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Surface water–groundwater exchange in transitional coastal environments by airborne electromagnetics: The Venice Lagoon example

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[1] A comprehensive investigation of the mixing between salt/fresh surficial water and groundwater in transitional environments is an issue of paramount importance considering the ecological, cultural, and socio-economic relevance of coastal zones. Acquiring information, which can improve the process understanding, is often logistically challenging, and generally expensive and slow in these areas. Here we investigate the capability of airborne electromagnetics (AEM) at the margin of the Venice Lagoon, Italy. The quasi-3D interpretation of the AEM outcome by the spatially constrained inversion (SCI) methodology allows us to accurately distinguish several hydrogeological features down to a depth of about 200 m. For example, the extent of the saltwater intrusion in coastal aquifers and the transition between the upper salt saturated and the underlying fresher sediments below the lagoon bottom are detected. The research highlights the AEM capability to improve the hydrogeological characterization of subsurface processes in worldwide lagoons, wetlands, deltas. **Citation:** Viezzoli, A., L. Tosi, P. Teatini, and S. Silvestri (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.

1. Introduction

[2] Understanding the hydrogeological processes is critical for a sound management of water resources in coastal areas. Wetlands, lagoons, and estuaries have unique flora and fauna depending on the groundwater-surface water processes. Here lies the majority of human settlements and industrial production. Moreover, human pressure on the environment is constantly increasing, and many studies predict a significant rising of seawater level.

[3] In order to have a better understanding of the surface-subsurface water exchange, it is crucial to acquire information both inland and within the lagoon or wetland, covering both its permanent wet areas and the tidal flats. The investigation of coastal surficial-groundwater, i.e. salt-freshwater, exchange in a unique, consistent, and homogeneous framework is usually still a challenge. Generally, inland and offshore surveys are carried out separately and with different methodologies as a result of logistic difficulties. Borehole electrical conductivity (EC) measurements [e.g., *Kim et al.*, 2006], vertical electric soundings (VES) [e.g., *Wilson et al.*, 2006], electrical resistivity tomography (ERT) [e.g., *de Franco et al.*, 2009], and time-domain electromagnetic (TDEM) investigations [e.g., *Goldman et al.*, 1991; *Kontar and Ozorovich*, 2006] are usually performed on coastlands to understand the structure and evolution of the saline interface. Offshore, direct measurements such as seepage meters [e.g., *Shinn et al.*, 2002], benthic chambers [e.g., *Rapaglia*, 2005], and surface water enrichments in natural isotopic tracers [e.g., *Gattacceca et al.*, 2009] are often used to measure submarine groundwater discharge (SGD). Geophysical investigation, e.g. sediment resistivity profiling [e.g., *Breier et al.*, 2006] and towed geo-electrical array surveying [e.g., *Allen and Merrick*, 2007] are implemented to delineate salinity gradients below the sea bottom.

[4] Airborne electromagnetics (AEM) can greatly improve the data quality and coverage in tidal and coastal areas, lagoons, estuaries, and river deltas while significantly cutting the acquisition costs and time. The application of AEM for groundwater monitoring and modeling has been steadily rising in the past decade [e.g., *Steuer et al.*, 2009], due to parallel developments of better AEM systems together with processing and inversion methodologies. However, so far there have been extremely limited attempts of applying AEM to areas such as lagoons, wetlands, rivers or bays, mainly to recovery bathymetric data [e.g., *Vrbancich and Fullagar*, 2007]. Undeniably, the presence of a conductor like saline surface water decreases the penetration depth of the AEM signal. However, in the recent past, AEM systems have increased their magnetic moment, i.e., their penetrating power, and their data quality. This, together with advanced AEM modeling and inversion procedures, can produce quantitative results useful for groundwater modeling in these areas. We prove the suitability of the SkyTEM helicopter borne transient EM system [*Sørensen and Auken*, 2004] to investigate the surface water-groundwater exchange in transitional coastal environments with the application in an area at the southern margin of the Venice Lagoon, Italy (Figure 1a), where very shallow surface water (less than 1 m), tidal marshes, large rivers and several reclamation channels, together with a complex morpho-geo-hydrological setting have precluded an in-depth investigation up to date.

