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Simulation and interpretation of borehole flowmeter results under laminar and turbulent flow conditions

By Keith J. Halford

ABSTRACT

The hydraulic conductivity of an aquifer is frequently assumed to be directly proportional to the change in measured velocity in the analysis of flowmeter profiles. In screened wells, the measured velocity can be affected as much by the well screen, gravel pack, and flowmeter itself as by the hydraulic conductivity profile of the adjacent aquifer where the overall transmissivity of the aquifer is high.

An existing ground-water flow model was modified to allow for simulation of the presence of a flowmeter in a screened or open borehole when there is turbulent flow throughout the well-aquifer system. Pipe flow through the flowmeter, annular flow around the flowmeter, and slot flow across the well screen are simulated with an equivalent hydraulic conductivity that varies as a function of Reynolds number. Solving the problem sequentially with two models of the well-aquifer system minimizes numerical instabilities. A transient model with time-varying specified heads in the wellbore is simulated first to define the far-field flow profile in the aquifer. The lateral, specified-flow boundary for the second model is defined by the far-field flow profile simulated in the first model. The velocity profile is simulated by sequentially changing the conductances in the wellbore between stress periods to approximate moving the flowmeter up the borehole.

Interpretations of hydraulic conductivity profiles from flow profiles in screened wells completed in a highly transmissive aquifer can be problematic. Bypass flow through the annular space can occur if the annular space between the screen and aquifer were left open with most the measured flow being near the top of the screen. Annular fill that has a much lower hydraulic conductivity than the hydraulic conductivity of the aquifer reduces the contrast in hydraulic conductivity inferred from a flow profile. An aquifer with beds of differing hydraulic conductivity could be incorrectly interpreted as homogeneous from the flow profile if the hydraulic conductivity of the annular fill is much less than the hydraulic conductivity of the aquifer. Thus, flow profiles in a screened well may provide misleading estimates of the hydraulic conductivity profile in the aquifer.

INTRODUCTION

Conventional interpretation of flow logs assumes that hydraulic conductivity is proportional to flow contributed from a measured interval. Flow redistribution through a gravel pack and in the aquifer usually is assumed to be minimal. This interpretation also assumes that little flow occurs in the well under static conditions. If flow through the well were significant when the well is not being pumped, the difference in flow between the pumped and static flow logs would be analyzed (Molz et al; 1989). Analyzing the difference between flow profiles removes the effect of background flow in a manner that is analogous to analyzing drawdowns in aquifer tests.

Flow redistribution through gravel packs has been reported and characterized by an anomalously large flow increase at the top of the screen (Bowman et al; 1997). For a small diameter well with a gravel pack of high hydraulic conductivity, flow can move preferentially through the gravel pack until the bypassed flow is forced in at the top of the screen. Results from numerical simulations of the borehole and flowmeter showed that more flow bypassed the flowmeter as the hydraulic conductivity of an aquifer increased (Dinwiddie et al; 1999). The simulation approach of Dinwiddie et al. (1999) assumed that flow through a flowmeter and head loss across the flowmeter was known. The flowmeter was simulated as no-flow cells with specified heads above and below that differed by the known head loss.

Geohydrologic investigations in South Florida (Weedman et al; 1999) highlighted a need for additional methods of analyzing the potential for flow redistribution. Many flow profiles have been collected from boreholes that penetrate the Gray Limestone aquifer. Previous investigations have described the aquifer as a highly permeable limestone, shell, and sand sequence (Parker et al; 1955). The flow profiles were obtained through screens because the occurrence of many unconsolidated materials precluded logging of open holes (Weedman et al; 1999).

The purpose of this paper is to describe a numerical method for testing the effects of the well screen and annular fill on flow measurements in screened holes. Interaction between flowmeter, well screen, annular fill, and aquifer are simulated for lithologies and completions used at test holes in South Florida. Results indicate that the effects of well screen and annular fill can noticeably affect borehole flowmeter measurements.

SIMULATION OF PIPE AND ANNULAR FLOW

The relation between flow rate and head losses due to laminar flow in a pipe is solely a function of the viscosity of the fluid (Craft et al; 1962). As such, the average velocity (v) in a pipe can be described by

$$v_{WELL} = -\frac{\rho g d^2}{32\mu}\frac{\Delta h}{\Delta L} = -K_{WELL}\frac{\Delta h}{\Delta L} \qquad (1)$$

where, ρ is density (M/L^3), g is gravitational constant (L/T^2), d is pipe diameter (L), μ is viscosity of water (M/L-T), and $\Delta h/\Delta L$ is hydraulic gradient (L/L). Water has a density of about 1000 kg/m^3 and a viscosity of 0.001 kg/m-s at standard conditions.

