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Numerical evaluation of the flowmeter test in a layered aquifer with a skin zone

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Abstract

In this study, we used a two-dimensional groundwater flow model to numerically evaluate the single flowmeter test in a series of two-layer confined aquifers for a fully penetrating well with a skin zone (i.e. a disturbed zone, filter-pack envelope, etc.). The skin zone causes errors in estimates of the vertical distribution of horizontal hydraulic conductivity by acting as a channel for cross-flow between layers of contrasting hydraulic conductivity. The bias in measured layer discharge rates, Q_i, is dependent on the ratios of the skin zone hydraulic conductivity to the layer hydraulic conductivities, K_s/K_i, and on the ratios of the skin zone thickness to the thickness of the individual layers, $(r_s - r_w)/b_i$. For any given K_s/K_i, the cross-flow increased with increases in the skin zone radius relative to the well radius, r_s/r_w. The error in estimated K_i due to a skin zone of reduced hydraulic conductivity ($K_s/K_i < 1$) is greater than that of a skin zone of a correspondingly enlarged hydraulic conductivity ($K_s/K_i > 1$). As K_s/K_1 increases, the ratios $\hat{K}_1/K_1$ and $\hat{K}_2/K_2$ converge approximately to the ranges 0.9–0.95 and 1.0–1.25, respectively. As K_s/K_1 decreases from value 1, the ratios of $\hat{K}_1/K_1$ and $\hat{K}_2/K_2$ diverge from these asymptotic ranges. In all simulated flowmeter tests, where $K_1/K_2 = 10$, $\hat{K}_1$ underestimates K_1 and $\hat{K}_2$ overestimated K_2. © 1997 Elsevier Science B.V.

Keywords: Evaluation; Numerical; Flowmeter; Layered aquifer; Skin zone

1. Introduction

In an aquifer-well system, the porous material in the annular region between the well screen or casing and the undisturbed aquifer is often characterized by hydraulic properties different from those of the naturally occurring formation. This annular region typically consists of a disturbed zone, an artificial filter-pack, or both. A disturbed zone usually implies a region of reduced hydraulic conductivity in contrast to the aquifer, and thus imposes a resistance for groundwater flow from the undisturbed formation to the well face (Moench and Hsieh, 1985). These disturbed zones are formed in various ways including the clogging of aquifer material at the borehole surface by textural fines, the compaction of the aquifer material beyond the borehole radius during drilling, and the presence of drilling mud left over from the well construction. The filter-pack is developed during well construction by backfilling the space between the well screen and the formation with a porous material typically of greater hydraulic conductivity than that of the natural formation (Fetter, 1994). The main purposes of the filter-pack are to capture textural fines which may clog the screen or be removed with the extracted fluid and to reduce hydraulic head losses.

Whereas the filter-pack is purposely constructed,

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the development of a disturbed zone is undesirable. Nevertheless, the presence of either or both can bias estimates of the vertical distribution of horizontal hydraulic conductivity obtained by flowmeter tests performed in a test well possessing these attributes. Throughout the remainder of this study we refer to the disturbed zone or the filter-pack envelope by the general term *skin zone*. We consider only skin zones of finite thickness, as opposed to an infinitesimal skin. The skin zone thus represents the porous material between the well face or casing and the undisturbed aquifer.

All single-borehole tests can be significantly affected by the hydraulic properties of the skin zone. If not accounted for, this will lead to biased estimates of formation properties. This problem is well documented in the petroleum engineering field (van Everdingen and Hurst, 1949; Hurst, 1953; Hawkins, 1956; Agarwal et al., 1970; Ramey and Agarwal, 1972; Ramey et al., 1975; Chu et al., 1980; Tongpenyai, 1981; and others) and in subsurface hydrology by Rehfeldt et al. (1989); Molz et al. (1989, 1990), and Xiang (1994, 1995) for the flowmeter test, Novakowski (1993) for the constant-head test, Hyder et al. (1994) for the multi-level slug test, Bidaux and Tsang (1991) for a number of complicated flow patterns, and by many others.

