A multidisciplinary study of sediments' connectivity and transport parameters for aquifer analogues

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Abstract A multidisciplinary approach is applied to the study of aquifer analogues, i.e. outcrops of geological structures which can be easily investigated and which resemble the buried aquifers. The application of this approach to some cases selected to represent typical structures of the alluvial aquifers in the Po Plain (northern Italy) shows the importance of joining field work (sedimentological, petrographical, geophysical, hydrological) with stochastic simulation, modelling tools and connectivity analysis. The final goal of this research programme is to enhance the match between the heterogeneity of hydrofacies at a fine scale and the behaviour of flow and transport at a large scale.

Key words groundwater; aquifer analogues; alluvial aquifers; hydrostratigraphy; mathematical modelling; geostatistical simulations; connectivity

INTRODUCTION

Since a couple of decades ago the study of "virtual aquifers" or "aquifer analogues" (Jussel *et al.*, 1994; Anderson, 1997; Aigner *et al.*, 1999; Huggenberger & Aigner, 1999; Heinz & Aigner, 2003; Heinz *et al.*, 2003; Bridge & Hyndman, 2004; Lunt *et al.*, 2004; Bersezio, 2007) has become quite common to obtain a deeper understanding of the effects that hydrofacies heterogeneity on a fine scale has on solute transport in the subsurface on a large scale (from mesoscopic to mega- or gigascopic scales, following the definitions of Giudici, 2010). Aquifer analogues are geological bodies which are quite well exposed so that they can be analysed with geological, geophysical and hydrogeological surveys, and which can be assumed to be similar to the buried aquifers from the geometric and lithological point of view.

Therefore, the spatial distribution of hydrofacies in the aquifer analogues can be assumed as a good representation of the architecture of the buried aquifers. Moreover it can be assumed as a proxy of the spatial variation of hydraulic conductivity (K), which controls, together with the hydraulic gradient and the stresses on the aquifer system, groundwater flow and the fate of contaminants. However, several field and numerical tests show that the presence of connected subsets of conductive or nonconductive materials could be more important than the K values of the dominant hydrofacies to determine the behaviour of solute transport because they control the existence of preferential flow paths or of hydraulic barriers.

In this paper we summarise the workflow of the multidisciplinary studies that were conducted by our research team on some aquifer analogues representative of the hydrostratigraphic features of the alluvial Po Plain (northern Italy) and some of the results obtained so far.

METHODS

The multidisciplinary characterisation of the studied aquifer analogues has been conducted through the following steps.

(a) Field work to collect sedimentological, geophysical and hydraulic data. In particular:
 (i) Sedimentological logs are directly measured on the outcrops;

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(ii) Photographs of the whole outcrop are taken;
(iii) Electrical resistivity ground imaging (ERGI) and ground penetrating radar (GPR) surveys are conducted;
(iv) Infiltration tests are conducted in order to obtain values of *K* at saturation to validate the results of upscaling with numerical flow models.