The velocity in the pipe described by equation (1) can be recast into a form of Darcy's law where the equivalent hydraulic conductivity of the well (K) (Chen and Jiao, 1999) is defined by

$$K_{WELL} = \frac{\rho g d^2}{32\mu} \tag{2}$$

Flow and head losses in annular spaces and screen slots also are needed to describe flow around flowmeters, through gravel packs, and across screens. The equivalent hydraulic conductivity for an annular space (Craft et al; 1962) is defined

$$K_{ANNULAR} = \frac{\rho g (d_o - d_i)^2}{48\mu} \tag{3}$$

where, d_o is the outer annular diameter (L) and d_i is the inner annular diameter (L). The equivalent hydraulic conductivity across a well screen can be defined

$$K_{SCREEN} = N_{SPL} \frac{\rho g w_S^{\ 3}}{12\mu} \tag{4}$$

where, N_{SPL} is the number of slots per unit length of screen (1/L) and w_S is the width of the screen slots (L).

Flow in and near the wellbore frequently is turbulent and cannot be adequately described by laminar flow equations. Laminar and turbulent flow regimes are defined with the Reynolds number

$$\mathrm{Re} = \frac{\rho v d'}{\mu} \tag{5}$$

where, d' is the pipe diameter (d), annular space (d_o - d_i), or screen slot (w_S). Flow generally is characterized as turbulent when Re exceeds 2,000 in smooth pipe (Craft et al; 1962). For example, turbulent flow could be expected in 25-mm passage through a flowmeter when the flow exceeds about 2.4 l/min. Turbulent flow is more likely to occur as the velocity or slot width increases.

Pipe velocity for both laminar and turbulent flow has been defined in terms of a friction factor (f) and is proportional to the inverse-root of the friction factor ($v \propto \sqrt{1/f}$). The Darcy-Weisbach formula (Streeter, 1961) defines the friction factor for laminar flow as

$$f_{LAMINAR} = \frac{64}{\mathrm{Re}} \tag{6}$$

The Sacham formula (Geankoplis, 1993) empirically defines the friction factor for turbulent flow in a pipe as

$$f_{TURBULENT} = \left[-2\log\left(\frac{\varepsilon}{3.7d} - \frac{5.02}{\mathrm{Re}}\log\left(\frac{\varepsilon}{3.7d} + \frac{14.5}{\mathrm{Re}}\right)\right)\right]^{-2} \quad (7)$$

where ε is the pipe or slot roughness (L). The laminar and turbulent friction factors vary as a function of Reynolds number for a given pipe diameter.

Flow rates can be related to head losses in terms of Darcy's Law over the range of laminar and turbulent flow conditions by means of a relative hydraulic conductivity where

$$K_{REL} = \sqrt{\frac{f_{LAMINAR}}{f_{TURBULENT}}} \quad (8)$$

when flow conditions are turbulent. K_{REL} equals 1 for all *Re* numbers when flow is laminar.

Flow through the aquifer, gravel pack, screen, and well can be solved simultaneously with MODFLOW (McDonald and Harbaugh, 1988) because pipe and annular flow have been recast in terms of hydraulic conductivity. The flexibility of a numerical solution allows for investigating the potential interactions between flowmeter, well, and aquifer under many conditions.

MODIFICATIONS TO NUMERICAL MODEL

Turbulent flow was simulated with MODFLOW (McDonald and Harbaugh, 1988) by creating a package (TRB1) that allows conductance between nodes to vary as a function of Reynolds number. The TRB1 package multiplies conductances that have already been calculated by the block-centered flow package (BCF) by a relative hydraulic conductivity as defined in equation (8). Relative hydraulic conductivities are computed within the package from a specified surface roughness or read directly into a look-up table over a range greater than the expected Reynolds numbers and are interpolated from the look-up table during a simulation.

