Journal of Applied Geophysics 98 (2013) 288–297

Contents lists available at ScienceDirect

Journal of Applied Geophysics

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

Constraining complex aquifer geometry with geophysics (2-D ERT and MRS measurements) for stochastic modelling of groundwater flow

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ARTICLE INFO

Article history:
Received 27 September 2012
Accepted 13 September 2013
Available online 20 September 2013

Keywords:
Ground water flow
Electrical resistivity tomography (ERT)
Random layer thickness
Non-Gaussian distribution
Conditional simulation and Monte Carlo simulations

ABSTRACT

Stochastic modelling is a useful way of simulating complex hard-rock aquifers as hydrological properties (permeability, porosity etc.) can be described using random variables with known statistics. However, very few studies have assessed the influence of topological uncertainty (i.e. the variability of thickness of conductive zones in the aquifer), probably because it is not easy to retrieve accurate statistics of the aquifer geometry, especially in hard rock context. In this paper, we assessed the potential of using geophysical surveys to describe the geometry of a hard rock-aquifer in a stochastic modelling framework.

The study site was a small experimental watershed in South India, where the aquifer consisted of a clayey to loamy–sandy zone (regolith) underlain by a conductive fissured rock layer (protolith) and the unweathered gneiss (bedrock) at the bottom. The spatial variability of the thickness of the regolith and fissured layers was estimated by electrical resistivity tomography (ERT) profiles, which were performed along a few cross sections in the watershed. For stochastic analysis using Monte Carlo simulation, the generated random layer thickness was made conditional to the available data from the geophysics. In order to simulate steady state flow in the irregular domain with variable geometry, we used an isoparametric finite element method to discretize the flow equation over an unstructured grid with irregular hexahedral elements.

The results indicated that the spatial variability of the layer thickness had a significant effect on reducing the simulated effective steady seepage flux and that using the conditional simulations reduced the uncertainty of the simulated seepage flux.

As a conclusion, combining information on the aquifer geometry obtained from geophysical surveys with stochastic modelling is a promising methodology to improve the simulation of groundwater flow in complex hard-rock aquifers.

1. Introduction

In natural geologic formations, the properties governing groundwater flow are highly heterogeneous in space at all scales, especially in hard rock aquifers, which makes it difficult to model accurately flow and solute transport in a deterministic way. Stochastic subsurface hydrology was developed during the last two decades based on the hypothesis that hydrological processes/properties can be modelled using random variables with known statistics (Tartakovsky, 1999). In a large majority of the studies reported in the literature, the analysis is based on the effect of the spatial distribution of the hydraulic conductivity (Cushman, 1997; Dagan, 1989; Gelhar, 1993; Hsu et al., 1996; Kapoor and Kitanidis, 1996; Lu and Zhang, 2003; Neuweiler et al., 2001; Rajaram, 1997; Rubin et al., 1997). The effect of uncertainty associated with input/boundary conditions was also studied (Chaudhuri and Sekhar, 2006, 2008; Hantush and Mariño, 1994; Li and Graham, 1999; Wang and Zheng, 2005). Another way of describing the structure heterogeneity is by considering the geometry of "hydrofacies", a concept developed by Eaton (2006). The uncertainty related to the spatial variability of the hydrofacies (variation of the thickness) is called as topological uncertainty. Due to such variability, the system may offer more resistance to the groundwater flow and result in enhancing solute spreading or dispersion in the solute transport problem and may increase the prediction uncertainty of seepage flux or solute concentration. Only few studies attempted using this concept in stochastic modelling (Tartakovsky et al., 2000), probably because it is not easy to retrieve accurate statistics of the aquifer geometry, especially in hard rock aquifers.

Mapping of aquifer properties has historically been performed using 2D geological maps based on interpreted cross sections

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http://dx.doi.org/10.1016/j.jappgeo.2013.09.005

obtained from borehole data from which isopachs or aquifer thicknesses are then derived. Geophysical methods such as electrical-resistivity and electro-magnetic surveys have been extensively used in the literature to interpret with higher reliability the aquifer lithology between boreholes (Vereecken et al., 2011). In hard rock aquifers, close relationships between geophysical and hydraulic properties have been demonstrated (e.g. Chandra et al., 2008). In spite of their capabilities, the number of 2D geophysical surveys that could be performed even in a small catchment is often limited. In such cases methods are developed which combine geophysics and geostatistics to create several heterogeneous realizations of the aquifer that contain representations of the lithological layers for flow and transport simulation (Engdahl and Weissmann, 2010; Lallahern et al., 2007; Mariethoz et al., 2010). Moreover, geostatistical toolboxes were also developed for uncertainty analysis, visualisation and modelling (Wingle et al., 1999).

Despite the recognized strong potential of using information from geophysics to constrain groundwater modelling (Zimmerman et al., 1998), few studies have actually been proven successful in such an attempt. Numerical approaches have been proposed for the generation of transmissivity fields conditional to transmissivity data, secondary information (such as geophysics), and hydraulic head data (Bi et al., 2000; Braun et al., 2009; Capilla et al., 1997; Georgsen and Omre, 1993a, 1993b; Harter and Yeh, 1996; Oliver, 2002; Rodriguez-Iturbe and Valdes, 1979). A moment equation based method was presented by Morales-Casique et al. (2006) for conditional stochastic analysis of solute transport under both steady state and transient flow regimes in bounded, randomly heterogeneous porous domains. Alcolea et al. (2004) proposed a method for generating equally likely realizations (conditional simulations) of the transmissivity field, that honour measurements of transmissivity and dependent variables (heads, concentrations, etc.) and the method can also include the geophysical data in the conditioning procedure. Recently, Massuel et al. (2006) validated a complex hydrological model using electrical resistivity tomography (ERT) geophysical data.