In recent years, the flowmeter test has emerged as a popular single-borehole method for providing an estimate of the vertical distribution of horizontal hydraulic conductivity in a fully penetrating well situated in layered confined aquifer (Hufschmied, 1983; Hess, 1986; Sudicky, 1986; Morin et al., 1988; Rehfeldt et al., 1989, 1992; Molz et al., 1989, 1990, 1994; Hess et al., 1992; Taylor et al., 1990; Young, 1995; and others). The single flowmeter test (Molz et al., 1989) estimate of layer horizontal hydraulic conductivity is given by

$$K_i = \frac{Q_i}{Q}\frac{b}{b_i}\bar{K} \qquad (1)$$

where K_i is the ith layer horizontal hydraulic conductivity (L/T), Q_i is the ith layer steady-state discharge rate (L^3/T), b_i is the ith layer vertical thickness (L), Q is the constant pumping rate (L^3/T), b is the total vertical aquifer thickness (L), and $\bar{K}$ is an estimate of the effective aquifer hydraulic conductivity (L/T) as obtained by performing a traditional pumping test (Theis, 1935). Note that the derivation and subsequent application of Eq. (1) assumes that the well response of the aquifer system has achieved a quasi-steady state. In Eq. (1) the presence of a skin zone can introduce bias into the measured Q_i due to cross-flow through it between layers of contrasting hydraulic conductivity. Estimates of $\bar{K}$ for an n-layered aquifer will also be biased due to this effect and can no longer by represented by the simple relation $\sum_{i=1}^{n} K_i b_i / \sum_{i=1}^{n} b_i$. The magnitude of error in the measured layer discharge rate Q_i will be a function, among other things, of the skin zone thickness, the skin zone hydraulic conductivity in contrast to the layer hydraulic conductivities, the layer thicknesses, and the interlayer hydraulic conductivity contrasts.

In a previous study, Xiang (1994) investigated the steady-state flux distributions along the well face of a fully penetrating well. For a formation consisting of an arbitrary number of layers, he developed formulae for the bias in the measured layer discharge rates due to cross-flow through the disturbed zone and related formulae for the errors introduced into layer hydraulic conductivity estimates in the flowmeter test (Rehfeldt et al., 1989). Xiang (1994) also evaluated these formulae for a two-layer confined aquifer. However, in this analysis he used a model based on the questionable assumption that the flux distribution at the interface between the skin zone and the formation is uniform in each layer. Xiang (1994) claimed that this assumption follows from the results of Javandel and Witherspoon (1969). Xiang (1994) stated that

> ... Because the water in the borehole can be considered a medium with an infinitely large hydraulic conductivity and the disturbed zone can be considered as the same medium with finite hydraulic conductivity, the flow distribution on the outer surface of the disturbed zone is the same as the one on the inner face of the (same) layered aquifer without a disturbed zone during a constant pumping.

But Javandel and Witherspoon (1969) demonstrated in numerically simulated constant rate pumping tests that the groundwater flow in a layered formation is nearly horizontal and follows the Theis (1935) model in the vicinity of a fully penetrating well *without* a skin zone. The Theis (1935) model implies a uniform well-face flux distribution. In their simulations, at any given time Javandel and Witherspoon (1969) kept the drawdown at any point on the well face the same. However, when the skin zone is present, the situation is different. In this case, vertical drawdown gradients develop in the skin zone and, therefore, the drawdown at the interface of the skin zone and the undisturbed formation varies with depth rather than being constant. Consequently, the results of Javandel and Witherspoon (1969) do not justify Xiang's 1994 assumption.

From the analysis of the two-layer systems, Xiang (1994) then drew two questionable conclusions. First, he implied that it is the absolute rather than relative size of the skin zone that determines the quality of the hydraulic conductivity estimates from the flowmeter test. However, the distribution of the well-face flux should be dependent on the ratio of the skin zone thickness to the layer thicknesses, rather than on the skin zone thickness only. Consequently, the quality of the horizontal hydraulic conductivity estimates from the flowmeter test should depend on the relative size of the skin zone to the layer thicknesses rather than on the absolute size of the skin zone. Second, Xiang (1994) concludes that the well-face flux distribution is independent of the skin zone hydraulic conductivity. However, the well-face flux distribution should be a function of the hydraulic conductivity contrasts between the skin zone and the individual layers.