A single look-up table is used for the entire model domain because K_{REL} is weakly affected by variations in the ratio ε/d. The surface roughness of smooth pipe is 0.017 mm (Craft et al; 1962) that is a ε/d ratio of 0.0007 for a 25-mm pipe. The relation between *Re* and K_{REL} differs little for ratios of ε/d from 0.00001 to 0.01 for Reynolds numbers less than 50,000 (Figure 1). This is the maximum range of Reynolds numbers that is expected for simulating a flowmeter.

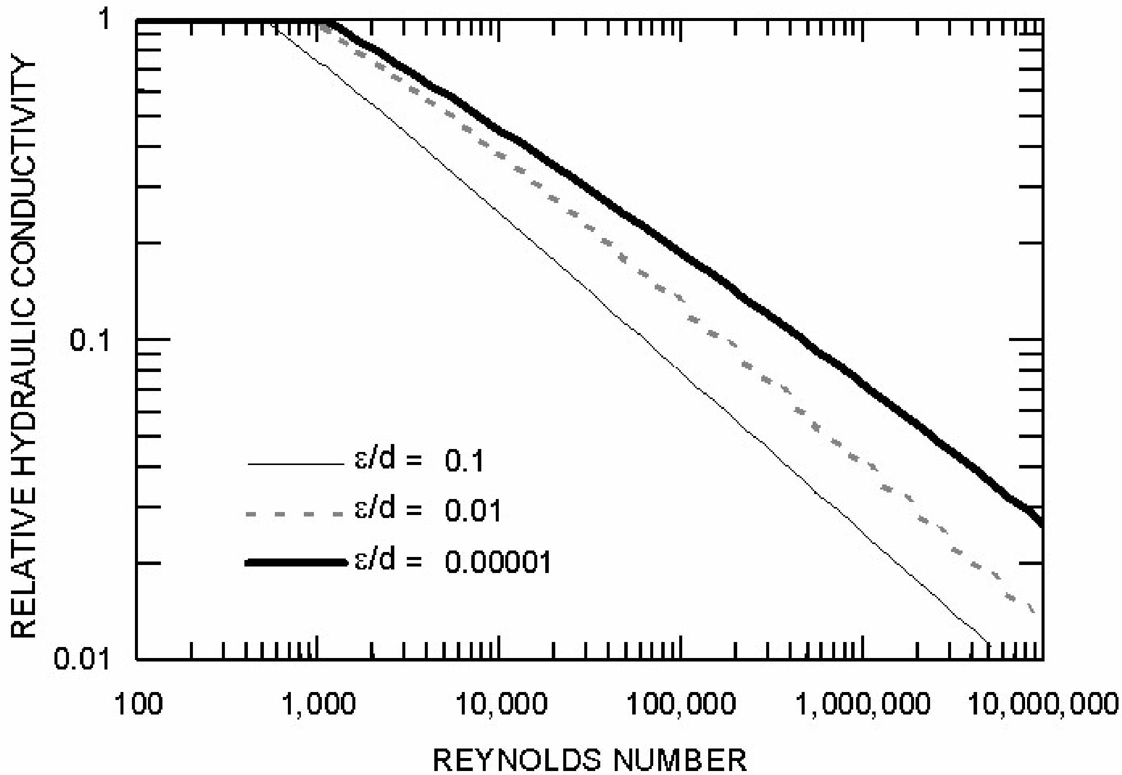

Figure 1.--Relative hydraulic conductivity as a function of Reynolds number for e/d ratios of 0.00001, 0.01, and 0.1.

Reynolds numbers are computed with velocities at the interface between cells, which are the volumetric flows between cells divided by areas and porosities. The diameter or slot width (d') used to compute *Re* is read from the TRB1 package because d' frequently is not related to model geometry. For example, the inner diameter of a well is radially divided into 3 columns to simulate the flowmeter. The radial widths of these 3 columns are each less than the inner diameter of the well which is the appropriate value of d' where the flowmeter is not present.

To simulate movement of the flowmeter within the well, the hydraulic properties of the well and the flowmeter were modified with the Time-Variant Hydraulic-Property Package, VAR1 (Halford, 1998). The VAR1 package allows hydraulic properties to be modified step-wise from one stress period to the next by either being multiplied or replaced.

SIMULATION OF FLOWMETER

Well and aquifer flow systems were simulated with axisymmetric, radial geometries. Radial distance increased with increasing column indices and depth increased with increasing row indices. Hydraulic conductivities and storages of the $i^{\underline{th}}$ column were multiplied by $2\pi r_i$ to simulate radial flow where r_i is the distance from the outer edge of the first column to the center of the $i^{\underline{th}}$ column.

