial water depth (L) when the stopwatch is started, D is the depth of water (L) at time t (T), λ is the macroscopic capillary length (L) [see *White and Sully*, 1987], and L_G is the ring installation scaling depth (L). Thus with a series of experiments monitoring $D(t)$, an examination of the K_{fs} estimates through time can be used to evaluate the field-saturation assumption. Equation (1) is sufficiently simple that this evaluation can be performed in the field with a laptop or calculator.

[8] Typical values for λ range from 0.25 m for fine textured soils without macropores to 0.03 m for coarse and gravelly soils. Because K_{fs} value exhibits minimal sensitivity for this range, a standard value of 0.08 m is appropriate for most soils applications [*Elrick et al.*, 1989]. The value of L_G is calculated based on the geometry of the BB installation:

$$L_G = C_1 d + C_2 b \tag{2}$$

where d is the depth of ring insertion (L), b is the inside diameter (L) of the BB, and the dimensionless constants C_1 = 0.993 and C_2 = 0.578, as defined by *Reynolds et al.* [2002]. One key element of the BB experimental design is that the range of ponding depths for individual falling-head tests are limited to within 0.03–0.10 m [see *Nimmo et al.*, 2009a]. The method thus favors several repeated infiltration experiments over a narrow range of ponding depths, rather than fewer and longer experiments over a wider range of depths. Equations (1) and (2) are developed assuming the experiments use a straight-walled bucket with a uniform diameter, which is preferred. However, it is also acceptable to use a bucket with slightly tapered walls where the diameter decreases with depth, in which case the average diameter of the originally filled portion of the bucket is used [see *Nimmo et al.*, 2009a].

3. Modified Bottomless Bucket for Bedrock Outcrops

[9] The minor modifications we develop here allow the BB method to be applied successfully to estimating K_{fs} for bedrock outcrops. As with the application for soils, the site selection for a bedrock outcrop requires a relatively level surface with sufficient area to allow placement of the BB.

Dust, vegetation or litter can be cleared away from the surface prior to installation, but surface crusting or lichen cover can be left in place to characterize in situ infiltration under natural conditions. Instead of inserting the lower BB rim into the subsurface, the BB is sealed to the surface using a nontoxic, quick-drying silicone gel, which is designed for sealing gaps between surfaces in kitchen and bathroom construction or renovation. Gaps between the bottom ring of the bucket and the bedrock greater than 0.5 cm should be avoided to prevent failure of the seal; if necessary, the bottom of the bucket can be cut with a saw or knife to accommodate any irregularities in the bedrock microtopography. A thick bead of gel is applied around the bottom rim of the BB, which is placed securely on the rock; visible gaps are sealed around the outside with additional gel using a rubber glove. Depending on field conditions, 1.0 oz of the gel is generally sufficient for each BB test (using a 0.14 m diameter bucket). Note that for the bedrock tests, it is important to minimize the application of excess gel to the inner rim of the BB to avoid reducing the surface area of infiltration. The gel is then left to set for at least 8 h (check manufacturer's specifications) before conducting any experiments.

[10] The lack of ring insertion into the bedrock eliminates the impact of d on L_G. Therefore, equations (1) and (2) are combined to become:

$$K_{fs} = \frac{0.578b}{t} \ln\left(\frac{0.578b + \lambda + D_o}{0.578b + \lambda + D}\right) \tag{3}$$

Any significant reduction in the area of infiltration resulting from excess silicone gel on the inner BB rim should be accounted for in equation (3) using an effective diameter b_{eff}, which can be taken as the mean diameter of the exposed bedrock within the BB not covered by gel.

[11] The lower K_{fs} for bedrock and correspondingly slower infiltration rate often result in the need to monitor falling head levels over several hours or even days, which necessitates the use of a cover for the bucket to prevent evaporative losses. Additionally, we recommend using a solar shield to minimize the impact of temperature variations on the viscosity of water. In the case of extreme temperature variations this could lead to roughly a factor-of-two uncertainty in K_{fs} estimates. In such cases the temperature-viscosity effect can be accounted for by monitoring water temperature and calculating the intrinsic permeability for a given time interval. In contrast, the effect of temperature on the density of water has a negligible impact on K_{fs} estimates.

