Driving the modeling of saltwater intrusion at the Venice coastland (Italy) by ground-based, water-, and air-borne geophysical investigations

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ABSTRACT

The coastland surrounding the southern Venice Lagoon, Italy, is a precarious environment subject to both natural changes and anthropogenic pressure. One major environmental problem is the saltwater contamination in shallow aquifers. Since the early 2000s, a significant effort has been devoted to understand the process dynamics by integrating different geophysical techniques, i.e. TL-ERT (Time Lapse - Earth Resistivity Tomography), MRT (Marine RT), AEM (Airborne ElectroMagnetic), and shallow water VHRS (Very High Resolution Seismic) surveys. The monitoring results have been used to drive the development of a reliable numerical model for the simulation of the saltwater intrusion along the margin of the southern Venice Lagoon. The model solves the coupled density dependent flow and transport equations by a highly accurate numerical approach based on the mixed hybrid finite element (MHFE) method and a combination of MHFE with high resolution finite volumes (HRFV) for the discretization of the flow and transport equations, respectively. Modeling application provides a clear picture of the relative importance of the factors that contribute to the soil contamination in the study area.

INTRODUCTION

Groundwater/seawater exchange in coastal areas impacts both onshore and offshore the quality of water resources through saltwater intrusion into water-supply aquifers and the discharge of contaminated groundwater into the coastal sea. Saltwater intrusion represents a threat to drinking water quality (Qahman and Larabi,

2006), enhances the risk of soil desertification (Pousa et al., 2007), compromises the agricultural practices (Paniconi et al., 2001) and diminishes freshwater storage capacity. Meanwhile, submarine groundwater discharge can transport significant chemical loads to the sea (Church, 1996) that can affect coastal ecological systems. Water and chemical fluxes across the land/sea margin are thus important from both a human and an environmental health perspective, and an understanding of the geophysical and geological processes controlling flow dynamics in coastal aquifers is a worthwhile endeavour.

In wetlands, lagoons and estuaries the groundwater-surface water exchange also has a strong impact on flora and fauna. Moreover, the hydrologic setting of the transitional environments is complicated by their Late Quaternary subsoil architecture. The deposits represents the transition through the fluvial in tide-dominated depositional systems triggered by the sea level changes (Zecchin et al., 2008).

The coastland surrounding the Venice Lagoon, Italy (Figure 1a), is a precarious environment subject to both natural changes and anthropogenic pressure. A number of critical issues affect this lowlying area, i.e. relative land subsidence, periodic flooding during severe winter storms, and saltwater intrusion. The combined effect of sea level rise and land subsidence has enhanced the saltwater contamination and the related soil salinization with serious environmental and socio-economic consequences (Carbognin et al., 2006). Moreover, several buried morphological features can act as preferential pathways for groundwater contaminant exchange with the mainland subsurface.

