GEO-ELECTRICAL DATA FUSION BY STOCHASTIC CO-CONDITIONING SIMULATIONS FOR DELINEATING GROUNDWATER PROTECTION ZONES

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ABSTRACT

In hydrogeology, advances in the delimitation of protection zones are made by the use of stochastic simulations integrating all available data. In practice, due to the few available measurements of the main parameters (hard data), it is very useful to integrate several secondary properties of the media as indirect data (soft data) to reduce the uncertainty of the results. In aquifers, most of the solute spreading is governed by the hydraulic conductivity (K) spatial variability, which is generally considered as the main uncertain parameter. A stochastic approach integrating hydraulic conductivity measurements (hard data), head observations and shallow electrical resistivity tomography (soft data) is presented. Results are discussed on a synthetic and on a practical case. It is shown in practice how the uncertainty of the well capture zone probability distribution (CaPD) can be reduced. Since geophysical data and head observations are easier to collect on the field then hydraulic conductivity measurements, they are generally more abundant. The methodology presented can even be used in real applications when little or no information is available about the hydraulic properties, through the conditioning on geophysical data and/or head observations.

1. INTRODUCTION

Protection zones, corresponding to particular isochrones, are foreseen in local regulations providing a time-related protection of groundwater sources or pumping wells. For example, in Walloon Region of Belgium, as in other regions, 'prevention zones' corresponding to the 1-day and 50-days isochrone contours must be delineated. It brings essentially an effective protection against accidental pollution. Ensuring a delay between an eventual injection of pollutant and its arrival at the pumping well, allows timely decisions in each case on a priority intervention scheme. In heterogeneous formations, numerical computational methods are often combined to geophysical and hydraulic tests data to obtain the most adequate perimeter (Kinzelbach *et al.*, 1992; Dassargues, 1994; Derouane and Dassargues, 1998). If many and various data are available in terms of geological and hydrogeological information in the studied domain, a very detailed geological interpretation is possible with a possibly reasonable, but unquantifiable error. Measured parameters can be extrapolated consistently based on geological interpretation to condition ideally the model calibration. In a deterministic framework, even if the model is calibrated accurately on many data, these computed protection zones cannot be known exactly due to the limited knowledge of the aquifer parameters.

To assess the uncertainty in the delineation of time-related capture zones, different stochastic methods using Monte Carlo simulation approaches have been developed (Bair *et al.*, 1991; Varljen and Shafer, 1991). Recently, developments integrating conditioning procedures on hydraulic conductivity values (van Leeuwen *et al.*, 2000), on head observations (Gomez-Hernandez *et al.*, 1997; Vassolo *et al.*, 1998; Feyen *et al.*, 2001) and on additional data (Nunes and Ribeiro, 2000) have allowed to decrease prior uncertainty of hydraulic conductivity and therefore to reduce the uncertainty of the well protection zone.

A stochastic approach is used for an ideal fusion of hydraulic conductivity measurements ('hard data') with head observations and shallow electrical resistivity tomography results ('soft data'). For the purpose of the demonstration, a synthetic but realistic case was designed and the obtained results presented and discussed previously (Rentier and Dassargues, 2002). Results discussed here are relative to a practical case study made of a pumping well in a gravel aquifer in the alluvial sediments of the river Meuse near the city of Dinant in Belgium. The 1-day and 50-days protection zones are calculated taking into account the uncertainty of the delineation.

2. METHODOLOGY AND APPLICATION RESULTS

The stochastic methodology developed by Varljen & Shafer (1991) is applied but additional steps are added in order to condition on the other data like geophysical data and piezometric heads (figure 1). First, stochastic simulations of equiprobable hydraulic conductivity fields are generated and subsequently conditioned on the hydraulic conductivity measurements by a kriging technique. Geophysical data are directly integrated in the

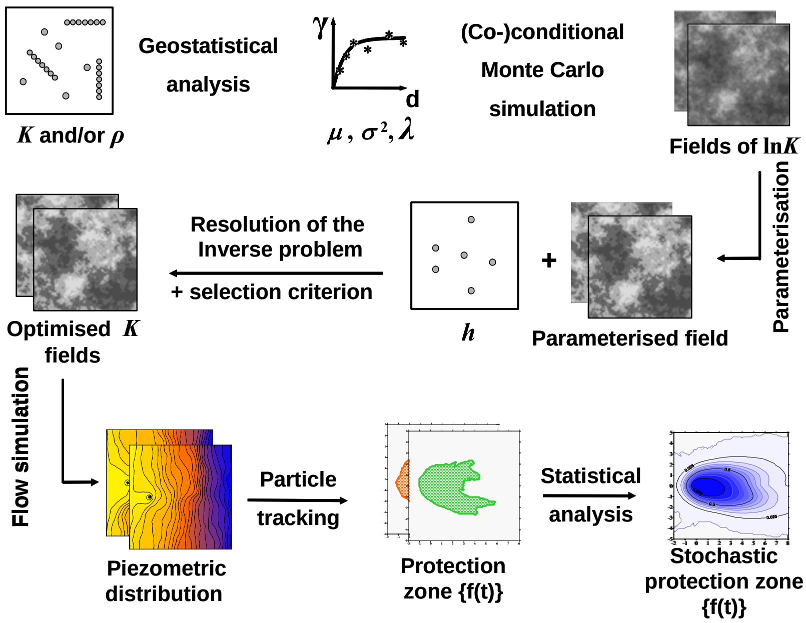

FIGURE 1. The different steps of the co-conditional simulations combined with inverse modelling for delineation of groundwater well capture zones.

