sessione 3.1

Applicazioni della Geofisica all'Ingegneria, ai Beni Culturali e all'Ambiente

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GROUNDWATER INVESTIGATION IN LAGOON SUBSURFACE WITH AIRBORNE ELECTROMAGNETICS: THE VENICE LAGOON SKYTEM SURVEY EXAMPLE

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Introduction. Understanding the hydrogeological processes is critical for a sound management of groundwater resources in costal areas. Here lie majority of human settlements, industrial production, and fish farming. Human pressure on the coastland environment is constantly increasing, and many studies predict a rising of seawater level in the next 50 years raging from few cm up to several tens of cm, with expected threatening consequences (e.g., Carbognin et al., 2009). If these are common characteristics of most costal areas, wetlands, lagoons and estuaries also have often unique flora and fauna depending on the groundwater-surface water processes. 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. In particular, in the Venice area numerous geomorphological features representing i.e. fluvial paleoriver beds, ancient tidal channels, and paleobeach ridges occur (Tosi et al., 2009). These features are generally filled by sandy deposits and can be considered preferential path for the groundwater flow, both in the horizontal and vertical directions.

In order to have a better understanding of the hydrogeological setting of these areas, and also to produce more useful models, it is crucial to acquire information both inland and within the lagoon or wetland, covering both its permanent wet and tidal areas. Acquiring information that can be used to model the groundwater processes of these areas is often logistically challenging and therefore expensive and slow. This applies both to punctual, invasive and direct measurements such as depth to groundwater table and salinity from boreholes, to non invasive, area covering, indirect data such as resistivity or seismic investigations. Apart from the logistics, in many cases the quality of the data reflects the spatial and or temporal alternation of dry land and ponds-marshes-surface water in general. Airborne electromagnetics (AEM) can greatly improve the data quality and coverage in such areas, while cutting significantly the acquisition costs. Its direct output is geoelectrical cross sections or maps that are then used as input for hydrogeological models. The application of AEM for groundwater monitoring and modeling has been steadily rising in the past decade, due to parallel developments of better AEM systems and processing, e.g. inversion methodologies. However, so far there have been extremely limited attempts of applying AEM to areas such as lagoons, wetlands, rivers or bays. This manuscript shows that AEM can produce quantitative results useful for groundwater modeling also in these areas, presenting the results of a survey carried out in the central and southern sectors of the Venice Lagoon, Italy, by the SkyTEM system.

We present some of the inversion outcome as horizontal average resistivity maps at different depth intervals and cross sections obtained by SkyTEM application in the two areas where different hydrogeological processes are under investigation.

Results of the AEM survey. The SkyTEM system is often used for groundwater mapping. Examples of other systems often applied in hydrogeophysical investigations include the fixed wing transient (i.e., time domain) Tempest system, and the frequency domain helicopter borne systems Resolve from Fugro and a DiGHEM alike from BGR. SkyTEM was chosen as its dual moment provides a bandwidth, i.e., a penetration range (from shallow to intermediate depths) suitable for this particular target. The excellent signal to noise ratio at late times due to the presence of the good conductor allows for using a base frequency of 12.5 Hz, thus reaching deeper penetration than usual. Data are processed to eliminate artifacts and assign noise levels at late times, and stacked to increase signal to noise ratio while preserving lateral resolution. They are then inverted starting from a homogeneous half space, using the Spatially Constrained Inversion (SCI) technique (Viezzoli et al., 2008). In semi-layered geologic sequences, the SCI increases the resolution of the models at both the upper and the lower boundary of the penetration range of the system, thus enforcing a degree of spatial horizontal coherency. It is therefore perfectly suitable for this application, where both near surface and deep information are important for refining the hydrogeological model.

The central area, comprising about 100 line km of data, is located completely over water, just a few km southwest of the city of Venice. In this area the main objectives are to confirm the presence of fresher water underneath the lagoon saline water, and to identify potential areas of discharge of fresh groundwater into the lagoon.

The southern area, totalling 50 line km, extends in equal length over the lagoon and the dry land. In this case the focus is on the saltwater intrusion in the coastal aquifers, and possibly on tidal lands at the lagoon margin. The records are first processed to eliminate the data affected by infrastructures, and to increase signal to noise ratio while preserving lateral resolution and then inverted using the SCI. We used both multi- (smooth) and few layers (blocky) model. In almost-layered subsoils, the SCI can improve the inversion output with respect to other methodologies, especially at depth and near surface. Transmitter altitude is also inverted as the laser altimeters often produce erratic readings over surface water. Failure to do so would, in many cases, produce artifacts in the hydrogeological models that account for the wrong altitude. We present some of the inversion outcome as horizontal average resistivity maps at different depth intervals, and vertical cross sections. Fig. 1 shows the results of the central survey for the depth intervals between 20 and 30 m and from 40 to 60 m.