We note that in practice individual layers are difficult, if not impossible, to distinguish. Typically, layer boundaries and thicknesses are operationally defined by the interval separating successive flowmeter measurements. The resultant estimate of the layer hydraulic conductivity is actually some kind of average of the hydraulic conductivities of the heterogeneous porous media located within the measurement interval. Intuitively, decreasing the measurement interval should lead to increased resolution of the downhole heterogeneity. However, as noted by Molz et al. (1989), the assumption of horizontal flow is violated once the measurement interval becomes too small. Moreover, in the presence of a significant skin zone, the layer discharge as measured between successive flowmeter sampling points may include contributions from adjacent layers due to cross-flow through the skin zone. Hence, the problem of identifying the true layer boundaries, if they exist at all, becomes even more complicated. Although the need for assessing the combined effects of the skin zone and the size of the measurement interval on the characterization of the downhole distribution of horizontal hydraulic conductivity is a problem worthy of investigation, it is not the focus of this study.

2. Objectives

The main objective of this paper then is to study the combined effects of the skin zone thickness and hydraulic conductivity, and the layer thicknesses and hydraulic conductivities on single flowmeter test (Molz et al., 1989) estimates of layer horizontal hydraulic conductivity in two sets of two-layer confined aquifers of a priori known skin zone and hydraulic properties.

To achieve this, we use a two-dimensional groundwater flow model (Ruud and Kabala, 1996) to numerically simulate the single flowmeter test in each set of two-layer confined aquifers. In this model, the wellbore drawdowns and the well-face flux distributions are computed subject to an *integrated well-face flux* boundary constraint (Ruud and Kabala, 1996, 1997) with no a priori assumptions about the nature of the well-face flux. The model and the proposed synthetic pumping tests are described below.

3. Mathematical model of well response

The governing equation which describes cylindrical axisymmetric groundwater flow to a well situated in a two-dimensional heterogeneous confined aquifer is (Hantush, 1964)

$$S_s(r,z)\cdot\frac{\partial s}{\partial t}=\frac{K(r,z)}{r}\cdot\frac{\partial s}{\partial r}+\frac{\partial}{\partial r}\left(K(r,z)\cdot\frac{\partial s}{\partial r}\right)+\frac{\partial}{\partial z}\left(K(r,z)\cdot\frac{\partial s}{\partial z}\right) \quad (2)$$

where $s(r,z,t)$ is the drawdown (L), $K(r,z)$ is the hydraulic conductivity, $S_s(r,z)$ is the specific storativity ($1/L$), r is the radial distance from the center of the well, z is the vertical distance measured from the top of the aquifer, and t is time.

The drawdown distribution around a steadily discharging fully penetrating well with negligible wellbore storage is governed by Eq. (2) subject to the following initial and boundary conditions

$$s(r,z,0)=0 \quad (3)$$

$$s(\infty,z,t)=0 \quad (4)$$

$$\frac{\partial s(r,0,t)}{\partial z}=\frac{\partial s(r,b,t)}{\partial z}=0 \quad (5)$$

$$s(r_w,z,t)=s_w(t)\ 0<z<b \quad (6)$$

and also to the well face boundary constraint

$$Q=-2\pi r_w\int_0^b K(r_w,z)\cdot\frac{\partial s(r_w,z,t)}{\partial r}dz \quad (7)$$

where r_w is the well radius (L), s_w is the drawdown in the well (L), b is the aquifer thickness (L), Q is a constant total pumping rate (L^3/T), and $\partial s(r_w,z,t)/\partial r$ is the hydraulic gradient at the well face Eq. (1).

We solve Eqs. (2)–(7) numerically using a fully implicit finite difference code developed and validated by Ruud and Kabala (1997, 1997).

