A Modification to the Bouwer and Rice Method of Slug-Test Analysis for Large-Diameter, Hand-Dug Wells

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Abstract

The Bouwer and Rice method of estimating the saturated hydraulic conductivity (K_s) from slug-test data was evaluated for geometries typical of hand-dug wells. A two-dimensional, radially symmetric and variably saturated, ground water transport model was used to simulate well recovery given a range of well and aquifer geometries and unsaturated soil properties, the latter in terms of the van Genuchten parameters. The standard Bouwer and Rice method, when applied to the modeled recharge rates, underestimated K_s by factors ranging from 1.3 to 5.6, depending on the well geometry and the soil type. The Bouwer and Rice analytical solution was modified to better explain the recovery rates as predicted by the numerical model, which revealed a significant dependence on the unsaturated soil for the shallow and wide geometries that are typical of traditional wells. The modification introduces a new parameter to the Bouwer and Rice analysis that is a measure of soil capillarity which improves the accuracy of K_s estimates by tenfold for the geometries tested.

Introduction

The large number of hand-dug wells in developing areas of the world present an important resource for estimating the saturated hydraulic conductivity, K_s, of unconfined aquifers over large areas, yet accurate single-well field methods are lacking for these conditions. A slug test, which consists of an initial rapid head change in the well followed by observation of the well recovery rate, has the benefits of being low-cost and simple to perform, and of having existing convenient methods of data analysis. Hand-dug wells, however, often have diameters exceeding 1 m and therefore large storage relative to their depth, which complicates the analysis of well recovery data (see Mace [1999] for a discussion of the practical implications of using data from hand-dug wells).

Three common methods of analyzing slug-test data for aquifer parameters are those of Hvorslev (1951), Cooper et al. (1967), and Bouwer and Rice (1976). Of these, only that of Bouwer and Rice (1976) (also Bouwer [1989]) applies to an unconfined aquifer and can be used with either fully or partially penetrating wells. The Bouwer and Rice method is based on four assumptions: (1) drawdown of the water table around the well is negligible; (2) flow above the water table (in the capillary fringe) can be ignored; (3) head losses as the water enters the well (well losses) are negligible; and (4) the aquifer is homogeneous and isotropic.

Though these assumptions would seem to be routinely violated under many types of field conditions, the method is still used frequently because it is easy to apply and its performance is considered acceptable for many engineering applications. Of particular concern is the first assumption, as it would seem that the displacement of a large amount of water in the case of a wide and shallow well would cause significant drawdown of the water table.

Recent studies have attempted to evaluate the performance of the Bouwer and Rice method by comparing it to numerical ground water model results (Brown et al. 1995; Hyder and Butler 1995). Brown et al. (1995) evaluated the method of Bouwer and Rice by applying it to synthetic slug test data generated by numerical modeling where the value of K_s was known. Errors for K_s as derived from the Bouwer and Rice method ranged from 10% to 110%, leading Brown et al. (1995) to conclude that the method achieves reasonably good results. However, their worst cases are precisely the ones that most closely resemble that of a large-diameter hand-dug well: a low well screen length to well radius ratio and a well screen which extends up to the water table.

Hyder and Butler (1995) examined the performance of the Bouwer and Rice method for a variety of scenarios simulated with a mathematical model. They observed that the Bouwer and Rice estimate of K_s tends to increase with an increase in the screen length to well radius ratio. They also noted that the Bouwer and Rice K_s increases with specific storage and decreases with degree of anisotropy. In general, the Bouwer and Rice method underestimated the value of K_s for geometries consistent with hand-dug wells, except for where the specific storage was very large.

Mace (1999) estimated K_s from large diameter wells in confined, semiconfined and unconfined aquifers using a variety of methods, including three slug test methods (Hvorslev 1951; Cooper et al. 1967; Bouwer and Rice 1976) and two methods of interpret-

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Received May 2000, accepted October 2000.

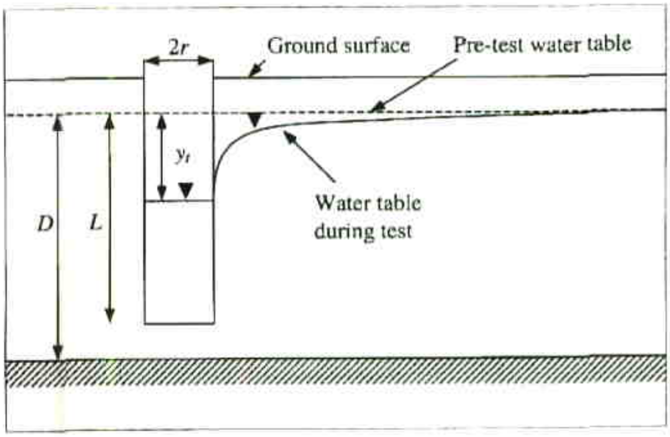

Figure 1. Geometry of a large-diameter hand-dug well in an unconfined aquifer.

ing recovery rates in large diameter wells (Herbert and Kitching 1981; Barker and Herbert 1989). In total, eight methods were used since the Hvorlsev (1951) method was used with three different shape factors. For the unconfined aquifers, Mace (1999) limited the drawdown in each test to no more than 10% of the aquifer thickness in order to approximate conditions for a confined aquifer (Herbert and Kitching 1981). Mace (1999) found that for the 12 wells presented and eight methods used, the Bouwer and Rice estimate of K_s compared most favorably overall to that predicted by a numerical model, ranking first for four of the wells and second for another four.

