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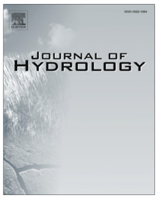

Characterisation of river–aquifer exchange fluxes: The role of spatial patterns of riverbed hydraulic conductivities

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SUMMARY

Interactions between surface water and groundwater play an essential role in hydrology, hydrogeology, ecology, and water resources management. A proper characterisation of riverbed structures might be important for estimating river–aquifer exchange fluxes. The ensemble Kalman filter (EnKF) is commonly used in subsurface flow and transport modelling for estimating states and parameters. However, EnKF only performs optimally for MultiGaussian distributed parameter fields, but the spatial distribution of streambed hydraulic conductivities often shows non-MultiGaussian patterns, which are related to flow velocity dependent sedimentation and erosion processes. In this synthetic study, we assumed a riverbed with non-MultiGaussian channel-distributed hydraulic parameters as a virtual reference. The synthetic study was carried out for a 3-D river–aquifer model with a river in hydraulic connection to a homogeneous aquifer. Next, in a series of data assimilation experiments three different groups of scenarios were studied. In the first and second group of scenarios, stochastic realisations of non-MultiGaussian distributed riverbeds were inversely conditioned to state information, using EnKF and the normal score ensemble Kalman filter (NS-EnKF). The riverbed hydraulic conductivity was oriented in the form of channels (first group of scenarios) or, with the same bimodal histogram, without channelling (second group of scenarios). In the third group of scenarios, the stochastic realisations of riverbeds have MultiGaussian distributed hydraulic parameters and are conditioned to state information with EnKF. It was found that the best results were achieved for channel-distributed non-MultiGaussian stochastic realisations and with parameter updating. However, differences between the simulations were small and non-MultiGaussian riverbed properties seem to be of less importance for subsurface flow than non-MultiGaussian aquifer properties. In addition, it was concluded that both EnKF and NS-EnKF improve the characterisation of non-MultiGaussian riverbed properties, hydraulic heads and exchange fluxes by piezometric head assimilation, and only NS-EnKF could preserve the initial distribution of riverbed hydraulic conductivities.

1. Introduction

Exchange processes between surface water and groundwater play an essential role for hydrology, hydrogeology, ecology, and water resources management (Brunke and Gonser, 1997; Hayashi and Rosenberry, 2002; Sophocleous, 2002). The main uncertain factors for predicting river–aquifer water exchange fluxes are riverbed and aquifer properties (Saenger et al., 2005; Storey et al., 2003). A better characterisation of riverbed structures representing more realistic properties may lead to an improved estimation of river–aquifer exchange fluxes (Kurtz et al., 2012). Traditionally, these media are considered homogeneous (Fox and Durnford, 2003) and the models for quantifying the exchange fluxes are simplified.

Field measurements and inverse modelling show that in the real world riverbed hydraulic conductivities may vary over several orders of magnitude (Calver, 2001). Several field surveys also indicate that the spatial distribution of river bed hydraulic conductivities exhibit non-Gaussian features (e.g., Cheng et al., 2011; Genereux et al., 2008; Leek et al., 2009; Sebok et al., 2015; Springer et al., 1999). Springer et al. (1999) found a bimodal distribution of hydraulic conductivity for five reattachment bars in the Colorado River (Grand Canyon National Park, USA). Genereux et al. (2008) conducted a detailed field experiment in a 250 m long river reach of West Bear Creek (North Carolina, USA) and found that measured river bed hydraulic conductivities are neither

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normally nor log-normally distributed. Cheng et al. (2011) measured vertical streambed hydraulic conductivities at 18 sites along a 300 km reach of Platte River (Nebraska, USA) and evaluated whether the measured values were normally distributed. For nine sites a normal distribution could be confirmed by several statistical tests. However, for the other sites the statistical tests were not significant, which was attributed to the presence of river tributaries with varying sediment loads. Several studies also suggest that there can be a distinct spatial pattern of cross-sectional river bed hydraulic conductivities (e.g., Genereux et al., 2008; Min et al., 2013; Sebok et al., 2015), which is thought to be related to flow velocity dependent spatially distinct sedimentation and erosion patterns. Some papers (e.g., Genereux et al., 2008; Leek et al., 2009; Sebok et al., 2015) additionally provide maps of the spatial distribution of measured river bed conductivities showing spatial patterns that can hardly be described by a purely Gaussian distribution.