[12] With the bucket lid and sun shield, the bedrock BB can be monitored intermittently throughout the day or week to determine when field-saturated infiltration conditions are reached. It is possible for one individual to monitor multiple bedrock BB tests at once, with the optimal number depending on the rate of head decline and the distance between buckets. To avoid removing the bucket lid (and potentially causing leakage or evaporative water loss), we recommend using a clear plastic bucket, such that changes in water level through time can be measured from the outside of the bucket either with a ruler or noted with a permanent marker and measured at the end of the test(s). Measurements should be taken to the nearest millimeter and second to maximize precision of the method. Once the desired experiments have been completed, the plastic bucket can be removed quite easily and the silica gel should be scraped off with a dull knife leaving only a minor residual ring.

4. Testing and Analysis

[13] The potential downsides of the modified BB method are that the assumptions regarding the geometry of lateral spreading accommodated for in the analytical solution in equation (3) were developed largely for unconsolidated materials and have not been fully tested for bedrock. To evaluate the reproducibility of the method for bedrock we conducted laboratory experiments and used the results to perform a cursory sensitivity analysis of the influence of the bucket diameter and the analytical solution on K_{fs} estimates.

[14] The laboratory experiments were conducted on calcarenite, which is a type of limestone composed of detrital carbonate grains. Calcarenite is relatively homogeneous and highly permeable, so it is often considered to be roughly the carbonate equivalent of sandstone. We employed a 40 × 24 × 15 cm rectangular block of Plio-Pleistocene calcarenite taken from a quarry in the southern Puglia region of Italy. Calcarenite from this quarry has been the focus of previous efforts toward laboratory characterization of hydraulic properties [*Caputo and Nimmo*, 2005] and in situ measurements of bedrock infiltration [*Caputo and de Carlo*, 2011].

[15] We elevated the sample with the largest surface facing up by supporting it on cinder blocks in a big sink, which allowed free drainage from its base. Our series of laboratory experiments explored a range of bucket diameters and initial conditions to quantify their influence on K_{fs} estimates from the modified BB method. We first employed a 20 cm diameter, straight-walled bucket, followed by a 14 cm diameter, tapered bucket, and then a 10 cm diameter straight-walled bucket. Finally, we conducted experiments with a minidisk tension infiltrometer. For each bucket diameter, we repeated falling-head experiments throughout the day or until seepage occurred at the base of the block, indicating the entire block was reaching near-saturated conditions. For all bucket diameters and each falling-head experiment the initial and final ponding depths were approximately 7 cm and 3 cm, respectively, +/−1 cm. We allowed the sample to air dry for one week between the experiments for each bucket diameter (as well as the mini disk), and assumed field-saturated conditions were reached once the cumulative infiltration curve with time for successive experiments could be reasonably approximated as a single linear relation. The assumption of field-saturated conditions can also be evaluated by comparing the variations between successive K_{fs} estimates within a given falling-head experiment and the geometric mean K_{fs} from one experiment to the next. In general, any assumption of field-saturated conditions should meet the criteria that performing additional experiments does not significantly alter the K_{fs} estimates.

[16] Figure 1 shows graphs of K_{fs} estimates as a function of cumulative water volume added and times series of cumulative infiltration depths for the successive falling-head experiments conducted with each bucket diameter. Measurements taken under the assumption of field-saturated conditions are shown with filled symbols. Examination of Figure 1a reveals that after approximately 1 L of water is added, the K_{fs} estimates are similar, regardless of bucket diameter, so the assumption that field-saturated conditions

