



Research papers

Identification of high-permeability subsurface structures with multiple point geostatistics and normal score ensemble Kalman filter



Francesco Zovi^{a,1}, Matteo Camporese^{a,*}, Harrie-Jan Hendricks Franssen^b, Johan Alexander Huisman^b, Paolo Salandin^a

^a Department of Civil, Environmental and Architectural Engineering, University of Padova, Padova, Italy

^b Agrosphere (IBG3), Forschungszentrum Jülich, Jülich, Germany

ARTICLE INFO

Article history:

Received 29 September 2016

Received in revised form 6 February 2017

Accepted 27 February 2017

Available online 3 March 2017

This manuscript was handled by P. Kitanidis, Editor-in-Chief, with the assistance of Wolfgang Nowak

Keywords:

Multiple point geostatistics

Normal score transform

Ensemble Kalman filter

Groundwater modeling

ABSTRACT

Alluvial aquifers are often characterized by the presence of braided high-permeable paleo-riverbeds, which constitute an interconnected preferential flow network whose localization is of fundamental importance to predict flow and transport dynamics. Classic geostatistical approaches based on two-point correlation (i.e., the variogram) cannot describe such particular shapes. In contrast, multiple point geostatistics can describe almost any kind of shape using the empirical probability distribution derived from a training image. However, even with a correct training image the exact positions of the channels are uncertain. State information like groundwater levels can constrain the channel positions using inverse modeling or data assimilation, but the method should be able to handle non-Gaussianity of the parameter distribution. Here the normal score ensemble Kalman filter (NS-EnKF) was chosen as the inverse conditioning algorithm to tackle this issue. Multiple point geostatistics and NS-EnKF have already been tested in synthetic examples, but in this study they are used for the first time in a real-world case study. The test site is an alluvial unconfined aquifer in northeastern Italy with an extension of approximately 3 km². A satellite training image showing the braid shapes of the nearby river and electrical resistivity tomography (ERT) images were used as conditioning data to provide information on channel shape, size, and position. Measured groundwater levels were assimilated with the NS-EnKF to update the spatially distributed groundwater parameters (hydraulic conductivity and storage coefficients). Results from the study show that the inversion based on multiple point geostatistics does not outperform the one with a multiGaussian model and that the information from the ERT images did not improve site characterization. These results were further evaluated with a synthetic study that mimics the experimental site. The synthetic results showed that only for a much larger number of conditioning piezometric heads, multiple point geostatistics and ERT could improve aquifer characterization. This shows that state of the art stochastic methods need to be supported by abundant and high-quality subsurface data.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

Hydrogeological modeling plays a fundamental role for a large number of earth sciences and engineering problems, such as groundwater management, aquifer remediation, and underground waste disposal and management. In order to be capable of reliable predictions, models require a detailed knowledge of the aquifer geological structure (e.g., extent and thickness of hydrogeological units, boundary conditions for flow and transport) and flow and transport parameters of the aquifer (e.g., hydraulic conductivity

and porosity, dispersivity). In practice, only limited information on the spatial variation of these parameters is available. Therefore, we must often deal with highly uncertain hydrogeologic models, especially with reference to the hydraulic conductivity. Current practice in stochastic hydrogeologic modeling consists of assuming a multivariate Gaussian distribution for log-transformed hydraulic conductivity (De Marsily, 1986). However, cases in nature where this assumption is not valid are abundant, e.g., when highly permeable preferential flowpaths such as alluvial paleo-channels lie within a statistically homogeneous hydraulic conductivity field. Traditional geostatistical simulators based on two-points correlation models (i.e. the variogram) cannot describe such shapes and can yield inappropriate stochastic realizations failing to reproduce the true probability distribution of the analyzed property

* Corresponding author.

E-mail address: matteo.camporese@unipd.it (M. Camporese).

¹ Now at Lloyds Banking Group General Insurance, Leeds, UK.

(Gómez-Hernández and Wen, 1998). Therefore, more advanced approaches that can tackle these limitations are increasingly being used.

By using copula functions (e.g. Bárdossy, 2006; Bárdossy and Li, 2008) or multiple point geostatistics (MPG) (Caers and Zhang, 2005; Hu and Chugunova, 2008), it is possible to generate any kind of morphological structure, such as curvilinear facies and interconnected channels that often characterize fluvial deposits. Copulas describe the dependence structure between random variables without information on the marginal distributions by representing the dependence between the random variables over the range of quantiles. MPG algorithms do not require the definition of a variogram model, but instead rely on a training image from which the empirical probability distribution of the shapes and structures that need to be mimicked is obtained. MPG algorithms were successfully applied in groundwater flow and transport problems to describe multimodal spatially heterogeneous parameter fields (Feyen and Caers, 2005; Huysmans and Dassargues, 2009). However, in real-world applications, an adequate training image may not always be available. Moreover, the use of an inappropriate training image can lead to unrealistic stochastic realizations, drastically affecting the modeling results (Jafarpour and McLaughlin, 2009).

