Journal of Hydrology 539 (2016) 88–101

Contents lists available at ScienceDirect

Journal of Hydrology

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

Identification of groundwater flow parameters using reciprocal data from hydraulic interference tests

Marianna Marinoni [a], Frederick Delay [a,*], Philippe Ackerer [a], Monica Riva [b,c], Alberto Guadagnini [b,c]

[a] Laboratoire d'Hydrologie et de Géochimie de Strasbourg, Univ. Strasbourg/EOST, CNRS UMR 7517, 1 rue Blessig, 67000 Strasbourg, France
[b] Dipartimento di Ingegneria Civile e Ambientale, Politecnico di Milano, P.zza Leonardo da Vinci 32, 20133 Milano, Italy
[c] Department of Hydrology and Water Resources, The University of Arizona, Tucson, AZ, USA

ARTICLE INFO

Article history:
Received 2 February 2016
Received in revised form 30 April 2016
Accepted 6 May 2016
Available online 14 May 2016
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Niklas Linde, Associate Editor

Keywords:
Groundwater flow
Model parameter identification
Lorentz reciprocity
Hydraulic interference
Hydraulic tomography

SUMMARY

We investigate the effect of considering reciprocal drawdown curves for the characterization of hydraulic properties of aquifer systems through inverse modeling based on interference well testing. Reciprocity implies that drawdown observed in a well *B* when pumping takes place from well *A* should strictly coincide with the drawdown observed in *A* when pumping in *B* with the same flow rate as in *A*. In this context, a critical point related to applications of hydraulic tomography is the assessment of the number of available independent drawdown data and their impact on the solution of the inverse problem. The issue arises when inverse modeling relies upon mathematical formulations of the classical single-continuum approach to flow in porous media grounded on Darcy's law. In these cases, introducing reciprocal drawdown curves in the database of an inverse problem is equivalent to duplicate some information, to a certain extent. We present a theoretical analysis of the way a Least-Square objective function and a Levenberg–Marquardt minimization algorithm are affected by the introduction of reciprocal information in the inverse problem. We also investigate the way these reciprocal data, eventually corrupted by measurement errors, influence model parameter identification in terms of: (a) the convergence of the inverse model, (b) the optimal values of parameter estimates, and (c) the associated estimation uncertainty. Our theoretical findings are exemplified through a suite of computational examples focused on block-heterogeneous systems with increased complexity level. We find that the introduction of noisy reciprocal information in the objective function of the inverse problem has a very limited influence on the optimal parameter estimates. Convergence of the inverse problem improves when adding diverse (nonreciprocal) drawdown series, but does not improve when reciprocal information is added to condition the flow model. The uncertainty on optimal parameter estimates is influenced by the strength of measurement errors and it is not significantly diminished or increased by adding noisy reciprocal information.

1. Introduction

Employing a given groundwater flow model in the context of environmental and industrial applications is always associated with the challenge of identifying the appropriate values of model parameters and quantifying the uncertainty of model parameter estimates. This task is remarkably complex and the typical lack of information plaguing subsurface systems (in terms of structure and spatial distribution of parameters/attributes of geological materials) and the relevant processes (affecting the key patterns of flow) taking place therein hinder our ability to obtain a deterministic depiction of a target flow setting.

A way to condition groundwater flow models on data is through inverse approaches such as those illustrated, among others, in the works of Carrera and Neuman (1986), Yeh (1986), Kitanidis (1995), Lavenue et al. (1995), Zimmerman et al. (1998), de Marsily et al. (2000), Doherty (2003), Moore and Doherty (2005), or recently reviewed by Hendricks Franssen et al. (2009) and Zhou et al. (2014). The increased complexity of recent hydrological models, eventually associated with the need to integrate coupled surface and subsurface flow simulators (e.g., Furman, 2008; Goderniaux et al., 2009; Frei et al., 2010; Weill et al., 2013), is matched by increased model parametrization and demand for information to constrain/condition model predictions, thus contributing to maintain the topic as a modern and ever growing research area.

With reference to the information content required to build and test the reliability of a groundwater flow model, recent progresses

* Corresponding author. Tel.: +33 3 68 85 04 16; fax: +33 3 68 85 04 02.
E-mail address: fdelay@unistra.fr (F. Delay).

http://dx.doi.org/10.1016/j.jhydrol.2016.05.019
0022-1694/

in subsurface geophysics may assist in providing improved characterization of the internal structure of a subsurface reservoir and its feedback on the spatial distribution of hydraulic parameters (e.g., Mari et al., 2009; Pourpak et al., 2009). This notwithstanding, these advancements cannot fully compensate for the lack of information on flow patterns and observations of associated state variables, including, e.g., hydraulic heads, water fluxes, solute concentrations, and water temperatures (e.g., Paillet, 1998; Le Borgne et al., 2006; Chatelier et al., 2011).

Even if there is some debate on the relevance and usefulness of assembling ever increasing and diversified information to condition a groundwater flow model (e.g., McLaughlin and Townley, 1996; Gupta and Sorooshian, 1998; Tarantola, 2005; Vrugt et al., 2007), a general trend is to develop technologies and approaches aimed at designing experimental campaigns capable of probing the groundwater system to extract augmented datasets. In this context, modern field investigations on aquifers are oriented toward the so-called hydraulic tomography, a flavor of which is based on the concept that performing multiple hydraulic tests in a suite of wells would increase our ability to probe flow conditions and achieve improved control on model parameter identification (e.g., Brauchler et al., 2013; Illman, 2014). As application-oriented examples, experimental observations from hydraulic tomography campaigns based on slug tests and interference testing between wells have been employed in various analytical and numerical models to estimate hydraulic parameters in highly heterogeneous karstic aquifers (Audouin et al., 2008; Riva et al., 2009; Trottier et al., 2014).

