Geostatistical modelling of a heterogeneous alluvial aquifer by indicator variables

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Abstract We have explored the applicability of indicator geostatistical methodologies for mapping the probabilistic spatial distribution of high and low permeability facies within the alluvial aquifer system of the city of Bologna in northern Italy. The first step was to analyse stratigraphic and sedimentological well data, identifying the main hydrogeological units of the area. After this, we focused our attention on the detailed reconstruction of the spatial pattern of the aquitard that serves as the separating element between superficially contaminated aquifers and deep aquifers, both exploited for drinking-water purposes. The spatial distribution of materials within the aquifer was then reconstructed on the basis of three data selection criteria, using two indicator geostatistical methodologies: (a) hydrostratigraphic analysis via indicator point kriging and probability cut-off, and (b) Monte Carlo conditional indicator simulations. The reliability of the resulting material distribution images within the aquitard was analysed using the available hydrogeological information.

Key words aquitard; geostatistics; indicator point kriging; Monte Carlo conditional indicator simulations

INTRODUCTION

The study area comprises part of the high–medium alluvial plain close to the city of Bologna in the Regione Emilia Romagna in northern Italy.

The study area of about 50 km² is located within the Reno alluvial fan. Three major well fields, yielding nearly 80% of all the groundwater used for drinking water and industrial purposes in the Bologna area, are located within the study area. Figure 1 depicts the limits of the area investigated, together with the location of data points of an aquitard called “Alpha”.

The plain around Bologna is part of the Po Basin fill, which is a syntectonic sedimentary wedge (Ricci Lucchi, 1984) forming the infill of the Pliocene–Pleistocene fore-deep. The sedimentary evolution of the basin is characterized by an overall regressive trend from Pliocene open marine facies to Quaternary marginal marine (cycle Qm from Ricci Lucchi et al., 1982) and alluvial deposits (cycle Qc). An array of coalescent fan complexes (Reno, Savena and Idice rivers) characterizes the uppermost portion of the Po Basin at its southern border (Apennines Piedmont area).

Alluvial deposits in the Bologna area are more than 300 m thick (Francavilla et al., 1980). According to recent studies (Regione Emilia Romagna, 1998) cycle Qc is
such units, about 100–150 m thick, are separated by clayey deposits and located in Cycle C, which in turn is the upper portion of Cycle Qm. The stratigraphy of cycle Qc has been investigated in the subsurface by well correlation. Cycle Qc is essentially composed of coarse deposits with subordinate clay, while sand deposits are scarce. Gravels are concentrated in the Reno area. Amorosi & Farina (1994a, 1994b, 1995) noted that a rhythmic alternation of coarse-grained bodies and laterally extensive pelitic horizons occurs at various scales and represents the basic cyclic motif of the depositional system. Cycles A, B and C (gravel-rich and characterized by gravel/mud values generally found between 1/2 and 3) consist of a sequence of clayey bodies of up to 20–25 m thickness, representing large-scale cyclicity. Medium-scale cyclicity can be observed in Cycles A and B because of four laterally persistent gravel-dominated bodies of approximately 30–50 m thickness; clayey bodies separating coarse deposits are 5–15 m thick. Small-scale cyclicity is developed on 15–20 m gravel/mud couplets.
The alluvial deposits form large and productive aquifer systems. Three Pleistocene aged fresh water aquifers have been identified: Aquifer Group A (between 0 and 150–200 m), Aquifer Group B (between 150 m and 300–350 m) and Aquifer Group C (more than 300–350 m deep) (Regione Emilia Romagna, 1998). These correspond to Cycles A, B and C, respectively, and are composed of alluvial and sea deposits, both coarse and fine. The coarse deposits are essentially related to the fluvial activity of the Apennine streams and of the Po River. Generally, these aquifers are separated by discontinuous horizons (aquitards) of variable thickness and lithology.

Here, we focus on the detailed reconstruction of the spatial pattern in the Alpha Aquitard, which is located within Aquifer Group A. Its spatial pattern plays a major role as it is the separation element between superficially contaminated aquifers and deep aquifers, currently heavily exploited for drinking-water purposes.

METHODOLOGY

The geological structure of the study area was defined by analysing well data and correlating appropriate cross-sections parallel and normal to the Apennine foothills.

Hydraulic head data were also analysed to discern the behaviour of the groundwater surface. The available data were organized into an efficient database and used to create geological cross-sections, maps of the base and top surfaces of each recognized geological unit, together with their total thickness and content of permeable sediments. These were measured on the basis of the cumulative thickness of gravel (gravel and sand for the aquitards) divided by total thickness.

