Inversion of Borehole Flowmeter Measurements Considering Well Screen Clogging and Skin

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ABSTRACT

If the pressure drop across a well screen is large because the screen is clogged by fines then inflow to a pumped well may be influenced by vertical flow components near the wellbore. The effect is larger if well emplacement has enhanced the hydraulic conductivity around the well. These phenomena complicate the interpretation of borehole flowmeter data.

A cylindrical geometry version of MODFLOW-2000 was created to investigate these phenomena. The formulation of the RADMOD code by Reilly and Harbaugh (1993) was used as the basis of the modification. Whereas RADMOD is a preprocessor for MODFLOW, the present modification is to the MODFLOW-2000 code. The wellbore, screen and disturbed zone can be modeled with varying parameters making the modification more flexible than RADMOD. A new observation type was added to accommodate borehole flowmeter measurements.

For a horizontally layered aquifer, the inversion capability of MODFLOW-2000 permits the investigation of how near-well disturbances may influence flowmeter interpretation. Thin, highly-permeable layers can be significantly underestimated if the influences of non-horizontal flow near the wellbore are not considered.

INTRODUCTION

A borehole flowmeter measures the vertical flow in a well. The net inflow or outflow can be determined by taking the difference between the vertical flow at two elevations. If the aquifer can be assumed to be a sequence of horizontal layers with the flowmeter measurements acquired at the boundaries between layers, then the hydraulic conductivity of the layers can be determined from net inflows using a calculation developed by Javandel and Witherspoon (1969). The Javandel and Witherspoon formulation is based on an assumption of radially-symmetric horizontal flow into the wellbore. If the flow near the wellbore deviates substantially from horizontal then the hydraulic conductivities determined from the this method will be in error.

Dinwiddie *et al.* (1999) have shown that bypass flow through a gravel pack about a wellbore can significantly affect flow measurements of a flowmeter that uses a skirt to force flow through the throat of a flowmeter. In this paper, we consider the vertical deflection of flow near the wellbore caused by clogging of the well screen. The impact of screen clogging is similar to that of a positive skin zone around the well, a problem investigated by Young (1998). Motivation for this investigation comes from apparent well-screen clogging observed at the Boise Hydrogeophysical Research Site (Barrash *et al.* (in prep).

The MODFLOW-2000 code (Harbaugh et al., 2000; Hill et al., 2000) was modified to incorporate the two-dimensional cylindrical geometry formulation enabled by the RADMOD code (Reilly and Harbaugh, 1993). RADMOD is incompatible with MODFLOW-2000 but is compatible with earlier versions of MODFLOW using the Generalized Finite-Difference Package (Harbaugh, 1992) that allows more flexible model geometry compared to standard MODFLOW. Incorporating cylindrical geometry directly into MODFLOW-2000 allows the inversion capabilities of the code to be used in the well screen clogging investigation.

The cylindrical geometry modifications have been made more general than the RADMOD code. While angular symmetry is still assumed, the radial spacing can be specified explicitly and each cell in the model can be assigned individual properties. This allows the borehole itself to be simulated as well as a surrounding disturbed zone. A well screen and cased zones can be simulated either by including the screen thickness in the model definition or using the horizontal barrier package. To allow simulation of a flowmeter measurement in the well, an internal flow observation type was added. A report (Clemo, 2002) with more detailed descriptions of the changes and access to source code can be found in the technical report section of http://cgiss.boisestate.edu/cgiss_pub.html.

CYLINDRICAL GEOMETRY

The structure of MODFLOW is convenient for changing the coordinate system. The basic flow equations are formulated in terms of conductances between cell nodes and storage capacitance of the nodes. The geometry influences the calculation of these terms but is thereafter no longer used directly to simulate the head dynamics. MODFLOW-2000 allows calculation of the conductances for different averaging equations for hydraulic conductivity. The variable LAYAVG is used to control which equation is applied. The modifications for cylindrical geometry use the value of LAYAVG to signal the use of cylindrical geometry to calculate the conductances.