2. Airborne Electromagnetics

2.1. Methods

[5] Various airborne electromagnetics (AEM) systems are applied in hydrogeophysical investigations, e.g. the fixed wing transient (i.e., time domain) Tempest system [*Lane et al.*, 2000], the frequency domain systems Resolve

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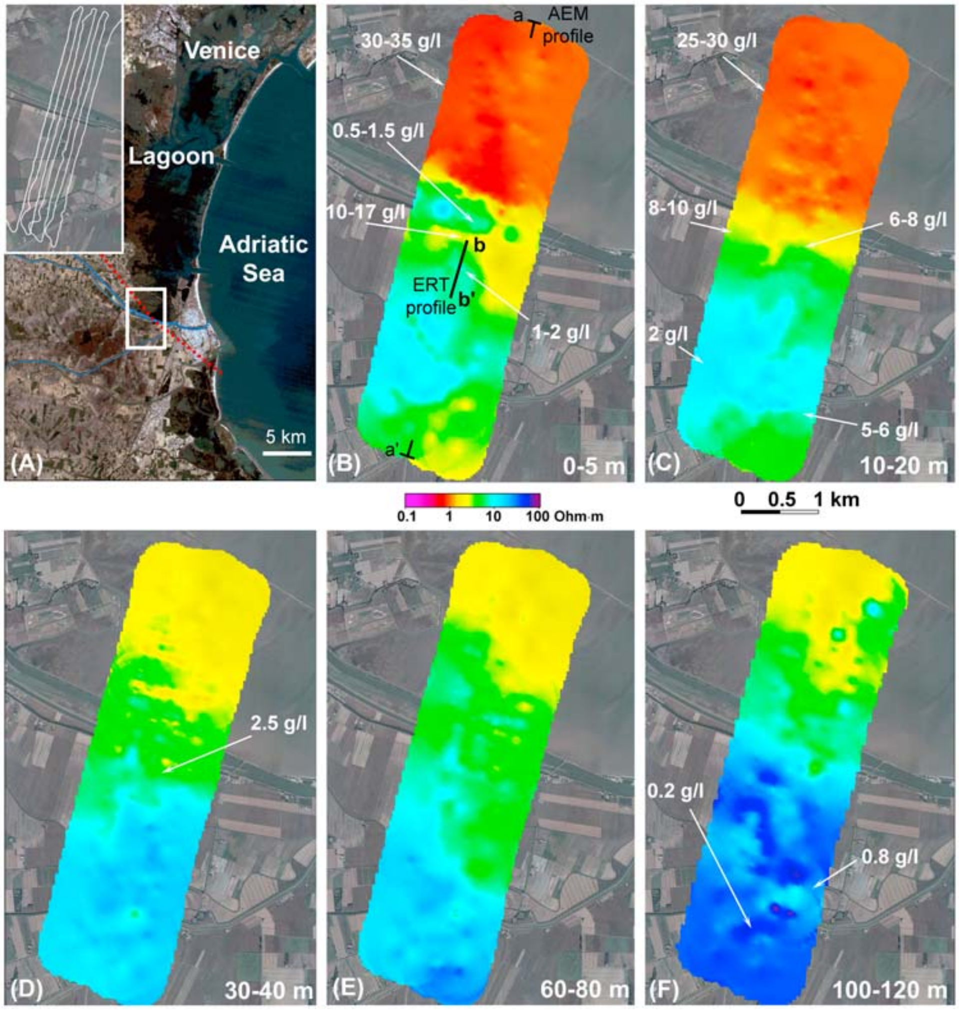

Figure 1. (a) Satellite image of the southern Venice Lagoon with the location of the investigated area. The position of the AEM survey is shown in the inset; the sampling interval of 2 s provides sampling distances of 25–30 m at a fly velocity of about 50 km/h. Average resistivity maps for the (b) 0–5, (c) 10–20, (d) 30–40, (e) 60–80, and (f) 100–120 m depth intervals obtained by the SkyTEM system in spring 2009. The salinity values measured in some boreholes scattered in the study area are shown in Figures 1b–1f according to the well depth. The red dotted alignment in Figure 1a represents the trace of a possible tectonic line.

from Fugro [*Mullen et al.*, 2007], the HEM system of BGR [*Siemon*, 2009], and the time domain helicopter EM systems like SkyTEM [*Sørensen and Auken*, 2004].

