Connectivity of an alluvial aquifer: from theory to practice

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Abstract: The heterogeneity of the alluvial aquifer controls both water flow and contaminant transport. In particular, the presence of organised features such as permeable connected levels (connectivity) has a significant effect on water flow rates and travel times, because it can lead to channelling. The task of defining a rigorous quantitative measure of connectivity for continuous variables has failed so far, and thus there exist a suite of connectivity indicators which are dependent on the specific hydrodynamic processes and the interpretation method. Nevertheless, limited effort has been devoted to apply the connectivity concept in real case. In the present paper, the effects of connectivity on flow and transport are studied for a large-scale real aquifer: the alluvial plain of Milan (Northern Italy). Based on geological and hydrogeological field data, numerical modelling of flow and non-reactive transport was carried out and results were used for testing several types of connectivity indicators. Also scale dependency of connectivity was analysed, pointing out empirical laws describing connectivity as a function of observational scale. Finally, upscaling method based on connectivity was applied to verify its effectiveness in a large-scale real aquifer.

Key-Words: Connectivity, groundwater, heterogeneity, Italy, numerical modeling, scale effects, stochastic simulations

1 Introduction

In alluvial aquifer systems, geometry and interconnectedness of high permeability materials are strongly responsible for controlling groundwater flow patterns [5] and solute transport [7], and for the delineation of protection areas [19]. Despite the recognized importance of connected features little attention has been paid to their characterization, quantification, and use in hydrogeological studies, nor in upscaling methods.

The first evidence of the role of hydraulic connectivity in flow and transport processes arose in the 1980s with the blossoming of groundwater studies in fractured media. A key idea was that only small subset of the fractures was actually contributing to total flow and transport [3]. The idea was soon transferred to porous media by Fogg [4], who argued that the flow system was mainly controlled by the continuity and interconnectedness of high conductivity lenses, rather than by their actual local hydraulic conductivity values. The concept of connectivity employed in percolation theory is probably the most mature one (e.g. [17]) and has also been used in hydrogeological studies for fractured rock masses (e.g. [2]). Yet, a binary (connected/not connected) treatment of connectivity in porous media does not allow for more refined analysis of the impact of preferential paths on flow and transport [20]. The standard geostatistical techniques do not properly reproduce connectivity, because they are based on variogram analysis, which represents correlation but not connectivity [15], [7]. Therefore different methods were proposed to describe structures typically non multi-Gaussian. Among others, indicator geostatistics [24], multiple point geostatistics [18], [10], the connectivity function [1], and the integral connectivity scale [21].

As such, a single quantitative definition of connectivity in heterogeneous porous aquifers is not possible, and a number of connectivity indicators has been developed. Recently, Knudby and Carrera compared and analyzed nine connectivity measures including flow and transport connectivity measures [11]. Later on, the same authors analyzed the use of apparent diffusivity as a measure of connectivity [13], and proposed a new formula for upscaling able to consider the effect of connectivity [12].
The list of papers dealing with theoretical aspects or numerical tests on synthetic aquifers is very long. However, few papers deal with field applications of these concepts. Actually, in real case studies, the application of these connectivity indicators could be difficult, because of uncertainties on the three-dimensional heterogeneity. In this paper, numerical experiments are performed on the Milan’s alluvial aquifer (Northern Italy) to evaluate the applicability and usefulness of different connectivity indicators in a large scale real aquifer, also considering different observational scales. In particular, the results of numerical experiments on groundwater flow and non-reactive transport are compared with connectivity analysis in order to improve the understanding of the effects of heterogeneity on flow and transport processes at large scale site. Flow and transport indicators are compared with each other so their ability to explain the differences in flow and transport in terms of spatial distribution of the facies in the domain is discussed and new connectivity indicators are proposed.

