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# Geostatistical Techniques to Obtain the 3-D Hydraulic Conductivity Distribution Model in the Southern Po River Plain

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**Abstract:** The main objective of this research is to assess the hydraulic conductivity ( $k$ ) distribution in the Southern Po River plain (Emilia Romagna region), where fine silty and silty-sandy deposits are interdigitated with coarser sandy and sandy-gravelly sediments. The  $k$  distribution is the main issue to be faced in hydrogeological numerical modeling. Usually, this parameter is assigned to each hydrogeological complex, considering values coming from point permeability tests (e.g. pumping tests, slug tests, etc.). Although the calibration methods allow a good model optimization, the natural variability of the hydraulic properties cannot be reproduced in detail using deterministic and point approaches to calibration. For this reason, a 3-D geostatistical method was applied to draw estimations of the hydraulic conductivity of a continuous 3-D model of the subsoil. A mechanical model was built through 182 Cone Penetration Test (CPT) profiles of tip  $q_c$  and shaft  $f_s$  resistances, collected by the Emilia Romagna Regional Geological Survey. In particular, the Ordinary Kriging technique was applied to the  $q_c$  and  $f_s$  variables which allow to obtain the  $I_c$  index 3-D model and the relative  $k$  3-D model, by means of the equations available in literature. The geostatistical results show a clear variation of the hydraulic conductivity among the different deposits identified in the study area. Moreover, the proposed method provided a good reliability of  $k$  estimated values, which could be used as a good starting point for hydrogeological modeling and as constraints for model calibration.

Keywords: Hydraulic conductivity; CPTs; geostatistics; heterogeneous aquifer; Po plain.

## 1 Introduction

In the last decades, numerical modeling has become one of the most important instruments to manage groundwater resources, especially in sustainable groundwater exploitation (Rossetto et al. 2018; Stefania et al. 2018), contamination fate assessment (Greskowiak et al. 2006; Mastrocicco et al. 2012, 2014), and remediation scheme design and efficiency evaluation (Prommer et al. 2000).

Beside the definition for the hydrogeological boundary conditions, the hydraulic conductivity ( $k$ ) distribution assessment is an important issue to be faced, especially when the considered aquifer is complex (Di Curzio et al. 2018). In general, the automated model calibration represents a valid instrument to improve both the boundary conditions and the  $k$  of the geological bodies (e.g. PEST; Doherty 2015). Regarding the hydraulic conductivity, these calibration procedures adapt the initial values, generally obtained by site and/or laboratory tests, either considering the aquifers homogeneous (i.e. one  $k$  value for a defined volume), or heterogeneous (i.e. by means of the Pilot Point Method, PPM). The first approach is very simplified, while the second one (i.e. the PPM) is more refined, because it is geostatistically based. Nevertheless, the  $k$  values are modified in selected points in an iterative manner, comparing every time the measured, not always sufficiently representative, and the simulated hydraulic heads (Moeck et al. 2015). In this way, the obtained heterogeneity only depends on both the hydraulic head measurement and pilot point distributions, and it is not physically based. Furthermore, the geostatistics behind the PPM is quite simple and not flexible, considering that the geostatistical features should be adapted case by case, because these are data-driven methods (Castrignanò 2011; Chilès and Delfiner 2012; Oliver and Webster 2015). In addition, the initial  $k$  values are generally obtained by pumping tests that provide mean values, which are not always representative of the multi-scale geological heterogeneities that can influence substantially the groundwater flow (Bianchi and Pedretti 2017). Combining the Cone Penetration Tests (CPTs) parameters (i.e.  $q_c$  and  $f_s$ ) by the equations present in literature (Lunne et al. 1997; Robertson 2009; Elhakim 2016), a more detailed hydraulic conductivity estimation can be achieved.

In this general framework, the main objective of this research is to draw a 3-D model of  $k$  in a portion of the southern Po plain (alluvial aquifer) using the Ordinary Kriging technique on CPT data, to be adopted as a physically based starting point for the hydrogeological modeling. The methodological approach proposed in this case study can be applied to other cases where the deposit heterogeneity could affect substantially the groundwater flow.