Flow and transport modelling indicates that heterogeneity of riverbed properties has a large impact on river–aquifer exchange fluxes (Irvine et al., 2012; Kalbus et al., 2009; McCallum et al., 2014; Salehin et al., 2004; Woessner, 2000; Wroblicky et al., 1998). In earlier work, we analysed temporal changes in river bed hydraulic conductivities, which could be generated by floods and sedimentation processes (Kurtz et al., 2012). It was found that sequential data assimilation can detect the changes in the river bed with some delay. Kurtz et al. (2014) analysed the value of temperature measurements to characterise heterogeneous riverbeds. In other works it was analysed whether heterogeneous riverbeds (with Gaussian distributed heterogeneous riverbed conductivities) can be replaced with a few zones with spatially homogeneous riverbed conductivities (Kurtz et al., 2013). In practice not enough detailed knowledge is available on the spatial variation of riverbed hydraulic conductivities and Gaussian statistics are used for modelling, if heterogeneity is taken into account at all. However, non-Gaussian patterns probably have a significant influence on the magnitude and the spatial patterns of river–aquifer exchange fluxes, which can be of great importance for the prediction of transport processes of heat and contaminants in river–aquifer systems. Non-MultiGaussian patterns of riverbed hydraulic conductivities could result in very different net exchange fluxes between streams and aquifers compared to MultiGaussian distributions with the same geostatistical parameters. It was demonstrated that non-MultiGaussian patterns in aquifers result in a flow and transport behaviour which is very different from MultiGaussian patterns with the same global statistics (e.g., Gómez-Hernández and Wen, 1998; Zinn and Harvey, 2003). Fleckenstein et al. (2006) and Frei et al. (2009) represented facies distribution of aquifer heterogeneities and investigated the dynamics of river–aquifer exchange fluxes. However, in their studies, only aquifer heterogeneities were treated as non-MultiGaussian and riverbed hydraulic conductivities were the same as the underlying aquifer hydraulic conductivities. Consequently, until now, such non-MultiGaussian patterns have not been taken into account for the generation of riverbed hydraulic conductivities; neither were non-MultiGaussian distributed conductivities updated using inverse methods or data assimilation. This study therefore focuses on investigating the impact of the non-MultiGaussian distribution of riverbed hydraulic conductivities on model states and river–aquifer exchange fluxes.

A number of already established simulation techniques developed to characterise the spatial variability of aquifer heterogeneities (Khodabakhshi and Jafarpour, 2013; Zinn and Harvey, 2003) can also be applied for the characterisation of spatially variable riverbed structures. Geostatistical simulation techniques can model spatial heterogeneity by generating equally likely stochastic realisations of the spatially variable geological medium. One typical approach is the sequential simulation algorithm (Gómez-Hernández and Journel, 1993) based on a variogram to generate a conditional realisation from a MultiGaussian random function. Elfeki and Dekking (2001) proposed a Markov chain model to characterise geological heterogeneities constrained on well data. Another approach is the multiple-point (MP) geostatistical technique (Guardiano and Srivastava, 1993) which expanded the traditional sequential simulation by avoiding the definition of a random function based on two-points geostatistics (Hu and Chugunova, 2008). A comparison between simulations generated by the multiple-point geostatistical method and variogram-based geostatistics showed that the reproduction of the hydraulic conductivity field generated by MP methods can better represent certain geological media (Mariethoz et al., 2010). We assume that the multiple-point geostatistical method can also be used to generate more realistic parameter distributions of riverbeds. A next step is the inverse conditioning of the non-MultiGaussian parameter distribution to hydraulic head data.

Inverse modelling techniques are also called indirect methods which encompass model identification and parameter estimation. Carrera et al. (2005) reviewed the recent progress of inverse modelling for aquifer characterisation and tried to find similarities between well-established methods, including the pilot point method, zonation method and sequential self-calibration. Carrera and Neuman (1986) used a maximum likelihood method called the zonation method to estimate hydraulic conductivities and possibly other parameters for a limited number of zones in which the aquifer is divided. The division of the aquifer in a limited number of zones reduces the number of parameters to be estimated and allows a unique, stable solution of the inverse problem. Carrera and Neuman (1986) proposed the solution of the inverse problem by an iterative approach solving the groundwater flow problem, which results in a hydraulic head solution which is consistent with the parameters. RamaRao et al. (1995) proposed the pilot point method for solving the inverse problem in groundwater flow systems, locating pilot points where there are no measurements. The sequential self-calibration method was proposed by Gómez-Hernánez et al. (1997) and generates equally likely realisations of transmissivity fields conditioned to both transmissivities and heads. The main step forward of this approach is that a non-unique solution is sought to the inverse problem and multiple equally likely solutions are calculated. A comparison of seven inverse modelling methods for groundwater flow was presented by Hendricks Franssen et al. (2009). They showed that Monte Carlo based inverse modelling methods, which calculate multiple equally solutions to the inverse problem, generally outperform other inverse methods.

The Ensemble Kalman Filter (EnKF) (Evensen, 1994) is a Monte Carlo based inverse method. Instead of calculating one solution with a dynamical simulation model (in this paper a hydrological model) multiple solutions are calculated. The multiple solutions are calculated for different model inputs, like for example different spatial distributions of input parameters. Also other model input can be made uncertain. The different model inputs characterise the model input uncertainties and are sampled from multivariate probability density functions. The multiple solutions are used to calculate the model covariance matrix, containing the covariances between all model states. EnKF is a purely stochastic method because the observations are treated as random variables by adding perturbations to the measurements (Burgers et al., 1998). EnKF can be extended to estimate parameters together with states and was applied for estimating hydraulic conductivities for a transient groundwater flow problem by Chen and Zhang (2006). As it is suited to condition to observations and performs well for non-linear models, it becomes a robust tool to deal with flow and transport problems in complex geological media. Hendricks Franssen and