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Subsoil architecture and morphological setting shaping the saltwater intrusion in the coastal plain south of the Venice lagoon, Italy

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RESUMEN

Procesos de salinización en suelos y acuíferos someros afectan la región sur de Venecia (Italia), abarcando una franja litoral del Adriático de hasta 20 km. En este caso, la contaminación por agua salada no se debe al bombeo intensivo, sino que está condicionada por otros factores tales como la elevación del terreno, las estructuras geológicas, el ingreso de la marea, las condiciones climáticas y las prácticas de drenaje implementadas en zonas recuperadas. El objetivo del trabajo es generar un modelo conceptual del proceso de contaminación salina que muestre los mecanismos de intercambio de agua dulce y salada. Los resultados muestran que la profundidad de la interfaz de agua dulce – salada varía de 1 a 30 m por debajo del nivel del suelo y presenta variaciones principalmente de tipo estacional. La salinización en el suelo es sensible a los cambios en la descarga de los ríos (Brenta, Bacchiglione, Adige, Gorzone) y en los niveles del agua subterránea y canales, los cuales están regulados por el bombeo y las condiciones climáticas. Estructuras geomorfológicas relictas, con sedimentos de alta permeabilidad, pueden facilitar la intrusión salina, o por el contrario, actuar como reservorio de agua dulce proporcionada por las precipitaciones, el riego o canales.

Palabras clave: contaminación salina, morfología costera, estructuras hidrogeológicas, Venecia.

ABSTRACT

The southern catchment of the Venice watershed (Italy) is threatened by shallow aquifer and soil salinization. The saltwater may extend inland up to 20 km from the Adriatic coastline and deepen down to some tens of meters. Here, saltwater contamination is driven by other forcing factors than excessive pumping, such as ground elevation, buried geological structures, tide encroachment along watercourses, climate and tide conditions, and drainage practices implemented in reclaimed areas. This work aims to outline a conceptual model of the saltwater contamination highlighting the mechanisms driving the saltwater-freshwater exchanges. Results show that the fresh/salt-water interface depth varies from 1 to 30 m below the ground level and exhibits a significant, mainly seasonal, time variation. The dynamics of the soil salinization process is especially sensitive to changes in river (Brenta, Bacchiglione, Adige, Gorzone) discharges, groundwater and channel levels, which are regulated by a number of pumping stations, and climate conditions. Relict geomorphological features, filled with high permeability sediments, act as preferred pathways for groundwater flow and solute transport. In fact they provide a hydraulic connection between freshwater aquifers and sea, possibly facilitating saltwater intrusion landward or, conversely, acting as reservoir of freshwater provided by precipitation, irrigation, percolation through channel beds.

Keywords: Saltwater contamination, coastal morphology, hydrogeological structures, Venice.

1 INTRODUCTION

Understanding the mixing between salt/fresh surficial water and groundwater in lagoons and coastal wetlands all over the world is an issue of paramount importance considering the ecological, cultural, and socio-economic relevance of coastal plains. Moreover, fresh groundwater in coastal aquifers is vital for the community and ecosystems. In view of the expected climate changes, coastal fresh aquifers are becoming strategically important for water supply (e.g., Pousa et al. 2007; Tosi et al. 2013). Due to the relative sea level rise, precipitation decrease and groundwater withdrawal, a noteworthy saltwater intrusion in shallow aquifers with low hydraulic gradients has occurred along many worldwide coastal plains (Barlow, 2003; Narayan et al. 2003; Giambastiani et al. 2007; Carbognin et al. 2009).

The coastland surrounding the Venice Lagoon (Fig. 1) is a precarious environment subject to both natural changes and anthropogenic pressures. A number of critical problems affect this low-lying area, i.e. land subsidence, periodic flooding during severe winter storms, and saltwater intrusion (e.g., Carbognin et al. 2010). 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 impacts. In particular, saltwater intrusion threats drinking water quality, enhances the risk of soil desertification, compromises the agricultural practices, and decreases freshwater storage capacity (e.g., Carbognin et al. 2006).