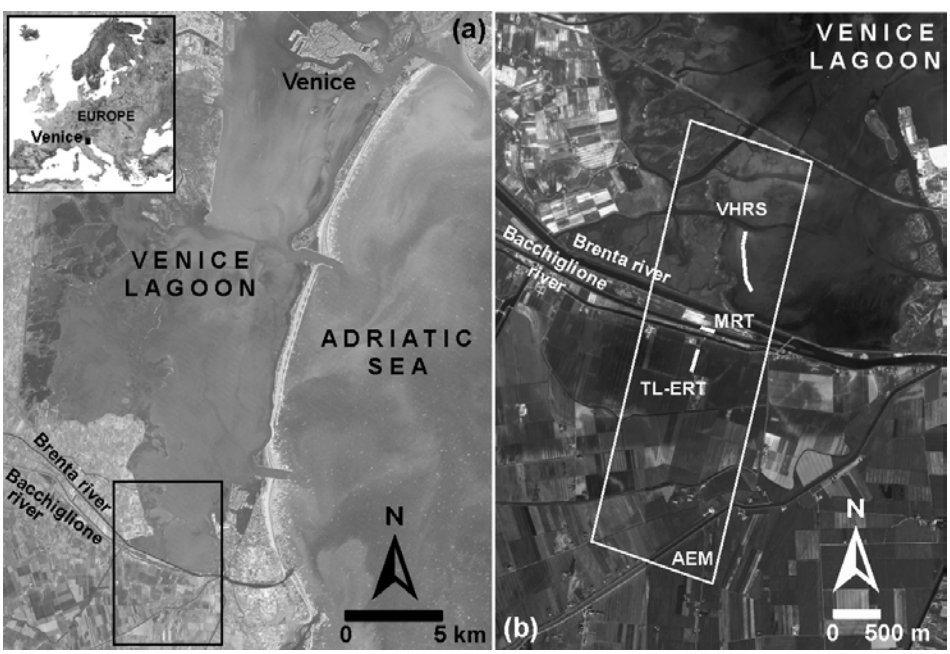

Figure 1. (a) Map of the southern part of the Venice Lagoon with the location of the study area (black box). (b) The area of interest with the trace of the geophysical surveys.

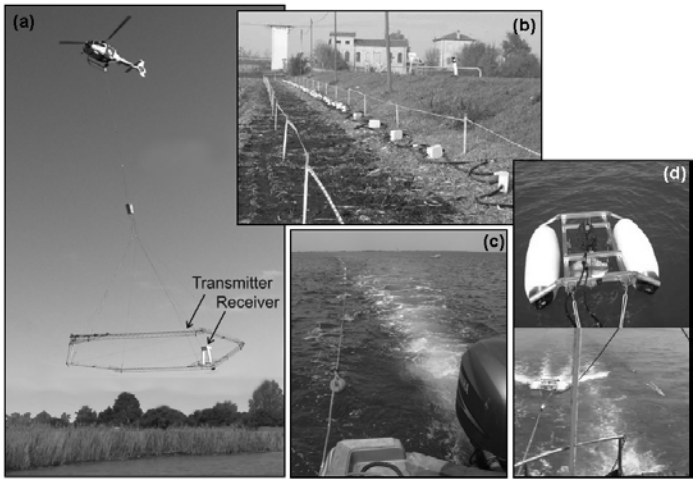

Figure 2. The different geophysical techniques used in the southern Venice Lagoon: (a) AEM, (b) TL-ERT, (c) MRT, and (d) VHRS.

Several hydrogeological investigations have been carried out in the Venice Lagoon over the last decade to improve the knowledge of the continental-marine groundwater interaction and the subsoil deposit architecture. Here we present a few results provided by the geophysical surveys in an area at the southern margin of the lagoon (Figure 1b).The zone is representative of typical transitional environments, with tidal flats, salt marshes, and recently reclaimed lowlying farmlands. The surveys have been used to drive the application of a density dependent flow and transport numerical model aimed at understanding the processes governing the saltwater contamination of the shallow aquifers underlying the farmland at the lagoon margin.

GEOPHYSICAL INVESTIGATIONS

We shortly review the different geophysical techniques that have been recently used in the Venice Lagoon to characterize the hydrogeological setting of the lagoon subsurface and the saltwater – freshwater exchange (Figure 2): *i*) the airborne electromagnetics (AEM), *ii*) the time lapse earth resistivity tomography (TL-ERT), *iii*) the marine resistivity tomography (MRT), and *iv*) the very high resolution seismic (VHRS).

AEM Various AEM systems are applied in hydrogeophysical investigations. In the Venice Lagoon we have used SkyTEM (Viezzoli et al., 2010). In this system, a large current is switched on and off very quickly and repeatedly in a multi turn coil wound around a non metallic frame hanging underneath the helicopter 30-40 m high above the ground, or water. When the current is abruptly turned off, the primary magnetic field associated to it collapses, and as a result, eddy currents are induced in the ground. They in turn decay over time due to ohmic loss and propagate in depth. The variation over time of secondary magnetic moment associated with these eddy current is recorded by the receiver and then inverted into geoelectric models using the Spatially Constrained Inversion (SCI) technique (Viezzoli et al., 2008).