4. Synthetic pumping tests

The first set of tests are designed to investigate the effects of the skin zone thickness, and the skin zone hydraulic conductivity in contrast to the layer hydraulic conductivity, on the computed layer discharge rates and the subsequent accuracy of flowmeter test estimates of layer hydraulic conductivity K_i. For this we consider 25 different two-layer confined aquifers (see Fig. 1) each defined by a particular value of r_s/r_w and K_s/K_1, where r_s is the skin zone radius (L), K_s is the hydraulic conductivity of the skin zone (L/T), and K_1 is the isotropic hydraulic conductivity of layer 1 (L/K). The skin zone thickness is defined as the difference ($r_s - r_w$). The 25 systems are defined using the values $K_s/K_1 = 0.03, 0.1, 0.3, 1.0$, and 3.0, and $r_s/r_w = 1.25, 1.5, 1.75, 2.0$, and 2.25. For each test, $K_1/K_2 = 10$, $K_1 = 5\times10^{-5}$ m s^{-1}, $r_w = 0.1$ m, and the vertical thicknesses of layer 1 and layer 2 are $b_1 = b_2 = 5$ m. In general, values of $K_s/K_1 < 1$ represent a disturbed zone of reduced permeability whereas $K_s/K_1 > 1$ implies a filter-pack. For the first set we use a constant pumping rate of $Q = 5.0$ m^3 h^{-1}.

The second set of tests are designed to investigate the effects of layer thickness and skin zone thickness again on the measured discharge rates and the subsequent accuracy of flowmeter test estimates of layer hydraulic conductivity. Here we consider six different two-layer confined aquifers as defined by $(r_s - r_w)/b_i = 0.01, 0.02, 0.04, 0.08, 0.16$, and 0.32, where $K_s/K_1 = 3$, $r_s/r_w = 2$, and $r_w = 0.1$ m. For these parameters, $b_1 = b_2 = 0.3125, 0.625, 1.25, 2.5, 5$, and 10 m, to produce $(r_s - r_w)/b_i = 0.01, 0.02, 0.04, 0.08, 0.16$, and 0.32. Again, we specify $K_1/K_2 = 10$ where $K_1 = 5\times10^{-5}$ m s^{-1}. The pumping rate is $Q = 10.0$ m^3 h^{-1} for $b_1 = b_2 = 10$ m, and is halved for each factor of 2 reduction in b_i.

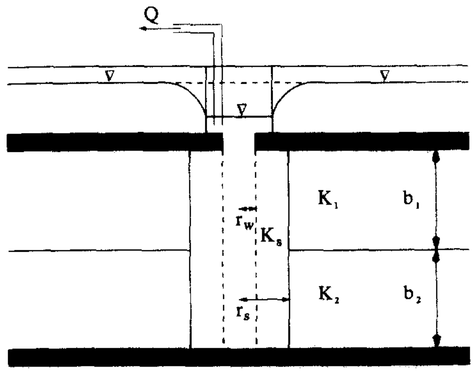

Fig. 1. Diagram of a fully penetrating well with a skin zone situated in a two-layer confined aquifer.

As mentioned earlier, Eq. (1) assumes that the well response of the aquifer system has achieved a quasi-steady state. Consequently, the estimation of layer K in each test is conducted only after the well response, as simulated by solving the groundwater flow model Eqs. (2)–(7), has reached a quasi-steady state.

5. Results and discussion

From the first set of tests, we plot in Fig. 2 the ratio of the discharge in layer 1 for a well with a skin zone to the expected discharge in layer 1 with no skin zone, $Q_1^{\text{skin}}/Q_1^{\text{no skin}}$, versus the hydraulic conductivity contrast of the skin zone and layer 1, K_s/K_1, for the cases $r_s/r_w = 1.25, 1.5, 1.75, 2.0$, and 2.25. The corresponding plot of $Q_2^{\text{skin}}/Q_2^{\text{no skin}}$ versus K_s/K_1 for layer 2 is presented in Fig. 3. These figures illustrate how the cross-flow of discharge from layer 1 through the skin zone into the screen interval corresponding to layer 2 biases the measured layer discharge rates Q_1 and Q_2 by the flowmeter. The error is computed Q_1 and Q_2