generation process by co-conditioning the stochastic simulation on both hydraulic conductivity measurements and electrical resistivity values by a cokriging technique. In each cell of a 2D horizontal groundwater model, anequivalent value of electrical resistivity (ρ) of the gravels (figure 2) is obtained using:

$$\frac{e_{tot}}{\rho} = \sum_{i=1}^{n} \frac{e_i}{\rho_i} \tag{1}$$

where ρ_i is the electrical resistivity in a cell of thickness e_i . In the studied alluvial aquifer, 293 measurements along 6 profiles are used.

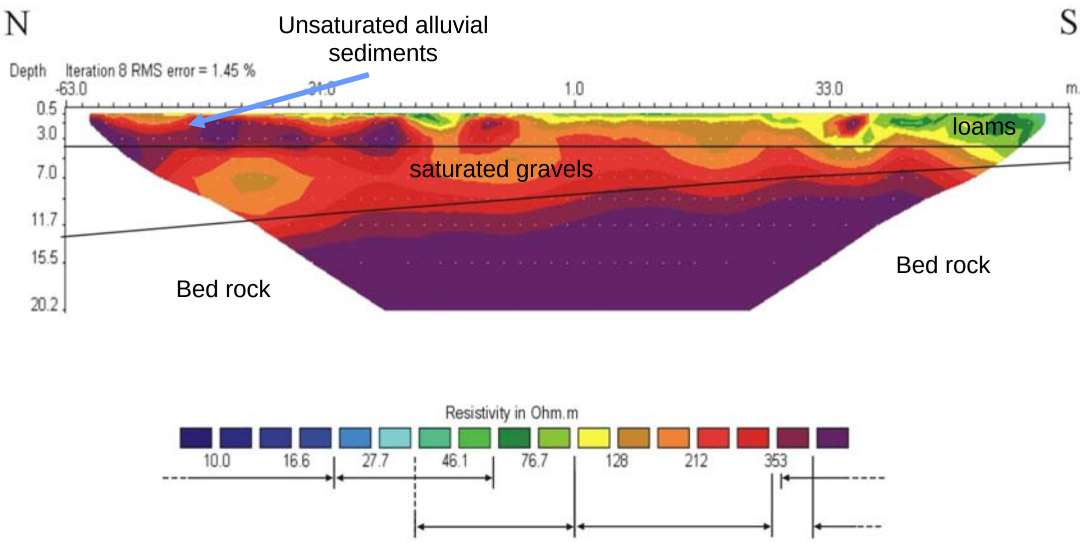

FIGURE 2. One of the 2D vertical profiles of geo-electrical resistivity values in the alluvial sediments.

The co-conditional simulation of a variable z can be expressed by:

$$z_j^{CS}(\underline{x}) = z^*(\underline{x}) + z_j^{NCS}(\underline{x}) - z_j^{NCS*}(\underline{x}) \tag{2}$$

where $z_j^{CS}(\underline{x})$ is the CS (Co-conditional Simulated) value of the variable z of generalized coordinates $\underline{x}$, $z^*(\underline{x})$ is the cokriged value, $z_j^{NCS}(\underline{x})$ is the NCS (Non Conditional Simulated) value, and $z_j^{NCS*}(\underline{x})$ is the estimated value obtained by cokriging of the NCS.

Another additional conditioning can also be obtained by calibrating the groundwater flow on head measurements (inverse modelling) for each simulated medium generated previously. For this particular step, resolution of the inverse problem requires usually a zonation of the domain and a parameterisation: reducing the number of adjustable parameters. Therefore a zonation is performed that consists, based on specified threshold values (S_i), in dividing the hydraulic conductivity variation interval in classes (C_i) of uniform value (K_{Ci}), representing the adjustable parameters. The threshold values are defined by determining the best hydraulic conductivity data combination that minimizes the variability within each class (Rentier and Dassargues, 2002) by minimizing the following equation:

$$f = \sum_{i=1}^{N_c} \sum_{j=1}^{N_{d_i}} \left(\ln K_{ij} - \overline{\ln K_i} \right)^2 \qquad \text{with} \qquad \overline{\ln K_i} = \frac{1}{N_{d_i}} \sum_{j=1}^{N_{d_i}} \ln K_{ij} \quad , i = 1, N_c \qquad (3)$$

where N_c is the number of classes, N_{d_i} is the number of data in each class (varying from one combination to another) and, $\sum_i N_{d_i} = N_D$ the total number of K data.

