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Reconstructing hydraulic conductivity field for hydrogeological modeling in an urban environment

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A B S T R A C T

Hydrogeological analysis of flow is largely based on the concept of hydraulic conductivity. In numerical hydrogeological modeling, a value of hydraulic conductivity must be assigned at each element of mesh. In heterogeneous geological formations, this value governs the average behavior of groundwater flow within an aquifer. The goals of this study are twofold: (1) development of a methodology to transform the description of lithological units into local hydraulic conductivity values and (2) development of a methodology for reconstruction of hydraulic conductivity fields on a 83 km^2 of the Bordeaux urban area. Two approaches, a 2D approach and a 3D approach, based on geostatistical analysis are explained in details and compared. For both approaches, variographical analysis and ordinary kriging are carried out on the logarithmic of hydraulic conductivity and composite hydraulic conductivity is calculated using thickness-weighting to get horizontal and vertical hydraulic conductivities. The comparison of both approaches and the assessment of their potential and limitations suggest that the 2D approach is more appropriate than the 3D approach.

1. Introduction

1.1. Framework

Improving the asset management of underground utilities requires a detailed knowledge of the geological and hydrogeological environment of the pipes. It is well known that climate disruption may affect the service life of buried pipe networks (Laffrechine, 1999) but the interaction of climatic and geological variables is rarely considered in predictive breakage models of pipes. The PC3 project, French acronym for "Climatic disturbance and pipe breakages" aims at anticipating the effects of climate change on the aging of infrastructures. The project aims to develop possible scenarios of future evolution of underground networks by establishing statistical and mechanical analysis based on the hydrogeological model. It is thus necessary to estimate the groundwater level in order to compare it at any point with the depth of buried pipes.

Numerical modeling for studying groundwater flow has become a common practice in hydrogeology (Jankovic′ et al., 2003a,b; Rushton, 2003; Carrera et al., 2005; Wang and Zhang, 2007; Chebud and Melesse, 2009; Le Delliou, 2009; Smaoui et al., 2011) because it offers a way to better understand aquifer systems besides being a simulation tool. Furthermore, numerical models can have an exploratory nature and may be the support for a conceptual hydrogeological model (Betancur and Palacio, 2009).

Groundwater modeling is faced with difficulties in estimating some crucial input data:

- Groundwater recharge and evapotranspiration are difficult to measure directly (Ladekarl et al., 2004; Jiménez-Martínez et al., 2010) but may be estimated by numerical models that are calibrated on indirect experimental data such as soil moisture. Tracer experiments can also be used to study the water balance and to estimate recharge.
- Hydraulic conductivity, which is the focus of this paper, is often the most dominant hydraulic property while it may vary over several orders of magnitude in the studied field.

The aims of this article are twofold:

(1) Development of a methodology to transform the description of a lithological unit into a local hydraulic conductivity value.
(2) Development of a methodology based on geostatistical tools for the reconstruction of hydraulic conductivity fields at urban scale (83 km^2) by two approaches. Among all available estimation methods, we have only used ordinary kriging in this work.

The urban site on which this study is carried out has previously been the support of several works pointing on the variability of soil properties (Breysse et al., 2005; Bourgine et al., 2006; Marache et al., 2009a,b) but modeling hydraulic conductivity properties is a new challenge.

1.2. Hydraulic conductivity

One of the key parameters in reservoir characterization is hydraulic conductivity (K) which controls fluid and energy transfer in the

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Nomenclature

K	local hydraulic conductivity
K_{arith}	arithmetical mean of hydraulic conductivity
K_{eff}	effective hydraulic conductivity
K_{eq}	equivalent hydraulic conductivity
K_g	geometrical mean of hydraulic conductivity
K_{g2D}	geometrical mean of hydraulic conductivity obtained by 2D approach
K_{g3D}	geometrical mean of hydraulic conductivity obtained by 3D approach
K_{harm}	harmonical mean of hydraulic conductivity
K_{h2D}	horizontal hydraulic conductivity obtained by 2D approach
K_{h3D}	horizontal hydraulic conductivity obtained by 3D approach
$K_{\max}$	maximal hydraulic conductivity
$K_{\min}$	minimal hydraulic conductivity
K_{v2D}	vertical hydraulic conductivity obtained by 2D approach
K_{v3D}	vertical hydraulic conductivity obtained by 3D approach

geological formations. Because this parameter exhibits various definitions and because it is impossible to measure it everywhere, one of the main questions is to estimate what hydraulic parameter value should be used in numerical models. The answer lies in the link between the hydraulic parameters and heterogeneity of geological formations. The heterogeneity of hydraulic parameters is the most salient feature of hydrogeology (Dassargues, 1998; Sanchez-Vila et al., 2006) perhaps even more in an urban context. Sanchez-Vila et al. (2006) synthesized works undertaken during the last 30 years about heterogeneity and offer a critical appraisal of results related to the problem of finding representative hydraulic conductivities (i.e. controlling the average behavior of groundwater flow within an aquifer at a given scale). This notion involves effective hydraulic conductivity (K_{eff}) and equivalent hydraulic conductivity (K_{eq}). The first one (K_{eff}) is defined mathematically as the negative of the expected value of the flow divided by the expected value of the hydraulic gradient. It is an intrinsic property of an aquifer system that does not depend on the existing flow conditions (Dagan, 1989; Ababou and Wood, 1990; Dagan, 1993; Copty et al., 2006). Matheron (1967) demonstrated that in two-dimensional infinite domains and under not very restrictive conditions, K_{eff} is equal to the geometrical mean K_g of the local values of K. The second one (K_{eq}) would be defined as the constant permeability tensor that should be assigned to the global area to obtain the same total outflow than that observed in the heterogeneous scenario under the same boundary conditions (Sanchez-Vila et al., 2006). A complete equivalence between the real heterogeneous medium and the fictitious homogeneous one is impossible. It is therefore defined in a limited sense, according to certain criteria (flow at the boundary of the domain and energy dissipated by the viscous force) that must be equal for both media (Renard and de Marsily, 1997).