The wedge-shaped Reno alluvial fan within the study area, which rests on marine clayey deposits with saline water, widens in the northerly direction and tapers in the southerly direction. The three aquifer groups previously defined are separated by two main aquitards about 20–30 m thick and other aquitards of lower standing (thickness between 8 and 15 m).

A detailed analysis of the vertical geological structure has led to identification of the following hydrogeological units: (1) Aquifer A1; (2) Aquitard Alpha; (3) Aquifer A2, A3, A4 (named A234); (4) Aquitard Delta; (5) Aquifer B; (6) Aquitard Epsilon; (7) Aquifer C. Figure 2 shows a cross-section of the aquifer system. Orientation of the cross-section is shown in Fig. 1.

Aquitard Alpha constitutes an element of subdivision within Aquifer Group A. It has a variable thickness of 1–3 m in the areas nearer the peak of the alluvial fan, rapidly increasing in the vicinity of the well fields and in the northern part. This has been described using 39 logs of geognostic boreholes and 183 well-logs.

The deposits are mainly silty-clayey, with local interbedding of coarser material. The quantity \( \frac{[gr + sa]}{th} \), representing the cumulative thickness of gravel (gr) and sand (sa) divided by the total thickness (th), is generally less than 0.2. However, it displays local peaks larger than 0.8, highlighting possible discontinuities within the aquitard itself. Such discontinuities can be attributed to three situations related to depositional modalities: (A) occurrence of ribbon gravel bodies located in mud horizons; (B) a body of coarse material resulting from erosion of a previous mud horizon; and (C) local cessation of deposition of the mud horizon. In the case of Aquitard Alpha we think that the discontinuities can be correlated to case (A) in the
lateral and distal portions, to case (B) in the central and western areas, and to case (C) in the apical areas. The strategic importance of Aquitard Alpha lies in its capacity to separate the surface aquifers from the subsurface aquifers, since the low-permeability facies may form an efficient barrier to the vertical movement of groundwater and contaminants from the upper to the lower aquifers.

The spatial distribution of materials within Aquitard Alpha was reconstructed using two indicator geostatistical methodologies: (a) hydrostratigraphic analysis via indicator point kriging and probability cut-off; and (b) Monte Carlo conditional indicator simulations.

The first analysis was carried out according to the following steps: (a) transforming the sedimentological values of the variable into the indicator random variable \( I(x) \); (b) analysing the spatial correlation structure of the indicator random variable; (c) estimating the spatial distribution of the probability of the occurrence of the high-permeability facies; (d) contouring the probability of the high-permeability facies and computing their extent relative to the study area; and (e) comparing the value obtained with the mean of the indicator data.

Using the available data, we explored the effect of using values of \((gr + sa)/th\) corresponding to 60% and 80% as threshold values. Furthermore, we coupled both sedimentological and stratigraphic information by considering both percentages of coarse-grained materials and thickness of the aquitard. Table 1 summarizes the three cases analysed. The high-permeability facies appeared at 12%, 7% and 21%, respectively, of the sampled locations for the three scenarios investigated. The spatial mean of the indicator was equal to 0.88 in case (A), 0.93 in case (B), and 0.787 in case (C). The spatial correlation of \( I(x) \) was estimated by computing the sample variograms. Directional variograms were computed using an angular tolerance of 30° along directions oriented to azimuths of 0, 45, 90 and 135°, taking north as the reference point. Sample variograms showed no clear evidence of anisotropy. An isotropic exponential model with no nugget was fitted to the sample variograms resulting in: sill = 0.145 and range = 600 m for scenario (A); sill = 0.094 and range = 500 m for scenario (B), and sill = 0.206 and range = 650 m for scenario (C).

Monte Carlo reconstruction was based on 2000 conditional realization of two-dimensional (2-D) facies distributions in Aquitard Alpha. The SISIM code (Deutsch & Journel, 1998) resulted from synthetic generation by using the indicators' data points and their sample variograms as input parameters. Convergence of the computations was checked and sensitivity of ensemble results to grid spacing was analysed by using

<table>
<thead>
<tr>
<th>Scenario/data selection criterion</th>
<th>([gr + sa]/th) (%)</th>
<th>(th) (m)</th>
<th>(I(x))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>≤ 60</td>
<td>data lumped together</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>&gt; 60</td>
<td>data lumped together</td>
<td>0</td>
</tr>
<tr>
<td>(B)</td>
<td>≤ 80</td>
<td>data lumped together</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>&gt; 80</td>
<td>data lumped together</td>
<td>0</td>
</tr>
<tr>
<td>(C)</td>
<td>≤ 30</td>
<td>≤ 15</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>≤ 60</td>
<td>&gt; 15</td>
<td>1</td>
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<tr>
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<td>0</td>
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<tr>
<td></td>
<td>&gt; 60</td>
<td>&gt; 15</td>
<td>0</td>
</tr>
</tbody>
</table>
three different squared grid sizes (60, 75 and 100 m). This was done with consistent data spacing, structure and range of sample variogram range.