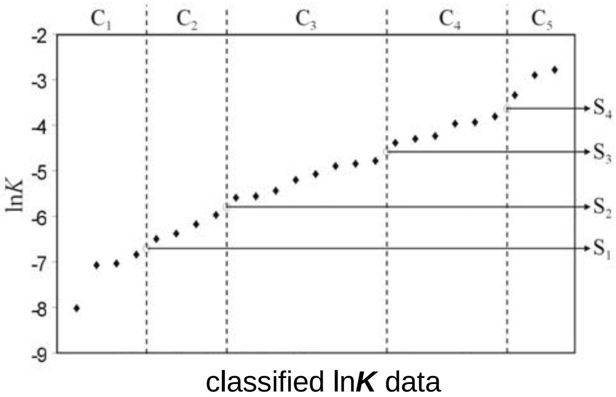

FIGURE 3. Minimising the variance within each class, 4 thresholds values are determined

Then, the inverse procedure is applied to optimize the value of hydraulic conductivity in each class. Rentier (2003) has shown that provided the rejection of realisations not respecting the prior relative order $K_{Ci} < K_{C(i+1)}$, the spatial structure of the optimised remaining equiprobable media is not drastically disturbed by these parameterisation and inverse procedures.

Groundwater flow and a particle tracking process are then computed for each remaining realization. The ensemble of obtained capture zones is then treated statistically to infer the capture zone probability distribution (CaPD). This CaPD gives the spatial distribution of the probability that a conservative tracer particle released at a particular location is captured by the well within a specified time span (van Leewen, 2000), in this particular case, 1 day or 50 days.

Results for to the well capture zones corresponding to 1 day and 50 days are given in figure 4, for the practical case study located in the alluvial plain of the River Meuse. Location of the isoline Γ(0.5) for which 50% probability of capture is obtained can easily be compared to results from previous deterministic studies.

3. CONCLUSIONS

Advances in the delimitation of protection zones are made by fusion of direct and indirect available data through the use of conditional and co-conditional stochastic simulations. Introduction of additional available data decreases the prior uncertainty of the parameters and, in consequence, reduces the uncertainty of the well capture zone probability distribution (CaPD). This observation was demonstrated previously (Rentier and Dassargues, 2002). Since geophysical data and head observations are easier to collect on the field then hydraulic conductivity measurements, they are generally more abundant. Here, the methodology has been fruitfully tested on a real application to quantify the uncertainty in the location and extent of the well capture zones …when little or no information is available about the hydraulic properties. Conditioning on geophysical data and on head observations (through parameterisation and inverse procedures) allows to decrease the uncertainty of the delineated perimeters.

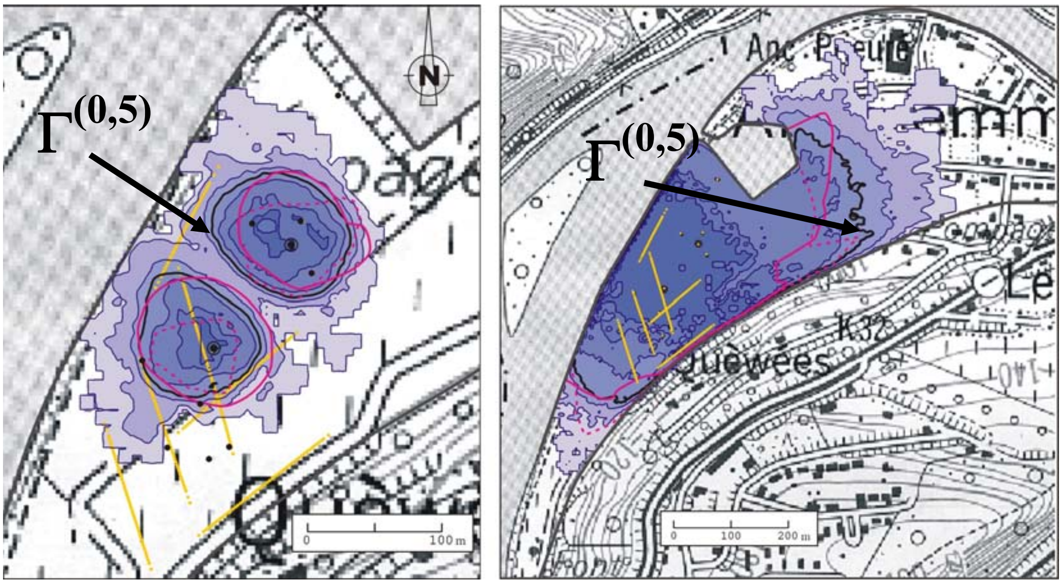

FIGURE 4. Spatial distribution of well capture zones of 24 hours (on the left) and 50 days (on the right). Isoline $\Gamma_{(0.5)}$ is compared to other contours from previous deterministic studies. CaPD values are given by the grey ranges from 95% (dark grey) to 5% (light grey).

From the presented case study, it is clear that including all available geological /hydrogeological/ geophysical data in a conditional stochastic modelling procedure is advantageous for solving practical problems in geological media of high or low heterogeneity. However, the co-conditional stochastic simulation methods, described here, assume that the geostatistical properties of each data-set are known from calculated (co-)variances and/ or (co-)variograms. If these statistics are also unknown or partly unknown, a Bayesian framework (Feyen *et al.*, 2003) can be used.

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