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# Modeling the effect of clay drapes on pumping test response in a cross-bedded aquifer using multiple-point geostatistics

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SUMMARY

This study investigates whether fine-scale clay drapes can cause an anisotropic pumping test response at a much larger scale. A pumping test was performed in a sandbar deposit consisting of cross-bedded units composed of materials with different grain sizes and hydraulic conductivities. The measured drawdown values in the different observation wells reveal an anisotropic or elliptically-shaped pumping cone. The major axis of the pumping ellipse is parallel with the strike of cm to m-scale clay drapes that are observed in several outcrops. To determine (1) whether this large-scale anisotropy can be the result of fine-scale clay drapes and (2) whether application of multiple-point geostatistics can improve interpretation of pumping tests, this pumping test is analyzed with a local 3D groundwater model in which fine-scale sedimentary heterogeneity is modelled using multiple-point geostatistics. To reduce CPU and RAM demand of the multiple-point geostatistical simulation step, edge properties indicating the presence of irregularly-shaped surfaces are directly simulated. Results show that the anisotropic pumping cone can be attributed to the presence of the clay drapes. Incorporating fine-scale clay drapes results in a better fit between observed and calculated drawdowns. These results thus show that fine-scale clay drapes can cause an anisotropic pumping test response at a much larger scale and that the combined approach of multiple-point geostatistics and cell edge properties is an efficient method for integrating fine-scale features in larger scale models.



## 1. Introduction

Clay drapes are thin irregularly-shaped layers of low-permeability material that are often observed in different types of sedimentary deposits (Reineck and Singh, 1973). Their thicknesses are often only a few centimetres (Houthuys, 1990; Stright, 2006). Despite their limited thicknesses, several studies indicate that they may influence subsurface fluid flow and solute transport at different scales (Ringrose et al., 1993; Willis and White, 2000; Morton et al., 2002; Mikes, 2006; Stright, 2006; Li and Caers, 2011; Huysmans and Dassargues, 2009). It seems that structural heterogeneity (such as clay drapes) at fine scale might yield anisotropy at large scale, whereas "random" heterogeneity may yield an isotropic behavior at large scale. However, many studies show that the effect of fine-scale heterogeneity is limited to fine scales and averaged out on larger scales and that consequently the type of geological heterogeneity that needs to be taken into account depends on the scale of the problem under consideration (Schulze-Makuch and Cherkauer, 1998; Schulze-Makuch et al., 1999; Beliveau, 2002; Neuman, 2003; Eaton, 2006). Van den Berg (2003) found for example that anisotropy caused by lamination is small compared to the influence of larger scale heterogeneities so that these sedimentary structures only cause anisotropy on a smaller scale. It is therefore unclear whether centimeter-scale clay drapes can influence groundwater flow and solute transport at scales exceeding the meter-scale. This study therefore investigates whether fine-scale clay drapes can cause an anisotropic pumping test response at a much larger scale. This study is based on measured drawdown values from a pumping that reveal an anisotropic or elliptical-shaped pumping cone: the major axis of the pumping ellipse is parallel with the strike of the centimetre to meter-scale clay drapes that are observed and measured in several outcrops and quarries. This study quantitatively investigates whether this large-scale anisotropy can be the result of fine-scale clay drapes.

It is very difficult to incorporate clay drapes in aquifer or reservoir flow models, because of their small size and the complexity of their shape and distribution. In standard upscaling approaches (Renard and de Marsily, 1997; Farmer, 2002), the continuity of the clay drapes is not preserved (Stright, 2006). Multiple-point geostatistics is a technique that has proven to be very suitable for simulating the spatial distribution of such complex structures

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(Strebelle, 2000, 2002; Caers and Zhang, 2004; Hu and Chugunova, 2008; Huysmans and Dassargues, 2009; Comunian et al., 2011; dell'Arciprete et al., 2012). Multiple-point geostatistics was developed for modelling subsurface heterogeneity as an alternative to variogram-based stochastic approaches that are generally not well suited to simulate complex, curvilinear, continuous, or interconnected structures (Koltermann and Gorelick, 1996; Fogg et al., 1998; Journel and Zhang, 2006). Multiple-point geostatistics overcomes the limitations of variogram by directly inferring the necessary multivariate distributions from training images (Guardiano and Srivastava, 1993; Strebelle and Journel, 2001; Strebelle, 2000, 2002; Caers and Zhang, 2004; Hu and Chugunova, 2008). In this way, multiple-point geostatistics provides a simple mean to integrate a conceptual geological model in a stochastic simulation framework (Comunian et al., 2011). In the field of groundwater hydrology, application of multiple-point geostatistics to modeling of groundwater flow and transport in heterogeneous media has become an active research topic in recent years. Feyen and Caers (2006) apply the method to a synthetic two-dimensional case to conclude that the method could potentially be a powerful tool to improve groundwater flow and transport predictions. Several recent studies apply the method to build realistic (hydro)geological models based on field observations on geological outcrops and logs (Huysmans et al., 2008; Ronayne et al., 2008; Huysmans and Dassargues, 2009; Bayer et al., 2011; Comunian et al., 2011; Le Coz et al., 2011; dell'Arciprete et al., 2012). In large-scale three-dimensional grids multiple-point geostatistics may be computationally very intensive. Several studies focus on improved implementations of the multiple-point statistics techniques to make the algorithms more powerful and computationally efficient (e.g., Mariethoz et al., 2010; Straubhaar et al., 2011). Huysmans and Dassargues (2011) developed the method of "direct multiple-point geostatistical simulation of edge properties" which enables simulating thin irregularly-shaped surfaces with a smaller CPU and RAM demand than the conventional multiple-point statistical methods. This method has been applied on simple test cases (Huysmans and Dassargues, 2011) and the present study is the first to apply the method of "direct multiple-point geostatistical simulation of edge properties" to a full-scale three-dimensional groundwater model. In this way, this study investigates whether the combined approach of using multiple-point geostatistics and edge properties is an efficient and valid method for integrating fine-scale features in larger scale models.

A last scientific goal of this paper is to determine the added benefits of explicitly incorporating clay drape presence for inverse modelling of pumping tests. Several authors have shown that incorporating heterogeneity can result in improved correspondence between calculated and observed hydraulic heads (e.g., Herweijer, 1996; Lavenue and de Marsily, 2001; Kollet and Zlotnik, 2005; Ronayne et al., 2008; Harp and Vesselinov, 2011). However, some authors show that incorporating additional data about heterogeneity does not always result in better calibration (e.g., Hendricks Franssen and Stauffer, 2005). This paper quantifies the change in calibration error when clay drapes are incorporated in groundwater flow models.

## 2. Material and methods

The methodology followed in this study consists of the following steps. First, field data are obtained in an extensive field campaign mapping sedimentary heterogeneity and fine-scale air permeability. Secondly, a training image displaying clay drape occurence is constructed based on the geological and hydrogeological field data obtained from this field campaign. Thirdly, this training image with small pixel size is converted into an upscaled edge training image which is used as input training image to perform multiple-point SNESIM (Single Normal Equation SIMulation) simulations. The SNESIM algorithm (Strebelle, 2002) allows borrowing multiple-point statistics from the training image to simulate multiple realizations of facies occurrence. SNESIM is a pixel-based sequential simulation algorithm that obtains multiple-point statistics from the training image, exports it to the geostatistical numerical model, and anchors it to the actual subsurface hard and soft data. In this study, the resulting simulations indicate at which cell edges horizontal or vertical clay drapes are present. This information is incorporated in a local 3D groundwater model of the pumping test site by locally adapting vertical leakance values and by locally inserting horizontal flow barriers. All hydraulic parameters including the clay drapes properties are calibrated using the measured drawdown time series in six observation wells.

### *2.1. Geological setting*

The pumping test site is situated in Bierbeek near Leuven (Belgium) as shown in Fig. 1. The subsurface geology in this area consists of a 4 m-thick cover of sandy loam from Pleistocene age, 35 m of Middle-Eocene Brussels Sands and 12 m of low permeable Early-Eocene Ieper Clay (Fig. 2). At the pumping test site the Brussels Sands aquifer acts as an unconfined aquifer. All pumping and observation wells of the pumping test are screened in the Brussels Sands. The Brussels Sands formation is an early Middle-Eocene shallow marine sand deposit in Central Belgium (Fig. 1). Its geological features are extensively covered in Houthuys (1990, 2011). This aquifer is a major source of groundwater in Belgium and was studied at the regional scale by Peeters et al. (2010). The most interesting feature of these sands in terms of groundwater flow and transport is the complex geological heterogeneity originating in its depositional history. The Brussels Sands are a tidal sandbar deposit. Its deposition started when a strong SSW-NNE tidal current in the early Middle-Eocene produced longitudinal troughs, that were afterwards filled by sandbar deposits. In these sandbar deposits, sedimentary features such as cross-bedding, mud drapes and reactivation surfaces are abundantly present (Houthuys, 1990, 2011). The orientation of most of these structures is related to the NNE-orientation of the main tidal flow during deposition.

### *2.2. Pumping test*

In February 1993, a pumping test was performed in Bierbeek (Belgium) under the authority of the company TUC RAIL N.V. in the framework of high-speed train infrastructure works. One pumping well (PP1) and six observations wells were drilled in the 35 m-thick coarse facies of the Brussels Sands (Fig. 3). The observation wells are situated between 4 m and 75 m from the pumping well and are located in different orientations. Before pumping the water table was at 49.8 m. During the pumping test, there was 72 h of pumping in well PP1 with a flow rate of 2120 $m^3$/day. Water level in six observation wells was continuously monitored during pumping and during an additional 24 h of recovery after pumping. The pumping test was interpreted by inverse modelling using a numerical method described in Lebbe and Debreuck (1995). This analysis showed that the best calibration was obtained assuming horizontal anisotropy in the coarse facies of the Brussels Sands. The maximal horizontal hydraulic conductivity was found to be 28.3 m/day while the minimal horizontal hydraulic conductivity was 13.4 m/day. The principal direction of maximal horizontal hydraulic conductivity corresponds to N 115°48′ E (TUC RAIL N.V., 1993). This principal orientation is exactly perpendicular to the SSW-NNE orientation of the main tidal flow during deposition and the mud drapes in the Brussels Sands.