## 2 Study Area

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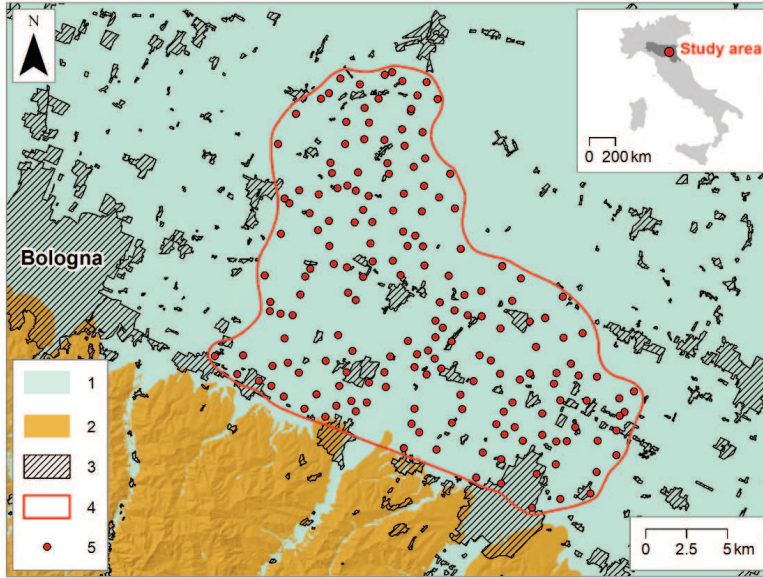
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The study area (900 km<sup>2</sup> wide) is located in the southern part of the Po plain, in the eastern Bologna district (Figure 1). This area is characterized by mainly alluvial deposits made up of undifferentiated fine silty-sandy deposits (i.e. flooding plain). Within these deposits, coarser (i.e. alluvial fans and paleo-channels) and finer (i.e. lacustrine lenses) geological bodies can be detected (Amorosi and Farina 1995; ISPRA 2009). From a lithological point of view, these inclusions consist of sandy, gravelly and silty-clayey soils. The gravelly alluvial fans are prevalent nearby the Apennines reliefs, while the sandy paleo-channels become predominant northward. Instead, the lacustrine lenses can be found all over the study area. Since these geological bodies are detectable only by direct investigations, their shape, size and depth cannot be predicted in detail within the whole volume.



**Figure 1.** The location and geological features of the selected study area. In legend: 1) alluvial deposits; 2) bedrock; 3) urban areas; 4) the geostatistical domain; 5) the Cone Penetration Test (CPTs) locations.

### 3 Material and Methods

#### 3.1 Dataset

The dataset considered in this study consists of 182 Cone Penetration Test profiles (CPTs), provided by the Emilia Romagna Regional Geological Survey and collected throughout the eastern Bologna district. The parameters are cone tip resistance ( $q_c$  in MPa) and sleeve friction ( $f_s$  in MPa), measured every 2 cm, to a maximum depth of 30 m depth.

#### 3.2 Geostatistics

In this study, the Ordinary Kriging (OK), one of the most widespread geostatistical techniques, was selected to estimate the cone tip resistance ( $q_c$ ) and sleeve friction ( $f_s$ ) within the considered 3-D underground volume. This stationary method, as well as all the geostatistical techniques, is based on the concept of Spatial Dependency and on the Regionalized Variable Theory (Matheron 1973), which states that the values of a particular variable in the space are not independent each other (Chilès and Delfiner 2012; Oliver and Webster 2015). According to this theory, every measurement of a dataset, in addition to the dataset mean and the residual non-systematic error, includes a casual component that is spatially correlated and describes the variation around the mean value. In geostatistics, the function that describes the spatial dependency of a given variable  $z$ , as a relation between the semi-variance ( $\gamma(\mathbf{h})$ ) and distance (i.e. lag  $\mathbf{h}$ , a separation vector), is the Semi-variogram that is defined as follow:

$$\gamma(\mathbf{h}) = \frac{1}{N(\mathbf{h})} \sum_{i=1}^{N(\mathbf{h})} [z(\mathbf{x}_i) - z(\mathbf{x}_i + \mathbf{h})]^2 \quad \text{with } i = 1, \dots, N(\mathbf{h}) \quad (1)$$

where  $z(\mathbf{x})$  and  $z(\mathbf{x} + \mathbf{h})$  are distinct measurement separated by a lag  $\mathbf{h}$ , related to a defined position  $\mathbf{x}_i$  within the considered domain;  $N(\mathbf{h})$  is the number of pairs separated by the same lag  $\mathbf{h}$ .