Numerous methods have been developed to estimate hydraulic conductivity for heterogeneous porous media such as hydraulic tests interpretation or inverse modeling (Gómez-Hernández, 1991; Renard, 1996; Wen and Gómez-Hernández, 1996; Renard and de Marsily, 1997; Renard et al., 2000; Sanchez-Vila et al., 2006; Feng et al., 2007; Zhang et al., 2007). For Zhang et al. (2010), the formulation of the inverse problem in hydrogeology is approximately contemporary with the development of the first numerical models for solving groundwater flow equations (Nelson, 1960; Jacquard and Jaïn, 1965; Kinzelbach, 1986; de Marsily et al., 1999; Carrera et al., 2005; Hendricks Franssen et al., 2009). This leads to describe the field as a set of constant hydraulic conductivity zones whose geometry is defined a priori.

After a description of the studied area and the corresponding hydrogeological context, the methodology to transform the description of lithological unit into local hydraulic conductivity value is explained. The reconstruction of hydraulic fields is then developed in details for the 2D and 3D approaches. Both approaches are compared and finally applied to the studied case.

2. Local context and methods

2.1. Site of study and subsurface geology description

The site of study is located in the Southwest of France and covers partially three cities belonging to the Bordeaux urban area (Figure 1). The study encompasses a total area of 8300 ha (approximately 11 km long and 7.5 km wide); 30% is occupied by vineyards and green woods and 70% by roads, railway, and buildings. The model will be built by processing geological and geotechnical data gathered from a large series of boreholes (1965 boreholes). The density of boreholes is uneven, with a greater density of data in the most urbanized areas. The climate of the region is mild and humid oceanic (Laroussi, 1969). The mean annual rainfall on area, calculated on the last 30 years is about 950 mm/year and the mean annual actual evapotranspiration is about 1000 mm/year. Several rivers flow towards East across the area. The main ones are Le Peugue and Ruisseau d'Ars (which have many tributaries) which join the Garonne river close to the eastern limit of the studied area (Figure 1). The Ruisseau d'Ars and downstream part of Peugue are situated in the most urbanized zones where they are canalized.

Regional stratigraphy of Aquitaine basin region has been the topic of many studies (Laroussi, 1969; Pratviel, 1972; Alvinerie et al., 1976, 1977; Dubreuilh and Alvinerie, 1978; Platel et al., 2000). The geological map of Bordeaux area is presented in Fig. 2 and litho-stratigraphical description of formations, according to Platel et al. (2000) is summarized in Table 1.

The surface geology is mostly composed of Quaternary formation which almost completely covers the older formation units of lower Oligocene (Rupelien), upper Oligocene (Chattien) and Miocene. A brief description from the oldest to the newest is as follows:

(a) The Rupelien thickness ranges between 40 and 80 m (Laroussi, 1969) and is formed by a varying marine limestone series, which is masked in the western part of the study area by deposits that are more recent. It outcrops sporadically along the banks of Le Peugue river in the Eastern part of the study area. The Garonne river, by digging the bed, moved gradually to the East, partially hacking "limestone starfish".
(b) The Chattien does not appear at the surface of the study area. The maximum thickness of these green clays is about 10 m. This deposit results from the marine regression at the end of Rupelien.
(c) The Miocene has a thickness ranging from 60 m in the western part of the study area to almost zero at the eastern limit. The common feature of this formation is shellfish facies.
(d) Quaternary formation is the most recent geological formation in the study area. Its thickness is variable and does not exceed 30 m. It consists of deposits of various lithologies like sand, silt, clay, gravels, and many others. According to Laroussi (1969) and Dubreuilh (1976), the continental deposits of Castets, Brach and Belin formations (Figure 2) were deposited by Southwest winds. From the eastern boundary (Belin formation) to the Garonne river, there are alluvial deposit series of staircase terraces including: upper terrace (Fxa-b), middle terrace (Fxb1) and modern terrace (Fxc, Fxb2). These terraces are separated by Colluvial deposits and result from the erosion of continental deposits by the Garonne.

These formations constitute an aquifer system composed by the Miocene/Quaternary aquifer and the Oligocene aquifer (Table 1). Both are separated by the Chattien unit that although saturated cannot transmit significant quantities of water because of its low hydraulic conductivity. This aquitard (Chattien unit) is discontinuous at some locations, which makes interconnections between aquifer systems possible. In