2 Case study

2.1 Hydrogeological setting
The city of Milan (Lombardy, Northern Italy) lies on the northern margin of the alluvial plain of the Po River (Fig. 1). This study focuses on a nearby area of about 580 km². The hydrogeological structure of the area has been subject of numerous investigations ([14] and references therein). The alluvial deposits in the area are more than 250 m thick and can be subdivided into four large-scale geological units denoted by A, B, C and D Aquifer Groups (from the youngest to the oldest). These depositional cycles are separated by clayey deposits which form aquitards. More in detail, the aquifers traditionally exploited in the study area (A and B) consist of a hydrogeological system of unconfined and semi-confined aquifers within a system of very heterogeneous layers. The groundwater flow occurs from North to South, with a piezometrical gradient ranging between 0.5% in the Northern area and 0.3% in the Southern area.

2.2 Field data
For the hydrogeological characterization of the study area the data-base developed within the Italian geologic cartography project (CARG) was used. In particular, more than 1,000 stratigraphies were analyzed, generally arising from wells and drillings which interest mainly the Aquifer Groups A and B, i.e., the first 100-150 m of depth. The stratigraphical analysis allowed to identify the main grain size fractions which can be considered significant for hydrogeological purpose. On the basis of some hundreds of grain size distributions, through the Hazen formula [9] the hydraulic conductivity values of the different units were statistically defined (Table 1).

<table>
<thead>
<tr>
<th>Facies</th>
<th>$\mu(\log K)$</th>
<th>$\sigma(\log K)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>3.62</td>
<td>0.87</td>
</tr>
<tr>
<td>Sand</td>
<td>5.07</td>
<td>1.00</td>
</tr>
<tr>
<td>Silt/clay</td>
<td>6.92</td>
<td>0.64</td>
</tr>
<tr>
<td>Cemented gravel</td>
<td>5.50</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Figure 1. Geographical location of the study area.

Figure 2. Hydrogeological cross-sections network.
2.3 Training images construction

Training images of gravel, sand and clay occurrence in different orientations were constructed (Fig. 2), based on stratigraphical data. On each training image, a visual analysis was subsequently carried out to obtain a rough indication on the connectivity degree; generally, a good level of connectivity is shown, particularly for those sections located in the central area of Milan. The N-S sections, aligned along the groundwater flow direction, show a slight dip of the finest deposits, with a trend characterized by grain size reduction from North to South: sand and clay take the place of gravel, which in the Southern part of the study area are almost absent. As example, two cross-sections are reported, representative of structures having respectively high (Section C in Fig. 3) and low (Section G in Fig. 3) connectivity.

3 Numerical experiments

3.1 Method

The training images and correlated simulated hydraulic conductivity realizations were used as input to a groundwater flow and non-reactive transport model. Simulations results were then used to calculate connectivity indicators. Among the several connectivity indicators proposed in the literature, in this paper the flow and transport connectivity indicators suggested by Knudby and Carrera are considered [11]. Two new indicators are also proposed. The employed procedure consists of the following steps:

1. generation of the real case domains;
2. simulation of the steady-state flow and non-reactive transport;
3. computation and comparison of connectivity indicators;
4. scale-dependence analysis of connectivity indicators.

These steps are described below, in the following section 3.2 (points 1 and 2) and in the next section 4 (points 3 and 4).

3.2 Groundwater flow and transport model

Steady state and non-reactive transport were simulated using the finite-difference code MODFLOW-2000 [8], for all the N-S sections (Fig. 2), i.e., along the main flow direction. The domains have all a length of 22 km and an height of 120 m, and they were discretized with a mesh of 40 layers (having constant thickness equal to 3 m) and 110 cells (having dimension equal to 200 m). Constant heads boundary conditions were applied to the Northern and Southern boundaries. The assigned values were afterwards modified within the calibration procedure.

Afterwards, the model was used for simulating with a stochastical approach both the groundwater flow and the non-reactive transport, and then the probability distributions of both groundwater discharges and solute arrival times were extracted.
4 Connectivity assessment

4.1 Definition of connectivity indicators

Among the connectivity indicators proposed by Knudby and Carrera [13], two indicators of flow connectivity (CF1 and CF2) and the first transport indicator (CT1) were chosen in the present study (Table 2), according to the results of same authors they better succeed in identifying the presence of connected high-K features. Since the interval of possible CF1 values is bounded (from -1 to +1), it is more easily interpreted than CF2, especially when comparing different hydrogeological settings. Therefore, the flow indicator CF2 was normalized (Table 2) for having comparable results. In addition, a new global connectivity indicator was proposed (CG in Table 2), which accounts for connectivity effects controlling both the average plume movement and the flow rate.