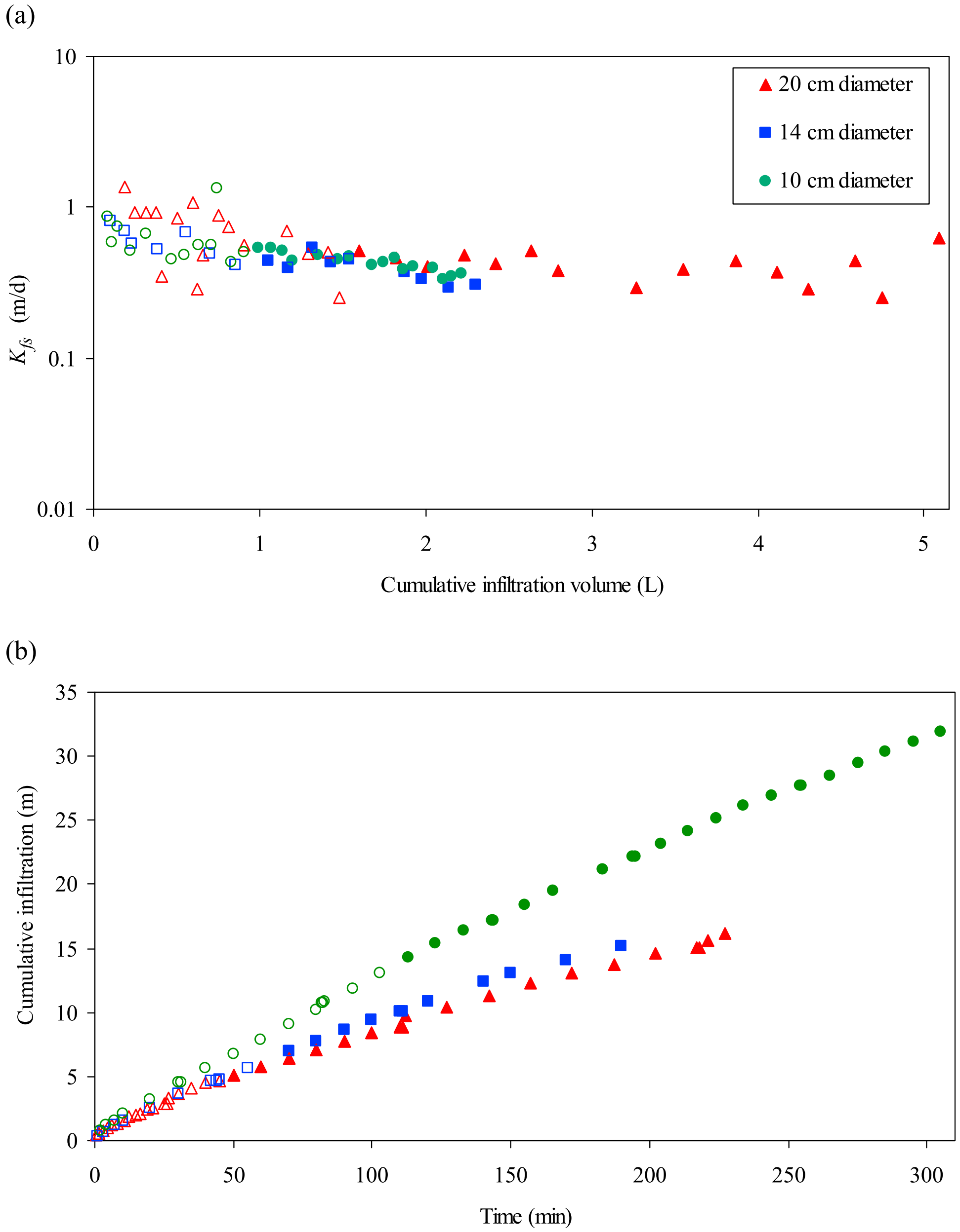

Figure 1. Graphs showing results from laboratory experiments on the calcarenite block for three bucket diameters: (a) field-saturated hydraulic conductivity (*Kfs*) estimates as a function of cumulative infiltration volume and (b) cumulative infiltration depth with time. Solid symbols represent measurements taken with the assumption of field-saturated conditions.

are reached seems reasonable. We also performed a series of two-sample *t* tests assuming unequal variance to examine the influence of bucket diameter. Results showed that the difference among the three bucket sizes is not statistically significant at the 99% confidence level. Figure 1b shows that the cumulative depth of infiltration to reach field saturation is greater for the 10 cm diameter bucket, but similar for the 14 and 20 cm diameter buckets.

[17] Figure 2 shows the K_{fs} estimates from the laboratory experiments for the three bucket diameters taken as the geometric mean of measurements acquired under field-saturated conditions (see Figure 1) and the mini disk tension infiltrometer, as well as independent estimates reported in the literature. Given the range of acceptable values for macroscopic capillary length scale, λ, reported by *Elrick et al.* [1989], we calculate the relative impact of $\lambda = 0.03$ m and $\lambda = 0.25$ m. The sensitivity to λ is thus shown on Figure 2 using error bounds, which illustrates that its influence is small. Examination of Figure 2 reveals that estimates using the BB method compare quite well to the alternative approaches, particularly to the results derived using a much larger infiltration ring [*Caputo and de Carlo*, 2011]. The variability between the estimates for the different core samples from *Caputo and Nimmo* [2005] suggests that at smaller scales, calcarenite is less homogeneous than one might assume. The minidisk infiltrometer provides a considerably lower estimate than all