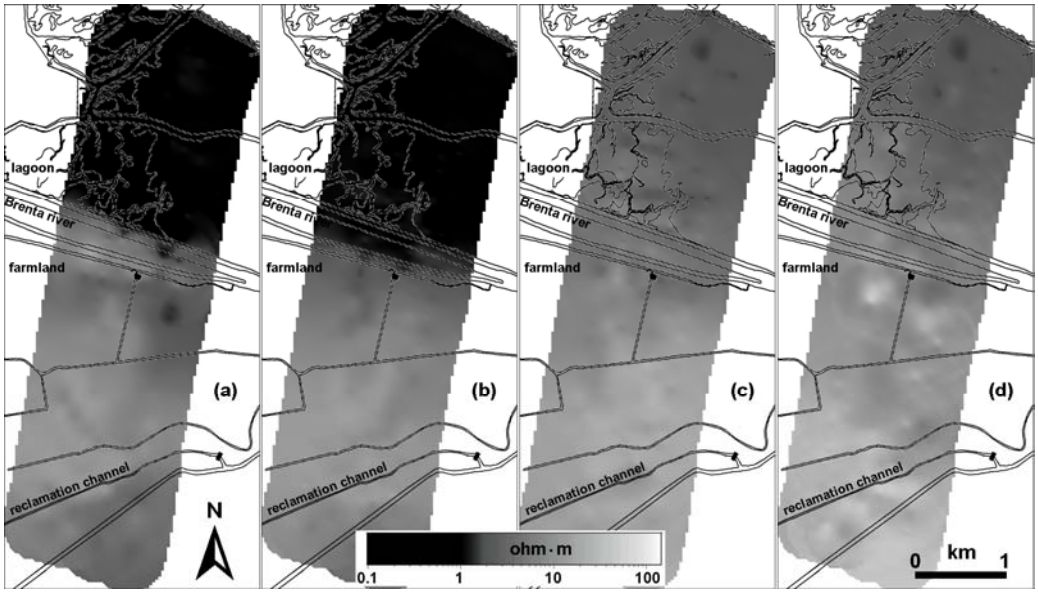

Figure 3. Average resistivity maps for the (a) 0–5, (b) 10–20, (c) 30–40, and (d) 80–100 m depth intervals obtained by the SkyTEM system in spring 2009.

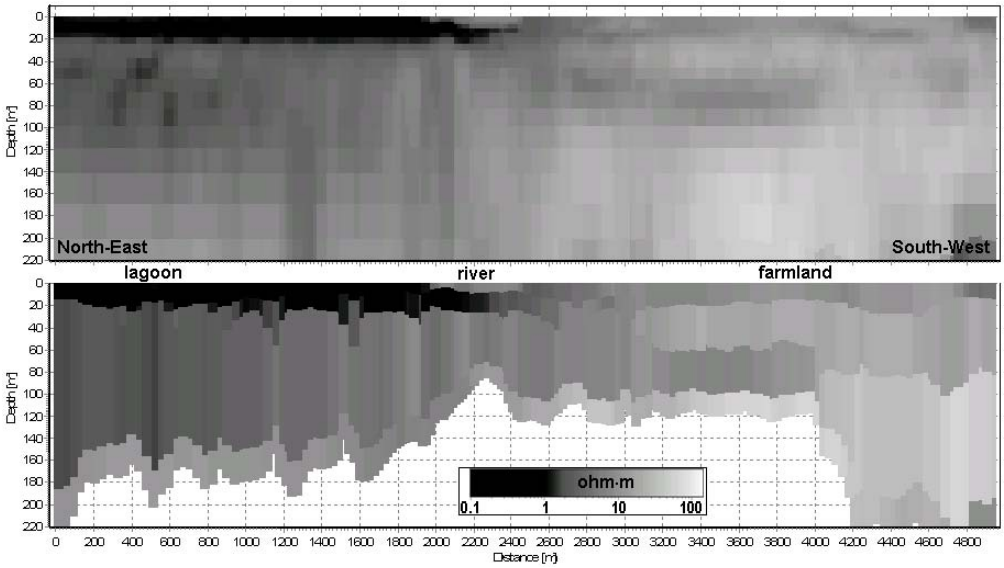

Figure 4. Multi-layer (above) and few layer (below) cross sections for one line of the AEM survey orthogonal to the lagoon margin.

The SkyTEM system has been applied in 2009 over the central and southern basins of the Venice Lagoon providing meaningful resistivity information down to about 180 m depth. The first site, which is located between the industrial zone on the mainland and the Venice historical center, is characterized by wide tidal flats. Here, AEM has highlighted possible significant submarine groundwater discharge (SGD). In this work we show some results for the survey at the southern margin of the lagoon. Both multi- (smooth) and few layers (blocky) model have been used in the

SCI. The results of the inversion of AEM data are presented as horizontal average resistivity maps at a few depth intervals (from the multi-layered models results), and vertical cross sections. Figure 3 shows the average resistivity maps at 0–5, 10-20, 30-40 and 80-100 m depth intervals. In the lagoon sector the resistivity (ρ) values increase from less than 1 Ohm·m in the shallower layer to about 4 Ohm·m down to 100 m depth. The resistivity vertical section shown in Figure 4 points out that, below the lagoon bottom, ρ never exceeds 10 Ohm·m down to about 180 m. The AEM clearly shows how the salt plume intrudes from the lagoon bottom, passes underneath the rivers and canals, and extends for about 2 km in the farmland subsoil.

TL-ERT The dynamics of saltwater intrusion along a profile perpendicular to the lagoon margin has been studied by a TL-ERT experiment. This was carried out by means of an apparatus implemented for this purpose and capable to acquire ten electro-tomographies per day over about one year starting from November 2005: five tomographies down to a 15-20 m depth are acquired at a high resolution by a 97.5 m long and 2.5 m electrode spacing ERT line, and five by a 300 m long and 5 m electrode spacing line that allow for the investigation to reach a 50-60 m depth (De Franco et al., 2009).

Figure 5 shows two representative tomographic sections obtained by TL-ERT data in November 2005 and May 2006. With the exception of the upper 2-4 m, the contamination reached the maximum inshore extent from the lagoon margin during the wet season in contrast to the general behaviour observed in other coastal sites governed by temperate climate. This occurrence is likely to be due to the superposition of the pumping station activities, which keep the lowest groundwater levels in the winter to minimize the risk of lowland flooding, spring/summer irrigation and deep fresh groundwater supply from the mainland, and the seasonal lagoon water levels that usually reach the maximum values from November to March. The resistivity changes in the first confined aquifer are probably due to an increased fresh water recharge coming from mainland at regional scale.

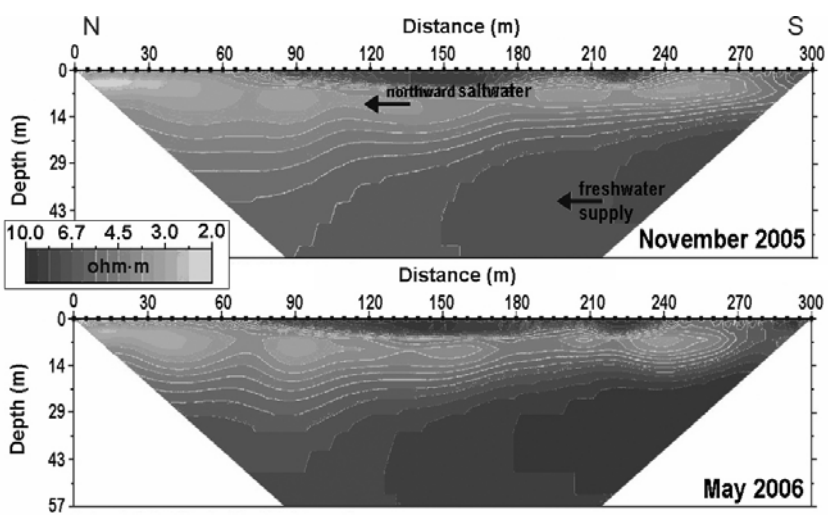

Figure 5. TL-ETR resistivity models showing the evolution of saltwater intrusion between November 2005 and May 2006.

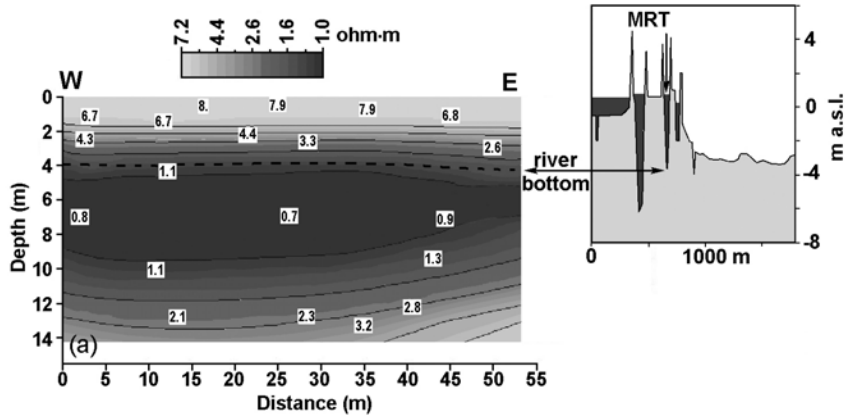

Figure 6. MRT profile acquired along the Bacchiglione river.