Table 2. Connectivity indicators discussed in this paper. $K_{\text{eff}}$ = effective conductivity, $V$ = domain volume, $K_a$, $K_G$ and $K_H$ = respectively arithmetic, geometric and harmonic mean of the K field, $t$ = average arrival time of the solute, $t_{5\%}$ = arrival time of the fastest 5% of the solute.

<table>
<thead>
<tr>
<th>Flow connectivity indicators</th>
<th>$K_{\text{eff}} = \left( \frac{1}{V} \int K(x) \text{CF1} , dx \right)^{1/\text{CF1}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{CF2} = K_{\text{eff}} \cdot K_a^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Transport connectivity indicators</td>
<td>$\text{CT1} = \frac{t}{t_{5%}}$</td>
</tr>
<tr>
<td>New defined indicators</td>
<td>$\text{CF2form} = \frac{\text{CF2} - K_H/K_a}{K_a/K_H - K_H/K_a}$</td>
</tr>
<tr>
<td>$\text{CG} = \text{CF2} \log \text{CT1}$</td>
<td></td>
</tr>
</tbody>
</table>

4.2 Evaluation of connectivity indicators

The average value of connectivity indicators for the different cross-sections (Table 3) shows higher connectivity in the central zone of the study area, in agreement with the hydrogeological setting; in this central zone, actually, several paleo river-beds are localized; generally, the connectivity shows a decreasing trend from West (section A) to East (section G) as a consequence, form an hydrogeological point of view, of the increasing of the finest grain size fractions. According to the previously described hydrogeological setting, sections A and C result to be the most connected according to all the considered indicators. The case of section A seems to be significant as it shows high values of all the connectivity indicators even if all the mean values of the K field are the lowest one.

Table 3. Average values of the different means of the K filed and the corresponding effective hydraulic conductivity obtained by numerical simulation. Also the connectivity indicators for the simulated cross-sections are shown (Fig. 2).

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\text{G}}$ ($10^{-6}$ m/s)</td>
<td>4.67</td>
<td>9.06</td>
<td>7.53</td>
<td>27.1</td>
<td>12.4</td>
<td>22.6</td>
</tr>
<tr>
<td>$K_{\text{H}}$ ($10^{-7}$ m/s)</td>
<td>2.52</td>
<td>3.22</td>
<td>3.17</td>
<td>5.84</td>
<td>4.46</td>
<td>5.31</td>
</tr>
<tr>
<td>$K_{\text{A}}$ ($10^{-4}$ m/s)</td>
<td>1.01</td>
<td>1.17</td>
<td>1.05</td>
<td>1.47</td>
<td>1.11</td>
<td>1.40</td>
</tr>
<tr>
<td>$K_{\text{eff}}$ ($10^{-5}$ m/s)</td>
<td>7.36</td>
<td>8.69</td>
<td>7.77</td>
<td>12.3</td>
<td>7.83</td>
<td>10.8</td>
</tr>
<tr>
<td>CF1</td>
<td>0.72</td>
<td>0.64</td>
<td>0.70</td>
<td>0.73</td>
<td>0.65</td>
<td>0.64</td>
</tr>
<tr>
<td>CF2</td>
<td>15.8</td>
<td>9.04</td>
<td>10.3</td>
<td>4.67</td>
<td>6.40</td>
<td>4.81</td>
</tr>
<tr>
<td>CF2 norm</td>
<td>0.73</td>
<td>0.70</td>
<td>0.74</td>
<td>0.86</td>
<td>0.72</td>
<td>0.77</td>
</tr>
<tr>
<td>CT1</td>
<td>477</td>
<td>15</td>
<td>250</td>
<td>116</td>
<td>126</td>
<td>36</td>
</tr>
<tr>
<td>CG</td>
<td>42.2</td>
<td>10.6</td>
<td>24.8</td>
<td>9.6</td>
<td>13.4</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Some contradictions can also be detected observing the indicators values. For example, according to CF1 the section having minor connectivity is the section G, whereas according to CF2 the lowest values of connectivity correspond to sections D and F, and finally CT1 shows a minimum for section B. Particularly significant appears the case of section B, which results to have very low transport connectivity but medium value of flow connectivity. The new defined global indicator CG instead shows a good capability of synthesizing the behavior of both flow and transport indicators.