The inversion capability of MODFLOW-2000 requires the determination of the sensitivity of observations to parameters. By the chain rule of calculus the sensitivity of observations to parameters can be calculated as the sensitivity of the observations to conductance multiplied by the sensitivity of the conductance to the parameters. The required modification of the MODFLOW-2000 sensitivity process is quite limited because the sensitivities of the observations to conductance remain unchanged.

As an example, consider an internal flow observation that is defined as the radial flow from cell i to cell $i+1$. The observation, Q, can be written as

$$Q = C_r \left(h_{i+1} - h_i\right) \tag{1}$$

where C_r is the conductance between the cells and $h_{i+1} - h_i$ is the head difference between the nodes. The sensitivity to a hydraulic conductivity parameter, K, is

$$\frac{\partial Q}{\partial K} = \frac{\partial C_r}{\partial K}\left(h_{i+1} - h_i\right) + C_r\left(\frac{\partial h_{i+1}}{\partial C_r} - \frac{\partial h_i}{\partial C_r}\right)\frac{\partial C_r}{\partial K} \tag{2}$$

The terms $\frac{\partial h}{\partial C_r}$ do not require modification for cylindrical geometry. We only need to provide a calculation of $\frac{\partial C_r}{\partial K}$. The conductance between cells is formed from internal conductances of each cell as

$$C_r = \frac{C_{r_i} C_{r_{i+1}}}{C_{r_i} + C_{r_{i+1}}} \tag{3}$$

where C_{r_i} is the conductance within cell i from the cell node to the cell boundary (McDonald and Harbaugh, 1988; Reilly and Harbaugh, 1993). The internal conductance in the radial direction is

$$C_{r_i} = \frac{K_{r_i} 2\pi \Delta z}{\ln\left(\frac{sr_i}{r_i}\right)} \tag{4}$$

where r_i is the radial position of the note and sr_i is used to represent the radial position of the cell boundary. By the chain rule and some reorganization of terms

$$\frac{\partial C_r}{\partial K} = \frac{C_{r_{i+1}}^2}{\left(C_{r_i} + C_{r_{i+1}}\right)^2}\frac{\partial C_{r_i}}{\partial K} + \frac{C_{r_i}^2}{\left(C_{r_i} + C_{r_{i+1}}\right)^2}\frac{\partial C_{r_{i+1}}}{\partial K} \tag{5}$$

with,

$$\frac{\partial C_{r_i}}{\partial K} = \frac{2\pi\Delta z}{\ln\left(\frac{sr_i}{r_i}\right)}\ \text{, and}\ \frac{\partial C_{r_{i+1}}}{\partial K} = \frac{2\pi\Delta z}{\ln\left(\frac{r_{i+1}}{sr_i}\right)} \tag{6}$$

likewise in the vertical direction the internal conductance is given by

$$C_{v_i} = \frac{KA}{\frac{1}{2}\Delta z} \tag{7}$$

where Δz is the cell thickness and A is the cross-sectional area of the cell. We get

$$\frac{\partial C_{v_i}}{\partial K} = \frac{\pi\left(sr_{i+1}^2 - sr_i^2\right)}{\frac{1}{2}\left(\Delta z_u + \Delta z_l\right)} \tag{8}$$

where Δz_u and Δz_l refer to the thickness of the upper and lower layers respectively.

COMPARISON TO WTAQ

The test case and model geometry described in Reilly and Harbaugh (1993) were used to test the cylindrical geometry modifications. The case simulates a homogeneous unconfined aquifer - 100 ft thick with a horizontal hydraulic conductivity of 100 ft/day, vertical hydraulic conductivity of 10 ft/day, specific yield of 0.2 and a specific storage of $5\text{x}10^{-6}$/ft. A pump rate of 125670 ft^3/day is applied over the lower 25 ft of the aquifer. The WTAQ (Barlow and Moench, 1999) code was used as a benchmark.

