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Direct estimation of hydraulic parameters relating to steady state groundwater flow

Kerang Sun [a,*], Mark N. Goltz [b]

[a] CH2M HILL, Inc., 6 Hutton Center Drive, Santa Ana, CA 92707, United States
[b] Air Force Institute of Technology, Wright-Patterson AFB, OH 45433, United States

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ABSTRACT

Groundwater as an important, life-sustaining resource for humankind is being threatened by massive over-extraction and wide-spread contamination. Wise development and protection of this crucial resource requires a thorough understanding of groundwater flow in the subsurface. This paper presents a novel direct method to estimate important hydraulic parameters characterizing steady state groundwater flows for confined and unconfined isotropic aquifers. The method is appropriate for application in aquifers where horizontal flow dominates. The governing equations for the direct estimation method are superposed extensions of the well-known Thiem equation governing steady-state radial flow toward a pumping well under confined and unconfined conditions. This new approach has the following advantages over conventional methods: (1) simultaneously provides estimates of both hydraulic conductivity and hydraulic gradient, (2) can be applied using historical data without the need to conduct a pumping test, and (3) is a simple analytical method that can be applied easily. Verification of the direct estimation method is achieved by applying it to hypothetical homogeneous and heterogeneous aquifers simulated by three-dimensional finite element models. The usefulness of the method is also demonstrated with data from an actual field site.

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1. Introduction

Groundwater is the largest fresh water body on the Earth and supplies drinking water to approximately two billion people worldwide (Richey et al., 2015). It may be the only source of water in some arid regions (Clarke et al., 1996). To protect this crucial life-sustaining resource from the progressively escalating crisis of aquifer depletion (Clarke et al., 1996; Richey et al., 2015; Konikow, 2011; Wada et al., 2010; Werner and Gleeson, 2012), the increasingly frequent occurrence of aquifer contamination (Clarke et al., 1996), and the potential impacts of climate change (Taylor et al., 2013), we must have detailed knowledge of aquifer hydrogeologic properties. Such knowledge is obtained through aquifer characterization which typically requires substantial field efforts. Given the complex nature of subsurface flow along with financial and technological limitations, it is often difficult or impossible to generate sufficient data from field testing to adequately characterize the subsurface in order to construct hydrogeological models that will support good management decision making.

Hydraulic conductivity and hydraulic gradient are the key parameters needed to model groundwater flow. Aquifer pumping tests are conventionally used to obtain estimates of hydraulic conductivity, with piezometers used to determine gradient. A pumping test involves extracting groundwater at known rates and measuring the hydraulic responses at selected locations. The response data at monitoring wells are analyzed to estimate hydraulic conductivity values. Various deterministic and stochastic models have been developed to suit different pumping and aquifer conditions (Batu, 1998; Kruseman and de Ridder, 1994; Li et al., 2005). While other techniques such as geophysical surveys (Capriotti and Li, 2015; Hinnell et al., 2010; Singha et al., 2015), borehole flow meters (Li et al., 2008; Paillet, 1998; Paradis et al., 2011), and empirical estimation methods (Domenico and Schwartz, 1998) have been applied to indirectly determine aquifer hydraulic conductivity, pumping tests remain the prevailing characterization method. One advantage of pumping test is that it interrogates a relatively large subsurface volume; thus, the estimate

* Corresponding author.
E-mail addresses: Kerang.Sun@gmail.com (K. Sun), mark.goltz@afit.edu (M.N. Goltz).

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of hydraulic conductivity obtained from a pumping test is a large-scale volume-average. However, conducting a pumping test is by no means a trivial task. Firstly, it costs both time and money to plan and execute a test. Secondly, there are situations where a meaningful pumping test cannot be conducted. For example, aquifers with low conductivity may not be able to sustain a large enough pumping rate to induce measureable drawdown at monitoring wells. Lastly, there are often regulatory and economic hurdles imposed by the need to dispose of the potentially contaminated water that was extracted during the test. An alternative method that can be applied to directly estimate aquifer hydraulic conductivity while avoiding pumping tests would be of great benefit.

Here we present a novel approach to quantitatively estimate hydraulic conductivity and regional hydraulic gradient without the need to conduct a dedicated pumping test. So long as long term pumping data from at least one pumping well and monitoring data from at least three observation wells are available, the method can simultaneously obtain estimates of hydraulic conductivity and gradient of the background flow in the aquifer. While the method has the advantage of sampling a large subsurface volume, it avoids the disadvantages of pumping tests discussed above.

2. Method development

The equations upon which the direct estimation method is based require a number of simplifying assumptions. The closer these assumptions come to describing the real physical system, the more appropriate it is to apply the direct estimation method to that system. The simplifying assumptions are:

1. Isotropic aquifer of infinite extent with a homogeneous hydraulic conductivity (K) field.
2. Steady-state flow conditions.
3. Two-dimensional flow. In the case of a confined aquifer, the aquifer thickness (b) is constant. In the case of an unconfined aquifer, the Dupuit assumptions hold.
4. Uniform, regional flow. In the case of a confined aquifer, constant Darcy velocity ($q = -K\nabla h = -Ki$) where h is the hydraulic head and $i = \nabla h$ is the regional hydraulic gradient. In the case of an unconfined aquifer, constant total discharge per unit width of aquifer ($\overline{Q} = -\frac{K}{2}\nabla(h^2) = -Kh\nabla h$))