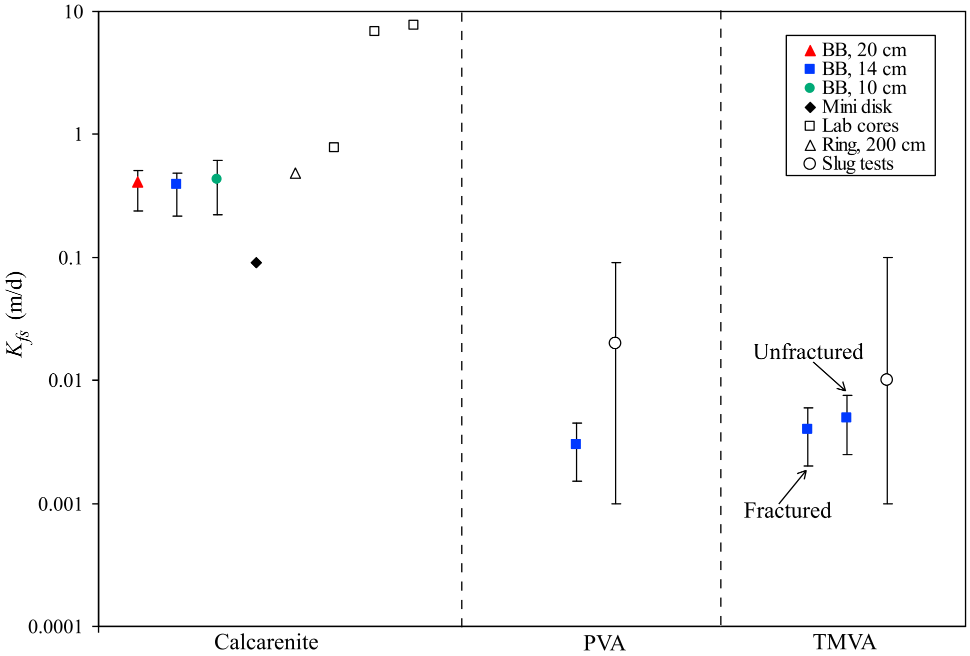

Figure 2. Field-saturated hydraulic conductivity (*Kfs*) for calcarenite and volcanic tuffs estimated using bedrock bottomless bucket (BB) and alternative approaches, with uncertainty bounds shown when available. Results from this study are shown with solid symbols, and open symbols are values reported elsewhere. Values for lab cores are from *Caputo and Nimmo* [2005], results for the 200 cm diameter infiltration ring are from *Caputo and de Carlo* [2011], and slug tests analysis for the paintbrush volcanic-rock aquifer (PVA) and Thirsty Canyon/Timber Mountain volcanic-rock aquifer (TMVA) are reported by *Belcher et al.* [2002].

the other approaches, which is not surprising given that the apparatus employs a 4.5 cm diameter plate with the water supplied under tension and relies on the assumption of known water retention and hydraulic conductivity relations. When compared to the variability in estimated K_{fs} values from other methods, the lack of sensitivity to bucket diameter and the minimal sensitivity to λ suggest that estimates from the modified BB are accurate and highly reproducible in the field.

5. Applications at Pahute Mesa

[18] Nuclear testing at the NNSS has introduced radionuclide contaminants into the subsurface, which pose a potential threat to water quality in the underlying aquifers. The PM is of particular interest within the NNSS because it was the site of numerous underground nuclear tests, including some of the largest and deepest tests ever conducted at the site [*U.S. Department of Energy*, 2000]. Estimates of K_{fs} of surface soil and bedrock outcrops are needed to determine infiltration and the recharge boundary condition for saturated flow models of the PM; due to the remote location and substantial access restrictions no direct estimates are available to date. In particular, the unknown properties for vast areas of exposed bedrock across PM present the greatest source of uncertainty in developing regional-scale infiltration models (Dan Levitt, personal communication, 2011).

[19] Field experiments were conducted on PM by the USGS between 7 and 9 November 2011 at seven sites for a total of 13 surface measurement locations on bedrock and soils. The results from the experiments on soils and measured soil depths are summarized in the auxiliary material[1], whereas the results from the bedrock BB method are shown in Figure 2 with the error bars indicating the range of uncertainty in λ as described above. Application of the bedrock BB method at PM included three tests at one location (PM.BR1) on the paintbrush volcanic-rock aquifer (PVA) and individual tests at two adjacent locations (PM.BR2 and PM.BR3) on the Thirsty Canyon/Timber Mountain volcanic-rock aquifer (TMVA).