A critical point which is often raised when considering applications of hydraulic tomography (e.g., Leven and Dietrich, 2006; Raghavan, 2009; Bohling and Butler, 2010; Delay et al., 2012; Jiménez et al., 2013) is the assessment of the number of available independent (and/or redundant) drawdown observations and their impact on the solution of the inverse problem. The issue arises when interpretation and inverse modeling are based on mathematical formulations of the classical single-continuum approach to three-dimensional flow grounded on Darcy's law. Let us consider, by way of example, the hydraulic investigation relying on interference testing between multiple wells. A test is typically performed by pumping in a given well at a prescribed flow rate and recording at a set of other wells/boreholes drawdowns due to the pumping stress. A three-dimensional tomographic campaign is then obtained by pumping sequentially each well within the system while monitoring drawdowns at the others. When interpretation is based on Darcian flow concepts and the system is depicted as a single continuum (a common assumption in many applications), drawdowns obey the Lorentz (1896) reciprocity principle. Initially evidenced in the field of electromagnetism, the latter states that the drawdown observed in a well *B* when pumping takes place from well *A* should coincide with the drawdown observed in *A* when pumping in *B* with the same flow rate as in *A* (see, e.g., Bruggeman, 1972; Delay et al., 2011, 2012; Mao et al., 2013, additional details being also provided in Section 2). Employing reciprocal information in the model inversion procedure is tantamount to bring twice the same data, even as these are obviously linked to diverse spatial locations (i.e., wells *A* and *B*).

Several studies associated with cross-hole hydraulic testing directly include observations displaying reciprocal behavior in classical flow models that inherently lead to reciprocity of modeled drawdowns. Intuitively, one should expect that the weight of data which are duplicated in the model inversion tends to increase, irrespective of the type of objective function or of the optimization techniques employed to infer model parameters. Instead of relying solely on intuition, it is relevant to provide a rigorous study of the effects of reciprocity in an inverse problem. The interest in this is also related to the observation that actual field data are typically corrupted by measurement errors that force the data to show some deviations from strict reciprocity. To the best of our knowledge, no detailed studies are available about the consequences on system parameter (e.g., conductivity/transmissivity and specific storage/storativity) identification of conditioning a flow model inversion on sets of reciprocal information, eventually corrupted by measurement uncertainty/error. We note that groundwater flow is not linear with respect to model parameters, i.e., the model response is not a linear combination of model parameters. As a consequence, one cannot simply rely upon the linear inverse problem theory and conclude that duplicating information essentially corresponds to solve exactly the same equations that one would employ when reciprocal data are not considered for estimating model parameters. Groundwater flow is usually inverted by way of second-order techniques based on sensitivity of model outputs to parameters to infer optimal parameter estimates. In this context, the effect of adding reciprocal information to the available data base is remarkably less intuitive than in the linear setting. As such, a rigorous study should be based on a solid theoretical evidence of the incidence of introducing reciprocal flow data in a classical inversion technique.

We are here interested in exploring the answer to the following questions: (i) is the model inversion hampered or helped when reciprocal data are employed, and (ii) do these reciprocal data lead to improved parameter estimates and uncertainty quantification? We address these questions for groundwater flow parameter identification by way of a suite of simple flow scenarios that avoid complexity in the conceptual system model and enable us to probe the effects of reciprocal flow information on the above issues. Section 2 (and Appendix A) is devoted to the illustration of the theoretical framework we rely upon. Inverse modeling leading to parameter estimates is performed through an automated model calibration technique which is based on the minimization of a given objective function, being otherwise free from any constraints on model parameters. Section 3 presents our applications which are based on two series of computational analyses organized in terms of increased degree of system complexity. Considering synthetic cases in which we control the data that are employed in the inversion procedure enables us to clearly demonstrate the key features of our theoretical study before tackling concrete field scale applications.

2. Theoretical background

We are interested in solving the inverse problem of groundwater flow on the basis of observations of drawdowns of piezometric heads collected from interference testing. Interference testing is conducted by extracting a constant flow rate in a well at vector location $\mathbf{x}_\alpha$ and monitoring at other wells the temporal dynamics of head drawdowns, $\psi_\alpha(\mathbf{x},t) = h_0(\mathbf{x}) - h(\mathbf{x},t)$, $h(\mathbf{x},t)$ and $h_0(\mathbf{x})$ respectively being the hydraulic head in the aquifer at time t after the beginning of the test and the observed hydraulic head at $t = 0$, i.e., when pumping is started. Pumping is then sequentially performed from other wells while observing drawdowns in the remaining boreholes (including those previously pumped). Drawdowns monitored in open boreholes typically equilibrate at a uniform value (varying in time) along the vertical direction of the observed boreholes. This feature constitutes a challenge to our ability of capturing the critical signatures characterizing a three-dimensional flow behavior (e.g., Delay et al., 2011). Several applications, also depending on the spatial scale associated with the problem investigated, are grounded on models of two-dimensional groundwater flow developed under the Dupuit assumption. Considering Darcian flow in a single continuum and in the absence of significant variations of water mass density, the equations