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Numerical study identifying the factors causing the significant underestimation of the specific discharge estimated using the modified integral pumping test method in a laboratory experiment

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ABSTRACT

A three-dimensional finite element model is constructed to simulate the experimental conditions presented in a paper published in this journal [Goltz et al., 2009. Validation of two innovative methods to measure contaminant mass flux in groundwater. Journal of Contaminant Hydrology 106 (2009) 51–61] where the modified integral pumping test (MIPT) method was found to significantly underestimate the specific discharge in an artificial aquifer. The numerical model closely replicates the experimental configuration with explicit representation of the pumping well column and skin, allowing for the model to simulate the wellbore flow in the pumping well as an integral part of the porous media flow in the aquifer using the equivalent hydraulic conductivity approach. The equivalent hydraulic conductivity is used to account for head losses due to friction within the wellbore of the pumping well. Applying the MIPT method on the model simulated piezometric heads resulted in a specific discharge that underestimates the true specific discharge in the experimental aquifer by 18.8%, compared with the 57% underestimation of mass flux by the experiment reported by Goltz et al. (2009). Alternative simulation shows that the numerical model is capable of approximately replicating the experiment results when the equivalent hydraulic conductivity is reduced by an order of magnitude, suggesting that the accuracy of the MIPT estimation could be improved by expanding the physical meaning of the equivalent hydraulic conductivity to account for other factors such as orifice losses in addition to frictional losses within the wellbore. Numerical experiments also show that when applying the MIPT method to estimate hydraulic parameters, use of depth-integrated piezometric head instead of the head near the pump intake can reduce the estimation error resulting from well losses, but not the error associated with the well not being fully screened.

1. Introduction

Driven by the current contaminant concentration based environmental regulatory standards, characterization and management practices at environmental sites with groundwater contamination have mostly focused on contaminant concentration measurements. It has been recognized, however, that concentration data alone cannot answer all questions critical to site assessment and long-term management (ITRC, 2010). Compared with point-in-space and point-in-time contaminant concentrations, mass flux as a measure of the rate of contaminant migration in an aquifer provides more insight into the environmental and human risks posed by groundwater contamination (Einarson and Mackay, 2001; Buscheck et al., 2003; ITRC, 2010). In response to this recognition, there has been a rising trend in the industry to characterize and monitor contaminant mass fluxes as a supplement to collecting concentration data

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for the purpose of developing better optimized remediation strategies (ITRC, 2010).

Mass flux estimation has traditionally been achieved using the transect method, where estimations of contaminant concentrations and groundwater fluxes (specific discharges) are made at a series of planes oriented perpendicular to principal groundwater flow. The major drawback of the transect method is that it requires intensive data collection to achieve reliable mass flux estimates, which is often cost-prohibitive for large scale environmental sites. The recent increase in interest of mass flux characterization has led to the development of several emerging estimation techniques (IRTC, 2010). One of the newly developed methods is the modified integral pumping test (MIPT) method (Brooks et al., 2008; Goltz et al., 2009; ITRC, 2010), which is considered a modified and simpler version of the previously developed integral pumping test (IPT) technique (Bockelmann et al., 2001; Bauer et al., 2004; Jarsjo et al., 2005). Among other factors, the need to frequently sample the effluents of multiple pumping wells when conducting IPT limits the practical use of this technique. In comparison, the MIPT method can be implemented in the field with ease, making it more attractive (ITRC, 2010). The MIPT method involves conducting multiple pumping tests with successively increased pumping rates and measuring steady-state piezometric heads at two or more locations for concurrent estimation of hydraulic conductivity and specific discharge. Mass flux can subsequently be estimated as the product of the specific discharge and the contaminant concentration measured at the wellhead of the pumping well.

Brooks et al. (2008) first proposed and applied the MIPT method at two field sites in the United States. Goltz et al. (2009) conducted physical experiments on an artificial aquifer with an intention to validate the MIPT method and another emerging method, the tandem circulation well (TCW) method. The experiments found that the MIPT method consistently underestimated the mass fluxes by as much as 70%, while the TCW method estimated the mass fluxes with accuracies within 2% to 16%. This was unexpected given the same artificial aquifer and apparatus were used to test both methods. Goltz et al. considered the following factors as potential source of error in their MIPT experiments: (1) well screen head loss; (2) the fact that the MIPT pumping wells were not fully screened; and (3) other violations of the method assumptions (e.g., steady-state flow not reached).

