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Technical Note

Misleading reconstruction of seawater intrusion via integral depth sampling

N. Colombani [a], G. Volta [b], A. Osti [b], M. Mastrocicco [c,*]

[a] Department of Earth Sciences, "Sapienza" University, P.le A. Moro 5, 00185 Rome, Italy
[b] Department of Physics and Earth Sciences, University of Ferrara, Via Saragat 1, 44122 Ferrara, Italy
[c] Department of Environmental, Biological and Pharmaceutical Sciences and Technologies, Second University of Naples, Via Vivaldi 43, 81100 Caserta, Italy

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SUMMARY

Saltwater intrusion in coastal aquifers is an urgent issue for the actual and future groundwater supply and a detailed characterization of groundwater quality with depth is a fundamental prerequisite to correctly distinguish salinization processes. In this study, interpolated Cl^- maps of the Po River delta coastal aquifer (Italy), gained with Integrated Depth Sampling (IDS) and Multi-Level Sampling (MLS) techniques, are compared. The data set used to build up the IDS and MLS interpolated Cl^- maps come from numerous monitoring campaigns on surface and ground waters, covering the time frame from 2010 to 2014. The IDS interpolated Cl^- map recalls the phenomenon of actual seawater intrusion, with Cl^- concentration never exceeding that of seawater and the absence of hypersaline groundwater all over the study area. On the contrary, in the MLS interpolated Cl^- maps the lower portion of the unconfined aquifer presents hypersaline groundwater making it necessary to consider salinization processes other than actual seawater intrusion, like upward flux from a saline aquitard. Results demonstrate the obligation of using MLS in reconstructing a reliable representation of the distribution of salinity, especially in areas where the density contrast between fresh and saline groundwater is large. Implications of the reported field case are not limited to the local situation but have a wider significance, since the IDS technique is often employed in saltwater intrusion monitoring even in recent works, with detrimental effect on the sustainable water resource management of coastal aquifers.

1. Introduction

The threat to freshwater supplies and groundwater-dependent ecosystems in coastal areas has intensified the research on saltwater intrusion (Barlow and Reichard, 2010; Custodio, 2010). Because of the potentially irreversible impact of groundwater salinization, it is essential to untangle the mechanisms governing seawater intrusion, so that policy makers can take the appropriate actions to protect groundwater resources (Werner et al., 2013).

Salinization may occur from natural and anthropogenic sources (Cartwright et al., 2004; Lenahan and Bristow, 2010; Sanchez-Martos et al., 2002) and in many cases salinity problems arise from more than one salt source. In some coastal areas, the issue of saline groundwater origin involves, beyond actual seawater, relict seawater and hyper-saline waters (Fass et al., 2007; Ridd and Stieglitz, 2002; Wood et al., 2003). In these cases, distinguishing between modern versus relict saltwater intrusion is vital to build a robust conceptual model of groundwater salinization through which a sustainable management program could be designed (Werner and Gallagher, 2006).

Whatever the salt source is, its identification is often puzzled by the sediment–water interaction which resulted to be amplified by the increased water ionic strength (de Montety et al., 2008) and/or by mixing processes enhanced by human activities, namely over-exploitation and land reclamation (Custodio, 2010; Kass et al., 2005).

A critical issue in distinguishing salinization processes is to correctly characterize the vertical variability of groundwater quality (de Louw et al., 2010; Netzer et al., 2011). The variability in the vertical chemical composition of groundwater has been described both between different hydrological units of the same aquifer (Nativ and Weisbrod, 1994) and over small sections of a given hydrological unit (Dhar et al., 2008). Coastal aquifers often consist of layered sequences with varying hydraulic properties (Bear et al., 1999) that can complicate the monitoring of the fresh–saltwater interface because of the heterogeneity of the aquifer matrix (Kim et al., 2008; Melloul and Goldenberg, 1997). Therefore, coastal

* Corresponding author. Tel.: +39 0823 274609; fax: +39 0823 274605.
E-mail address: micol.mastrocicco@unina2.it (M. Mastrocicco).

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monitoring wells may act as vertical short circuits between layers (Werner et al., 2013), inducing local vertical flow due to connection between higher and lower hydraulic head zones (Elci et al., 2003). A common consequence is that ambient flow within long-screen wells may cause solute transport (Konikow and Hornberger, 2006), even in homogeneous aquifers with small vertical hydraulic gradients (Britt, 2005) and it may also compromise hydraulic head measurements (Shalev et al., 2009).

Integrated Depth Sampling (IDS) provides water samples representing an undefined integration of groundwater quality over the entire screen length (Robbins and Martin-Hayden, 1991) and is thus largely deficient for the purposes of understanding salinization processes, being that in coastal aquifers groundwater stratification is the rule rather than the exception. On the contrary, Multi-Level Sampling (MLS) that sample multiple intervals of an aquifer is invaluable for providing a three-dimensional distribution of groundwater quality within a coastal aquifer system (Mastrocicco et al., 2012). MLS is routinely applied in contaminated sites to map contaminant spreading and to quantify biogeochemical reaction pathways (Henderson et al., 2009; Mastrocicco et al., 2011; Prommer et al., 2006), but less frequently in monitoring the salinization in coastal areas because of high costs and time involved (Einarson and Cherry, 2002). The expense, however, do not set aside the need for a dedicated depth-dependent groundwater monitoring to properly estimate the chemical composition of groundwater in coastal areas, to enhance the predictability of regional scale management models that will inevitably be required in the near future.