[6] In the SkyTEM 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. 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 then recorded by the receiver, another coil mounted above the frame. The raw data are therefore represented by the time decaying secondary magnetic field (dB/dt data), recorded almost continuously while the helicopter moves. Knowing the transfer function of the AEM system, which, involves its altitude, attitude, the full current waveform shape, the low pass filters, and so on, the dB/dt data can be inverted into geoelectric models.

[7] We chose to apply SkyTEM as its dual moment provides a bandwidth, i.e. a penetration range, from shallow to intermediate depths particularly suitable for our target. For this survey it had a magnetic moment of approximately 200000 Am^2. The excellent signal to noise ratio at late times due to the presence of the good conductor allowed using a base frequency of 12.5 Hz, permitting a better penetration depth. The nominal bird altitude is 30–40 m above the ground, or water.

[8] The AEM data are processed to eliminate the measurements affected by man made infrastructures, and to increase signal to noise ratio while preserving lateral resolution by applying time dependent trapezoid averaging filters [*Auken et al.*, 2008]. Data are then inverted using the Spatially Constrained Inversion (SCI) technique [*Viezzoli et al.*, 2008]. In semilayered environments the SCI increases the resolution of the models at both the upper and the lower boundary of the system penetration range, enforcing the expected degree of spatial horizontal coherency. It is there-

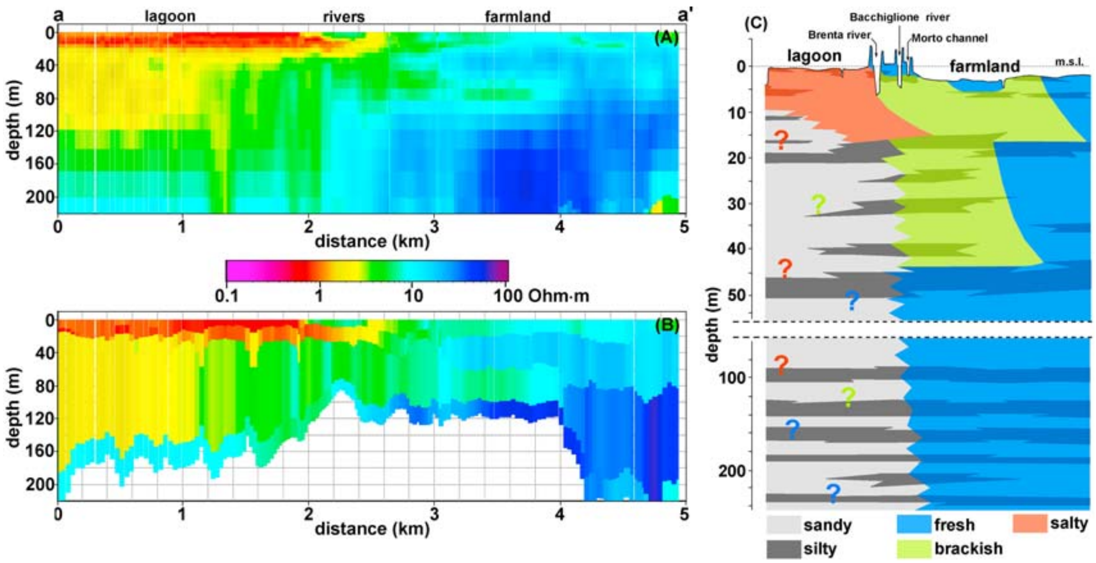

Figure 2. (a) Multi-layer and (b) few layer cross sections for one line of the AEM survey orthogonal to the lagoon margin. (c) Hydrogeological setting of the test site after *de Franco et al*. [2009] with the question marks indicating a lack/uncertainty of water quality information. Comparison between the AEM section (see Figure 1b) and the hydrogeological sketch shows a good correspondence below the farmland down to 50–60 m depth. Below 80–100 m depth, AEM supports the fresh water occurrence in the mainland even if the system is not capable to resolve the lithostratigraphic series. The transition between the resistivity units with ρ smaller and larger than 1 Ohm · m corresponds to the 20 m deep impermeable deposits representing the Pleistocene continental–Holocene marine boundary [*Tosi et al.*, 2009a, 2009b].

fore perfectly suitable for this application, where both near surface and deep information are important for refining the hydrogeological model. Both multi (smooth) and few layers (blocky) models are used. Transmitter altitude is also inverted for, as the laser altimeters often produce erratic readings over surface water.