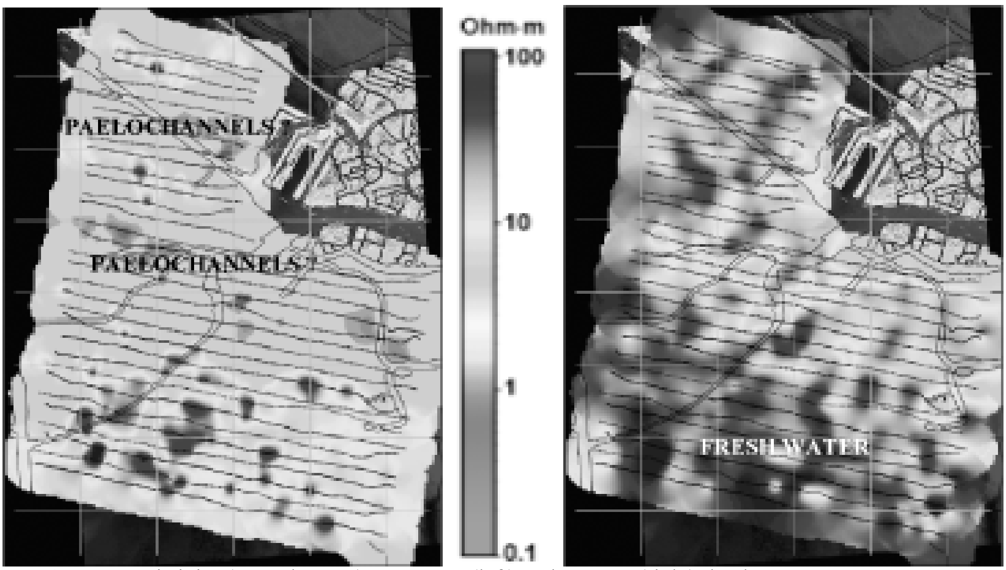

Fig. 1 - Average resistivity (central sector) at 2030 m (left) and 4060 m (right) depths.

The average resistivity maps (of which only few are presented here) display many interesting features. The most superficial map shows an interesting correspondence between more conductive patterns and the deeper channels in the lagoon. There is a clear increase in resistivity below 5 m, with zones of resistivity larger than 30 ohm◊m start appearing from 20 m depth. The strata down to about 40 m show distinct conductive features extending in the west-east direction. Most of these structures are probably linked to paleochannels, which control the dynamics of the groundwater flow under the lagoon. Below 30 m depth, high resistivity sectors point out the presence of fresh water seeps. The layers down to about 160 m are usually resistive, with exception of few deep conductive anomalies in the eastern part of the survey. The vertical variations are more evident in the cross sections. In general, they reveal a 3 to 4 layers model, with a conductive 3-10 m thick first layer (resistivity ρ < 0.5 Ohm · m) representing lagoon water plus saturated loose sediments overlaying a transition zone (1 Ohm · m < ρ <10 Ohm · m) of varying thickness (probably more compacted sediments). Then, there is a thick more resistive layer (30 Ohm · m < ρ < 80 Ohm · m) that implies the presence of fresher water underneath the lagoon, at moderate depths. The main exception to this general pattern is given by more extended layers of intermediate resistivity, mainly detected along the eastern portion of the central profiles, representing zones of extended mixing.

The southern study area is particularly complex from the hydrogeological point of view due to the morphological setting, a land elevation markedly below the mean sea level, reclaimed zones rich in organic matter, and watercourses with the bed above the surrounding farmland. Within the lagoon, interesting structures, e.g. conductive features, are detected in the near surface in correspondence with the location of patches of vegetation resting over the tidal areas (salt mashes and tidal flats). This is probably due to extensive evaporation that takes place in these areas and concentrates the salts in the sediments underneath the vegetation. A conductive zone representing shallow salt water intrusion infiltrates landward from the lagoon margin. This zone reduces westward due to a resistive area close to the rivers and canals. The latter have a distinctive decrease in resistivity towards the east. Intermediate depth slices show the initial extension and then retreat of the conductive layer inland. The sediments below the lagoon gradually decrease in conductivity with depth, and also display paleochannel like features elongated in the west-east direction. The vertical cross sections (see an example in Fig. 2) very clearly show the shallow conductive layer (salt water intrusion) protruding inland, passing underneath the rivers and canals. The canals and rivers, in turn, recharge the aquifers and push down the salty water. Fig. 2 also shows a thick layer of intermediate resistivity (i.e., fresher water) below the lagoon, and an alternation of resistive (fresher water) and conductive (saltier water) layers under the land. The conductive first layer in the lagoon is thicker (15 to 20 m) than the one in the central area, in agreement with the general understanding of the interface depth between shallow lagoon / back barrier sediments and the dipper, older, and more compacted alluvial ones. The SkyTEM acquisition in this area superposes with a ground based ERT