This work has been accomplished in order to compare the interpolated Cl^- maps gained with IDS and MLS techniques and to assess which one is more suitable at identifying the origin and the mechanism of groundwater salinization. For the first time, a direct comparison between IDS and MLS techniques at the aquifer scale was performed, to highlight the differences in reconstructing both the redox zonation and seawater intrusion, which have significant implications in the sustainable water resource management of coastal aquifers.

2. Site description

The study area is located in the coastal floodplain of the Po River (Northern Italy) and covers 750 km^2 (Fig. 1). Most of the territory is a recently reclaimed land with flat topography and an altitude ranging from 5 to -11 m above sea level (a.s.l.); the only topographic heights are dunes, paleodunes and riverbanks.

The alternation of glacial and interglacial periods, characterized by changing sea level position, had a significant impact on the evolution of this coastal area (Amorosi et al., 2003). During the last glacial maximum, the paleo-shoreline of the Po plain was about 250–300 km south of its present position and the study area was characterized by the sedimentation of well-drained middle alluvial-plain sands. During the Flandrian transgressive phase, coastal and marine sediments were deposited over the alluvial-plain sands and the paleo-shoreline moved 30 km inland with respect to its present position. During the early highstand period, large sand spits and barrier islands grew, turning the previous bays into confined marsh lagoons with widespread organic clay intercalations and peat horizons (Stefani and Vincenzi, 2005). Afterwards, the depositional dynamics were modified by both climatic change and anthropic events (infrastructures, reclamation works and fluvial diversions) causing coastal progradation and a consequent regressive succession of the deposits (Fig. 1).

The complex stratigraphic evolution led to a complex aquifer geometry. The coastal aquifer in the study area is generally unconfined but locally thin confining layers of fine deposits are present. The aquifer is mainly located within the littoral sands and the shallow marine wedge deposits and is underlie by fine-grained deposits of silt and clay. The aquifer thickness decreases inland and, in the study area, ranges between 2 and 24 m. The aquifer hydraulic conductivity is variable, depending on the sorting of aquifer materials, and ranges from 1×10^{-6} m/s in depressed areas to 1×10^{-3} m/s in the coastal dunes (Mastrocicco et al., 2012). The average horizontal hydraulic gradient is 0.5‰ and the horizontal flow velocity is generally very low (about 7–10 m/y). The aquifer is often under anoxic conditions, rich in iron, manganese and ammonium ions or even with the presence of dissolved gas like hydrogen sulphide (Giambastiani et al., 2013). Moreover, the unconfined aquifer in the study area is characterized by connate brackish or salt water, with an active exchange with the surface water network (Colombani et al., 2015).

The recent anthropogenic activity has determined a change in the aquifer hydraulic equilibrium. The need to acquire new areas to be allocated to agricultural activities led to a succession of reclamation works, intensified from 1850 s to 1960 s. The resulting surface water system is very complex since it is constituted by numerous natural and non-natural water bodies (Fig. 1): the course of the Po River, its tributaries and an extended hydrological network of channels and drainage ditches. Natural and anthropogenic land subsidence has dropped most of the territory below sea level, modifying river and groundwater flow regimes. Nowadays, the drainage system is necessary to lower the phreatic level, guarantee water discharge toward the sea and maintain this lowland dry. The surface water level is maintained at a nearly constant level of about -0.5 m a.s.l. because of the agricultural requirements. The hydraulic head difference between the aquifer and the surface waters (about 1 m) causes a permanent upward groundwater flux in the study area (Giambastiani et al., 2013).

3. Materials and methods

The 11 monitoring wells selected for this study (Fig. 1) are part of the regional monitoring network of the Geological Survey of Emilia Romagna Region. The 2 in. wells are screened from -1 m a.s.l. to a maximum of -22.5 m a.s.l. to fully penetrate the unconfined aquifer. To minimize clogging and to prevent surface-water infiltration screens are surrounded by a geotextile sock and sealed with a mixture of cement and bentonite at the top.

For the IDS measurements a Proactive® electrical submersible pump with flow controller was placed in the middle of the screened interval and a minimum of four volumes were purged maintaining a flow rate of 0.1–0.5 l/min to minimize the piezometric lowering. A flow-through cell was employed to measure the water quality parameters (pH, EC, Eh and DO).

For the MLS measurements a Solinst® 800L straddle packers system was used to isolate a window of 0.2 m within the fully penetrating wells. After the selected ports were purged for 3 volumes (approximately 15 l), a groundwater sample was collected at each depth interval via a low-flow technique using an inertial pump.

The groundwater samples, both for the IDS and the MLS measurements, were collected after the stabilization of physical–chemical parameters monitored via a Hydrolab flow cell connected to the Hydrolab® MS-5 probe to acquire *in situ* pH, EC, Eh and DO. The Po River was sampled in four campaigns from 2010 to 2014 near the monitoring well P4. The seawater samples were collected at the shoreline in seven campaigns from 2010 to 2014 near the monitoring wells P1, P8 and P9. The bulk (wet and dry) atmospheric deposition was sampled in four campaigns from 2010 to 2014 using a HDPE bottle and a 20 cm diameter funnel equipped with a 100 μm Nitex® net to avoid external contamination. Samplers were installed near the monitoring wells P1 and P8 at a height of 1.5 m above the ground. Samples were filtered through