A flowmeter and diverter are simulated by manipulating inter-cell conductances within the first 3 columns that approximate the wellbore (Figure 2). Columns 1, 2, and 3 represent the passage through the flowmeter, wall of the flowmeter, and annular space between the flowmeter and screen, respectively. The flowmeter is simulated with two rows (j and j+1; Figure 2) such that all flow through the flowmeter is between those rows. The distance between the centers of rows j and j+1 is assumed to be the length of the passage through the flowmeter. Inter-cell conductances are set to zero where the flowmeter wall and the diverter are present. The well screen and gravel pack are simulated by columns 4 and 5, respectively (Figure 2). Vertical conductances of the well screen are set to zero.

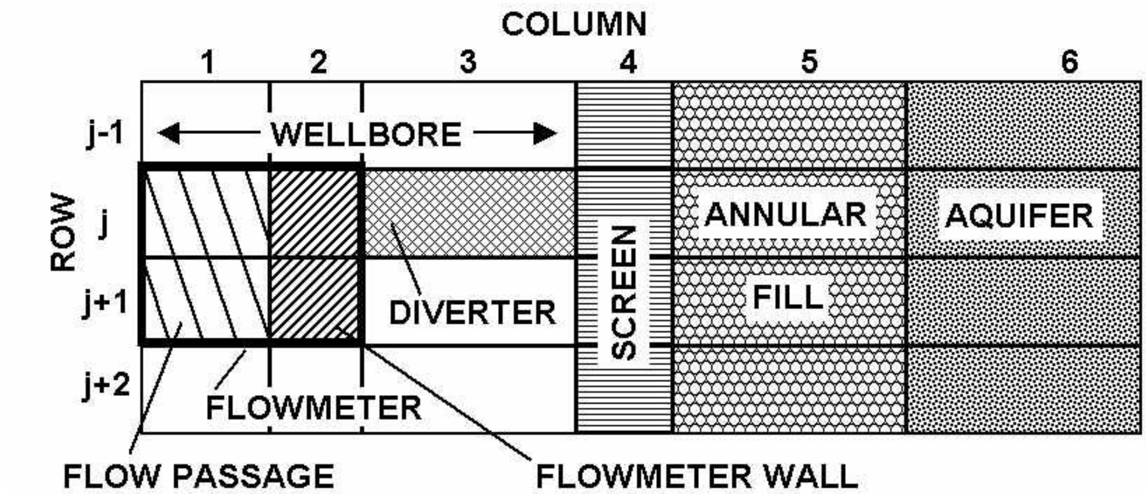

Figure 2.-- Discretization for simulating wellbore, flowmeter, diverter, screen, and gravel pack.

A flow profile across the entire section of screen is simulated with a transient model that has a stress period for each station occupied by the flowmeter in the well. Small values of storage were used to allow steady flow through the meter at each station. At a uniform pumping rate, steady flow to the wellbore is expected even if the aquifer is highly heterogeneous (Javandel and Witherspoon, 1969). Multiple stations that are occupied by the flowmeter and diverter are simulated by modifying the appropriate conductances from one stress period to the next. If the wellbore is divided vertically into 50 rows, 50 stress periods are needed to simulate the flow profile.

The combined well and aquifer flow system is not a numerically stable problem when solved directly because of the extreme contrast in hydraulic conductivities between the well and aquifer. For example, the equivalent hydraulic conductivity of a 100-mm well is about $3x10^8$ m/d (eq. 2) and ranges from 6 to 8 orders of magnitude greater than the hydraulic conductivities of many aquifers. Solving the problem sequentially with two models of the well-aquifer system minimizes numerical instabilities.

A transient model with time-varying specified heads in the wellbore and a radial extent of about 150 km is simulated first to define the far-field flow profile in the aquifer, where the flow in the aquifer is not affected by the flowmeter. The specified heads are solved with Thiem and Theis solutions that use the total transmissivity and storage of the aquifer. The Thiem solution estimates the drawdown across the screen and gravel pack, and the Theis solution estimates the time-varying drawdown from the aquifer response. The specified heads in the wellbore do not vary with depth because of the limitations of the Thiem and Theis solutions. The presence of the flowmeter minimally affected flow in the aquifer at distances of 10 m and greater from the wellbore.