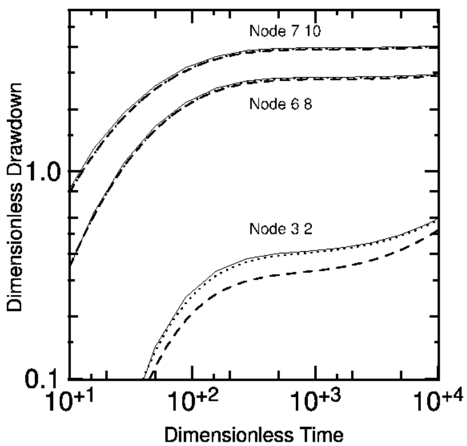


Figure 1 Comparison of WTAQ calculations (solid), cylindrical model without water table modification (dashed), and with the water table modification (dotted).

Figure 1 presents the simulated drawdown. WTAQ calculations are drawn as a solid line. The cylindrical model calculations are shown with a dashed line. The number above the curves are node positions in the model. Node 7 10 is 24 ft from the well and 90 ft deep. Node 6 8 is 16 ft from the well and 50 ft deep. Node 3 2 is 0.52 ft away from the well and 20 ft deep. The dotted line presents the calculations with the uppermost node following the water table as described by Clemo (2003).

INFLUENCE OF CLOGGED SCREEN ON FLOW

A clogged screen, like the positive skin investigated by Young (1998), causes flow near the well to deflect from the high conductivity layers to low conductivity layers as depicted in Figure 2. The cross-hatched region depicts the well. A narrow band on the outside of the well represents the well-screen. Three layers are shown; the upper and lower layers have a lower hydraulic conductivity than the middle layer. The arrows represent flow direction. The deflection shown in Figure 2B can be explained as follows. Within the wellbore, head is approximately constant. With an open screen the head drop across the screen is negligible if the screen is more conductive than the formation.

If the screen is clogged, the head drop across the screen can be large compared to the head variation in the formation near the well. Larger flow rates in the high conductivity layers lead to larger head drops across the screen. Thus a vertical head difference occurs just outside the screen. The vertical gradient induces a vertical flow component in the formation deflecting flow away from the high conductivity layer just near the borehole. The rerouting of flow is enhanced somewhat if there is a region of high hydraulic conductivity next to the borehole, which may be due to installation of a gravel pack or disturbance to the formation in the well installation process.

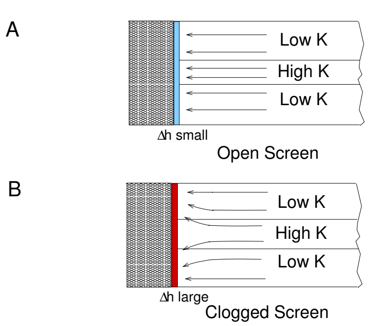


Figure 2 Flow deflection due to a clogged screen.

Incorporating cylindrical geometry into MODFLOW-2000 provides a tool to investigate the influence of screen clogging on flow into a borehole and to aid in the interpretation of flowmeter data. Figure 3 presents the lower left corner of a demonstration simulation of the effects of screen clogging. The main features are: explicit representation of the wellbore, flow observations between each layer, a region that has enhanced hydraulic conductivity in some simulations, and alternating layers with an order of magnitude difference in hydraulic conductivity.

The full model has eleven layers and extends to a distance of 5000 m where a constant head is applied. A confined aquifer is simulated. Hydraulic conductivity of 10^{-3} m/s was assigned to the even numbered layers and 10^{-4} m/s was assigned to the odd numbered layers. The odd numbered layers are all 1 m thick. The even numbered layers have thicknesses of 1.m, 0.5m, 0.3m 0.2m 0.1m from top to bottom.

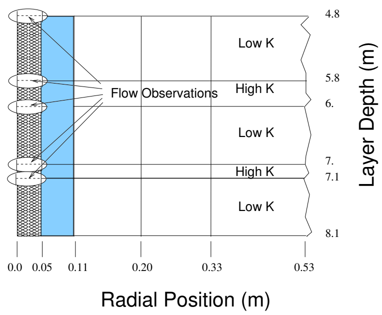


Figure 3 Schematic diagram of a portion of a cylindrical model. The cross-hatched area is the borehole. The circled regions are flow measurement locations. The shaded region may have enhanced conductivity.