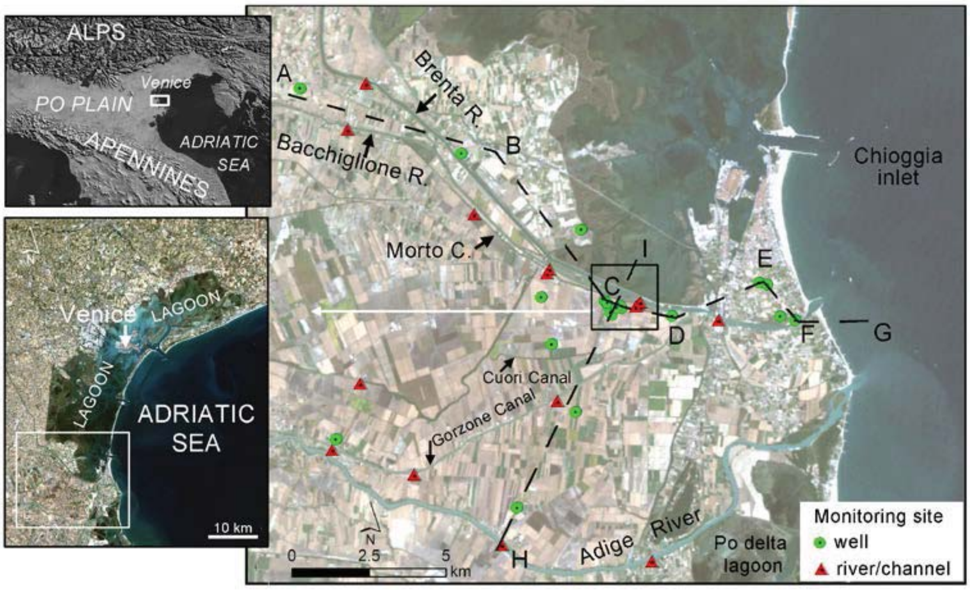

Figure 1 – Distribution of the monitoring sites superposed to a satellite image of the study area. The black dashed lines represent the trace along which the measurements have been processed. Landsat Image is obtained from U.S. Geological Survey's, Earth Resources Observation and Science (EROS) Center.

During the last decade a number of studies was undertaken to identify the area and the depth involved by the saltwater presence because of the various factors forcing the process, the dynamic of the saltwater contamination is not yet well known.

This work is aimed at quantifying the extent of the salt plume in the coastland surrounding the southern Venice Lagoon (Italy) and providing new informations to better understand the dynamics of the salinization process in relation to the potential forcing factors.

2 STUDY AREA SETTING

The investigated area is the coastal plain of Venice between the southern part of lagoon and the Adige River. The Brenta, Bacchiglione and Adige rivers, and the Cuori and Gorzone canals are the main watercourses. Moreover, in the farmlands lying below the mean sea level, a distributed drainage system collects the surficial water from a network of ditches and pumps the water excess into the lagoon, thus keeping the water table at levels suitable for farming.

The depth of interest corresponds to the upper 30 m thick subsoil, which is composed of late Pleistocene and Holocene sediments. The Late Pleistocene sedimentary record consists of an aggrading floodplain facies with fluvial channel fills accumulated during the decrease of the eustatic sea level, and is composed by silts, sands, and clays, frequently pedogenesized (Tosi et al. 2007a; Donnici et al. 2011; Zecchin et al. 2011). The boundary with the overlying Holocene units is often characterized by the presence of a paleosoil, locally named Caranto, developed in prolonged subaerial exposure and sedimentation starving conditions. The Caranto is mainly composed of very stiff clayey silts or silty clays and is relatively impermeable (Tosi, 1994; Tosi et al. 2007b). The Holocene deposit shows a rather complex sequence due to relative sea level and sediment supply changes and, over the last millennium, human-induced rivers diversions and engineering interventions (Tosi et al. 2009). The Holocene succession is up to 23 m thick and is composed of shoreface, deltaic, back barrier, and fluvial deposits, forming a transgressive-regressive cycle. The shore zone is mostly composed of marine to delta front/prodelta deposits, i.e. clays and silty clays, while in the coastal sector sands and silty sands of ancient littoral ridges and dunes occur. The mainland is characterized by a floodplain facies composed of silty-sand and clay sediments with organic matter connected to paleochannel systems and their inter-distributary zones, respectively.

Human interventions since the 15th century caused important modifications to the sedimentation dynamics, which led to significant morphologic changes. For instance, a large portion of the reclaimed marshy areas presently lies below the mean sea level, down to - 4m in the southernmost part of the Venice coastal plain (Rizzetto et al. 2003).