2.2. Survey at the Venice Lagoon Margin

[9] The test area, comprising about 50 line km, extends over a portion of the southern lagoon and the farmland (Figure 1a). This part of the Venice territory, which is devoted to agricultural activity, seriously suffers from land degradation due to salt water intrusion in connection with relative sea level rise, i.e. eustacy and land subsidence [*Teatini et al.*, 2007]. Although research had already been carried out in this area, we chose to test here the SkyTEM capability because of the complex interplay between groundwater, and lagoon and river surficial waters. Moreover the outcomes from previous hydrological studies provide the dataset for the validation of the AEM survey.

[10] We present the results of the inversion of AEM data both as horizontal average resistivity maps at different depth intervals (from the multi-layered models results), and as vertical cross sections (few and multi-layer). The data fit was below noise level over vast majority of the survey area.

[11] The average resistivity maps at 0–5, 10–20, 30–40, 60–80, and 100–120 m depth intervals are shown in Figures 1b–1f. 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 Figures 2a and 2b points out that ρ never exceeds 10 Ohm · m down to about 200 m. An interesting feature in the near surface of the lagoon is the more conductive zone ($\rho \approx 0.5$ Ohm · m) in correspondence with tidal marshes. The 0.5 km wide coastland just south of the lagoon margin is characterized by the highest ρ variability. The resistivity reaches its minimum values (ρ = 1–2 Ohm · m) within the 10–20 m depth layer and increases to 8 Ohm · m both upward at the ground surface and downward to about 100 m depth. Below this depth ρ significantly differs (from 5 to 30 Ohm · m) in the lagoon and the inland sides (Figures 2a and 2b). In the inland area two distinct layers with relatively low ρ (about 5 Ohm · m) are detected (Figures 2a and 2b) from the ground surface down to 20 m depth (Figures 1b and 1c) and within the 60–80 m depth interval (Figure 1e). Their landward intrusion is highly variable to a maximum of about 2 km from the lagoon margin. In the other portions of the farmland subsoil, the resistivity has a large increase, up to 70 Ohm · m.

3. Discussion

3.1. Hydrogeological Setting

[12] The hydrogeological setting of the study area is known, mainly in the inland part, from researches carried out over the last few years [*de Franco et al.*, 2009]. The mainland is characterized by low-lying farmland, markedly below the mean sea level (3–4 m) and keep drained by pumping stations. The soil is often rich in organic matter even if some sandy exposed and buried features occur (e.g., paleochannels).The investigated subsoil is the upper 220 m depth of the regional multi-aquifer system underlying the overall Venice plain. The upper 50 m depth are composed of a 15 m thick phreatic aquifer and locally confined aquifers between 20 and 40 m depth characterized by a complex architecture due to the presence of lateral heteropies and vertical transitions. Confined aquifers developed at the regional scale below 50 m depth (Figure 2c).

[13] *de Franco et al*. [2009] investigated the extent of the salt water intrusion in this area using electrical resistivity