In OK, the experimental Semi-variogram, obtained by the actual data, is fitted by a model function, that can be simple (i.e. one structure) or nested (i.e. two or more structures). The selected model allows to obtain the

weights ( $\lambda$ ) used in the interpolation. These weights are obtained by means of the Lagrangian method (Castrignanò 2011). The interpolation of the considered data is performed by a linear unbiased estimator ( $z^*(\mathbf{x}_0)$ ):

$$z^*(\mathbf{x}_0) = \sum_{i=1}^N \lambda_i z(\mathbf{x}_i) \text{ with } i = 1, \dots, N \tag{2}$$

where  $\mathbf{x}_0$  is the point where the variable is estimated;  $z(\mathbf{x}_i)$  are the values of the considered variable near  $\mathbf{x}_0$ .

In order to ensure unbiased and optimal estimations (i.e. minimum error), the  $\lambda$  values are calculated assuming that

$$E[Z^*(\mathbf{x}_0) - Z(\mathbf{x}_0)] = 0 \tag{3}$$

For each estimation in the defined domain, the OK provides the uncertainty, in terms of estimation variance:

$$\sigma^2(\mathbf{x}_0) = \mu + \sum_{i=1}^N \lambda_i \gamma(\mathbf{x}_i, \mathbf{x}_0) \tag{4}$$

where  $\gamma(\mathbf{x}_i, \mathbf{x}_0)$  is the Semi-variogram related to the pair sampled point ( $\mathbf{x}_i$ )-estimation point ( $\mathbf{x}_0$ );  $\mu$  is a Lagrangian multiplier.

In order to apply the OK method, the study area was converted in a mesh grid that consists in irregular cells (dimension 500x500x0.5 m). This anisotropic cell dimension was selected to preserve the vertical detail of the CPTs.

Because OK is a stationary method, the spatial variable to be interpolated must meet the stationarity properties (Castrignanò 2011). In detail, the considered spatial variable must be characterized constant mean (First-order stationarity) and sample variance (Second-order stationarity), regardless of the location. Hence, the statistical distribution must be Gaussian. Since the considered parameters have not a Gaussian distribution, the Gaussian Anamorphosis was applied. This is a mathematical function that transforms a variable  $Y$  with a non-Gaussian distribution into a new Gaussian-distributed variable  $Z=\Phi(Y)$ . The transformation is made by fitting a polynomial expansion (Chilès and Delfiner 2012):

$$\Phi(Y) = \sum \Psi_i H_i(Y) \tag{5}$$

where  $H_i(Y)$  is the Hermite polynomials;  $\Psi_i$  are the Hermite coefficients.

The Gaussian Anamorphosis allows the application of the OK to any variable. Once the Gaussian variable is estimated, it can be back-transformed to obtain the real values of the selected variable within the whole domain.

All the geostatistical analyses were performed by means of the software Geovariance ISATIS software.

### 3.3 Hydraulic conductivity calculation

The hydraulic conductivity of the deposits present in the study was estimated from the Soil Behavior Type index ( $I_c$ ) proposed by Robertson (1990) and defined by the following equation:

$$I_c = [(3.47 - \log(q_c/p_a))^2 + (\log R_f + 1.22)^2]^{0.5} \tag{6}$$

where  $q_c$  is the cone tip resistance (in MPa);  $p_a$  is atmospheric pressure (0,1 MPa);  $R_f$  is the friction ratio =  $(100 \cdot f_s/q_c)$  %;  $f_s$  is the sleeve friction (in MPa).  $I_c$  provides a lithological classification of the investigated deposits (Table 1). As a matter of fact, the higher the  $I_c$ , the finer are the studied deposits.

**Table 1.** The Soil Behavior Type classes defined by the  $I_c$  ranges, with the corresponding lithological description.

SBT class	Lithological description	$I_c$
2	Clay - organic soil	$I_c > 3.60$
3	Clay to silty clay	$2.95 < I_c < 3.60$
4	Silt mixtures (clayey silt to silty clay)	$2.60 < I_c < 2.95$
5	Sand mixtures (silty sand to sandy silt)	$2.05 < I_c < 2.60$
6	Sands (clean sands to silty sands)	$1.31 < I_c < 2.05$
7	Dense sand to gravelly sand	$I_c < 1.31$

By means of the  $I_c$  values, the soil hydraulic conductivity can be estimated, as proposed by Lunne et al. (1997) and Robertson (2010). Since the relation between the  $I_c$  and the grain size is inverse,  $k$  values (in m/s) are higher for low  $I_c$  values and lower for high  $I_c$  values. The equations that describe this inverse relation are exponential functions and different for granular and cohesive media, as shown below:

$$\text{for } 1.0 < I_c \leq 3.27, k = 10^{(0.952 - 3.04I_c)} \tag{7}$$

$$\text{for } 3.27 < I_c < 4.0, k = 10^{(-4.52 - 1.37I_c)} \tag{8}$$

Equations (6), (7), and (8) were applied to  $q_c$  and  $f_s$  values estimated within the whole domain. Hence, their transformation uncertainties (Lunne et al. 1997) were considered in the  $q_c$  and  $f_s$  estimation uncertainties,

calculated by Eq. (4). Nevertheless, the obtained  $k$  values can be considered representative of the actual hydraulic properties of the studied deposits.