(b) Hydrostratigraphic description of the studied aquifer analogues, by GIS-aided processing of field data, merging measured hydrostratigraphic logs with photomosaic and vertical facies maps of the complete exposures and geostatistical interpolation of the surfaces separating the hydrostratigraphic units.
(c) Laboratory analysis on samples to determine grain-size distribution and *K* of different facies. The *K* values can be evaluated from laboratory measurements on undisturbed samples of fine-grained facies along orthogonal directions, whereas they are determined with phenomenological relationships (Kozeny-Karman's equation) and literature data for the remaining facies, which are difficult to sample without introducing strong disturbances of the fabric.
(d) Geostatistical simulation of the hydrofacies distribution is conducted with the application of different techniques (Dell'Arciprete *et al.*, 2010a, 2012a): Sequential Indicator Simulation (SISIM), Transitional Probability Geostatistical Simulations (T-ProGS), Multiple Point Simulation (MPS).
(e) Flow modelling and determination of the equivalent conductivity tensor: this is done with 2D or 3D finite difference modelling of groundwater flow under stationary conditions, without source/sink terms and with linearly varying Dirichlet boundary conditions, so that the symmetric equivalent conductivity tensor can be computed (Bersezio *et al.*, 1999a; Felletti *et al.*, 2006; Zappa *et al.*, 2006; Giudici & Vassena, 2007; Vassena & Giudici, 2007; Vassena *et al.*, 2010).
(f) Numerical experiments of 3D convective transport of a non-reactive solute and determination of Lagrangian dispersion coefficients. For this, the flow model runs with boundary conditions that simulate a Darcy experiment, i.e. Dirichlet boundary conditions on two opposite sides of the block and no flow boundary conditions along the other four sides, so that an average 1D flow is maintained (see the sketch of Fig. 1). The transport of an instantaneously injected plume of solute is simulated with a particle tracking technique: the distribution of particles permits the computation of the Lagrangian dispersion tensor (Vassena *et al.*, 2010).
(a) Interpretation of transport numerical experiments for the determination of the eulerian dispersion coefficient with single (SDM) and dual domain models (DDM): in particular if groundwater flow for the numerical transport experiments, that have been shortly described at the previous point, can be assumed as 1D and if an average Fickian 1D transport is assumed to be a good approximation, then an analytical solution of the advection-dispersion transport equation can be found and the physical parameters (average pore water velocity, equivalent longitudinal dispersion coefficient) can be obtained by fitting the cumulative breakthrough curves obtained by the numerical experiments. This is done for both SDM and DDM, as the latter can provide better results for those cases which are characterised by preferential flow paths (Baratelli *et al.*, 2011).
(b) Computation of flow, transport, statistical and facies connectivity indicators. Several connectivity indicators have been defined in the literature (Western *et al.*, 2001; Knudby & Carrera, 2005; Vassena *et al.*, 2010) and some of them are useful to provide further insight into the hydrostratigraphic structures of the aquifer analogues and can be compared with the hydrodynamic and hydrodispersive equivalent parameters in order to enhance the comprehension of transport processes.

CASE STUDIES

The aquifer analogues that have been examined by our research team correspond to sandy-gravel fluvio-glacial deposits in the Po Plain (northern Italy, Fig. 2). The first tests were conducted on 2D outcrops of a proglacial delta (Bersezio *et al.*, 1999a), whereas successive case studies were located in the Ticino and Lambro valleys (Fig. 2) and are described in the next subsections.

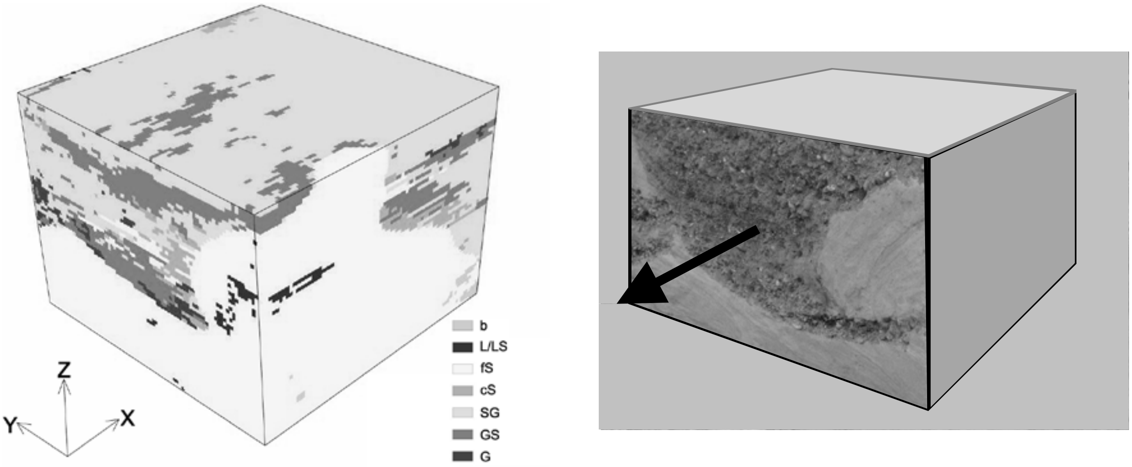

Fig. 1 Left: example of the facies distribution for a sedimentary block of about 3 m^3, as obtained after steps (a) to (d). Right: sketch of the geometry and the boundary conditions to simulate conservative convective transport along the *x* direction (shown by the arrow); no flow boundary conditions are assigned on the lateral sides.

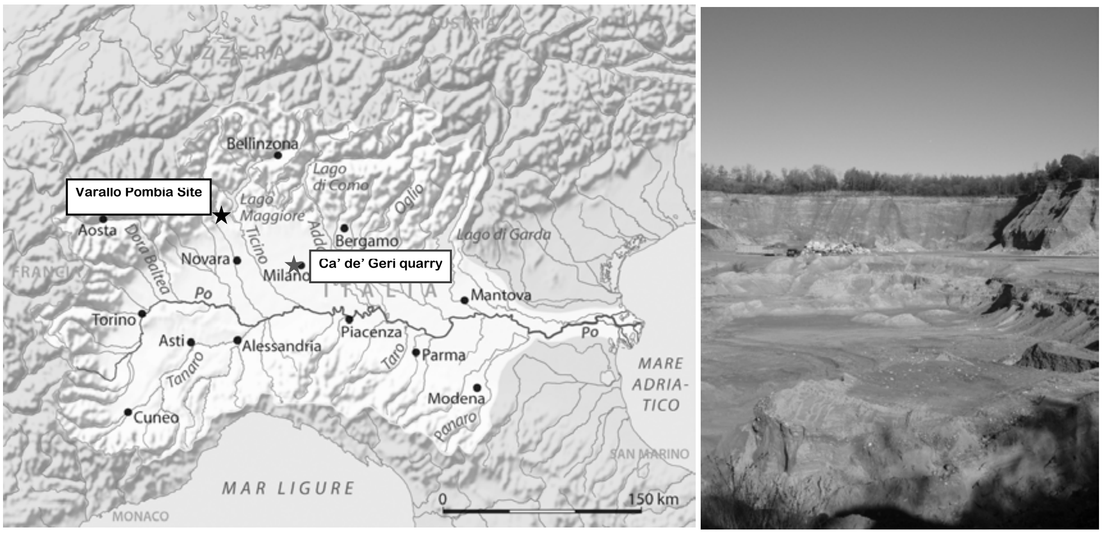

Fig. 2 Left: map of the Po River basin and location of the study sites. Right: picture of the Varallo Pombia site.

Varallo Pombia site (Valley of River Ticino)

An open sand and gravel pit was explored during three field campaigns. The study area belongs to the Middle Pleistocene outwash plain of the Verbano amphitheatre.

With the first survey two vertical, almost perpendicular faces, with dimensions of about 100 m $\times$ 33 m, were analysed. With these data it was possible to apply both 2D flow modelling in the vertical plane (Bersezio *et al.*, 1998, 1999b) and a more comprehensive study, by reconstructing the 3D operative facies distribution with SISIM and applying a 3D flow model (Felletti *et al.*, 2006).

Later, it was possible to investigate three blocks (Zappa *et al.*, 2006), each with a size of a few cubic metres. They correspond to different facies associations: (a) sand-gravel dunes, (b) gravel bedforms, and (c) poorly sorted sandy gravels resulting from mass gravity deposits. The facies distributions over the lateral faces of these blocks were reconstructed by direct field analysis with a resolution of 2 cm; these data were successively used to simulate the facies distribution inside the blocks with a hierarchical sequential indicator approach (Zappa *et al.*, 2006). The effect that the different hydrostratigraphic setting of the three blocks has on the flow and transport have been examined with 3D flow and transport modelling (Zappa *et al.*, 2006; Vassena *et al.*, 2010; Baratelli *et al.*, 2011), and has been coupled with a thorough analysis of connectivity indicators.

During the last field campaign another block (approximately 5 m × 4 m × 1.5 m) was dug in the pit to investigate the effects of strong K contrasts between fine sand and gravel hydrofacies (see detail in Fig. 1). Sedimentological logs, photomosaics and facies maps at a centimeter-scale resolution were acquired along vertical and horizontal intersecting planes, with a spacing of about 40 cm; geoelectrical and GPR surveys were conducted on the top of the block; infiltration tests were performed at several positions, with a spacing of about 50 cm. The 3D simulation of the block heterogeneity was obtained with SISIM, conditioned by the hydrofacies maps of the lateral faces of the block after GIS-aided modelling of the major stratigraphic boundaries. The results of upscaling with the flow model were compared with the outcomes of 16 infiltration tests and gave a satisfactory validation of the flow model; some tests of conservative solute transport have been conducted by simulating the fate of localized plumes, which are instantaneously injected at some particular positions, showing a quite complex behaviour, related to the geometry of the model block (Pessina *et al.*, 2011).

A geophysical survey with acquisition of ERGI and GPR data in the quarry site permitted to improve the reconstruction of some hydrostratigraphic features. The comparison of the geophysical images with the characteristics of the sediments observed by direct field analysis, both at the walls exposed by quarry activities and during the excavation of the dug block, made it possible to find a link between hydro- and radar-facies, which could guide the interpretation of geophysical data of buried structures.