There are two objectives of the present study. The first is to evaluate the performance of the Bouwer and Rice method for traditional wells in unconfined aquifers, where the unsaturated soil properties are believed to be important factors in the rates of recovery. By using a numerical ground water model that accounts for flow through variably saturated media, which was not done in the previously discussed studies, the importance of unsaturated soil properties can be assessed. The second objective of the present study is to develop alternative equations to those published by Bouwer and Rice that would improve estimations of K_s by accounting for the unsaturated zone while still maintaining the simplicity of the Bouwer and Rice method. This might be especially important in developing areas of the world where access to computers and software for numerical analysis is not readily available.

Bouwer and Rice Methodology

The Bouwer and Rice equation for estimation of K_s for a hand-dug well that has no impermeable casing (i.e., fully screened, Figure 1) can be expressed as (Bouwer and Rice 1976, Equation 5)

$$K_s = \frac{r^2 \ln (R_e/r)}{2\,L} \frac{1}{t} \ln\left(\frac{y_0}{y_t}\right) \qquad (1)$$

where

r = well radius
R_e = effective radius
L = distance from the bottom of the well to the water table
t = time
y_0 = well water depth below water table at beginning of slug test
y_t = depth to water, or drawdown, at time t.

This is a modification of the equation of Thiem (1906) and assumes that the flow occurs only in the radial direction.

According to Bouwer (1989), a value for the term $(1/t)\ln(y_0/y_t)$ can be obtained by plotting $\ln(y_t)$ versus t and fitting a straight line through the straightest portion of the curve. This line has the form

$$\ln (y_t) = at + b \qquad (2)$$

where a is the slope of the line and b is the y-intercept. If the y-intercept, b, is taken to be the estimate of y_0, then Equation 2 can be rewritten as

$$\frac{1}{t} \ln\left(\frac{y_0}{y_t}\right) = -a \qquad (3)$$

The only term on the right side of Equation 1 that is not directly measurable in the field is the effective radius, R_e, which is defined as "the distance over which the head difference between the equilibrium water table in the aquifer and the water level in the well is dissipated" (Bouwer and Rice 1976). An important feature of R_e as defined in the Bouwer and Rice method is that it is a function of well radius, well water depth, and aquifer thickness only.

Bouwer and Rice (1976) determined values of R_e by means of an electric resistance network analog. Because the resistance network could not simulate unsaturated conditions or variations on the geometry of the flow field, it is this technique that forced Bouwer and Rice (1976) to make the assumptions that the water table near the well does not drop and that flow in the capillary fringe can be ignored. These assumptions are reasonable for well tests in small diameter wells, but are less realistic for shallow and wide wells.

Values for $\ln(R_e/r)$ are determined for two classes of wells: fully- and partially-penetrating. In the case where the depth of the aquifer (D) is greater than the depth of the well water (L), Bouwer and Rice (1976) suggest the value of $\ln(R_e/r)$ may be calculated as

$$\ln\frac{R_e}{r} = \left[\frac{1.1}{\ln (L/r)} + \frac{A + B \ln [(D-L)/r]}{L/r}\right] \qquad (4)$$

Bouwer and Rice (1976) impose an upper limit on the term $\ln[(D-L)/r]$, recommending that a value of no greater than 6 be used for the term $\ln[(D-L)/r]$ when D is very much larger than L. Where the well extends to the bottom of the aquifer (D = L), $\ln(R_e/r)$ may be determined from

$$\ln\frac{R_e}{r} = \left(\frac{1.1}{\ln (L/r)} + \frac{C}{L/r}\right)^{-1} \qquad (5)$$

The coefficients A, B, and C are functions of the ratio L/r and are taken from curves published by Bouwer and Rice (1976) (Figure 2) which were based on tests of the electrical resistance network analog.

Methods

Simulations of slug tests were carried out for the present study using the Hydrus-2D model for variably saturated media (Simunek et al. 1999), for the axi-symmetric (vertical well) condition. The model numerically solves Richard's equation for saturated and unsaturated flow, using the water retention function and the unsaturated hydraulic conductivity function of van Genuchten (1980).