4 Results and Discussion

The results are shown in Figure 2. In detail, Figures 2a and 2b are related to the distribution of  $f_s$  and  $q_c$ , estimated by the Ordinary Kriging method selecting the Semi-variogram models shown in Table 2. The  $I_c$  distribution was calculated in the whole domain by the previously described equation (Robertson 1990), whose values, in turn, were used to estimate the  $k$  distribution (Lunne et al. 1997).

The  $f_s$  distribution (Figure 2a) presents its maximum values (i.e. in the range 0.30-0.40 MPa) in limited areas, at depths as high as 10-15 m. Nevertheless, its variability within the volume seems to be non-systematic. Contrariwise, the  $q_c$  distribution (Figure 2b) shows a vertical trend, that increases the values from less than 2 MPa to about 6 MPa. In addition, the maximum values are located in the limited areas as  $f_s$ . Analyzing the  $I_c$  distribution (Figure 2c), these limited areas consist mainly of sands and silty sands, sometimes gravelly sands, that can be attributable to the coarser alluvial fans of the southern Po plain, at a depth higher than 10-15 m. These alluvial fans assume a paleo-channels shape, as identified in the southern part of the considered domain. Furthermore, the deposits seem to evolve vertically from prevalent silty clays to silt mixtures with clayey lenses, that represent the undifferentiated fine flooding plain and/or lacustrine deposits. The same geological properties are reflected in the  $k$  distribution (Figures 2d and 3). The zones characterized by a low  $I_c$  values, which represent coarser deposits, show the highest hydraulic conductivities (about  $10^{-5}$ - $10^{-3}$  m/s). These zones are the alluvial fans and paleo-channels, which can be detected from 10 m downward (Figures 3b, 3c, and 3d). Around these geological bodies, the finer deposits are characterized by lower  $k$  values (about  $10^{-9}$ - $10^{-7}$  m/s), even though increasing downward (Figure 3), as for the grain size.

Table 2. The Semi-variogram models and related parameters.

Variable	Nugget	Nested model	Sill	Range (m)
$q_c$ horizontal	0.773	Spherical	0.082	1400
		Cubic	0.094	11000
$q_c$ vertical	0.073	Spherical	0.51	2
		K-Bessel	2.51	30
$f_s$ horizontal	0.602	Exponential	0.40	6000
$f_s$ vertical	0.082	Spherical	0.34	2
		Exponential	0.26	15