Velocity measurements in the flowmeter are simulated with the second model. Specified-flow rates are assigned to the top of the wellbore and to the lateral boundary away from the well. The sum of the inflow to the lateral boundary away from the well is equal in magnitude and opposite in sign from the well discharge. The vertical distribution of the lateral boundary away from the well is defined by the far-field flow profile simulated in the first model.

An arbitrary water level is specified at the bottom of the wellbore to make the second model numerically stable. The specified head is a source or sink that absorbs small errors from truncation of specified flow along the lateral boundary away from the well and numerical round-off. Flow to this specified head should be zero in theory and was less than 0.02 percent of the total discharge in fact.

AN APPLICATION

The effects of flowmeter configuration, well construction, and aquifer heterogeneity on flow profiles were tested with a series of hypothetical models. The simulated aquifer was 15 m thick, had an average transmissivity of about 23,000 m^2/d, and was bounded by impermeable units. The aquifer properties are similar to those observed in the Gray Limestone aquifer near Bear Island which is located at 26°10'58"N. and 81°14'52"W. about 100 km west-northwest of Miami, FL (Reese and Cunningham, 2000). The simulated well was a 76-mm diameter screen with 0.25-mm wide slots, 160 slots per m, and a 5-mm wall thickness in a 150-mm hole, which is similar to the completion at the Bear Island test site.

Each model was simulated with the same vertical discretization and radial discretization near the wellbore. The aquifer was discretized vertically into 50 uniform rows that were 0.3 m high. Five additional rows were added above and below the aquifer to simulate movement of the flowmeter through blank casing. The first 6 columns were discretized to simulate the wellbore, screen, annulus, and aquifer as shown in figure 2. The initial model that simulated the far-field profile for the second model expanded radially as multiples of 1.16 to a no-flow boundary 150,000 m away in 93 additional columns. The second model that simulated flow profiles expanded radially as multiples of 1.16 to a specified-flow boundary 50 m away in 39 additional columns. The flowmeter was simulated with two rows in the second column (Figure 2) and was assigned a 25-mm inner diameter, a 50-mm outer diameter, and a 0.6-m length. A surface roughness of 0.04 mm was assigned to all surfaces. The head and flow distributions of the models were solved with the modified version of MODFLOW (McDonald and Harbaugh, 1988) discussed in a previous section and the pathlines were computed with MODPATH (Pollock, 1994).

Four different flow profiles were simulated for a homogeneous aquifer with a hydraulic conductivity of 1520 m/d and a lateral-to-vertical anisotropy of 4. The flowmeter was simulated with a diverter for half of the scenarios and without a diverter for the other half. The annular space between the screen and the aquifer was open (K~1x10^8 m/d) for half of the scenarios and was filled with coarse rubble (K=100 m/d) for the other half. The flow profiles were simulated with a pumping rate of about 19 l/min. Turbulent flow can be expected whenever flow through the meter exceeds 2.4 l/min.

None of the flow profiles matched the theoretical response of a linear increase in discharge from 0 l/min at the bottom to 19 l/min at the top (Figure 3). The flow profile from the simulation with no diverter and a filled annulus best approximated the theoretical response. Both flow profiles with a filled annulus might provide adequate estimates of flow zones of differing hydraulic conductivity if the upper 3 m of the profiles are ignored. Flow profiles from the open annulus simulations were affected by the low hydraulic conductivity of the screen (K~200 m/d) relative to the hydraulic conductivities of the well (K~2x10^7 m/d) and the annular space (K~1x10^8 m/d). The relatively low hydraulic conductivity of the screen causes flow to gradually cross the screen over a longer interval instead of across a short interval near the casing above the aquifer (Figure 3).