As far as the trend of connectivity indicators with discharge percentile is concerned, CF2 and CT1 show an evident increasing trend with the increase of the discharge percentile (Fig. 4b and c). On the contrary CF1 (Fig. 4a) shows significant changes for discharge percentiles lower than 50%, whereas for discharge percentile higher than 50% the flow indicators assume values nearly constant. Yet, its trend appears to be anomalous, as the indicator values decrease with discharge percentile increase, which is contradictory with reasonable expectation and with the results obtained for the other indicators.

4.3 Scale dependency and upscaling

Connectivity causes a scale dependence of hydraulic conductivity [15]. Therefore, an experimentation on the behavior of connectivity indicators at different observation scales has been performed; for this purpose, sub-domains of 2, 5, 10 and 16 km length were sampled in different positions of the original domains. Afterwards, connectivity indicators were
estimated with the same numerical approach described above. The results show a general downward connectivity trend with the increasing of domains length, till a length of 10 km is reached. For length higher than 10 km the connectivity indicators are more or less constant (Table 4). The constant values obtained for lengths higher than 10 km can be considered the representative average connectivity values of the area, whereas for smaller dimension a scale dependency law has to be considered. The dimension of 10 km obtained through the scale dependency analysis is quite typical for the study area, for which previous geostatistical research outlined the presence of medium scale hydrogeological structure having dimension ranging between 3 and 6 km, whereas for dimension larger than 10 km the aquifer behavior is controlled by the regional scale setting [8]. The effectiveness of the connectivity measures in the study of porous media can also be captured by using these information in upscaling techniques; in this regard, the upscaling method by Knudby and Carrera was tested [12]; it allows to derive the effective permeability $K_{eff}$ from the geometric characterization of high permeability lenses and their connectivity degree. Results showed that the values of $K_{eff}$ obtained by upscaling slightly differ from the values obtained from the numerical simulations (Fig. 5), so confirming the effectiveness of the proposed upscaling method.

Table 4. Scale dependency equation of connectivity indicators.

<table>
<thead>
<tr>
<th>Connectivity indicator</th>
<th>Domain length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$L &lt; 10 \text{ km}$</td>
</tr>
<tr>
<td>$CF_1$</td>
<td>$0.88e^{-0.03L}$</td>
</tr>
<tr>
<td>$CF_2$ norm</td>
<td>$0.97e^{-0.04L}$</td>
</tr>
<tr>
<td>$CT_1$</td>
<td>$249.22e^{-0.11L}$</td>
</tr>
</tbody>
</table>

4 Conclusion
This study is one of the first researches that applies connectivity indicators on a real aquifer and it demonstrates that connectivity is of upmost importance, not just for correct flow and transport prediction, but for upscaling. A complete set of numerical experiments of flow and non-reactive solute transport on a real large scale aquifer has been performed. The results provide further evidence of the importance of heterogeneity on flow and solute transport in groundwater and have been interpreted using different sets of connectivity indicators. The connectivity indicators based on only flow or transport do not provide clear evidence of the characteristics of the porous medium. The estimate of the same indicators at different percentile of flow allowed to take further limits of the flow indicators, related to their different ability to capture the spatial evolution of the flow channels in a real aquifer. New indicators were therefore pointed out, useful to summarize the characteristics of flow and transport connectivity.
Figure 5. Comparison between $K_{eff}$ obtained by the upscaling method and the values pointed out by the previously described numerical simulations.

References:


