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Modeling heterogeneity of gravel-sand, braided stream, alluvial aquifers at the facies scale

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Abstract

The coarse-grained alluvial aquifers are recurrently considered as almost homogeneous and isotropic media. Nevertheless, water flow through these sediments is controlled by internal architecture, therefore, a better knowledge is necessary to understand the effects of facies heterogeneity on the conductivity magnitude and anisotropy within these aquifers. In this work, we search interactions at the facies scale within a glacio-fluvial aquifer among sedimentary heterogeneity, distribution of permeability and anisotropy. The case study concerns Pleistocene sequences of the Ticino basin (Northern Italy), where three 'model blocks', dug into real sediments at a quarry site, have been investigated at the meter scale. These 'model blocks' represent the most diffuse facies associations: (1) sand-gravel dunes, (2) gravel bedforms, and (3) poorly sorted, mass gravity deposits. Facies maps with 2 cm resolution were obtained for each block and used to condition 3D geostatistical simulation of the sediment volumes with a hierarchical modification of SISIM. Conductivities of samples were either measured with laboratory tests or estimated with empirical formulas. Conductivity values were finally introduced as input data into the numerical flow model to compute the upscaled tensor of equivalent conductivity at the model block scale. The results of field infiltration tests were used to verify the outcomes of upscaling experiments, which identified the primary influence on the most permeable facies (open framework gravel) on both conductivity magnitude and anisotropy ratio. The latter property is unrelated to the abundance of this facies, but is controlled by its spatial distribution within the blocks. As the connectivity of open framework gravel increases, model blocks become more anisotropic. On the other hand, the low-permeable sand facies of dunes do not produce significant anisotropy at the block scale. These results show the importance of introducing the hierarchical assemblage of different-rank depositional units in conceptual aquifer models. In addition, we identified the most significant depositional units to forecast the spatial distribution of aquifer heterogeneity at different scales.

Keywords: Aquifer sedimentology; Geostatistical simulation; Ground water flow; Hydrofacies; Numerical modeling

1. Introduction

Gravel-sand deposits of braided stream alluvial environment are among the most widespread and

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productive aquifer units in the Quaternary sedimentary basins of Europe. These units are formed by very heterogeneous assemblages of high- to medium-permeability facies, which are generally characterized by low contrasts of hydraulic conductivity. For these basic properties, the coarse-grained braided stream units tend to behave like homogeneous, but anisotropic, media with respect to groundwater flow at the scale of the high-rank depositional elements (hydrostratigraphic units; Maxey, 1964). In this case, linear dimensions are tens of meters in the vertical direction and thousands of meters in the horizontal direction. Both experimental studies and modeling attempts suggest that this homogeneous behavior is mostly due to the averaging effect of the multiple 3D interconnections among contrasting minor scale depositional units and facies (Anderson, 1989; 1997; Anderson et al., 1999). Nevertheless, hydrogeologists are interested in the distribution and continuity of the most permeable facies, which act as preferential flow paths, especially for contaminant transport (Tompson and Gelhar, 1990; Jussel et al., 1994; Ritzi et al., 1995). Therefore, there is a need for description and quantification of heterogeneity also at the fine scale of sedimentary facies (i.e. the sediment packets produced by a dominant depositional process, which are characterized by their own textural and structural properties) or hydrofacies (facies and/or fine-scale sediment units, which are also characterized by a distinct value of hydraulic conductivity; Anderson, 1989; Jussel et al., 1994). Among several papers that merge facies simulation and numerical upscaling, we recall Bierkens and Weerts (1994); Scheibe and Freyberg (1995); Bierkens (1996); Scheibe and Yabusaki (1998).

This brief discussion shows the importance of studying flow in geological porous media at several different scales ordered according to structural or functional hierarchy. This distinction is clearly defined by Cushman et al. (2002) as follows: structural hierarchy refers to the case when the porous domain 'can be decomposed into successively nested, interacting physical subunits', whereas functional hierarchy relates to 'hierarchical transport processes within the porous medium'. In order to reduce the degrees of freedom from fine scales to coarser scales, several upscaling techniques have been proposed and applied for different types of porous media and different flow and transport processes. Among the review papers, where a thorough collection of references is given, we recall those by Wen et al. (1996); Renard and Marsily (1997); Cushman et al. (2002); Farmer (2002).

In this work, we attempt to obtain some results about the effectiveness of facies heterogeneity in determining hydraulic conductivity at the fine scale in coarse-bedload braided stream deposits. The proposed approach can be categorized as an upscaling method applied to a structural discrete hierarchy because the porous medium is modeled at two distinct scales: fine and larger scales. The fine scale refers to facies with a resolution as small as 2 cm, whereas typical linear dimensions of the larger scale sedimentary aggregate are about 1 m. Our attempt is not addressed to simulation and modeling of the high rank sedimentary units that form aquifer groups and complexes. The general purpose of this study is to improve our knowledge about flow processes in fine scale and heterogeneous porous media. Such a study could find application to local-scale problems of aquifer remediation rather than to simulation of facies assemblages of larger aquifer units.

The depositional architecture of the studied class of aquifers consists of a relatively small number of facies, which includes: organized sandy gravels and sands originated by the accretion of different scale bedforms and bars within channels of different ranks, relatively rare clean gravels resulting from winnowing of sandy gravel bars, and rare and disorganized sandy gravels deposited by mass gravity flows.

Accounting for the textural component of the sedimentary heterogeneity in such a facies association, the facies-scale hydraulic conductivity should vary between the minimum, corresponding to the sand dunes, and the maximum corresponding to the clean gravel bars. The influence, if any, of the geometrical component of sedimentary heterogeneity (i.e. the sedimentary structure) on magnitude and anisotropy of the components of the equivalent tensor of hydraulic conductivity is less obvious. One specific goal of this work is the investigation of this point with field sedimentological and experimental work combined with geostatistical 3D simulation of the internal architecture of the facies units and numerical computation of the components of the equivalent conductivity tensor. The results of field infiltration