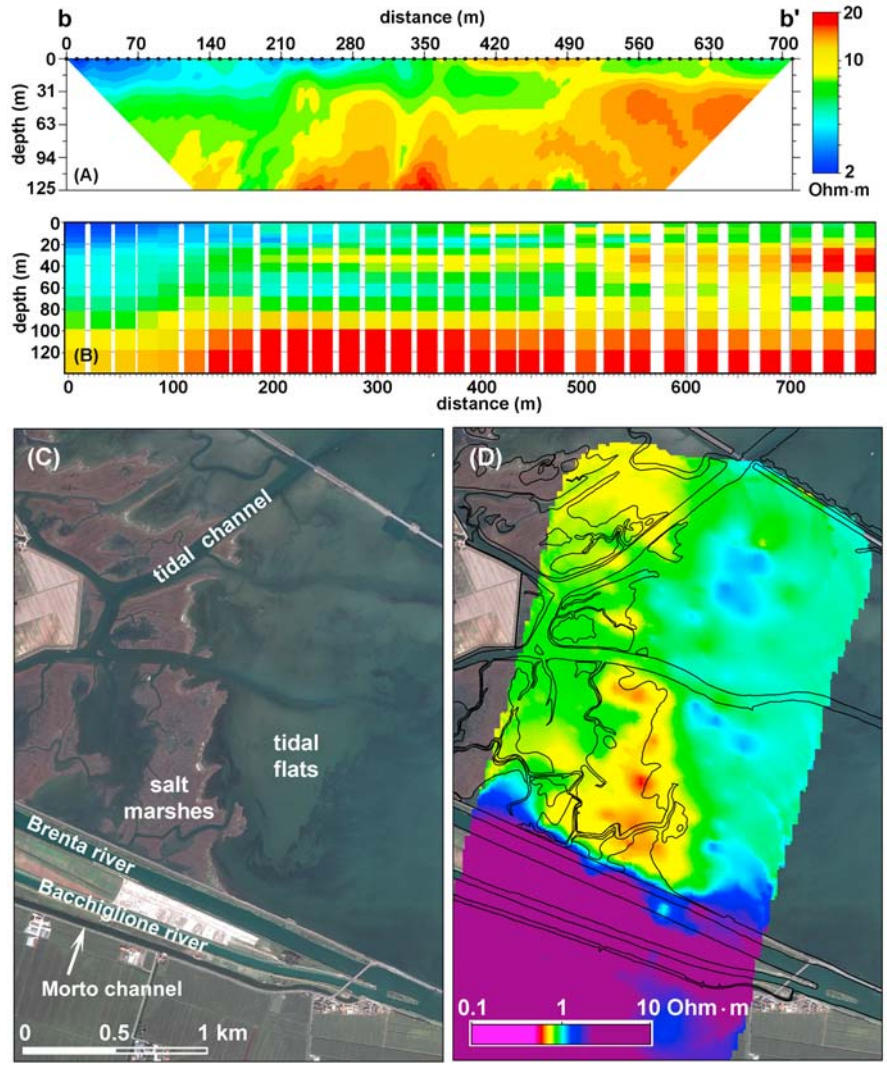

Figure 3. Comparison between (a) an ERT tomography and (b) the corresponding inversion results of SkyTEM along the b-b′ profile shown in Figure 1b. Note that data were acquired over different times. The ERT section is provided after *de Franco et al.* [2009]. (c) Satellite image of the salt marsh zone located in the study area and (d) average resistivity maps for the 0–5 m depth. Tidal zones are characterized by the lowest resistivity (highest salinity) within the lagoon area.

tomography (ERT) and water conductivity and level measurements in a few boreholes and monitoring points in the watercourses. Their results show that seawater intrusion seriously affects the upper 20 m depth and is characterized by a certain seasonal fluctuation whose dynamics is very sensitive to the extent of the seawater encroachment along the river mouths, and hence the riverbed seepage. Other important factors are the ground surface below mean sea level, the presence of several sandy paleo-channels crossing the farmland with a main direction from inland to the lagoon boundary [*Tosi et al.*, 2009a] and the climatic conditions, i.e. rainfalls and tidal regime.

[14] The lagoon sector is characterized by salt marshes, shallows (0.5–1 m deep), and few deeper channels connecting the inner lagoon to the Adriatic Sea. The lagoon bottom is usually composed by a 1–2 m thick unconsolidated silty-sand layer below which the clay and sand alternation is correlated with the regional facies [*Tosi et al.*, 2009a]. No information concerning the groundwater quality is available below the lagoon bottom.

3.2. Interpretation

[15] A first major result of the AEM survey in the study area concerns the assessment of the salt plume from the lagoon bottom to the farmland subsoil. The salt water intrudes from the lagoon margin, passing underneath the rivers and canals, and extends for about 2 km. The canals and rivers, in turn, recharge the aquifers and push down the salty water. The subsoil is contaminated down to 80 m depth with an alternation of fresher (resistive layer) and saltier waters (conductive layer). Figures 1b–1f shows a satisfactory agreement between the salinity values measured in some boreholes scattered in the study area and the results of the AEM survey.

[16] The SkyTEM acquisition in this area superposes with the ground based ERT survey carried out in 2006 [*de Franco et al.*, 2009]. Despite the fact that some time separates the two surveys, they compare very well identifying the same main conductive and resistive structures (Figures 3a and 3b). The AEM penetrates deeper than the ERT, which, in turn, displays higher lateral resolution.