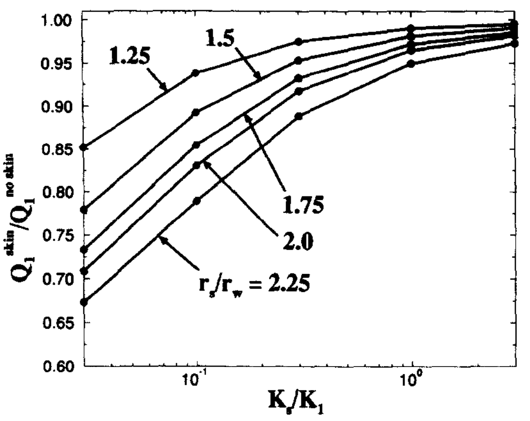

Fig. 2. The ratio of the discharge in layer 1 for a well with a skin to the expected discharge in layer 1 with no skin zone, $Q_1^{\text{skin}}/Q_1^{\text{no skin}}$, versus the hydraulic conductivity contrast of the skin zone and layer 1, K_s/K_1, for a two-layer confined aquifer for the cases r_s/r_w = 1.25, 1.5, 1.75, 2.0, and 2.25.

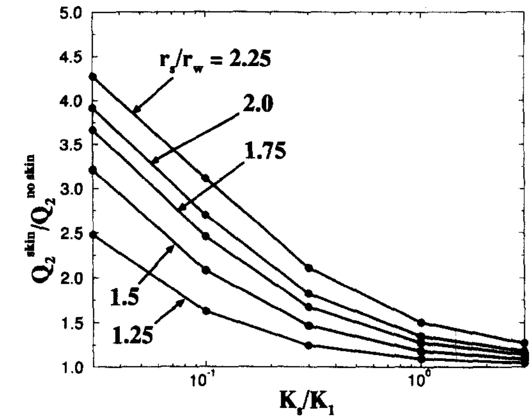

Fig. 3. The ratio of the discharge in layer 2 for a well with a skin zone to the expected discharge in layer 2 with no skin zone, $Q_2^{\text{skin}}/Q_2^{\text{no skin}}$, versus the hydraulic conductivity contrast of the skin zone and layer 1, K_s/K_1, for a two-layer confined aquifer for the cases r_s/r_w = 1.25, 1.5, 1.75, 2.0, and 2.25.

increases for decreasing K_s, relative to K_1, and for increasing skin zone thickness, as represented by r_s/r_w. The discharge from the more conductive layer 1 is then distributed non-uniformly across the total screen length b rather than uniformly over its own thickness b_1. Since $Q_1 + Q_2 = Q$, an increase in measured Q_2 due to this short-circuiting of fluid implies in a decrease in Q_1.

The bias in measured layer discharge rates result in errors in single flowmeter test estimates of K_1 and K_2. In Fig. 4 we plot the ratio of the hydraulic conductivity estimate in layer 1 to its actual value, $\hat{K}_1/K_1$, versus the hydraulic conductivity contrast between the skin zone and layer 1, K_s/K_1, for the cases characterized by r_s/r_w = 1.25, 1.5, 1.75, 2.0, and 2.25. A similar plot for $\hat{K}_2/K_2$ versus K_s/K_1 is presented in Fig. 5. In all 25 cases, $\hat{K}_1$ underestimates K_1 and $\hat{K}_2$ overestimates K_2. For any given K_s/K_1, increases in r_s/r_w result in decreases in $\hat{K}_1/K_1$ and in increases in $\hat{K}_2/K_2$. In both Figs. 4 and 5, as K_s/K_1 increases, the ratios $\hat{K}_1/K_1$ and $\hat{K}_2/K_2$ converge approximately to the ranges 0.9–0.95 and 1.0–1.25, respectively. The largest estimation error in both layers occurs when $r_s/r_w = 2.25$ and $K_s/K_1 = 0.03$. Clearly, errors in layer hydraulic conductivity estimates worsen for increases in the skin zone thickness or for decreases in the skin zone hydraulic conductivity relative to that of the layers. We note in passing that the latter behaviour is qualitatively described by an approximate skin-effect correction model proposed by Hufschmied (1983) and Rehfeldt et al. (1989), which does not account for the vertical cross-flow, and which requires the knowledge of drawdown both at the well face and the skin/formation interface. Since the latter is unknown, this correction model is not used in practice.

In the second set of tests, we examine the effects of layer thickness and of skin zone thickness on flowmeter test estimates of layer K. In Fig. 6 we present a plot of the ratio of the estimate of hydraulic conductivity in layer 1 to the actual value, $\hat{K}_1/K_1$, versus $(r_s - r_w)/b_i$ for a two-layer confined aquifer where $b_1 = b_2$, $K_s/K_1 = 3$, and $r_s/r_w = 2$. The corresponding plot of $\hat{K}_2/K_2$ versus $(r_s - r_w)/b_i$ is given in Fig. 7. As $(r_s - r_w)/b_i$ increases, the ratio $\hat{K}_1/K_1$ decreases and $\hat{K}_2/K_2$ increases. An explanation is implied by Fig. 8, where we present a plot of the ratio of the discharge in layer 1 for a well with a skin zone to the expected discharge in layer 1 with no skin zone, $Q_1^{\text{skin}}/Q_1^{\text{no skin}}$, versus $(r_s - r_w)/b_i$. Similarly for layer 2, a plot of $Q_2^{\text{skin}}/Q_2^{\text{no skin}}$ versus $(r_s - r_w)/b_i$ is given in Fig. 9. As b_1 and b_2 decrease, the computed Q_1 and Q_2 decrease and increase, respectively.

In this situation, the cross-flow from layer 1 distributes over the progressively smaller screen length corresponding to the decreasing thickness of layer 2. In an analogous manner, increases in the skin zone thickness $(r_s - r_w)$ lead to increases in the volume of

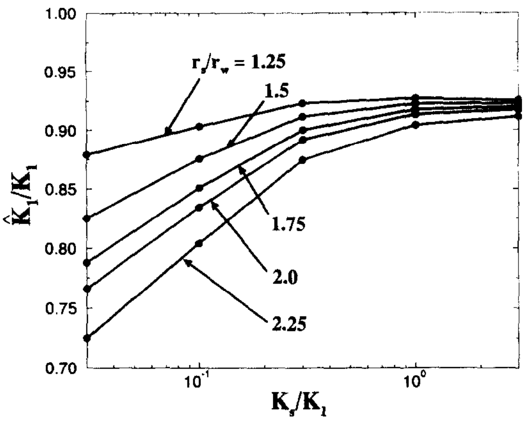

Fig. 4. The ratio of the estimate of hydraulic conductivity in layer 1 to the actual value, $\hat{K}_1/K_1$, versus the hydraulic conductivity contrast of the skin zone and layer 1, K_s/K_1, for a two-layer confined aquifer for the cases r_s/r_w = 1.25, 1.5, 1.75, 2.0, and 2.25.

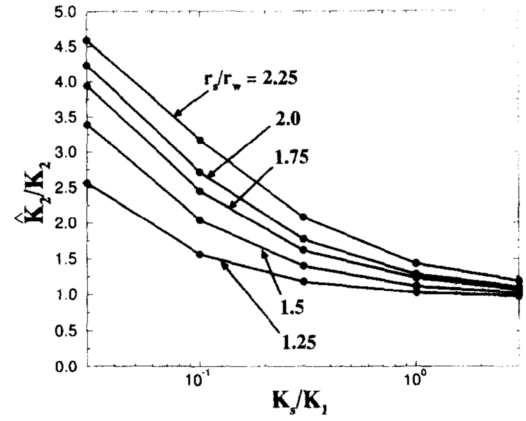

Fig. 5. The ratio of the estimate of hydraulic conductivity in layer 2 to the actual value, $\hat{K}_2/K_2$, versus the hydraulic conductivity contrast of the skin zone and layer 1, K_s/K_1, for a two-layer confined aquifer for the cases r_s/r_w = 1.25, 1.5, 1.75, 2.0, and 2.25.

cross-flow through this region and to subsequent biases in measured layer discharge rates. Again, input of these Q_1 and Q_2 in Eq. (1) produces underestimates of K_1 and overestimates of K_2, respectively. These results demonstrate that the bias in measured layer discharge rates is dependent not only of the absolute size of the skin zone thickness, $(r_s - r_w)$, but its size relative to the layer thicknesses, $(r_s - r_w)/b_i$.