Sand and gravel sediments at the “Ca’ de’ Geri” quarry (Valley of the River Lambro)

Another aquifer analogue shows two superimposed bar/channel units of sand and subordinate gravel formed in two meander loops of the Roman-Medieval Lambro River. The architectural hierarchical model was based on the data obtained from direct inspection of five quarry exposures that have been mapped and logged during excavation and supported by ERGI and GPR surveys (Bersezio *et al.*, 2007). In the analysed volume (approximately 30 000 m^3) four operative hydrofacies have been recognised: very fine sand and silt; sand; gravelly sand; open framework gravel. Transition-probability and variographic analysis of the operative hydrofacies were computed both for the entire dataset and for the individual depositional elements, after discretization of the facies maps with square cells (spacing 50 cm). The geostatistical simulations have been conditioned to: (a) the discretized facies maps, (b) the measured logs and (c) the facies proportions. Equiprobable realizations were computed for a test volume of approximately 400 m^3 and for the entire volume using SISIM, T-ProGS and MPS (Dell’Arciprete *et al.*, 2010a,b, 2012a). The comparison of the different simulations shows that the geological model is best reproduced for every method when the simulations are realised separately for each highest rank depositional element and subsequently merged. The three methods yield different images of the volume and in particular MPS is efficient in mapping the geometries of the most represented hydrofacies, whereas SISIM and T-ProGS can account for the distribution of the least represented facies.

Flow modelling, numerical experiments of solute transport and connectivity analysis (Dell’Arciprete *et al.*, 2010c, 2012b) confirm in a very clear way the role of facies connectivity in determining the solutes’ fate in groundwater. The differences among sets of equiprobable realisations of hydrofacies distributions reflect themselves in the frequency distribution of connectivity indicators and of the hydrodispersive parameters obtained from the interpretation of virtual experiments of conservative solute transport with SDM and DDM.

CONCLUSIONS AND PERSPECTIVES

The examples reviewed in this paper confirm the importance that the sediments’ connectivity has in determining the hydrodynamic and hydrodispersive parameters of alluvial aquifers, as it was also recognized several years ago by soil scientists.

In particular the results show that an accurate hydrostratigraphic characterisation permits identification of different units where stochastic simulations can be effectively applied; without such a first step, the results of stochastic simulations are often negatively affected by non-stationary effects which are quite difficult to handle in practice.

Flow and transport modelling yields further evidence of the sensitivity of upscaled hydrodispersive parameters and of solute transport behaviour at large scale to the facies heterogeneity at fine scales; this is less apparent for the equivalent *K* tensor. Moreover, the use of DDMs was important for some examples, even if the *K* contrasts are relatively small.

The results of flow and transport models are coherent with the values of the connectivity indicators.

From a practical point of view the importance of the identification of connected structures to assess the fate of solutes and therefore of contaminants and pollutants in the subsurface is apparent, i.e. it is important to plan field surveys and to collect data with multidisciplinary (sedimentological, petrographical, geochemical, geophysical, etc.) methods and with such an accuracy and resolution as to obtain proper images of the subsurface, which can then be included in reliable flow and transport models.

However, the analysis of aquifer analogues still leaves open problems and possibilities for further advances.

First, it is necessary to assess different connectivity indicators in order to predict the hydrodynamic and hydrodispersive behaviour of a porous medium; evidence of a single "best" indicator is still missing. Furthermore, for practical applications it is necessary to define connectivity indicators which are both complex enough to predict the flow and transport characteristics and simple enough to be estimated from field and subsurface borehole data, that are usually sparse and uncertain, and often purely descriptive. This is also important to close the gap between 3D analysis on small scale lengths, which is possible at the moment only for specific cases, and analysis at intermediate to great scale lengths, when most data come from borehole logs or 2D outcrops.

Numerical tests could be extended to reactive transport and to different scales.

Big efforts are still necessary to obtain direct estimates of *K* in the field or with undisturbed samples in the laboratory, mainly for coarse-grained hydrofacies. Also, Darcy's and Fick's experiments in the field over volumes of a few cubic metres would be very important to validate the most commonly adopted conceptual models, which are somehow debatable after the results of works on aquifer analogues. For instance, it is useful to recall that the use of DDMs was originally proposed and is generally accepted for transport in fractured rocks or in soils with macropores, i.e. for cases with strong *K* contrasts, but it seems to be appropriate and useful even when the contrasts of *K* are relatively small for the most abundant hydrofacies (from 10^{-5} m/s to 10^{-2} m/s).

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