[17] In opposition with general regional understanding, no fresh water has been detected below this portion of the lagoon bottom down to 150–180 m depth although the occurrence of fresh confined aquifers have been confirmed by several deep boreholes drilled in the past around the lagoon for drinking purposes. This surprising result is likely to be connected with the occurrence of a tectonic line [*Tosi et al.*, 2009b] that can act as preferential way for the upward migration of salty paleo-waters [*Di Sipio et al.*, 2006]. The saltiest 15 to 20 m thick upper layer in the lagoon corresponds to the Holocene deposits that are characterized by marine and lagoon-back barrier sediments more permeable and less compacted than the deeper alluvial ones [*Tosi et al.*, 2009a].

[18] AEM provides also interesting local features. Within the lagoon, the tidal areas are characterized by the highest salinity. This is probably due to extensive evaporation that takes place in patches of vegetation resting over the salt marshes and tidal flats that concentrates the salts in the sediments underneath the vegetation (Figure 4). The quasi-3D resistivity model obtained by AEM allows to map local complex hydro-geo-morphological structures also inland. An example is the resistivity anomaly clearly visible in the farmland centre of Figure 1b that corresponds to a salt contaminated paleoriver.

[19] The above results show the capability of AEM to provide 3D large-scale views of subsurface water and soil characteristics. From a general perspective, this has a strong hydrogeological relevance to define conceptual models (e.g. characteristic geometries, boundary conditions, major natural and anthropogenic forcing factors) representative of the actual subsurface system. Quantitative data can be used by hydrogeologists for process interpretation and hydrologic modelers for calibrating density dependent flow and transport numerical models.

4. Conclusions

[20] The study area is a transitional environment particularly complex from the hydro-geo-morphological point of view. As in many other lagoons and wetlands all over the world the knowledge of marine-continental water exchanges is of paramount importance for the understanding of hydrogeological processes in these unique ecological environments.

[21] It is evident that AEM provides valuable information of ground and surface water salinity, and their interaction, contributing significantly to the overall understanding of the hydrogeology in these delicate areas. The low base frequency of the SkyTEM, the inversion of the transmitter height, and the use of SCI allowed to obtain deeper penetration and spatially coherent models.

[22] In the Venice Lagoon, the SkyTEM system identifies the transition between salt saturated and fresher sediments inland and below the lagoon with an extreme benefit for the comprehension of the processes obtained by acquiring data both over water and land. Major results in this area are the unexpected absence of fresh waters in the confined aquifer system below this limited portion of the lagoon basin and the clear evidence of the role exerted by the rivers bounding the lagoon margin in mitigating the salt contamination plume from the lagoon.

[23] Concluding, AEM appears as a promising and powerful additional tool for the hydrogeological characterization of large fresh-salt transitional environments such as wetlands, lagoons, deltas.

[24] **Acknowledgments.** The SkyTEM survey has been supported by SkyTEM Aps, Aarhus Geophysics ApS, and M.A.R.TE. S.r.l.

References

Allen, D., and N. Merrick (2007), Robust 1D inversion of large towed geo-electric array datasets used for hydrogeological studies, *Explor. Geophys.*, *38*(1), 50–59, doi:10.1071/EG07003.

Auken, E., A. V. Christiansen, L. H. Jacobsen, and K. I. Sørensen (2008), A resolution study of buried valleys using laterally constrained inversion of TEM data, *J. Appl. Geophys.*, *65*, 10–20, doi:10.1016/j.jappgeo.2008.03.003.

Breier, J. A., C. F. Breier, and H. N. Edmonds (2005), Detecting submarine groundwater discharge with synoptic surveys of sediment resistivity, radium, and salinity, *Geophys. Res. Lett.*, *32*, L23612, doi:10.1029/2005GL024639.

Carbognin, L., P. Teatini, A. Tomasin, and L. Tosi (2009), Global change and relative sea level rise at Venice: what impact in term of flooding, *Clim. Dyn.*, doi:10.1007/s00382-009-0617-5, in press.

de Franco, R., et al. (2009), Saltwater intrusion monitoring by time lapse electrical resistivity tomography, *J. Appl. Geophys.*, *69*, 117–130, doi:10.1016/j.jappgeo.2009.08.004.

Di Sipio, E., A. Galgaro, and G. M. Zuppi (2006), New geophysical knowledge of groundwater systems in Venice estuarine environment, *Estuarine Costal Shelf Sci.*, *66*, 6–12, doi:10.1016/j.ecss.2005.07.015.