For a confined aquifer, by applying Darcy's Law and superposition (Bear, 1979), the following expression may be obtained, which relates the difference in head at two monitoring well locations (Δh) to aquifer characteristics (hydraulic conductivity (K) and aquifer thickness (b)), pumping well locations (x_{0j},y_{0j}), pumping rates (Q_j), and the regional hydraulic gradient prior to pumping (i):

$$\Delta h = i[(x_2 - x_1)\cos\alpha + (y_2 - y_1)\sin\alpha] + \frac{1}{4\pi bK}\sum_{j=1}^{n} Q_j \ln\frac{(x_2 - x_{0j})^2 + (y_2 - y_{0j})^2}{(x_1 - x_{0j})^2 + (y_1 - y_{0j})^2} \quad (1)$$

where.Q_j is the pumping rate of the jth well.(x_{0j},y_{0j}) are the x and y coordinates of the jth pumping well.α is the angle in radians between the Darcy velocity vector and the positive x-axis.n is the number of pumping wells.(x_1,y_1) and (x_2,y_2) are the x and y coordinates of the two monitoring wells.

Equation (1) has also been derived by Brooks et al. (2008), who used it as the foundation of a method, referred to as the Integral Pump Test (IPT) approach, to estimate contaminant flux. As the name implies, the Brooks et al. (2008) IPT approach involved conducting a number of pump tests that comes with all of the associated disadvantages that were noted above. Equation (1) has also been derived using complex potential theory (Javendal et al., 1984).

Defining transmissivity (T) as the product of hydraulic conductivity (K) and aquifer thickness (b), equation (1) can be rearranged to obtain:

$$T = \frac{iT[(x_2 - x_1)\cos\alpha + (y_2 - y_1)\sin\alpha]}{\Delta h} + \frac{1}{4\pi\Delta h}\sum_{j=1}^{n} Q_j \ln\frac{(x_2 - x_{0j})^2 + (y_2 - y_{0j})^2}{(x_1 - x_{0j})^2 + (y_1 - y_{0j})^2} \quad (2)$$

If we're interested in the total discharge per unit width of aquifer prior to pumping ($\overline{Q}$) we see for a confined aquifer $\overline{Q} = -Kb\nabla h = -T\nabla h = -Ti$ and we can rewrite equation (2) as:

$$T = \frac{-\overline{Q}[(x_2 - x_1)\cos\alpha + (y_2 - y_1)\sin\alpha]}{\Delta h} + \frac{1}{4\pi\Delta h}\sum_{j=1}^{n} Q_j \ln\frac{(x_2 - x_{0j})^2 + (y_2 - y_{0j})^2}{(x_1 - x_{0j})^2 + (y_1 - y_{0j})^2} \quad (3)$$

For an unconfined aquifer, so long as the Dupuit assumptions hold, Darcy's Law and superposition can again be applied to obtain (Bear, 1979):

$$\Delta h^2 = \nabla h^2 [(x_2 - x_1)\cos\alpha + (y_2 - y_1)\sin\alpha] + \frac{1}{2\pi K}\sum_{j=1}^{n} Q_j \ln\frac{(x_2 - x_{0j})^2 + (y_2 - y_{0j})^2}{(x_1 - x_{0j})^2 + (y_1 - y_{0j})^2} \quad (4)$$

where $\Delta h^2 = h_2^2 - h_1^2$ is the difference in the squares of the hydraulic heads measured relative to the aquifer bottom at two monitoring wells and ∇h^2 is the gradient of the square of the regional hydraulic head.

Rearranging terms results in:

$$K = \frac{\nabla h^2 K[(x_2 - x_1)\cos\alpha + (y_2 - y_1)\sin\alpha]}{\Delta \mathrm{h}^2} + \frac{1}{2\pi\Delta \mathrm{h}^2}\sum_{j=1}^{n} Q_j \ln\frac{(x_2 - x_{0j})^2 + (y_2 - y_{0j})^2}{(x_1 - x_{0j})^2 + (y_1 - y_{0j})^2} \quad (5)$$

If we're interested in the total discharge per unit width of aquifer prior to pumping ($\overline{Q}$) we see for an unconfined aquifer $\overline{Q} = -\frac{K}{2}\nabla h^2 = -Kh\nabla h$ and we can rewrite equation (5) as:

$$K = \frac{-2\overline{Q}\ [(x_2 - x_1)\cos\alpha + (y_2 - y_1)\sin\alpha]}{\Delta \mathrm{h}^2} + \frac{1}{2\pi\Delta \mathrm{h}^2}\sum_{j=1}^{n} Q_j \ln\frac{(x_2 - x_{0j})^2 + (y_2 - y_{0j})^2}{(x_1 - x_{0j})^2 + (y_1 - y_{0j})^2} \quad (6)$$

Note that equations (3) and (6) each have two unknowns. The unknowns in equation (3) are the transmissivity (T) and the total discharge per unit width of aquifer prior to pumping ($\overline{Q}$). The unknowns in equation (6) are the hydraulic conductivity (K) and the total discharge per unit width of aquifer prior to pumping ($\overline{Q}$).

Once these unknowns are determined, for a confined aquifer, the hydraulic conductivity and the regional hydraulic gradient prior to pumping (i) can be determined by the following formulas, respectively:

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