Hydrus-2D generated an unstructured finite element mesh (Figure 3) for a transport domain with defined boundary and initial

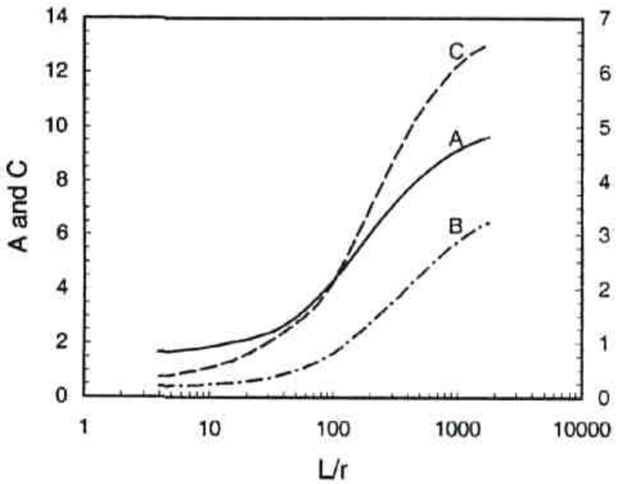

Figure 2. Dimensionless parameters A, B, and C as a function of L/r for calculation of ln(R_e/r) (adapted from Bouwer and Rice [1976]).

conditions. Node spacing was variable, with the greatest density occurring near the well wall, where nodes were located on approximately 0.04 m spacing. The number of simulation nodes was between approximately 9300 and 21,500, depending on the depth of the aquifer. The width of the transport domain was set wide enough to not significantly affect the refill rate in the well (20 to 30 m). This was verified using simulations in successively larger domains for the range of soil materials and well geometries used (data not shown). A constant equilibrium pressure head was specified at the vertical boundary on the opposite side of the well to allow water to enter the area of analysis. The well wall, and the well bottom in the case of a non-fully-penetrating well, were set as seepage faces when in contact with air, and as hydrostatic when submerged. The boundary condition along the well walls was automatically adjusted based on the actual water flux into the well. The remaining boundaries were defined as no-flux boundaries. The pressure head profile in the soil was assumed to be hydrostatic.

We assumed no loss of head as water enters the well. In the field, this assumption may result in an underestimation of K_s if a brick lining in the well or screen of other sort is causing significant head loss.

To cover the range of geometries one may expect to encounter with hand-dug wells, wells with L/r ratios of 2, 5, 10, and 20 were simulated, with L ranging from 1 to 10 m. For most of the simulations, r equaled 0.5 m, though it was also varied from 0.125 to 1.25 m. Additionally, the effect of the aquifer thickness, D, was examined by varying D between D = L and D = 41L, to simulate cases ranging from a fully penetrating well to a well in an essentially infinite aquifer. Tables 1a and 1b give the number of trials for each well-aquifer geometry simulated.

Each numerical simulation began with the well instantaneously emptied of water, even though it is most likely impractical in the field to administer a slug that has, for example, a length of 5 m and a radius of 0.5 m. However, for an aquifer of low permeability, which is common with hand-dug wells, this situation can be approximated in the field by pumping the well until it is dry at a rate much higher than the rate of recovery (Mace 1999). When the permeability is high enough that this cannot be accomplished, one would want to select a slug size that is practical to use yet provides a recovery curve that is satisfactory to the user. We chose to empty the well in every simulation to obtain the longest recovery curve possible and thus the clearest estimate of dln(y_t)/dt.

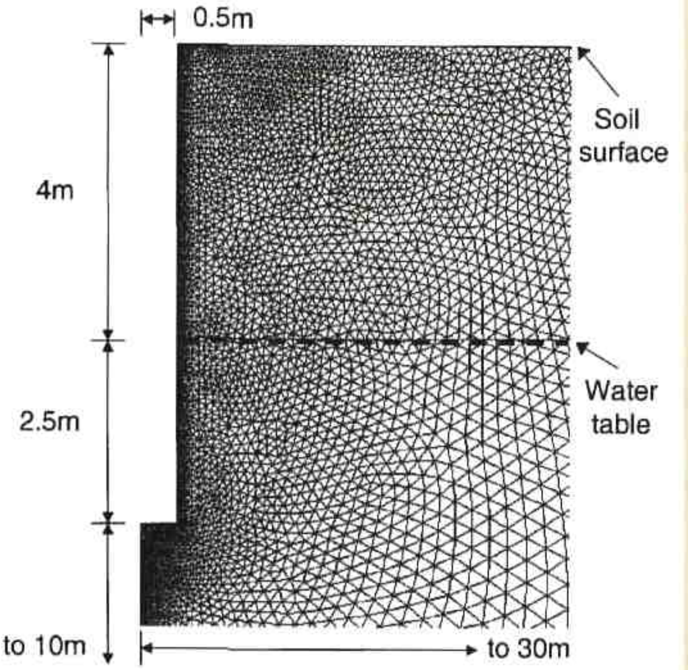

Figure 3. Example of a portion of the simulation mesh, for L = 2.5 m, r = 0.5 m, and D = 10 m. The total number of mesh nodes is about 22,000.