6. Conclusions

In this study, we used a two-dimensional groundwater flow model (Ruud and Kabala, 1996, 1997) to numerically simulate the single flowmeter test (Molz et al., 1989) in two different sets of two-layer confined aquifers. The first set of tests were designed to investigate the effects of the skin zone thickness, and the skin zone hydraulic conductivity in contrast to the layer hydraulic conductivities, on the computed layer discharge rates and the subsequent errors in layer hydraulic conductivity estimates by the single flowmeter test. For this we considered 25 different two-layer confined aquifers, each defined by a particular value of r_s/r_w and K_s/K_1. The second set of tests were designed to investigate the effects of layer thicknesses and of skin zone thickness again on the computed layer discharge rates and the error in layer hydraulic conductivity estimates. For this we considered 6 different two-layer confined aquifers each, defined by a different value of $(r_s - r_w)/b_i$.

The major findings of our study are the following:

1. We demonstrated that the presence of a skin zone (i.e. a disturbed zone, filter-pack envelope, etc.) in the annular region surrounding a test well can bias single flowmeter test estimates of the vertical distribution of horizontal hydraulic conductivity by acting as a channel for cross-flow between layers of contrasting hydraulic conductivity.
2. We find that the bias in measured layer discharge rates, Q_1 and Q_2, is dependent not on the absolute size of the skin zone hydraulic conductivity, K_s, but on its magnitude relative to that of the layer hydraulic conductivities, K_i. From the first set of flowmeter tests, we demonstrated that decreases in K_s relative to K_1 resulted in increased cross-flow through the skin zone from the more highly conductive layer 1 into the less conductive layer 2. Also, for any given K_s/K_1, the cross-flow increased with increases in the skin zone radius relative to the well radius, r_s/r_w.
3. We find that the error in estimated layer hydraulic conductivity caused by the presence of a skin zone of reduced hydraulic conductivity ($K_s/K_i < 1$) is greater than that of a skin zone of a relatively larger hydraulic conductivity ($K_s/K_i > 1$). As K_s/K_1 increases, the ratios $\hat{K}_1/K_1$ and $\hat{K}_2/K_2$ converge approximately to the ranges 0.9–0.95 and 1.0–1.25, respectively. As K_s/K_1 decreases from

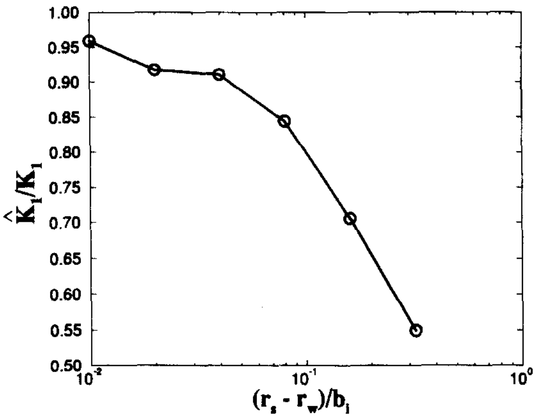

Fig. 6. The ratio of the estimate of hydraulic conductivity in layer 1 to the actual value, $\hat{K}_1/K_1$, versus $(r_s - r_w)/b_i$ for a two-layered confined aquifer where $K_s/K_1 = 3$.