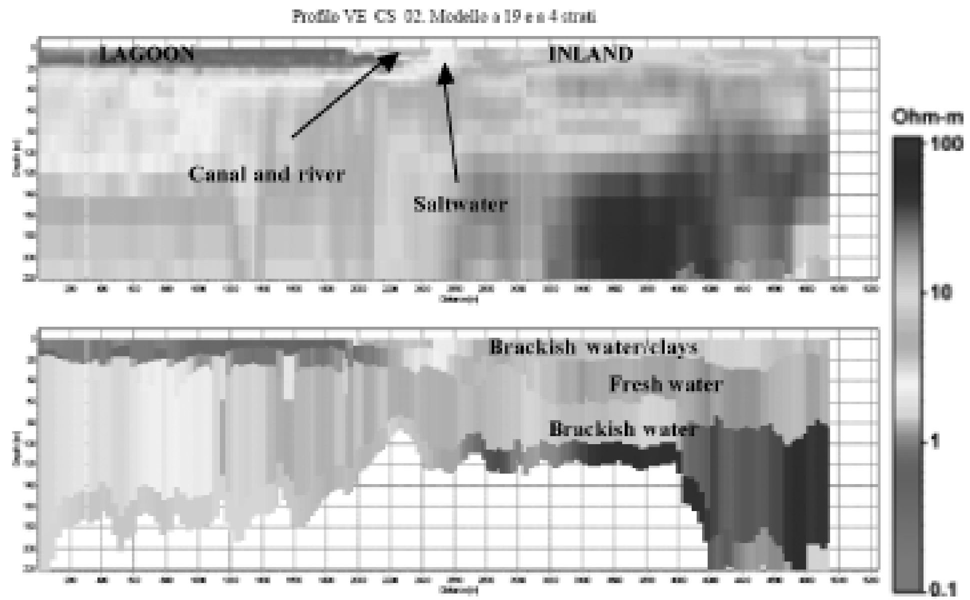

Fig. 2 - Vertical cross sections (multi and few layers) for one line of southern survey area across the lagoon boundary.

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. AEM data penetrate deeper than the ERT, which, in turn, displays higher lateral resolution.

Discussion. It is evident that AEM provides valuable information over ground and surface water salinity, and their interaction, contributing significantly to the overall understanding of the hydrogeology in these delicate areas. In the Venice Lagoon, the AEM system identifies the transition between salt saturated and fresher sediments inland, and the interface between surface and groundwater (i.e., the bathymetry) over the lagoon. This is little surprise, as the lagoon is very shallow, and there isn't enough information in the data regarding the thickness of the water column. Note that it is extremely beneficial to acquire data both over water and land, like it was done in the southern area. By doing this, it is possible to acquire a clearer comprehension of the processes between surface waters and groundwater at the coast, but also, thanks to the spatially constrained inversion, resolves better the layers underneath the lagoon.

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INDIVIDUAZIONE DI DISOMOGENEITÀ LATERALI ATTRAVERSO IL MULTI-OFFSET PHASE ANALYSIS DI ONDE SUPERFICIALI

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Introduzione. I metodi di analisi delle onde superficiali si basano sull'inversione delle curve di dispersione delle onde di Rayleigh. L'obiettivo è di stimare il profilo delle velocità delle onde S. Il modello che viene usato per l'interpretazione è 1D, e quindi i risultati che si ottengono ogniqualvolta siano presenti variazioni laterali non può essere considerato affidabile. In questo lavoro sono considerati modelli di sottosuolo in cui sono presenti eterogeneità laterali. Tutte le volte che l'intero sismogramma viene elaborato con l'approccio tradizionale (basato sull'analisi *f-k*), si ottiene un profilo 1D rappresentativo della parte di modello di maggiore estensione. Questo risultato mostra che l'analisi tradizionale trascura le variazioni laterali anche quando sono chiaramente presenti nel sismogramma grezzo. In questa ricerca è stato implementato un metodo innovativo (basato sul recente *Multi-Offset Phase Analysis*) che verifica l'assunzione di monodimensionalità e individua la posizione delle eventuali discontinuità laterali. Una volta che le discontinuità sono identificate si può procedere con la tradizionale estrazione ed inversione della curva di dispersione, separatamente per ogni lato della discontinuità; affiancando i profili 1D così ottenuti si ottiene una ricostruzione della distribuzione bidimensionale di velocità delle onde S, senza alcun'ipotesi supplementare.

Multi-Offset Phase Analysis (MOPA). Si consideri il caso in cui il sottosuolo sia composto da strati: orizzontali, dissipativi, isotropi, e omogenei, limitati superiormente dalla superficie libera e, nella parte inferiore, da un semispazio isotropo. In questa situazione la risposta del sistema in termini di onde superficiali può essere descritta (nel dominio delle frequenze) dalla sovrapposizione dei contributi dei diversi modi (Aki and Richards, 2002):