Table 1a
Number of Simulations by Well/Aquifer Geometry for r = 0.5 m

		L/r			
		2	5	10	20
D-L	0	20	20	20	20
	2	4	4	4	—
	5	4	4	4	—
	10	4	4	4	—
	Total	32	32	32	20

Table 1b
Number of Simulations by Well/Aquifer Geometry for r ≠ 0.5 m

		r (m)			
		0.125		0.25	1.25
		L/r		L/r	L/r
		2	20	10	2
D-L	0	—	4	4	4
	10	4	—	—	4

In addition to the effects of changing the physical dimensions of the well and aquifer, the role that the unsaturated hydraulic properties of the soil play was also investigated. The percent compositions of sand, silt, and clay and the bulk density were varied to obtain four basic soil types that cover a wide range of hydraulic conductivities likely to be encountered in the field. The four soil textural classes examined were sand (Sa), loamy sand (LSa), silty clay loam (SiCL), and silty clay (SiC), with respective values of the saturated hydraulic conductivity of 1.16×10^{-4}, 1.16×10^{-5}, 1.16×10^{-6}, and 1.16×10^{-7} m/sec (1000, 100, 10, and 1 cm/day, respectively). The soil textural classes are as those defined by the USDA Soil Conservation Service (Soil Survey Staff 1994). The *Rosetta Lite*,

Table 2											
Physical and Hydraulic Properties of Simulated Soils											
Soil	**Texture Class**	**% Sand**	**% Silt**	**% Clay**	**ρ (10^{-3} kg/m^3)**	**θ_s**	**θ_r**	**K_s (m/sec)**	**α (m^{-1})**	**n**	**Λ (m)**
Sa1	Sand	97	3	0	1.57	0.36	0.05	1.16×10^{-4}	3.3	4.05	0.41
Sa2	"	"	"	"	"	"	"	"	2.2	3.04	0.72
Sa3	"	"	"	"	"	"	"	"	4.3	3.04	0.36
Sa4	"	"	"	"	"	"	"	"	2.2	5.05	0.56
Sa5	"	"	"	"	"	"	"	"	4.3	5.05	0.28
LSa1	Loamy sand	80	15	5	1.57	0.36	0.04	1.16×10^{-5}	4.2	1.79	0.88
LSa2	"	"	"	"	"	"	"	"	2.8	1.53	2.61
LSa3	"	"	"	"	"	"	"	"	5.6	1.53	1.31
LSa4	"	"	"	"	"	"	"	"	2.8	2.06	0.92
LSa5	"	"	"	"	"	"	"	"	5.6	2.06	0.46
SiCL1	Silty clay loam	10	61	29	1.41	0.44	0.08	1.16×10^{-6}	0.7	1.56	9.53
SiCL2	"	"	"	"	"	"	"	"	0.5	1.37	37.48
SiCL3	"	"	"	"	"	"	"	"	0.9	1.37	18.88
SiCL4	"	"	"	"	"	"	"	"	0.5	1.74	8.68
SiCL5	"	"	"	"	"	"	"	"	0.9	1.74	4.33
SiC1	Silty clay	5	50	45	1.78	0.37	0.08	1.16×10^{-7}	1.3	1.27	39.19
SiC2	"	"	"	"	"	"	"	"	0.9	1.18	412.57
SiC3	"	"	"	"	"	"	"	"	1.8	1.18	207.80
SiC4	"	"	"	"	"	"	"	"	0.9	1.36	21.74
SiC5	"	"	"	"	"	"	"	"	1.8	1.36	10.95

v. 1.0, program (Schaap 1999), built in the HYDRUS-2D software package, was used to predict the hydraulic properties of the soil based on the sand-silt-clay composition and the bulk density, ρ. The program's predictive model estimates the saturated hydraulic conductivity, K_s, the saturated water content, θ_s, the residual water content, θ_r, and the van Genuchten water retention parameters, n and α, from an analysis of existing hydraulic conductivity and water retention data, as well as textural information (Schaap et al. 1998).

Within each of the four basic soil types, the van Genuchten parameters, n and α, were varied about the values predicted by *Rosetta Lite*, to obtain four additional soils per soil type. In total, 20 soils were examined, though for the simulations where D was greater than L, only the first soil in each of the four basic soil types were used. Table 2 lists the soil types along with their textural and hydraulic parameters. All soils were assumed to be homogeneous and isotropic. Though clearly these assumptions are not realistic under most field conditions, an analysis of their effects is beyond the scope of the present study.

From the rate of well recovery calculated for each simulation, a saturated hydraulic conductivity was estimated using the Bouwer and Rice method (K_{BR}). This estimate was then compared to the numerically modeled K_s, hereafter referred to as the target K_s, to obtain a measurement of error.

In order to improve the performance of the Bouwer and Rice method, the relation between the effective radius, R_e, and the geometric characteristics of the system was reevaluated. Also, the effect of the unsaturated soil hydraulic properties on R_e was examined. For that purpose we used a parameter Λ characterizing the soil capillarity that can be derived directly from the soil water retention curve of van Genuchten (1980):

$$\Lambda = \frac{1}{\alpha}\left[\Theta_{ref}^{\left(\frac{n}{1-n}\right)} - 1\right]^{\frac{1}{n}} \tag{6}$$

where

$$\Theta_{ref} = \frac{\theta_{ref} - \theta_r}{\theta_s - \theta_r} \tag{7}$$

and θ_{ref} is a reference soil moisture content that is soil dependent. Values for θ_{ref} are selected such that the degree of saturation Θ_{ref} remains constant over all soil types. It can be seen that Λ is simply the capillary pressure associated with moisture content θ_{ref} as predicted by the van Genuchten retention function.