The heteropic relationships among littoral, deltaic, lagoon and alluvional deposits together with the natural and man-induced morphologic evolution of the Venice coastland, led to the development of a very complex hydrogeologic system. It includes un-confined, semi-confined and locally confined aquifers down to about 50 m depth. Beneath, a regional multi-aquifer confined system develops (Da Lio et al. 2013).

The saltwater contamination extends inshore up to 20 km and the contaminant plume deepens from the near ground surface down to 30-50 m and locally to 100 m depth (Carbognin and Tosi, 2003). However, as the Caranto unit exhibits an important hydrogeologic function precluding the downward propagation of seawaters (Teatini et al. 2011), the salinity degree significantly reduces below 20-30 m depth, at least in some portions of the study area. The saltwater intrusion is generally connected to a land elevation below the mean sea level, the presence of several sandy paleo-channels, which enhance the groundwater flow from the lagoon to the farmland, and the sea water encroachment into the river mouths.

3 METHODS

The extent of the saltwater contamination plume between the southern Venice Lagoon and the Adige River has been systematically monitored since 1998. A first comprehensive image of this process was depicted in 2003 by means of hydrogeological and geophysical surveys (Carbognin and Tosi, 2003). From that time, a number of multidisciplinary monitoring campaigns (e.g., Viezzoli et al. 2010; Tosi et al. 2011; Fabbri et al. 2013) continuously provide data suitable for improving the hydro-mopho-geologic model to better understand the dynamics of the saltwater contamination (e.g., Tosi et al. 2007b; de Franco et al. 2009; Teatini et al. 2009).

As regards the data used in this study, we refer to the above mentioned works, including reference therein, and to new hydrologic surveys. These latter have been carried out in 2012 and 2013 in selected monitoring sites and are therefore representative of the present groundwater status.

In order to cost-effectively quantify the salinization extent at regional scale and its local dynamics, the saltwater contamination has been investigated measuring electrical conductivity (EC), temperature and water levels in wells, rivers and canals. The tidal regime and rainfalls have been monitored at the stations in Chioggia (www.venezia.isprambiente.it and www.adigeuganeo.it, respectively). Since in this portion of the Venice coastland the aquifer contamination by salty water seriously affects the agricultural activities, we refer the limit between freshwater and saltwater values to the tolerance limits for crops. Considering the characteristics of sands, rich in silt components in the study area, Carbognin and Tosi (2003) and Carbognin et al. (2006) identified three classes of the water quality: salty if EC exceeds 5 mS/cm, brackish if EC ranges between 2 and 5 mS/cm with salt concentration higher than 1 gr/l, and water unsuitable for irrigation purposes and fresh if EC is less than 2 mS/cm. The morphologic setting has been interpreted by a 20 m pixel digital elevation model (Gasparetto et al. 2012) from which two ground elevation profiles have been extracted.

4 DATA ANALYSIS

4.1 Analysis at regional scale

In order to quantify the extent of the saltwater contamination in phreatic and semi-confined aquifers, new and previous EC measurements carried out in wells have been analyzed. The EC logs representing the average situation for each monitoring sites have been selected and interpolated along two sections crossing the study area approximately in the West-East and North-South directions (Fig. 1).

In the littoral of Chioggia (E in Fig. 2a), a freshwater lens with EC ranging from 1 to 2 mS/cm and up to 15 m thick is stored in the sector where ground elevation is higher than the sea level. This lens floats on the saltwater, which intrudes both from the sea and the lagoon bottom (Fig. 2a).

Along the southernmost lagoon margin (D-B in Figs. 2a,b), the marine water infiltrates from the lagoon bottom and intrudes inland, passing underneath the Brenta and Bacchiglione rivers and the canals (Figs. 2a,b). In the proximity of lagoon margin, the EC spans from 20 to 40 mS/cm.