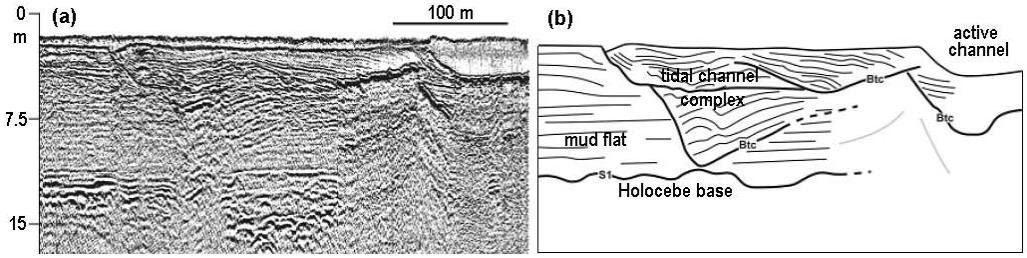

Figure 7. VHRS section acquired in the southern Venice Lagoon and (b) its sedimentological interpretation.

MRT A MRT profile have been acquired along the Bacchiglione river to explore the presence of the salt contamination below the river bottom (De Franco et al., 2009). The survey has confirmed that the rivers are likely to play an important role in the dynamics of the salt contamination. The resistivity model obtained by the measurement (Figure 6) shows the wide extent of the salt contamination. The profile shows very low formation resistivity values (between 0.7 and 1.1 Ohm·m) that can be referred to the subsoil just beneath the river bottom down to about 10 m below m.s.l. It pointed out the presence of brackish water (EC=2.5–4 mS/cm) in the deeper portion of the river while the shallower water was substantially fresh (measured EC=1.2 mS/cm).

VHRS The method allows the acquisition of images of the subsurface down to 15–20 m below m.s.l. with a resolution of about 10 cm operating in water depths less than 1 m. The system used in the southern Venice Lagoon consists of an impulsive energy source (boomer) and an electro-dynamic transducer UWAK05 mounted on a catamaran frame, together with a 8-hydrophone pre-amplified oilfilled streamer. The streamer is deployed parallel to the boomer and towed with a 2 m lateral offset at about 0.3 m beneath the water surface (Tosi et al., 2009).

Seismic data integrated with available core analyses have allowed the definition of seismicmorpho-stratigraphic model for the Venice Lagoon and provided detailed images of buried fluvial and tidal channels in the subsurface of lagoon shallows related to the Late Pleistocene and Holocene hydrology (Figure 7). Analysis

of the anatomy of these shallows provided details of the architecture of the deposit, such as lateral migration clinoforms, vertical accretion layers, bars, and channel-levee systems. This information contributes significantly to detect high-permeable morphological features connecting the lagoon subsurface with the surrounding farmland. These features act as preferential pathways for the inland saltwater movement.

MODELING THE SALTWATER INTRUSION AT THE VENICE LAGOON MARGIN

The mathematical model The mathematical model of density-dependent flow in porous media can be expressed in terms of an equivalent freshwater head $h = \psi + z$, where $\psi = p / (\rho_0 g)$ is the equivalent freshwater pressure head, p is the pore pressure, ρ_0 is the freshwater density, g is the gravitational constant, and z is the vertical coordinate directed upward. The density ρ of the saltwater solution is written in terms of the reference density ρ_0 and the normalized (actual divided by maximum) salt concentration c, $\rho = \rho_0(1+\varepsilon c)$, where $\varepsilon = (\rho_s - \rho_0) / \rho_0$ is the density ratio, typically equal to 0.025-0.030 for oceans and open seas, and ρ_s is the density of the solution at $c = 1$. The dynamic viscosity μ of the saltwater mixture is also expressed as a function of c and the reference viscosity μ_0 as $\mu = \mu_0(1+\varepsilon' c)$, where $\varepsilon' = (\mu_s - \mu_0) / \mu_0$ is the viscosity ratio and μ_s is the solution viscosity at $c = 1$.

With the above definitions, the mass conservation equations for the coupled flow and transport model in porous media can be written, in terms of the unknown pressure head ψ and normalized concentration c, as (Gambolati et al., 1999):

$$\sigma \frac{\partial \psi}{\partial t} = \vec{\nabla} \cdot \left[K_s \frac{1+\varepsilon c}{1+\varepsilon' c} K_r \left(\vec{\nabla}\psi + (1+\varepsilon c)\eta_z \right) \right] - \phi S_w \varepsilon \frac{\partial c}{\partial t} + \frac{\rho}{\rho_0} q^* + q \tag{1}$$

$$\vec{v} = -K_s \frac{1+\varepsilon c}{1+\varepsilon' c} K_r \left(\vec{\nabla}\psi + (1+\varepsilon c)\eta_z \right) \tag{2}$$

$$\phi \frac{\partial S_w c}{\partial t} = \vec{\nabla} \cdot \left(D \vec{\nabla} c \right) - \vec{\nabla} \cdot \left(c \vec{v} \right) + q c^* + f \tag{3}$$

where t is time, $\sigma = S_w S_s (1 + \varepsilon c) + \phi(1 + \varepsilon c) \mathrm{d}S_w / \mathrm{d}\psi$ is the general storage term with S_s the storage coefficient, $S_w = \theta / \theta_s$ with θ the volumetric soil moisture content and θ_s the saturated moisture content, ϕ is the porosity of the medium, K_s is the hydraulic conductivity tensor at the reference density, K_r is the relative hydraulic conductivity, η_z is a vector equal to zero in its x and y components and 1 in its z component, q^* is the injected and q the extracted volumetric flow rate, $\vec{v}$ is the Darcy velocity vector, D is the dispersion tensor given by $D = (\phi D_0 + \alpha_T |\vec{v}|) I + (\alpha_L - \alpha_T)\ \vec{v} \cdot \vec{v}^T / |\vec{v}|$, with D_0 the molecular diffusion coefficient and α_L and α_T the longitudinal and transverse dispersivity coefficients, c^* is the normalized concentration of salt in the injected/extracted fluid, and f is the volumetric rate of injected (positive)/extracted (negative) solute that does not affect the velocity field.

Appropriate initial and Dirichlet, Neumann, or Cauchy boundary conditions, and empirical relationships describing the pressure head dependencies of the relative

hydraulic conductivity for the case of variably saturated flow are added to complete the mathematical formulation of the coupled flow and transport problem.

A combination of the mixed hybrid finite element (MHFE) and a high resolution finite volumes (HRFV) methods with the time splitting technique is implemented to solve Eqs. (1)-(3). These numerical schemes guarantee an accurate and reliable solutions for both the velocity and the concentration field also where the transport equation is advection dominated or the flow is orthogonal to the concentration gradient. The numerical schemes have been implemented into the COUP_HYB simulator (Mazzia and Putti, 2006).

Model application COUP_HYB has been applied to simulate the saltwater intrusion at the southern margin of the Venice Lagoon. The salt contamination is generally the result of seawater intrusion from the lagoon bottom, but significant contributions can also be due to the water leakage from the bed of the major rivers to the subsurface. In fact, the reduced freshwater discharges that occur in the Brenta and Bacchiglione rivers during the dry periods allow the seawater to flow up from the river mouths for several kilometres. Saltwater intrusion is enhanced by a land elevation well below the mean sea level and by the presence of several ancient sandy fluvial ridges and buried paleo-channels, crossing the farmland with a main direction from inland to the lagoon boundary.

The modeling application has been carried out along a north-south vertical section (from the lagoon boundary and the watercourses to the inner farmland) that runs parallel to the geophysical surveys. The model domain is about 1000 m long and 30 m deep, i.e. from the ground surface down to -30 m above m.s.l. where an impermeable layer separates the shallow contaminated aquifers from the deeper freshwater systems. According to available measurements the following values are used: $K_{s,\mathrm{sand}} = 3\times10^{-4}$ m/s, $K_{s,\mathrm{silt}} = 6\times10^{-5}$ m/s, and $K_{s,\mathrm{clay}} = 3\times10^{-8}$ m/s. The other solute transport parameters are defined as: porosity $\phi = 0.20$, elastic storage $S_s = 1\times10^{-3}$ m^{-1}, density ratio $\varepsilon = 0.025$, viscosity ratio $\varepsilon' = 0.3$, molecular diffusion coefficient $D_0 = 0$, longitudinal α_L and transverse dispersivity and α_T equal to 1×10^{-1} and 1×10^{-3}, respectively.