Among many inversion modeling frameworks, one that is particularly appealing when dealing with groundwater problems with heterogeneous parameters is sequential data assimilation. The primary objective of data assimilation is to provide an optimal estimate of the system state and parameters given a set of measurements and a dynamical model with known uncertainties. The ensemble Kalman filter (EnKF) (Evensen, 1994; Burgers et al., 1998), in particular, has become popular in various scientific fields, such as meteorology, hydrogeology and petroleum engineering (e.g., Chen and Zhang, 2006; Hendricks Franssen et al., 2008; Crestani et al., 2013; Houtekamer and Mitchell, 1998; Aanonsen et al., 2009; Camporese et al., 2011). The main advantages of EnKF over other data assimilation methods are: (i) the ability to handle different sources of uncertainty in a relatively straightforward manner, thanks to its Monte Carlo-based approach; (ii) the computational efficiency (e.g., Hendricks Franssen and Kinzelbach, 2009); (iii) the possibility to estimate a posterior probability density function (pdf) rather than a single optimal solution; and (iv) the ability to include new observation data from on-line sensors in real-time.

One of the main limitations of the ensemble Kalman filter is that it provides an optimal solution (in a least-squares sense) only if the state variables follow a Gaussian distribution, a condition that is rarely met in practical problems. Therefore, different approaches were developed to account for non-Gaussian distributions. These approaches include: (i) particle filters (Rings et al., 2010; Pasetto et al., 2012), which do not rely on any assumption on the pdf of the states and parameters, but typically require larger ensemble sizes compared to EnKF and can therefore be computationally unaffordable; (ii) Gaussian mixture model methods, which approximate the non-Gaussian probability density functions using a probabilistic model with a finite number of Gaussian pdfs (Chen and Liu, 2000; Apte et al., 2007; Sun et al., 2009; Liu et al., 2016); (iii) transformed re-parametrization, where non-Gaussian system variables are replaced with alternative variables more suitable to be approximated by a Gaussian distribution (Chen et al., 2009; Chang et al., 2010); (iv) iterative EnKF, which addresses the issue of non-Gaussianity by repeating the updating process many times at each update step until the required match between observations and predicted state variables is obtained (Gu and Oliver, 2007; Li and Reynolds, 2007; Reynolds et al., 2006; Sakov et al., 2012; Hendricks Franssen et al., 2008); and (v) the normal score approach, where the non-Gaussian distribution of each state variable is transformed into a Gaussian distribution before each update step. After the update, the normal score transformed variables are

back-transformed to their original distribution. Applications of the latter approach in the field of groundwater hydrology can be found in Zhou et al. (2011), Schöniger et al. (2012), and Crestani et al. (2013).

Although the normal score ensemble Kalman filter (NS-EnKF) was already combined with multiple point geostatistics to develop a data assimilation framework for heterogeneous aquifers with bimodal hydraulic conductivity distributions, to date it was tested only in synthetic studies (Zhou et al., 2011; Li et al., 2012; Zhou et al., 2012; Xu et al., 2013; Xu and Gómez-Hernández, 2016). Only a few case studies can be found in the literature where EnKF-based data assimilation frameworks were tested in real field experiments for parameter estimation in groundwater hydrology (Hendricks Franssen et al., 2011; Panzeri et al., 2015; Crestani et al., 2015). However, such evaluations are essential because many assumptions, such as the adopted geostatistical model, remain highly speculative, due to the inherently limited amount of information that is available to characterize the subsurface.

The main objective of this paper is to evaluate the performance of a data assimilation framework for the estimation of heterogeneous subsurface parameters based on EnKF and MPG in a real-world test case. The study area is the Settolo experimental site, an alluvial phreatic aquifer with an extension of approximately 3 km² located in Northeastern Italy. The aquifer is characterized by the presence of paleo-riverbeds acting as preferential flowpaths. We use satellite data to obtain a training image that captures the plausible characteristic shapes of the paleo-riverbeds. Piezometric head data collected in the field are then assimilated with NS-EnKF into a two-dimensional groundwater flow model to update states and aquifer parameters. An additional novel aspect of this study is the use of electrical resistivity tomography images in the MPG simulator to condition the channel positions in the prior realizations of the hydraulic conductivity fields. Along with the application to the field case study, a synthetic case study that mimics the Settolo site is developed, in order to give further insights on the potential and drawbacks of the proposed assimilation/inversion framework.

2. Inversion approach

2.1. Groundwater model

Two-dimensional horizontal flow in an unconfined aquifer is described by the nonlinear Dupuit–Boussinesq equation (De Marsily, 1986):

$$\frac{\partial}{\partial x} \left[K_x (h - z_0) \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[K_y (h - z_0) \frac{\partial h}{\partial y} \right] = [S_s (h - z_0) + S_y] \frac{\partial h}{\partial t} + q_a, \quad (1)$$

where K_x and K_y (m/s) are the hydraulic conductivities along the x and y spatial coordinates, respectively, h (m) is the water table elevation, z_0 (m) is the elevation of the aquifer bottom (assumed impermeable), S_s (m⁻¹) is the specific storage, S_y is the specific yield (m³ m⁻³), and q_a (m/s) represents a generic nodal source or sink term. Eq. (1) is integrated in space by means of the linear finite element method. An unstructured mesh can be used, allowing variable element size according to different spatial discretization needs. For integration over time, an adaptive time stepping with backward Euler scheme is adopted. The model is completed by appropriate initial and boundary conditions that will be described in detail later.

We opted for a two-dimensional model after a preliminary comparison with a fully three-dimensional Richards equation solver (Zovi, 2014). The comparison highlighted that the groundwater dynamics in the Settolo aquifer is mainly horizontal and using a

Download English Version:

<https://daneshyari.com/en/article/5771223>

Download Persian Version:

<https://daneshyari.com/article/5771223>

[Daneshyari.com](https://daneshyari.com)