[20] We further evaluate the effectiveness of the bedrock BB tests by comparing our field estimated K_{fs} values and their uncertainty to the only other available estimates of hydraulic conductivity from the same geologic units [*Belcher et al.*, 2002]. *Belcher et al.* [2002] report that for nine slug tests analysis of the PVA the geometric mean saturated hydraulic conductivity K is 0.02 m/d with a 95% confidence interval of 0.001–0.09 for the geometric mean; for eleven analysis of the TMVA the geometric mean K is 0.01 m/d with a 95% confidence interval of 0.001–0.1 for the geometric mean (Wayne Belcher, written communication, 2012). The K_{fs} value for our BB tests on the PVA is 0.005 m/d; the BB test K_{fs} values for the TMVA are 0.004 and 0.003 m/d. Thus estimates using the modified BB method are within the reported ranges for the slug tests, though on the lower end of the 95% confidence intervals (Figure 2). It should be noted that slug tests estimates are based on measurements reflecting

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2012WR012053.

horizontal, saturated fluxes, whereas the BB estimates are based on measurements reflecting vertical, near-saturated fluxes.

[21] To illustrate the potential utility of the modified BB method we used it to explore a simple hypothesis regarding whether or not fractures on exposed bedrock influence infiltration. We conducted two adjacent BB experiments, one on unfractured (PM.BR2) and the other on fractured (PM.BR3) exposures of the TMVA. The fracture aperture ranges from 0.5 to 3 mm and extends through the middle of the infiltration ring. The similarity between effective K_{fs} values on the fractured and unfractured TMVA (Figure 2) suggests that the filling of fractures with weathering material may negate the impact of fractures on bedrock infiltration at the surface. Clearly, rigorous testing of this hypothesis would require additional BB experiments for a range of fractures exposed on the TMVA. However, this example illustrates how the simplicity of the modified BB method could facilitate sufficient experiments to conduct statistical analysis to test this or similar hypothesis.

6. Discussion and Conclusions

[22] The original BB method [*Nimmo et al.*, 2009a] has proven a useful approach for rapidly characterizing K_{fs} of soils to test hypothesis [*Perkins et al.*, 2012] or design more elaborate field experiments [*Nimmo et al.*, 2009b; *Perkins et al.*, 2011]. We present modifications to the BB method to allow useful estimates of bedrock K_{fs}, that are quite rapid relative to established alternatives [*Caputo and Nimmo*, 2005; *Caputo et al.*, 2010]. We test the reproducibility of our method for a range of bucket diameters in the laboratory and conduct a sensitivity analysis of the analytical solution employed. The issue of determining steady state or field-saturated conditions during ponded infiltration is a tricky one, particularly in the context of obtaining practical estimates of K_{fs} with limited time and resources. Our criterion for determining field-saturated conditions was adopted to avoid conducting multiple additional falling-head tests that do not constrain the accuracy of the K_{fs} estimates with precision greater than other sources of measurement and analytical error. Although the bedrock BB method is intended to provide practical estimates of K_{fs}, it produces reasonably accurate results for both the calcarenite from Italy and the volcanic tuffs in Nevada. The possible shortcomings of the BB method could be addressed more rigorously through further evaluation for different rock types and at contrasting field sites. Regardless, when employed consistently the method as described here can be applied in remote locations with minimal water and equipment for estimates that are sufficient for comparing rock types, and improving basic understanding of bedrock infiltration at a given field site. The method could also be useful for informing hydrologic models where near-surface flow through bedrock is important [e.g., *Woolhiser et al.*, 2006]. The simplicity of this practical method makes it a valuable tool for hypothesis testing or field reconnaissance with limited resources, which is becoming an increasingly necessary approach in hydrologic research.

[23] **Acknowledgments.** This work was prepared in cooperation with the U.S. Department of Energy, National Nuclear Security Administration, Nevada Site Office, under interagency agreement DE-AI52-07NV28100. Field assistance from Bill Dam, Wayne Belcher, and Charles Horowitz is greatly appreciated. Special thanks to Dan Levitt from Los Alamos National Laboratory for motivating the method development and for his field assistance and photography. Very special thanks to Maria Caputo for providing the calcarenite block. We are grateful to the editors and anonymous reviewers for their constructive comments and suggestions that have greatly improved the quality of this work. John Nimmo also provided valuable guidance and encouragement.

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