We present the results of some preliminary simulations aimed at investigating the effects of the natural factors controlling the dynamics of the saltwater intrusion in the coastal aquifers, i.e. the water level and salt concentration in the lagoon, the Brenta and Bacchiglione rivers, and the reclamation channel located south of Bacchiglione. A zero concentration initial condition is used throughout the domain so as to simulate the expected migration of the saltwater front from the lagoon and river boundaries. The water level in the lagoon and the rivers is prescribed at 0 and 0.8 m above m.s.l., respectively; the groundwater level at the inland boundary at -4 m above m.s.l, i.e. 1 m below the ground surface as maintained by the drainage system. Hydrostatic pressure distribution is prescribed along the vertical boundaries and no recharge occurs from the farmland surface. Relative water concentration is set to 1 in the lagoon and in the lower part (below -2 m amove m.s.l.) of the two rivers.

The maps of the relative concentration after 1 and 2 years from the beginning of the simulation are given in Figure 8. The results show that the lagoon is an important source of salt contamination, especially for the semi-confined aquifer.

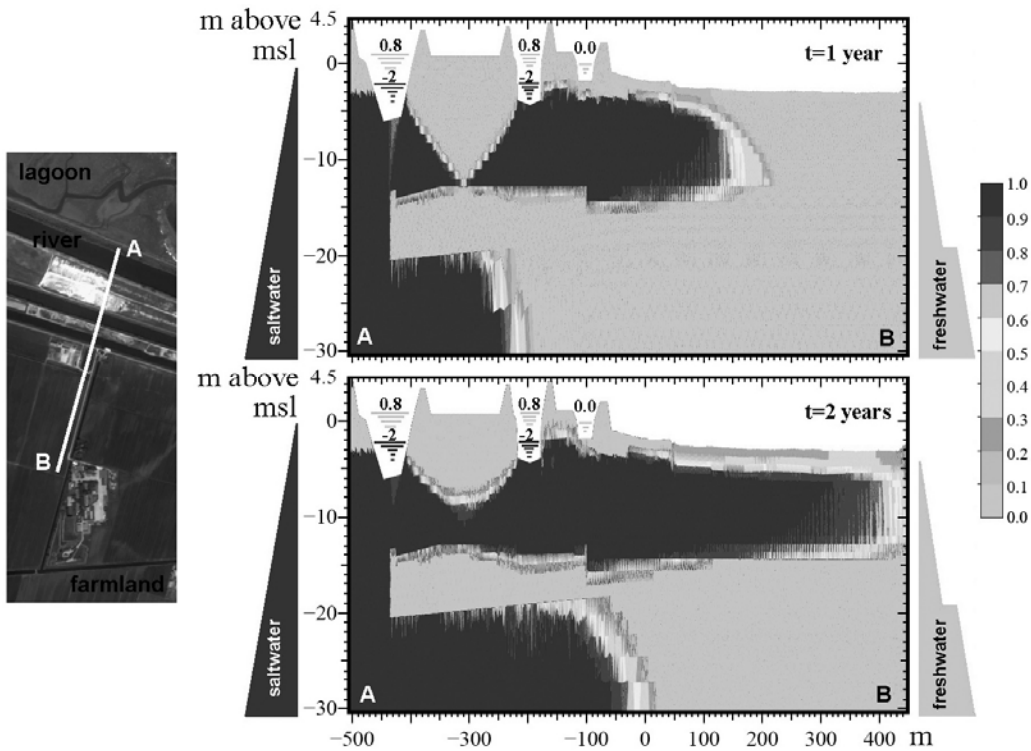

Figure 8. Relative concentration as obtained from the COUP_HYB after 1 year and 2 years. The boundary conditions are shown. Vertical exaggeration is 15. The trace of section is shown on the map.

