Journal of Hydrology 508 (2014) 157–169

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Inversion of a dual-continuum approach to flow in a karstified limestone: Insight into aquifer heterogeneity revealed by well-test interferences

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ARTICLE INFO

Article history:
Received 24 July 2013
Received in revised form 18 October 2013
Accepted 24 October 2013
Available online 5 November 2013
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Dr. Niklas Linde, Associate Editor

Keywords:
Interference testing
Karstic flow
Dual flowing continuum
Automatic inversion
Downscaling parameterization

SUMMARY

Two large sets of interference testing data from a karstic aquifer (Hydrogeological Experimental Site, HES – Poitiers – France) are inverted using a dual-continuum approach to groundwater flow. The parameterization technique used to infer spatially distributed hydrodynamic parameters is free of any prior estimation regarding the spatial structure of the parameter fields; it merely seeks the minimal number of local values to obtain the best fit between flow simulations and data. A previous work inverting without any prior geostatistical assumption the same set of data based on a single flowing continuum produced nicely structured (spatially correlated) parameter fields. The dual-continuum approach renders fields as patchworks of subareas of quite uniform values. The statistical distribution of the hydrodynamic parameters is generally skewed toward high values, especially when interference data bear traces of rapid channeled flow in karstic conduits. It is now well established that continuous approaches to flow are well suited to simulate diffusive flow in fractured – karstified rocks, although single continuums may result in artificially high contrasts of hydraulic diffusion values between flowing and non-flowing areas. In the case of a dual continuum, the model has in its physics the capability to clearly separate conduction properties attached to fractures and channels from capacitive properties of the host matrix. We show that high contrasts of hydraulic diffusion disappear, resulting in a mildly heterogeneous medium in which high values of hydraulic diffusion are only located in areas where channeled flow occurs.

1. Introduction

Groundwater flow inversion has received much attention in the last three decades, resulting in several reference papers (e.g., Carrera and Neuman, 1986; RamaRao et al., 1995; McLaughlin and Townley, 1996; Zimmerman et al., 1998; Doherty, 2003) and textbooks (e.g., Sun, 1994; Tarantola, 2005). However, inversion is still a challenging task, especially when flow occurs through highly heterogeneous media such as fractured and karstified limestone. The ongoing literature regarding fractured rocks opposes continuous approaches and discrete approaches. Continuous approaches consider that the fracture (karstic) network and the host matrix can be homogenized into a single or multiple continuum overlooking the geometry of fracture discontinuities and using effective hydraulic parameters (Barrenblatt et al., 1960; Warren and Root, 1963; Berkowitz, 2002; Neuman, 2005; Samardzioska and Popov, 2005; Delay et al., 2007). Discrete approaches dealing with fractured media represent specifically both the fracture discontinuities and the matrix. Some approaches map the fractures onto computation grids and only depict the main flow conductors (e.g., Gomez-Hernandez et al., 2000; Svensson, 2001; Langevin, 2003; Karimi-Fard et al., 2006; Fourno et al., 2013). Other methods attempt to explicitly describe the fracture network, although the network can be represented by simplified objects such as bonds, disks, and ellipsoids (e.g., Cacas et al., 1990; Dershowitz et al., 1991; Dverstorp et al., 1992; Tsang and Neretnieks, 1998; Cvetkovic et al., 2004; Adler et al., 2005; Nœtinger and Jarrige, 2012).

For direct problems, such as calculating flow or transport with well prescribed boundary conditions, source terms and parameters, it is difficult to state whether one approach is better than the other (Selroos et al., 2002; Neuman, 2005). Discrete approaches require specific meshing efforts, resulting in significant computational cost when dealing with a large number of fractures. The discrete approach, however, is presumed to be more precise, at least for transport problems, especially those dominated by advection in channeled flow (de-Dreuzy et al., 2013). One can mention that recent numerical developments based on the so-called non-matching grids appear promising for discretizing both fractures and

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0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.10.039

matrix with reduced computation costs (D'Angelo and Scotti, 2012; Fumagalli and Scotti, 2013). Continuum-based approaches are less demanding in terms of discretization, parameterization and computational effort, but at the expense of a loss of precision.

Regarding automatic inversion, it must be acknowledged that continuous approaches are most likely better suited. Usually, discrete approaches need for more parameters when their geometry is inverted. Lighter calculations and parameterizations are better handled by iterative procedures seeking optimal parameters for the model to fit data. Available data are often scarce and imprecise, and their processing does not require the degree of precision afforded by discrete approaches (Bodin et al., 2012). In addition, a rigorous inversion of a discrete fracture network would require not only evaluating the hydrodynamic parameters but also modifying the network geometry, including the associated cumbersome task of re-meshing the discrete problem. Except for a few attempts (Tran, 2007; Delay et al., 2008), most of the inversion exercises for flow and transport at the scale of underground reservoirs are performed by relying upon continuous approaches to the fracture medium (Capilla et al., 1997; Gomez-Hernandez et al., 2000; Pourpak et al., 2009; Ackerer and Delay, 2010).

