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Combining sedimentological and geophysical data for high-resolution 3-D mapping of fluvial architectural elements in the Quaternary Po plain (Italy)

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Abstract

Current approaches to the reconstruction of the geometry of fluvial sediments of Quaternary alluvial plains and the characterization of their internal architecture are strongly dependent on core data (1-D). Accurate 2-D and 3-D reconstructions and maps of the subsurface are needed in hydrostratigraphy, hydrogeology and geotechnical studies. The present study aims to: 1) improve current methods for geophysical imaging of the subsurface by means of VES, ERGI and GPR data, and calibration with geomorphological and geological reconstructions, 2) optimize the horizontal and vertical resolution of subsurface imaging in order to resolve sedimentary heterogeneity, and 3) check the reliability/uncertainty of the results (maps and architectural reconstructions) by comparison with exposed analogues. The method was applied to shallow (0 to 15 m) aquifers of the fluvial plain of southern Lombardy (Northern Italy). At two sites we studied fluvial sediments of meandering systems of the Last Glacial Maximum and post-glacial historical age. These sediments comprise juxtaposed and superimposed gravel–sand units with fining-upward sequences (channel-bar depositional elements), which are separated by thin and laterally discontinuous silty and sandy clay units (overbank and flood plain deposits). The sedimentary architecture has been studied at different scales in the two areas.

At the scale of the depositional system, we reconstructed the subsurface over an area of 4 km^2 to a depth of 18 m (study site 1). Reconstructed sequences based on 10 boreholes and water-well stratigraphic logs were integrated with the interpretation of 10 vertical electrical soundings (VES) with Schlumberger arrays and 1570 m long dipole–dipole electrical resistivity ground imaging profiles (ERGI). In unsaturated sediments, vertical and horizontal transitions between gravel–sand units and fine-grained sediments could be mapped respectively at the meter- to decameter scale after calibration of the VES with borehole data. Similar information could be obtained in waterlogged sediments, in which the largest units could be portrayed and the lateral continuity of major hydrostratigraphic units could be assessed. Maps of apparent resistivity were combined with sand-to-clay ratio maps obtained from stratigraphic data, which substantially increased their quality. ERGI profiles added substantial information about the horizontal transitions between fine- and coarse-grained units. At the scale of depositional elements (channel-bar systems) we studied quarry exposures, over an area of about 4000 m^2, down to 8 m below ground level (study site 2). In this case, facies analysis was performed on progressing quarry faces and integrated with a network of 165 m long ERGI profiles and 1100 m long ground-penetrating radar (GPR) profiles. Channel boundaries and accretion surfaces of point bars were resolved by both GPR and ERGI, which permitted 3-D mapping of these surfaces.

Comparison between the results obtained for the two study sites demonstrates that integration of sedimentological data with geophysical imaging (ERGI and VES) enables the identification of stratigraphic units at the scale of depositional elements. Moreover, fining-upward trends and other internal features of the deposits, such as the transitions from coarse to fine-grained

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sediments within channel-bar complexes, could be resolved. Hence, the combination of sedimentological and geophysical methods provides a more accurate 3-D reconstruction of hydrostratigraphically significant sedimentary units compared to reconstructions based solely on borehole/point data.

Keywords: Aquifer characterization; Electrical resistivity ground imaging; Fluvial sediments; Ground-penetrating radar; Hydrogeophysics; Hydrostratigraphy

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1. Introduction

Knowledge of the detailed geometry and architecture of fluvial sequences is crucial for hydrogeological studies, subsurface granular and aggregate mapping and for the development of quantitative models. Unfortunately, alluvial basin fills are extremely complex and reconstructions are often oversimplified models based on borehole data. In the field of hydrogeological applications, general agreement exists about the ideal procedure for aquifer characterization, as recently summarized for example by Bridge and Hyndman (2004). According to these authors, the first stage includes a) stratigraphic correlation of borehole and core data, b) analysis of the sedimentological and physical properties of sedimentary units, and assessment of their shapes, and c) determination of horizontal and vertical continuity of sediment packages between borehole data, assisted by geophysical exploration tools. The next stage comprises 3-D modeling of (hydro)-facies distribution, porosity and permeability by geostatistical methods. North (2005), who summarized some pitfalls of the most popular stochastic methods and geophysical techniques used to interpolate between boreholes, concluded that a good understanding of fluvial sedimentology and stratigraphic evolution is required for spatial modeling of aquifers and reservoirs. In this paper we focus on assessment of the spatial continuity of sedimentary units and their hydrological properties between boreholes. We attempt to improve upon existing methods by combining geological, geomorphological, stratigraphical and sedimentological data with common, quickly employable and inexpensive geophysical techniques. In our case study, the integration of different data sets yields good proxies of the location of features relevant to hydrogeology at different scales, such as the horizontal transitions and interfaces between sand–gravel bodies and fine-grained, less permeable units.

Several geophysical techniques are available to explore the stratigraphy of alluvial basins. High-resolution shallow seismic (HRSS) is a powerful tool for obtaining high-quality stratigraphic images in the presence of a reasonably high P-wave velocity contrast between lithologies. Such contrasts are generally present if clay–shale units alternate with coarse-grained units (Birkelo et al., 1987; Geissler, 1989; Bruno and Godio, 1997; Bradford et al., 1998; Liberty, 1998; Whiteley et al., 1998; Juhlin et al., 2002; Bradford, 2002a,b; Francese et al., 2002, 2005). Unfortunately, HRSS is an expensive and time-consuming method that may entail environmental and security risks.

Ground-penetrating radar (GPR) is at present very popular, and many aquifer analogue studies have been published so far (e.g. Jol and Smith, 1991; Stephens, 1994; Asprion and Aigner, 1999; Bristow and Jol, 2003; Heinz and Aigner, 2003). This technique is fast, inexpensive and relatively easy to use. Moreover, it can provide very high-resolution images if a small penetration depth is sufficient. Unfortunately, this technique cannot be readily applied in the presence of even very thin soil or shallow clay layers, and significant images of saturated sediments below the water table are difficult to obtain.

The inversion of seismic, electric, and electromagnetic data collected with cross-borehole acquisition arrays is another powerful geophysical tool, which requires appropriate wells. This technique cannot be applied with existing water wells, so that it tends to become very expensive (e.g., Tronicke et al., 2004; Binley et al., 2004). Also direct-push electrical conductivity logging has been used to characterize unconsolidated sediments, providing vertical logs with an extremely high resolution (Schulmeister et al., 2004). However, horizontal correlations between measurements are hampered by the uncertainties associated with the use of 1-D data.

The most common geoelectrical techniques are vertical electrical soundings (VES) and electrical resistivity ground imaging (ERGI) (Telford, 1990; Reynolds, 1996; Dahlin, 2001). These techniques have been traditionally used in hydrogeology and other environmental applications (Reynolds, 1996; Daily and Ramirez, 2000) but are rarely applied for