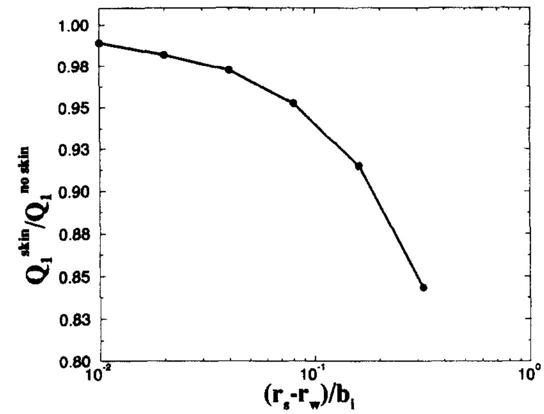

Fig. 8. The ratio of the discharge in layer 1 for a well with a skin zone to the expected discharge in layer 1 with no skin zone, $Q_1^{\text{skin}}/Q_1^{\text{no skin}}$, versus $(r_s - r_w)/b_i$ for a two-layer confined aquifer where $K_s/K_1 = 3$, $K_1/K_2 = 10$, and $K_1 = 5 \times 10^{-5}$ m s^{-1}.

the value 1, the ratios $\hat{K}_1/K_1$ and $\hat{K}_2/K_2$ diverge from the asymptotic ranges listed above. The relation of the bias in hydraulic conductivity estimation to the skin hydraulic conductivity contrast and the size of the skin zone is illustrated in Figs. 3 and 4.

4. We find that the bias in measured layer discharge rates is dependent not only on the thickness of the skin zone, $(r_s - r_w)$, but more importantly on its size relative to the thicknesses of the layers, $(r_s = r_w)/b_i$. Increases in $(r_s - r_w)$ or decreases in b_i result in measurement bias of layer discharge rates and subsequent errors in estimates of layer hydraulic conductivity by the single flowmeter test. The relation of the bias in layer hydraulic conductivity estimation to the relative size of the skin zone is illustrated in Figs. 5 and 6.
5. Our findings suggest that wells in which flowmeter tests are to be performed should be developed in such a manner that the size of their disturbed zones is minimized. Additionally, since a skin zone is usually unavoidable, it is important to ensure that its permeability is greater rather than smaller than that of the formation.

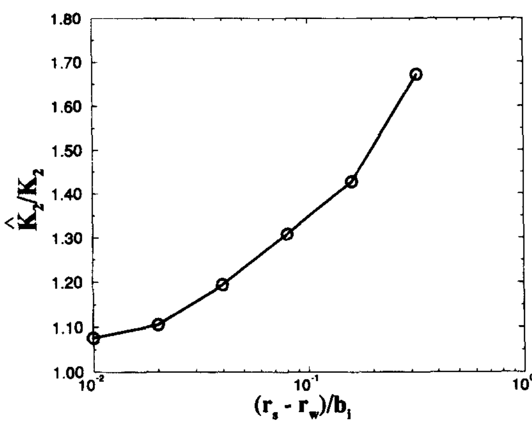

Fig. 7. The ratio of the estimate of hydraulic conductivity in layer 2 to the actual value, $\hat{K}_2/K_2$, versus $(r_s - r_w)/b_i$ for a two-layer confined aquifer where $K_s/K_1 = 3$.

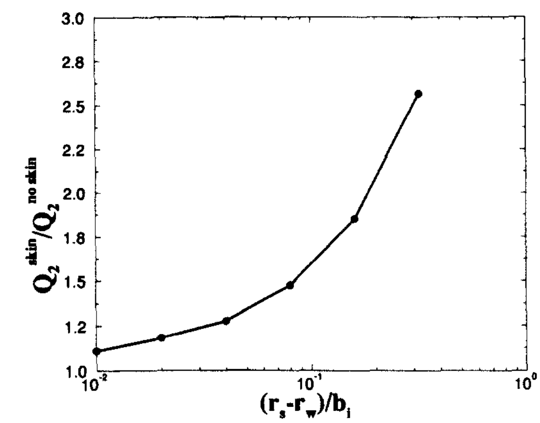

Fig. 9. The ratio of the discharge in layer 2 for a well with a skin zone to the expected discharge in layer 2 with no skin zone, $Q_2^{\text{skin}}/Q_2^{\text{no skin}}$, versus $(r_s - r_w)/b_i$ for a two-layer confined aquifer where $K_s/K_1 = 3$, $K_1/K_2 = 10$, and $K_1 = 5 \times 10^{-5}$ m s^{-1}.

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