Values of $\ln(R_e/r)$ were recalculated using Equation 1 and the target K_s, instead of Equations 4 and 5. We examined the empirical relationship of $\ln(Re/r)$ inferred from the numerical simulations to the parameters L, r, D, and Λ. In practice, this meant plotting $\ln(R_e/r)$ against different mathematical constructs of L, r, D, and Λ to reveal an apparent relation that could be modeled by a relatively simple empirical equation.

Results

One hundred thirty-six simulations were analyzed in this study. An example of one recovery curve (change in head in the well versus time) is shown in Figure 4. The portion of each ln(y) versus t curve used to estimate K_s corresponded to that portion of the curve that was most linear. Grouping the data by L/r, the earliest point in time at which the curve appeared linear corresponded to the wells having recovered to, on average, approximately 24%, 38%, 50%, and 60% full, for L/r = 2, 5, 10, and 20, respectively (Figure 5). The linearity of the recovery curves broke down when the wells were on average approximately 72%, 82%, 89%, and 92% full, for L/r = 2, 5, 10, and 20, respectively. Within L/r groupings, however, there

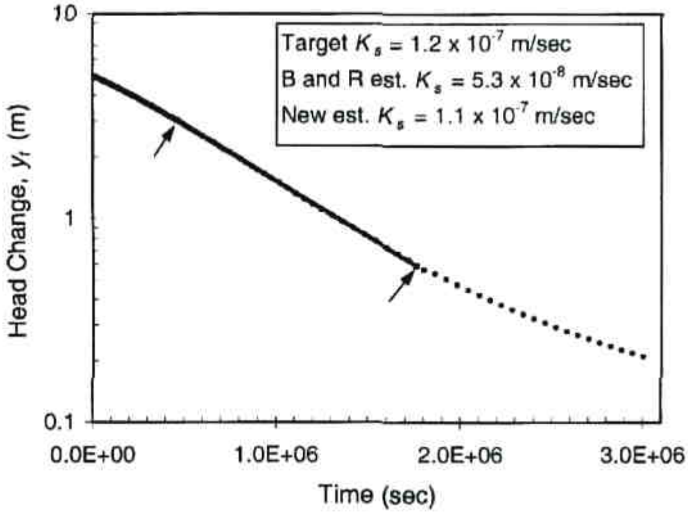

Figure 4. Well recovery curve for numerical simulation for soil type SiC1, L/r = 10, and D = L. The arrows indicate the end points of the straight portion of the curve used to estimate K_s. Given is the target K_s defined in the simulation, the K_s estimate using the Bouwer and Rice method, and the estimated K_s based on the modifications described in this study.

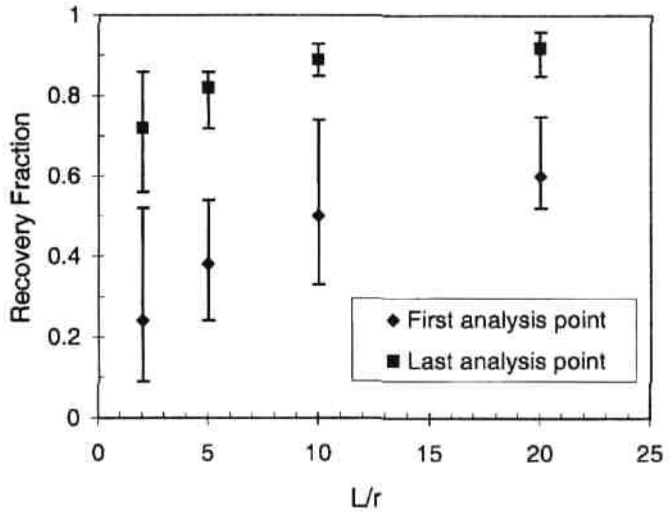

Figure 5. Mean levels of recovery corresponding to the average earliest point (diamond) and to the average final point (square) of the recovery curves used to estimate K_s. The whiskers indicate the maximum and minimum values.

was variation in the position of the linear portion (Figure 5), so each regression had a unique start and end percent recovery level.

The Bouwer and Rice method consistently underestimated K_s, with the error being as little as 23%, up to the worse case when K_{BR} differed from K_s by more than a factor of 5 (Figure 6). The tendency was for the Bouwer and Rice method to perform better as L/r increased, illustrating its utility in analyzing results in small diameter, deep wells, but its lesser application to broad and shallow, hand-dug wells. Additionally, the Bouwer and Rice method performed better for the sandier soils than the clayey soils, reflecting the disregard of capillarity in the method. Even for the sandy soils, however, the underestimation was significant for the wider and shallower wells (a factor of about 2 for L/r = 5 and a factor of about 3 for L/r = 2).