Gattacceca, J. C., C. Vallet-Coulomb, A. Mayer, C. Claude, O. Radakovitch, E. Conchetto, and B. Hamelin (2009), Isotopic and geochemical characterization of salinization in the shallow aquifers of a reclaimed subsiding zone: The southern Venice Lagoon coastland, *J. Hydrol.*, *378*, 46–61, doi:10.1016/j.jhydrol.2009.09.005.

Goldman, M., D. Gilad, A. Ronen, and A. Melloul (1991), Mapping of seawater intrusion in the coastal aquifer of Israel by the time domain electromagnetic method, *Geoexploration*, *28*, 153–174, doi:10.1016/0016-7142(91)90046-F.

Kim, K.-Y., H. Seong, T. Kim, K.-H. Park, N.-C. Woo, Y.-S. Park, G.-W. Koh, and W.-B. Park (2006), Tidal effects on variations of fresh–saltwater interface and groundwater flow in a multilayered coastal aquifer on a volcanic island (Jeju Island, Korea), *J. Hydrol.*, *330*, 525–542, doi:10.1016/j.jhydrol.2006.04.022.

Kontar, E. A., and Y. R. Ozorovich (2006), Geo-electromagnetic survey of the fresh/salt water interface in the coastal southeastern Sicily, *Cont. Shelf Res.*, *26*, 843–851, doi:10.1016/j.csr.2005.12.012.

Lane, R., et al. (2000), An example of 3D conductivity mapping using the TEMPEST airborne electromagnetic system, *Explor. Geophys.*, *31*, 162–172, doi:10.1071/EG00162.

Mullen, I. C., K. E. Wilkinson, R. G. Cresswell, and J. Kellett (2007), Three-dimensional mapping of salt stores in the Murray-Darling Basin, Australia, 2. Calculating landscape salt loads from airborne electromagnetic and laboratory data, *Int. J. Appl. Earth Obs. Geoinf.*, *9*, 103–115, doi:10.1016/j.jag.2006.08.005.

Rapaglia, J. (2005), Submarine groundwater discharge into Venice Lagoon, Italy, *Estuaries Coasts*, *28*(5), 705–713.

Shinn, E. A., C. D. Reich, D. Christopher, and D. T. Hickey (2002), Seepage meters and Bernoulli's revenge, *Estuaries*, *25*, 126–132, doi:10.1007/BF02696056.

Siemon, B. (2009), Levelling of helicopter-borne frequency-domain electromagnetic data, *J. Appl. Geophys.*, *67*, 206–218, doi:10.1016/j.jappgeo.2007.11.001.

Sørensen, K. I., and E. Auken (2004), SkyTEM—A new high-resolution helicopter transient electromagnetic system, *Explor. Geophys.*, *35*, 191–199, doi:10.1071/EG04194.

Steuer, A., B. Siemon, and E. Auken (2009), A comparison of helicopter-borne electromagnetics in frequency- and time-domain at the Cuxhaven valley in Northern Germany, *J. Appl. Geophys.*, *67*, 194–205, doi:10.1016/j.jappgeo.2007.07.001.

Teatini, P., T. Strozzi, L. Tosi, U. Wegmüller, C. Werner, and L. Carbognin (2007), Assessing short- and long-time displacements in the Venice coastland by synthetic aperture radar interferometric point target analysis, *J. Geophys. Res.*, *112*, F01012, doi:10.1029/2006JF000656.

Tosi, L., F. Rizzetto, M. Zecchin, G. Brancolini, and L. Baradello (2009a), 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.

Tosi, L., P. Teatini, L. Carbognin, and G. Brancolini (2009b), Using high resolution data to reveal depth-dependent mechanisms that drive land subsidence: The Venice coast, Italy, *Tectonophysics*, *474*(1-2), 271–284, doi:10.1016/j.tecto.2009.02.026.

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

Vrbancich, J., and P. K. Fullagar (2007), Improved seawater depth determination using corrected helicopter time-domain electromagnetic data, *Geophys. Prospect.*, *55*(3), 407–420, doi:10.1111/j.1365-2478.2007.00602.x.

Wilson, S. R., M. Ingham, and J. A. Mc Conchie (2006), The applicability of Earth resisitivity methods for saline interface definition, *J. Hydrol.*, *316*, 301–312, doi:10.1016/j.jhydrol.2005.05.004.

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