RESULTS AND DISCUSSION

Ordinary point kriging was used to compute the best linear unbiased estimate of the expectation of \( I(x) \) and thus the probability of the occurrence of the high-permeability facies. The resulting contour maps showing the probability of occurrence of the high-permeability facies are displayed in Fig. 3(a)-(c) for the three scenarios analysed.

A probability level can be used as a cut-off to delineate boundaries between facies types (e.g. Johnson & Dreiss, 1989; Ritzi et al., 1994). To distinguish among the different reconstruction scenarios, we compared the fraction of the total area covered by the high-permeability facies to that resulting from the raw data. The total area had

![Fig. 3](image-url)

\textit{Fig. 3 (a)-(c) Images of probability distribution based on indicator point kriging and (a) data selection criterion (A), with probability cut-off isoline 0.78 (bold); (b) data selection criterion (B), with probability cut-off isoline 0.79 (bold); (c) data selection criterion (C), with probability cut-off isoline 0.787 (bold); (d) ensemble Monte Carlo mean corresponding to simulation scenario (A). Grey scale: light = low probability; dark = high probability.}
resulted from the kriging estimate and was contoured by the probability cut-off isoline equal to the declustered global mean of the original indicator data.

In case (A), demarcation of facies types, resulting in a 12\% coverage of high-permeability facies, was ensured by use of a probability cut-off of 0.78 (as opposed to a mean of the original data equal to 0.88), Fig. 3(a). Similarly, reconstruction of scenario (B) yielded a 7\% high-conductivity coverage upon use of a probability cut-off of 0.79 (while the mean of the original indicator data was 0.93), Fig. 3(b). Finally, taking into account both sedimentological and stratigraphic data, as in case (C), resulted in a spatial distribution of high-permeability facies, in which both the original data and the mean of the indicator data were favoured (Fig. 3(c)). The contour lines corresponding to the adopted cut-off levels are also shown in Fig. 3(a)–(c).

It was then observed that Monte Carlo simulations resulted in facies distributions that markedly differ across the space realized, while still favouring the available data. Such behaviour is in general agreement with observations from the literature (e.g. Guadagnini & Neuman, 1999). It was confirmed that the use of grid spacing larger than one third or one quarter of the process correlation scale may in some cases generate images unable to enhance discontinuities defined by few data points. As an example, Fig. 3(d) depicts the ensemble Monte Carlo mean corresponding to simulation scenario (A). In general, point kriging produced a larger area of high-permeability facies than Monte Carlo simulation, thus highlighting a larger degree of spatial continuity in the variable.

Distinguishing between the conceptual reconstruction models adopted can be refined with the use of additional information, i.e. the methodology we adopted to evaluate the reliability of the resulting facies distribution images makes full use of local geology considerations. These are essentially based on the knowledge of the depositional occurrences within the area and available piezometric observations. Use of this information shows that reconstruction based on data selection criterion (C), which appears to be the most consistent, is in contrast with what was suggested by the available trend of hydraulic heads in the study area (not shown). Reconstruction of hydraulic heads seems to favour data selection criterion (A). The latter criterion allows correlation of the area characterized by the high probability of occurrence of the high-permeability facies, which have the following features:

- the lack of low permeability materials observed in the southern area and corresponding to both the unsaturated zone of the superficial aquifers, and to a direct contact between upper and lower part of aquifer, as indicated by piezometric levels;
- the existence of ribbon gravel bodies located in mud horizons in the eastern and western areas, where contact between the upper and lower parts of the aquifer is indirect. This is due to the presence of minor mud horizons, so that downward migration of contamination is possible. The hydrogeological features of the southern portion of the study area can only be enhanced by data selection criterion (B).

CONCLUSIONS

We used a series of sedimentological and stratigraphic data to reconstruct images of high- and low-conductivity materials distribution within the main aquitard controlling solute migration around the city of Bologna (Italy).
Hydrostratigraphic analysis via indicator point kriging and probability cut-off and Monte Carlo conditional indicator simulations were performed using three types of data selection criteria. Use of indicator geostatistics appears to favour a data selection criterion based on both types of data. The result is a spatial distribution of materials that favours both the original data and the global mean of the indicator data. However, when the images of the reconstructed aquitard, obtained through different data selection criteria, are viewed within the more general hydrogeological context of the study area, use of only sedimentological information appears to offer the best compromise in rendering the main controlling features of the area. In arriving at this conclusion, we took both historical and current piezometric trends and contamination history into account.

A subsequent step of the work will incorporate the generated reconstruction within a flow and transport model to validate the reliability of the different selection criteria.

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