The effective radius, R_e, was analyzed first for only those cases where the well was fully penetrating, or L = D, which accounted for the majority of the simulations (n = 92). Plotting the inferred effective radius, expressed as $\ln(R_e/r)$, versus the scaling

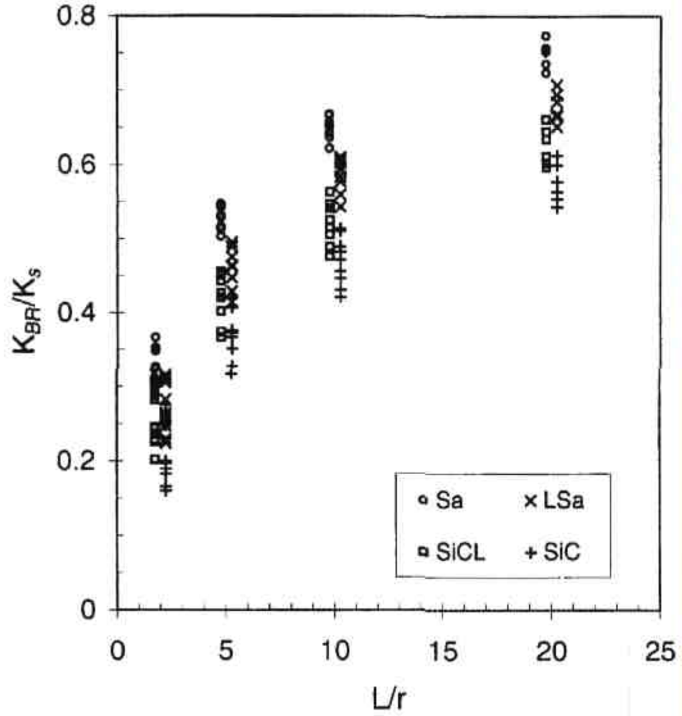

Figure 6. Bouwer and Rice estimate of hydraulic conductivity divided by the target hydraulic conductivity (K_{BR}/K_s) versus the ratio of well water depth to well radius (L/r). Points have been slightly offset along the abscissa to distinguish among the basic soil types.

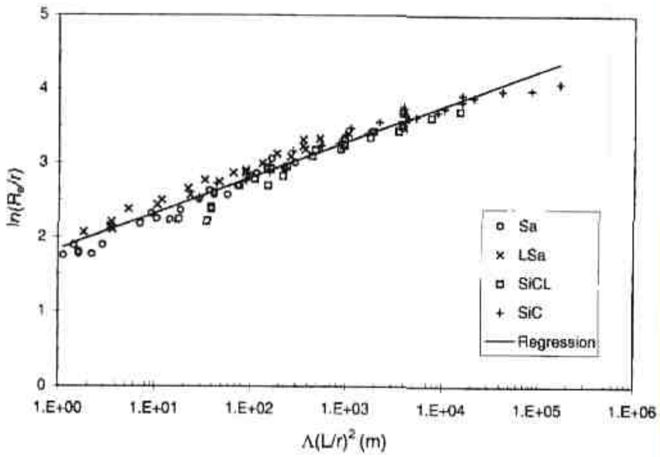

Figure 7. The inferred effective radius in terms of $\ln(R_e/r)$ versus the scaling parameter and well depth and radius expressed as $\Lambda(L/r)^2$.

parameter Λ times the square of the depth to radius ratio (L/r) reveals a highly linear relationship on a logarithmic scale (Figure 7). Performing a linear least squares regression for

$$\ln \frac{\hat{R}_e}{r} = C_0 + C_1 \ln\left[\Lambda(L/r)^2\right] \quad (8)$$

results in $C_0 = 1.839$ and $C_1 = 0.209$, where Λ has units of meters, and the coefficient of determination $R^2 = 0.96$. The degree of saturation Θ_{ref} from Equation 7 was taken to be 0.34, chosen to maximize the value of R^2. The corresponding value of Λ for each of the 20 soils is given in Table 2. To graphically illustrate how Λ varies among the soil types, the position of Λ on the water retention curves for each of the basic soil types, Sa, LSa, SiCL, and SiC, is shown in Figure 8.

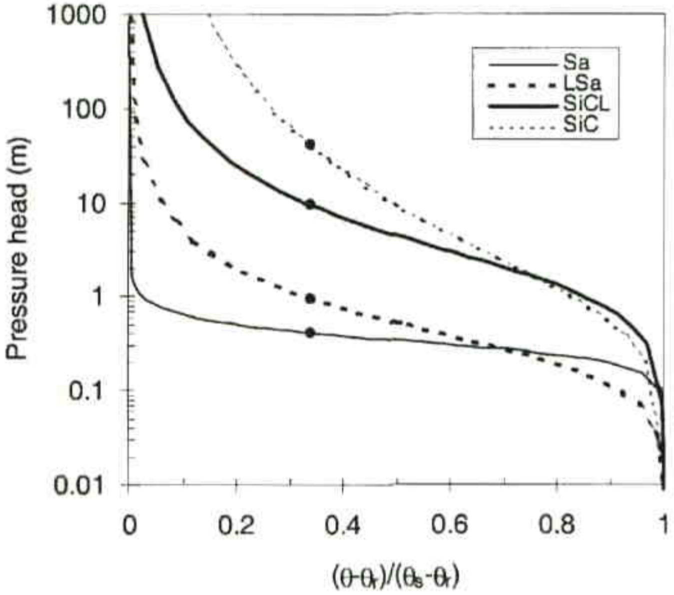

Figure 8. The location of Λ (filled circles) on the water retention curves of the four basic soil types examined.