Given the debatable questions mentioned above, the Hydrogeological Experimental Site (HES) – Poitiers (France) was built close to the University Campus for the sole purpose of research activity, including groundwater monitoring and various experiments bringing data for modeling flow and transport in fractured rocks (de Dreuzy et al., 2006). The site includes 35 wells fully penetrating a limestone aquifer of 100 m thickness confined beneath 20 m of Tertiary clays (see, e.g., Mari and Porel, 2008, for further details on the HES). Among the various data collected at the HES are two series of interference testing performed in 2004 and 2005 that have been intensively exploited (Bernard et al., 2006; Kaczmaryk and Delay, 2007a,b; Audouin et al., 2008; Pourpak et al., 2009; Riva et al., 2009; Ackerer and Delay, 2010; Delay et al., 2011; Bodin et al., 2012). Regardless of the method used to interpret the data, the results of these studies showed that the medium is highly heterogeneous with hydraulic diffusion (the ratio of hydraulic conductivity to specific storage capacity) varying more than four orders of magnitude for an investigated square field of approximately 300 by 300 m. The 2005 data are distinguished from the 2004 data by showing signatures of very rapid channeled flow. This typical behavior was interpreted as the consequence of a reopening of karstic features due to forced flow during the 2004 interference testing and the drilling work between 2004 and 2005 to complete the HES well settings. This reopening was imaged by geophysical investigations, including high-resolution seismic measurements (Mari et al., 2009; Mari and Delay, 2011), optic imaging of boreholes (Audouin et al., 2008; Mari et al., 2009), and water temperature monitoring in boreholes (Chatelier et al., 2011). These investigations revealed the presence of reopened karstic conduits mainly concealed in three to four sub-horizontal and discontinuous layers of 2–5 m thickness at depths of 30 m, (50 m – hardly visible), 85 m, and 110 m.

In terms of inversion, Kaczmaryk and Delay (2007a,b) interpreted interference testing data by using different dual-continuum approaches in a one-dimensional homogeneous radial flow and handling each drawdown curve one at a time. The authors did not observe significant variations in the statistical distributions of the inferred hydrodynamic parameters. Ackerer and Delay (2010) performed an inversion grounded in a two-dimensional (averaged over the vertical direction) heterogeneous single continuum while simultaneously handling all the drawdown curves in response to the stress generated by a single pumping well. They also inverted fictitious scenarios, merging drawdown responses to all the pumped wells of an interference testing campaign (see hereafter, in Section 3). Their calculations produced hydraulic conductivity fields that were spatially correlated in space, showing variograms of exponential type with a clear correlation length of approximately 100 m (and no significant correlation beyond) and a variance of the natural logarithm of conductivity $\sigma^2_{\ln K} = 6-8$. The reopening of karstic features between 2004 and 2005 was mainly indicated by a slight increase in $\sigma^2_{\ln K}$ and variograms of ln K becoming of composite type with an exponential shape at short lag distances and a linear shape at larger distances. Ackerer and Delay (2010) mentioned that rapid draining occurred even for the 2004 data (in addition to, of course, 2005 data), with the possible consequence for a single continuum of artificially increasing the ln K contrasts between highly and weakly conductive areas of the aquifer. Notably, Riva et al. (2009) found a $\sigma^2_{\ln K}$ value less than 2 by inferring the hydraulic conductivity covariance based on pseudo steady-state drawdowns in a single continuum (the so-called type-curve approach developed by Neuman et al. (2007)). It must be noted however that the type-curve approach used by Riva et al. (2009) frequently underestimates the hydraulic conductivity variance of highly heterogeneous media.

It appears interesting, therefore, to reassess the inversion of a heterogeneous flow problem by using a dual-continuum approach. The dual continuum has in its physics the following capabilities: 1 – clearly separating rapid flow in fractures from fluid storage in the matrix and 2– ensuring a progressive feeding from matrix to fractures in the case, for instance, of interference testing. By inverting the 2004 and 2005 interference data using this type of model, one expects to assess the possible bias induced by a single flowing continuum in the heterogeneity level and spatial structure stemming from an aquifer juxtaposing conductive and capacitive zones.

The present work can be considered a companion paper to that presented by Ackerer and Delay (2010) in that it investigates flow inversion in fractured-karstified rocks but this time resorting to a dual-continuum approach. Section 2 presents the direct model simulating flow and the parameterization technique used in the inversion tasks. This technique is based on an Adaptive Multi-scale Triangulation (AMT) progressively refining a parameter grid to identify the minimum number of spatially distributed point seeds allowing a good fit between flow simulations and data. Section 3 presents the setting of the inversion exercises and the main results in terms of the sought parameter fields and parameter statistical distributions. Finally, the inverse solutions for a dual continuum are discussed and compared with previous results, mainly those reported by Ackerer and Delay (2010).

2. The flow model and its inversion-parameterization

Mimicking at the large scale Darcian flow in a fractured aquifer is addressed by resorting to the classical dual-continuum approach initially proposed by Barrenblatt et al. (1960) and Warren and Root (1963). By omitting reference to space and time coordinates and overlooking the initial and boundary conditions for the sake of simplicity, the flow equations are written as follows

$$
\begin{aligned}
&Ss_f \frac{\partial h_f}{\partial t} + \nabla.(-K_f.\nabla h_f) = \alpha(h_m - h_f) + q \\
&Ss_m \frac{\partial h_m}{\partial t} = \alpha(h_f - h_m)
\end{aligned}
\tag{1}
$$

The indexes f and m refer to the fracture and matrix continua, respectively. h_λ (L) is the hydraulic head in the continuum λ ($\lambda = f, m$), Ss_λ (L^{-1}), K_λ ($L\,T^{-1}$) are the specific storage capacity and hydraulic conductivity in λ, and α ($L^{-1}\,T^{-1}$) is the rate of mass transfer between fractures and matrix. It is assumed in (1) that flow is negligible in the matrix, making the latter equivalent to a