The objective of this paper is to demonstrate the interest of using the information on aquifer hydrofacies geometry obtained from geophysics to constrain the stochastic modelling of groundwater flow. The study site is a small experimental tropical sub-humid catchment in South India comprising of a complex hard rock aquifer system. This aquifer lies in metamorphic context, with highly variable geometry (Braun et al., 2009) where 2D-ERT profiles (Braun et al., 2009; Descloitres et al., 2008), and magnetic resonance soundings (MRS) (Legchenko et al., 2006) are available. Information on the hydrofacies hydraulic properties of the same peninsular gneiss are also available from other studies (Dewandel et al., 2006, 2012; Maréchal et al., 2006). We used the stochastic groundwater modelling combined with the geophysical investigations to simulate the uncertainty in the groundwater flux in the fissure zone for conditional realizations from samples of 2-D electrical resistivity surveys to arrive at optimal field surveys. A conceptual model of the gneissic rock geology and hydraulic properties of this system was developed by Dewandel et al. (2006), with typical hydrofacies being from top to bottom a clayey to loamy–sandy zone (also referred to as regolith) underlain by a fissured rock layer (protolith) and the unweathered gneiss (bedrock). As the fissured rock layer has by far the highest hydraulic conductivity it is considered to assume the transmissive function of the aquifer (Dewandel et al., 2012). For the present analysis we make the hypothesis that the groundwater flow will depend on its geometry and we will perform the stochastic analyses of the ground water flux through this fissured zone. We present (1) the statistical representation random thickness of the layers and generation of the random fields, which are conditioned to the 2-D profile available from ERT inversion, (2) the analysis of the effect of the topological uncertainty and the conditional modelling of the random field on the probabilistic behaviour of the groundwater flux through the fissured zone in a sub-area near the outlet of the watershed.

2. Brief description of geophysical investigation

The topography and the geomorphic features of the Mule-Hole experimental watershed along with the location of the geophysical surveys that have been carried out to measure the electrical resistivity along various 2-D profiles (Braun et al., 2009) are presented in Fig. 1. These profiles outline the distribution of the electrical resistivity making the assumption of 2-D geometry. This assumption is made according to the geology that exhibits a formation, with a macroscopic foliation of tectonic origin oriented from N70° to N100° at the scale of the outcrop and with a dip angle from 70° to the vertical. According to this field observation, ERT profiles were oriented perpendicularly to the main direction of the foliation direction of the gneiss (Descloitres et al., 2008). Based on determination of weathering indices the relation between electrical resistivity and weathering profile was investigated in detail by Braun et al. (2009). Borehole data available in the watershed were used for calibration during ERT inversion. Braun et al. (2009) demonstrated that for thickness, the in-situ borehole data are sufficient to validate geophysical measurements.

In Fig. 1, the blue colours correspond to the low hydraulically conductive regolith, mainly composed of clayey to loamy materials. Its electrical resistivity is ranging from 20 Ωm (clayey) to 400 Ωm (loamy to sandy). The hydraulic conductivity is lower than 10^{-6} m/s, and cannot be easily determined using MRS. The colours ranging from green to yellow correspond to the hydraulically conductive fissured rock ranging from 400 to 1000 Ωm. The red colour above 1000 Ωm corresponds to the unweathered and fractured hard rock. The protolith is mainly composed of two parts: the upper part is defined by an electrical resistivity ranging from 400 to 1000 Ωm. The upper limit of 1000 Ωm has been derived from a comparison between ERT and MRS along a profile and presented by Descloitres et al. (2008). Within the range 400 to 1000 Ωm, the MRS method clearly defines a storage part (water content between 1 and 2 % of the total volume), which is hydraulically more conductive (value ranging from $2{\times}10^{-6}$ to $2{\times}10^{-5}$ m/s). This was clearly delineated through repeated experiments in different seasons as illustrated by Descloitres et al. (2008). This method provides an indirect estimate of the hydraulic conductivity along the highly permeable zone. The lower part of the protolith is the unweathered gneissic rock. It was not feasible to estimate with confidence the hydraulic conductivity values in this zone with MRS surveys (Legchenko et al., 2006) because water content is less than 0.3%. However, some fractures could play a role in aquifer functioning but remain undetectable with surface geophysics.

In this study, we focused on the upper conductive part of the protolith. We considered that this is the transmissive zone of the aquifer and following Dewandel et al. (2006, 2012) it has been referred to as the "fissured layer". The geophysical investigations using the ERT method, which were conducted along several 2-D profiles (Braun et al., 2009; Descloitres et al., 2008) revealed that the thickness of this layer below the ground surface exhibited large spatial variations in the watershed. These authors showed that correcting the routine ERT with an estimate of ERT uncertainty using a synthetic modelling approach allowed improving the profile delineation. In the present paper the fissured zone is modelled as a porous medium layer with spatially varying random thickness. As the objective is to assess the impact of the geometry of the fissured layer on groundwater modelling, we have mainly considered the uncertainty of thickness where measurements are not available. The epistemic uncertainty i.e. uncertainty associated in ERT inversion and measurement noise have not been accounted for with the stochastic representation of the fissured layer. MRS results also showed the random variation of hydraulic conductivity within the porous layer. For numerical modelling of flow using stochastic framework, the regolith and the fissured zone thicknesses are modelled as 2D random fields extended along horizontal plane.

The groundwater in this shallow watershed was identified to flow towards the southwest (Descloitres et al., 2008). The sub-area that