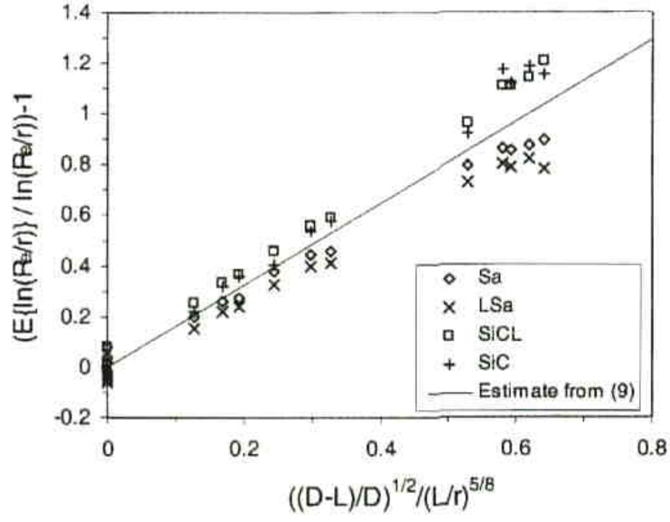

Figure 9. Deviation of the inferred effective radius expressed as $\ln(R_e/r)$ from the estimate $E\{\ln(R_e/r)\}$calculated from Equation 8 versus aquifer thickness D, well depth L, and well radius r.

The effect of the aquifer thickness D for a well that is not fully penetrating was evaluated by examining the deviation of the numerically inferred $\ln(R_e/r)$ from the estimate $\ln(\hat{R}_e/r)$ for the fully penetrating well calculated from Equation 8. The result of increasing D with respect to L was to increase the recovery rate and consequently decrease the effective radius, thus causing Equation 8 to overestimate $\ln(R_e/r)$ (Figure 9). Figure 9 shows the deviation of $\ln(R_e/r)$ expressed as $[\ln(\hat{R}_e/r)/\ln(R_e/r)]-1$ versus a combination of D, L, and r.

The data indicate that the effect of the unsaturated soil hydraulic properties has not been accounted for completely by Equation 8 since the data for each of the main soil types seem to follow a different curve in Figure 9. However, the error introduced by ignoring the effect of different soil properties in this step is small (less than 20% for L/r = 2) when compared to error that could be introduced by not knowing the true value of D (as much as 100% for L/r = 2). Therefore, and for the sake of simplicity, the data have been grouped to generate one empirical function that represents all the data. The form of the function used to explain the response is

$$\frac{\ln(\hat{R}_e/r)}{\ln(R_e/r)} - 1 = \frac{C_2[(D-L)/D]^{1/2}}{(L/r)^{5/8}} \qquad (9)$$

Varying the coefficient in Equation 9 to minimize the sum of squared error results in $C_2 = 1.614$. Combining Equation 8 with Equation 9 gives the following equation to estimate $\ln(R_e/r)$ for a hand-dug, broad and shallow well:

$$\ln\frac{R_e}{r} = \frac{C_0 + C_1\ln[\Lambda(L/r)^2]}{1 + C_2[(D-L)/D]^{1/2}(L/r)^{-5/8}} \qquad (10)$$

Equation 10 is quite sensitive to D, particularly for low L/r. Taking, for example, a well of r = 0.5 m and L/r = 2, if we assumed a fully penetrating well when in actuality the aquifer extended 0.5 m below the bottom of the well, the overestimation of K_s would be about 60%. If the aquifer were much deeper than the depth of the well, or essentially infinite in depth, the overestimation would be approximately 105%. On the other hand, if L/r were 20 for a well with a radius of 0.5 m, the maximum overestimation of K_s introduced by assuming a fully-penetrating well would be less then 25%. In the field it may be good practice to report the hydraulic conductivity for both a lower and upper limit for D, for example (D-L)/D = 0 and 1, when the aquifer thickness is unknown or poorly defined.

Table 3
RMSE of the Estimated K_s Using the Standard and the Modified Bouwer and Rice Method

Soil Type	Target Ks (m/s)	Standard RMSE (m/s)	Modified RMSE (m/s)
Sa	1.16×10^{-4}	3.44×10^{-3}	3.32×10^{-4}
LSa	1.16×10^{-5}	3.83×10^{-4}	3.95×10^{-5}
SiCL	1.16×10^{-6}	4.08×10^{-5}	3.87×10^{-6}
SiC	1.16×10^{-7}	4.39×10^{-6}	2.96×10^{-7}

When Equation 10 was used with Equation 1 to estimate K_s, the error, in terms of $(\hat{K}_s - K_s)/K_s$, ranged from −0.12 to +0.16. Grouping the estimates by the four major soil types (Sa, LSa, SiCL, and SiC) and calculating the root mean square error (RMSE) of the estimates, we see that using Equation 10 reduces the RMSE by a factor of about 10 in comparison with the standard Bouwer and Rice analysis (Table 3).