Three simulations were performed: one without well-screen effects or an enhanced zone, one with a horizontal barrier of $1.5\text{x}10^{-3}$ s^{-1} applied between columns 1 and 2 to simulate well-screen clogging, and one with the barrier and a hydraulic conductivity of $1\text{x}10^{-2}$ m/s in column 2 to simulate a 5.7 cm thick gravel pack. The vertical flow in the well was obtained from internal flow observations.

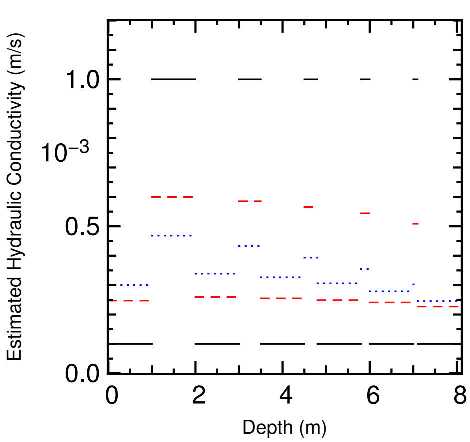
Hydraulic conductivity values were calculated using

$$K_i = \frac{Q_i Z \overline{K}}{\Delta Z_i Q} \tag{9}$$

from Javandel and Witherspoon (1969). In equation 9, K_i represents the hydraulic conductivity of a layer, $\overline{K}$ is the average K of the aquifer which is determined independently of the flowmeter tests, Q_i is the net inflow to the well at the layer, Q is the pumping rate, Z is the total aquifer thickness, and ΔZ_i is the the layer thickness. Figure 4 presents the estimated hydraulic conductivity obtained, using equation 9, from the internal flow measurements in the simulated well column. Horizontal bars are draw across the layer interval at the level of the estimate. The thinning of the high conductivity layers in the model is evident. Solid lines are plotted for the situation of an open screen and no disturbed zone. As expected, the calculation returns the true conductivity. The case with skin but no enhanced zone is drawn with dashed lines.

This case yields estimates between 50% and 60% of the true values for the high conductivity layers and increases of greater than two times for the low conductivity layers. There is a small increase in effect with decreasing layer thickness. The dotted lines show an increased effect when a high conductivity zone exists near the wellbore. The sensitivity to layer thickness is dramatically increased, with the ratio of estimated high conductivity to low conductivity changing from an order of magnitude to 20%.

INVERSION OF FLOWMETER MEASUREMENTS



Figrue 4 Estimated Hydraulic Conductivity using Equation 9. True - solid, clogged screen - dashed, and clogged screen with gravel pack - dotted.

The ability of the cylindrical geometry model to estimate hydraulic conductivity in the presence of well-screen clogging was tested. The flow measurements acquired from the simulation with a clogged screen but no enhanced conductivity zone were used with equal uncertainty. No measurement noise was added.
The inversion parameters were constant hydraulic conductivity in each layer. An accurate estimate of the effective screen conductivity was assumed to be available and assigned to the horizontal flow barrier. (A discussion of estimating screen clogging is beyond the scope of this paper. The subject is discussed in Barrash *et al.* (in prep.)) This creates an inversion problem with eleven unknowns and ten measurements. A constraint equation was added so that the average conductivity would be equal to the actual average conductivity of the simulated aquifer. The internal check in MODFLOW-2000 that there are more measurements than parameters was overridden. The inversion results were within 2% of the true values.

CONCLUSIONS

In heterogeneous coarse grained aquifers, clogging of a well screen can have a significant impact on the distribution of flow into a well. This can cause estimates of hydraulic conductivity obtained through the analysis method of Javandel and Witherspoon (1969) to be in error. The variability of hydraulic conductivity will be under-represented with low estimates of the highest conductive layers.

The MODFLOW-2000 code has been modified to simulate radial flow into a well. This modification includes the sensitivity calculations and allows the inversion capabilities of MODFLOW-2000 to be used in the interpretation of wellbore flowmeter measurements in the case of a clogged screen. The inversion requires an estimate of the hydraulic conductivity of the screen, an issue that has not been addressed in this paper.

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