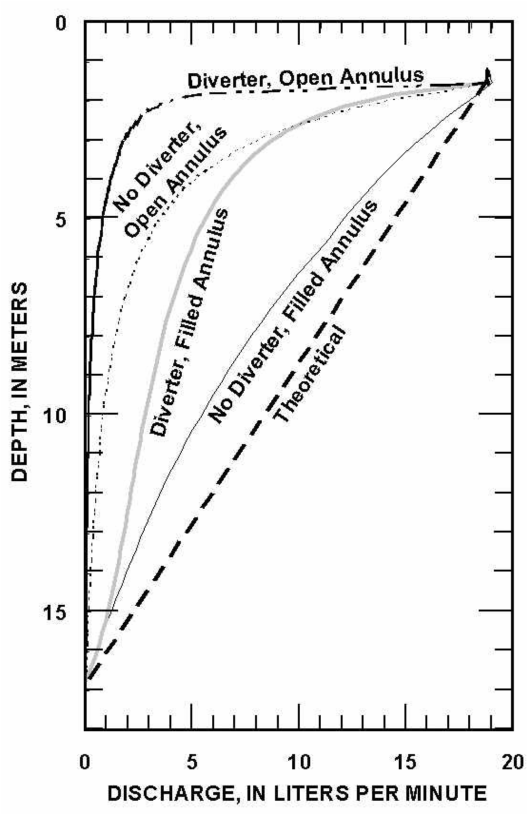

Figure 3.—Flow profiles through homogeneous aquifer.

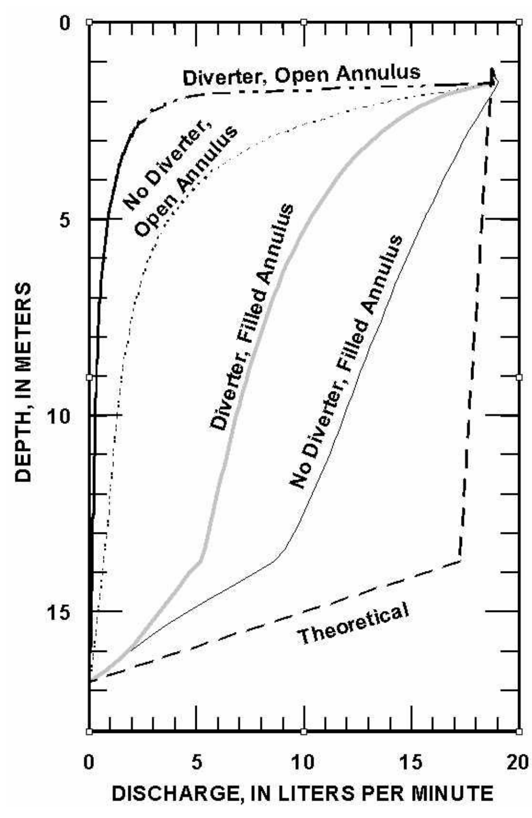

Figure 4.— Flow profiles through heterogeneous aquifer.

Under field conditions, measuring a flow profile without a diverter cannot be assumed automatically to be better than using a diverter. Flow through the meter was reduced by almost a factor of 9 when a diverter was not used. The reduction of flow also would reduce the sensitivity of a real flowmeter with a minimum level of resolution.

Another set of four flow profiles were simulated for a heterogeneous aquifer with a hydraulic conductivity of 150 m/d in the upper 12 m, a hydraulic conductivity of 7000 m/d in the lower 3 m, and a lateral-to-vertical anisotropy of 4 throughout the aquifer. The high hydraulic conductivity was placed at the bottom because flow redistribution was more likely to cause the high hydraulic conductivity unit to be incorrectly identified. The same perturbations with the diverter and annular fill were repeated for the heterogeneous aquifer and the flow profiles also were simulated with a pumping rate of about 19 l/min.

The transition between the 2 zones of hydraulic conductivity could be correctly identified in both flow profiles with a filled annulus (Figure 4). The hydraulic conductivity was assumed to be proportional to the inverse of the slope of the flow profile across each zone and only the contrast in hydraulic conductivity between zones could be determined. The flow profile from the simulation with no diverter and a filled annulus best approximated the theoretical response but greatly underestimated the contrast in hydraulic conductivity between the two zones. The hydraulic conductivity of the lower zone would be estimated as 4 times the hydraulic conductivity of the upper zone from the flow profile when in fact the hydraulic conductivities differ by a factor of 47.

The low hydraulic conductivity of the annular fill (K=100 m/d) relative to the high hydraulic conductivity of the lower zone (K=7000 m/d) diverts flow to the upper zone. Pathlines that originated 50 m from the well and were uniformly distributed across the lower zone show about half of the flow in the lower zone at 50 m was diverted into the upper zone before reaching the well (Figure 5). The simulation with no diverter and a filled annulus depicts the redistribution in the aquifer more so than near the well with about half of the flow entering below a depth of 13 m (Figure 4). Additional simulations, not discussed in detail in this paper, with hydraulic conductivities of the annular fill specified as 20 m/d and less caused the hydraulic conductivity to appear homogeneous throughout the aquifer.