The addition of a new parameter Λ to the method introduces a new source of potential error. However, because the logarithm of Λ is taken in Equation 10, a low-precision estimate of Λ should not result in a sizable error in the estimate of K_s, which is directly proportional to $\ln(R_e/r)$. The values of $\ln(R_e/r)$ over a range of Λ for the case of L/r = 2 and D = L are plotted in Figure 10. Included on the curve are the 12 main USDA textural classes. The Λ values of these classes are calculated from the predicted values of α and n based on knowledge of the textural class alone (Schaap 1999). Assuming, for example, we are analyzing data from well of L/r = 2 and misclassify a soil as a loam, Equation 10 underestimates K_s by about 24% if the soil texture is actually sandy, while it overestimates K_s by approximately15% if the soil is actually a sandy clay. Table 4 gives the error introduced by misclassifying a soil as loam when it belongs to one of the other main textural classes for the cases when L/r = 2, 5, 10, and 20.

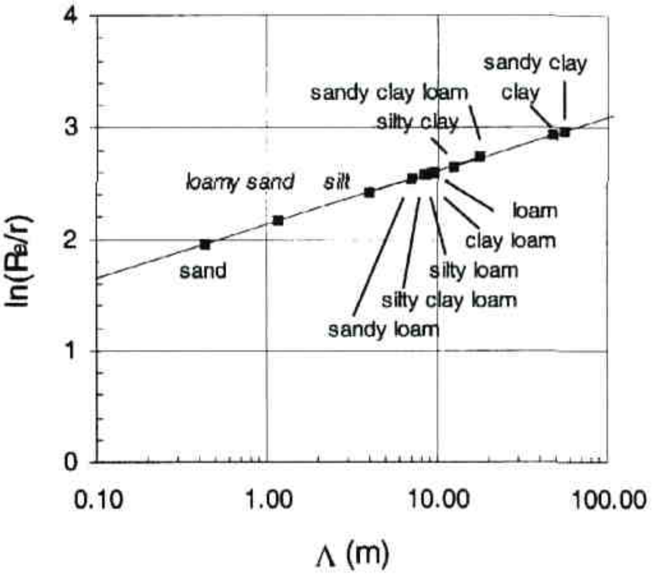

Figure 10. The effective radius expressed as ln(Re/r) versus Λ for L/r = 2 and L = D. The Λ values for the soil textural classes shown are based on the van Genuchten parameters predicted by *Rosetta* (Schaap 1999).

Table 4
Percent Error Introduced to Estimation of K_s by Misclassifying a Soil as Loam

"Actual" Soil Texture	Λ (m)	L/r 2	5	10	20
Sand	0.43	−24	−21	−19	−18
Loamy sand	1.17	−16	−14	−13	−12
Sandy loam	4.06	−6	−5	−5	−4
Silt	7.15	−1	−1	−1	−1
Clay loam	8.39	0	0	0	0
Loam	8.58	0	0	0	0
Silty clay loam	9.20	1	0	0	0
Silty loam	9.58	1	1	1	1
Sandy clay loam	12.36	3	3	2	2
Silty clay	17.68	6	5	5	4
Clay	47.30	14	12	11	10
Sandy clay	55.24	15	13	12	11

Conclusions

Numerical simulations of slug tests indicate that the unsaturated soil properties have a significant effect on recovery rates for wells that are wide and shallow (L/r less than at least 20). This range of geometries corresponds to that of traditional, hand-dug wells found throughout the world. That the assumptions of the Bouwer and Rice method cannot account for unsaturated soil conditions can result in large errors when estimating K_s for these types of wells, with the error increasing as the clay content increases. By introducing a capillarity parameter, Λ, that is a function of the water retention curve and formulating a new equation (10) for estimating R_e that replaces Equations 4 and 5 of Bouwer and Rice (1976), the ease of the method can be maintained while significantly improving its performance. When the shape of the water retention curve is not known, which will usually be the case, Λ may be estimated using soil texture class and Table 4, or readily available algorithms such as *Rosetta Lite*. The error, measured in terms of $(\hat{K}_s - K_s)/K_s$, varied from − 0.12 to + 0.16 using the new equation, compared with − 0.84 to − 0.23 for the Bouwer and Rice equations, which corresponds to approximately a tenfold reduction in the root mean squared error of the estimate.

Acknowledgments

We are very grateful for the support of the staff at the Instituto Nacional de Investigaciones Agropecuarias (INIA) – Quilamapu, Chillán, Chile, and thank Oscar Reckman and Jorge Vergara, INIA – La Platina, Santiago, Chile, for their helpful discussions. We also thank Ning Lu, Søren Hvilshøj, and an anonymous reviewer, whose comments improved the quality of the manuscript. This research was funded in part by the Agricultural Experiment Station, College of Agriculture, Oregon State University.

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