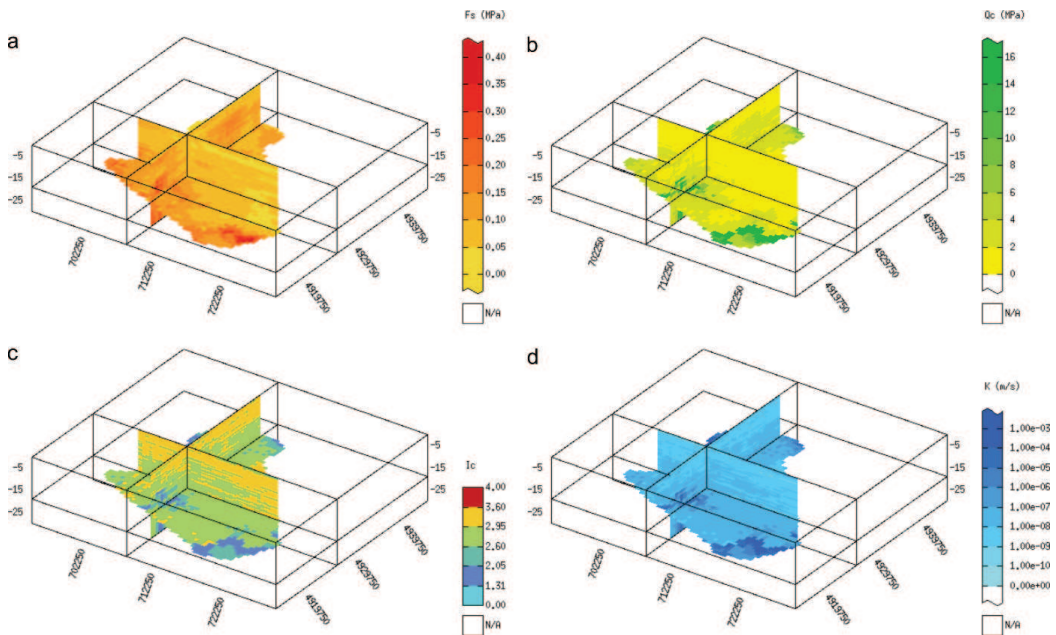
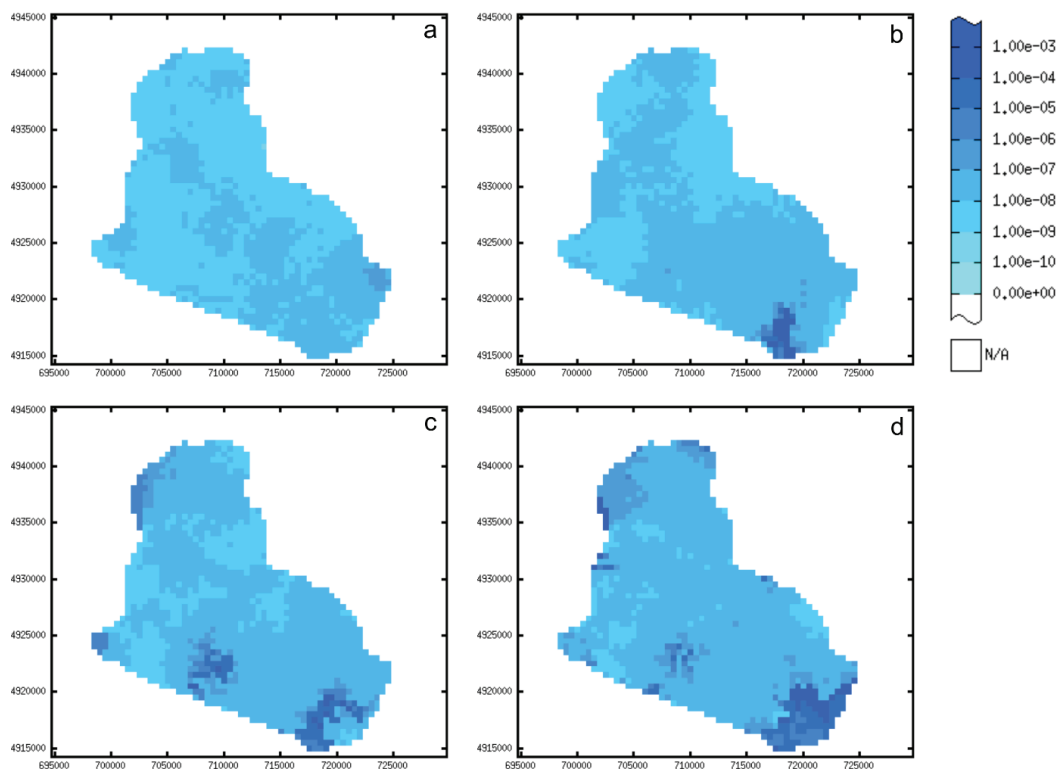


Figure 2. The 3-D slice visualization of the volumetric distribution of a)  $f_s$  (in MPa), b)  $q_c$  (in MPa), c)  $I_c$ , and d)  $k$  (in m/s), obtained by the geostatistical analyses. The x-, y-, and z- axes are in meters.



**Figure 3.** The  $k$  (in m/s) distribution at different depths of the considered domain: a) 5 m, b) 10 m, c) 15 m, and d) 20 m. The  $x$ -, and  $y$ -axes are in meters.

## 5 Conclusions

Summarizing, the Ordinary Kriging was used to estimate the  $k$  values in a 3-D model, starting from CPT data. The obtained model reproduces as closely as possible the actual geological and hydrogeological features of the considered part of the southern Po plain, not neglecting the multi-scale heterogeneity. As a result, the  $k$  values obtained by the geostatistical technique are consistent with the ones present in literature and adopted in the hydrogeological numerical modeling of other portions of the Po plain (Mastrocicco et al. 2014).

For these reasons, the proposed method, which consists in a geostatistical analysis of CPT data, provides a physically based 3-D hydraulic conductivity model, with a noticeable degree of detail. Thus, the model obtained by this methodological approach can represent a valuable starting point for hydrogeological modeling and/or a constraint for the model calibration, when the intrinsic deposit heterogeneity could affect substantially the groundwater flow (e.g. heterogeneous alluvial deposits).

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