Because of their location well above the surrounding farmland, the Brenta and Bacchiglione rivers are the main waterbodies impacting on the groundwater quality. If the two rivers contain seawater, they are a potential source of severe contamination for the aquifers in the surrounding farmland. Conversely they are likely to play a fundamental role in controlling the contamination level in the shallow aquifer when they contain freshwater

CONCLUSION

It is evident that integration of different geophysical techniques, such as AEM, TL-ERT, MRT, and VHRS, provide a valuable dataset over ground and surface water-bodies to improve the knowledge on *i*) the hydrogeological setting of transitional areas and *ii*) the vertical and horizontal mixing of salt- and freshwaters that usually takes place in these delicate areas.

In the Venice Lagoon, these techniques have been successfully implemented over the last decade in the southern basin. Their results have been used to set-up a coupled density-dependent groundwater flow and transport model to simulate the propagation of the contaminant plume along a vertical cross section orthogonal to the lagoon boundary. The modeling results allow to define the role played by the lagoon and the major watercourses. Although the lagoon is an important source of saltwater, it turns out that the rivers exert an important role in improving or worsening the

subsurface contamination. The rivers can act indeed as an effective hydraulic barrier to salt contamination from the lagoon if they contain freshwater or, viceversa, can represent a strong source of salinization if seawater encroaches along the final portion of the watercourses.

REFERENCES

Church, T.M. (1996). "An underground route for the water cycle". *Nature*, 380, 579–580.

De Franco, R., Biella, G., Tosi, L., Teatini, P., Lozej, A., Chiozzotto, B., Giada, M., Rizzetto, F., Claude, C., Mayer A., Bassan, V., and Gasparetto-Stori, G. (2009). "Saltwater intrusion monitoring by time lapse electrical resistivity tomography". *J. Appl. Geophysics*, 69, 117–130.

Gambolati, G., Putti, M., and Paniconi, C. (1999). "Three-dimensional model of coupled density-dependent flow and miscible salt transport in groundwater". In: *Seawater Intrusion in Coastal Aquifers; Concepts, Methods and Practices*, eds. J. Bear et al., Kluwer Academic Publishers: Dordrecht, The Netherlands, pp. 315–362.

Mazzia, A., and Putti, M. (2006). "Three-dimensional mixed finite element – finite volume approach for the solution of density-dependent flow in porous media". *J. Computational Applied Mathematics*, 185(1), 347–359.

Paniconi, C., Khlaifi, I., Lecca, G., Giacomelli, A., and Tarhouni, J. (2001). "Modeling and analysis of seawater intrusion in the coastal aquifer of Eastern Cap-Bon, Tunisia". *Transport in Porous Media*, 43, 3–28.

Pousa, G., et al. (2007). "Coastal processes and environmental hazards: the Buenos Aires (Argentina) and Venetian (Italy) littorals". *Environmental Geology*, 51, 1307–1316.

Qahman, K., and Larabi, A. (2006). "Evaluation and numerical modeling of seawater intrusion in the Gaza aquifer (Palestine)". *Hydrogeology J.*, 14, 713–728.

Tosi, L., Rizzetto, F., Zecchin, M., Brancolini, G., and Baradello, L. (2009). "Morphostratigraphic framework of the Venice Lagoon (Italy) by very shallow water VHRS surveys: Evidence of radical changes triggered by human-induced river diversion". *Geophys. Res. Lett.*, 36, L09406, doi:10.1029/2008GL037136.

Viezzoli, A., Christiansen, A.V., Auken, E., and Sørensen, K. (2008). "Quasi-3D modeling of airborne TEM data by spatially constrained inversion", *Geophysics*, 73, F105–F113, doi:10.1190/1.2895521.

Viezzoli, A., Tosi, L., Teatini, P., and Silvestri S. (2010). "Surface water–groundwater exchange in transitional coastal environments by airborne electromagnetics: The Venice Lagoon example". *Geophys. Res. Lett.*, 37, L01402, doi:10.1029/2009GL041572.

Zecchin, M., Baradello, L., Brancolini, G., Donda, F., Rizzetto, F., and Tosi, L. (2008). "Sequence stratigraphy based on high resolution seismic profiles in the late Pleistocene and Holocene deposits of the Venice area". *Marine Geology*, 253, 185–198.