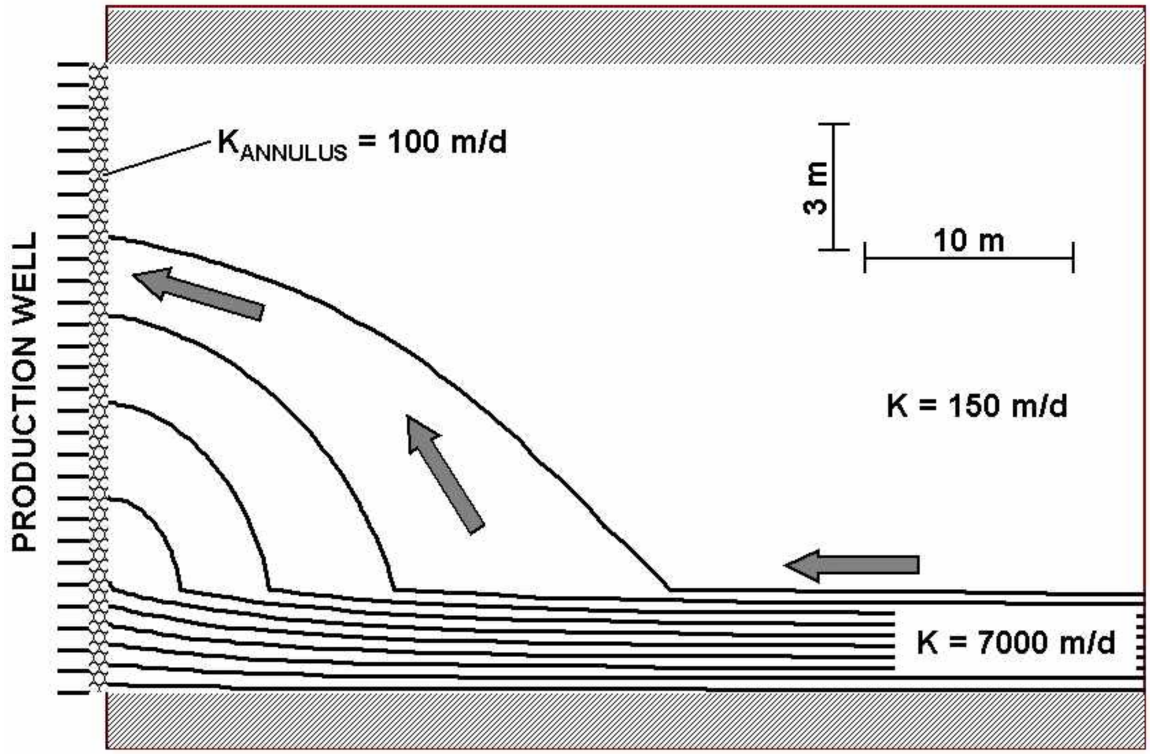

Figure 5.—Pathlines from diversion of flow in a highly transmissive, heterogeneous aquifer due to gravel pack.

CONCLUSIONS

Numerical methods have been presented for testing the effects of flowmeter, well screen, and annular fill on flow profile measurements in screened holes under laminar and turbulent flow regimes. The principal utility of these methods is to help understand the direction and degree of departure between measured and ideal flow profiles. Given the many unknowns in the construction of a well, these methods probably would not be useful for estimating the hydraulic properties of an aquifer through calibration of a model to a measured flow profile.

Analysis of results in this paper indicates that interpretations of hydraulic conductivity profiles from flow profiles in screened wells completed in a highly transmissive aquifer can be problematic. Bypass flow through the annular space can occur if the annular space between the screen and aquifer were left open with most of the measured flow being near the top of the screen. Annular fill that has a much lower hydraulic conductivity than the hydraulic conductivity of the aquifer reduces the contrast in hydraulic conductivity inferred from a flow profile. An aquifer with beds of differing hydraulic conductivity could be incorrectly interpreted as homogeneous from the flow profile if the hydraulic conductivity of the annular fill is much less than the hydraulic conductivity of the aquifer. Thus, flow profiles in a screened well may provide misleading estimates of the hydraulic conductivity profile in the aquifer.

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