Sun (2014) suggested that well screen loss was likely the primary source of error in Goltz et al.'s experiments by indicating that the difference in the configurations of the MIPT and the TCW experiments could explain the different performances of the two estimation methods. The mathematical model for the MIPT method describes two-dimensional groundwater flow in a homogeneous and isotropic aquifer of an infinite domain. Being two-dimensional, this model assumes ideal flow with uniform distributions of piezometric head and flux along the screen of the pumping well. In reality, however, groundwater flow within and in the vicinity of a pumping well is subject to the influence of energy losses as water enters into the wellbore and subsequently flows toward the pump intake (Bear, 1979). The energy or head loss is commonly known to occur: (1) in the damage zone consisting of filter cake and drilling debris; (2) in the filter zone; and (3) near and inside the wellbore commonly referred to as well losses (Williams, 1985; Rosecoe Moss, 1990). Well losses include head losses associated with the entrance of water through the well screen known as orifice losses and the subsequent axial flow of water toward the pump intake known as screen losses (Williams, 1985). For the MIPT experiments conducted by Goltz et al. (2009), the first two types of head losses do not apply, and only well losses could have occurred. Among other factors, longer well screens, smaller wellbore diameters, larger pumping rates, higher aquifer transmissivities, and partial screen penetration lead to larger well head losses (Cooley and Cunningham, 1979; Szekely, 1992).

The objective of this study is to, through numerical experiments, evaluate the accuracy of the MIPT estimated specific discharges under different wellbore conditions with an intention to determine if head loss near and along the wellbore is the primary source of error in the MIPT experiments presented by Goltz et al. (2009). Numerical models accounting for well screen head losses have been reported (Sudicky et al., 1995; Chen and Jiao, 1999; Therrien and Sudicky, 2001; Chen et al., 2003; Cheng et al., 2005; Mohamed and Rushton, 2006). Most of these previous modeling studies coupled the wellbore flow and the flow in the surrounding aquifer by treating the wellbore as a flow- or head-based boundary or as a special source or sink term. Chen and Jiao (1999) presented the concept of equivalent hydraulic conductivity describing in-well hydraulics, which makes it possible to implement the wellbore flow as an integral part of the flow in the aquifer without special treatment of the wellbore as an internal boundary. Chen et al. (2003) presented a hypothetical case study with this equivalent hydraulic conductivity approach where a polygon finite difference (PFD) model was constructed to simulate groundwater flow to a horizontal well. The numerical model in this study also uses the equivalent hydraulic conductivity approach, but with a finite element model to simulate the pipe flow in a vertical well. A finite element model provides the flexibility for a more accurate representation of the actual pumping well dimensions.

2. Mathematical model for the MIPT method

The MIPT method is based on a two-dimensional mathematical model describing the piezometric head difference between two monitoring locations in a confined, homogeneous and isotropic aquifer with one pumping well (Brooks et al., 2008).

$$\Delta h = -\frac{q[(x_2-x_1)\ \cos\alpha + (y_2-y_1)\ \sin\alpha]}{K} + \frac{Q}{4\pi bK}\ \ln\frac{(x_2-x_0)^2 + (y_2-y_0)^2}{(x_1-x_0)^2 + (y_1-y_0)^2} \tag{1}$$

where:

(x_1, y_1) and (x_2, y_2) are the coordinates of the two monitoring wells (L),
(x_0, y_0) are the coordinates of the pumping well (L),
Δh is the piezometric head difference between the two monitoring wells (L),
q is the specific discharge of groundwater flow (LT^{-1}),
Q is the pumping rate (L^3T^{-1}),
α is the angle between q and the positive x-axis,
K is the hydraulic conductivity (LT^{-1}), and
b is the aquifer thickness (L).