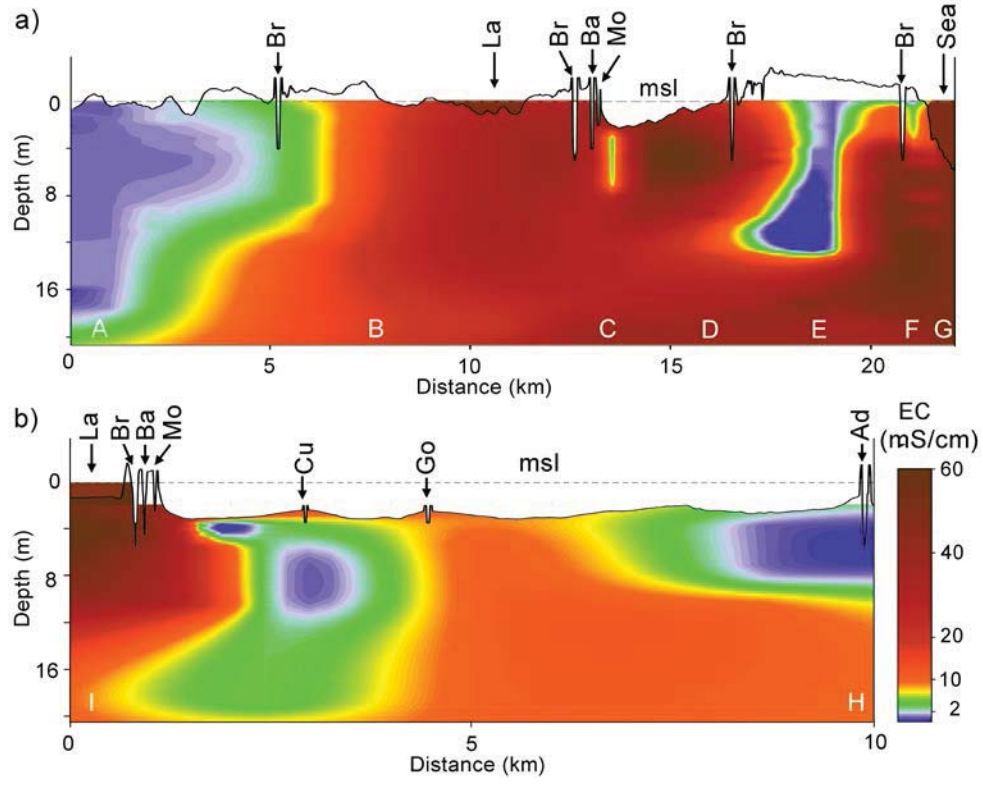

Figure 2 – Electrical conductivity cross sections (see traces and A-H positions in Fig. 1); lagoon (La); Brenta River (Br); Bacchiglione River (Ba); Cuori Cannel (Cu); Gorzone Cannel (Go); Adige River (Ad).

Towards the mainland, the salt contamination shows different behaviours in the areas west and south to the lagoon. In the former, the salinity rapidly decreases (EC values lower than 10 mS/cm) and to the west of the Brenta River (Fig. 2a) the continental freshwater flow begins to predominate (A in Fig. 2a). Conversely, in the farmlands between the Brenta and Adige rivers (I-H in Fig. 2b) the salt contamination persists (Fig. 2b), even though locally variable (EC ranges from 30 to 10 mS/cm). Some fresh and brackish groundwater occurrences (EC 0.5-5 mS/cm) are found alongside the watercourses. In fact, the Brenta, Bacchiglione rivers act in different way in the low-lying lands: they contaminate the aquifers by the seawater encroachment along the hanging last portion of the watercourses while slightly reduce the salinity when river discharges prevail on the tide encroachment.

A local contribute to the decreasing in the groundwater salinity is given by the freshwater seepage from the irrigation canals. Moving to the Adige River, the saltwater intrudes less from Venice Lagoon and more from the sea and the Po delta lagoons.

4.2 Dynamic of the process at local scale

The dynamics of the seawater contamination has been analyzed in specific sites where it is driven by multiple forcing factors resulting from the complexity of the hydro- geo- morphologic setting.

In the littoral of Chioggia the freshwater-groundwater dynamics is controlled by sea/lagoon and precipitations. The thickness of the freshwater lens seasonally fluctuates between 10 and 15 m (IS16 well, Fig. 3), depending on the amount of precipitation. Measurements recorded in IS15 well and in the BrBa1 surface water monitoring site (Fig. 3) show that next to the Brenta River, the river discharge (freshwater) and tide encroachment (saltwater) significantly influence the short term groundwater dynamics. High river discharge and high encroachment occurred in 2013 and 2003, respectively, as consequence of a wet and very dry season.

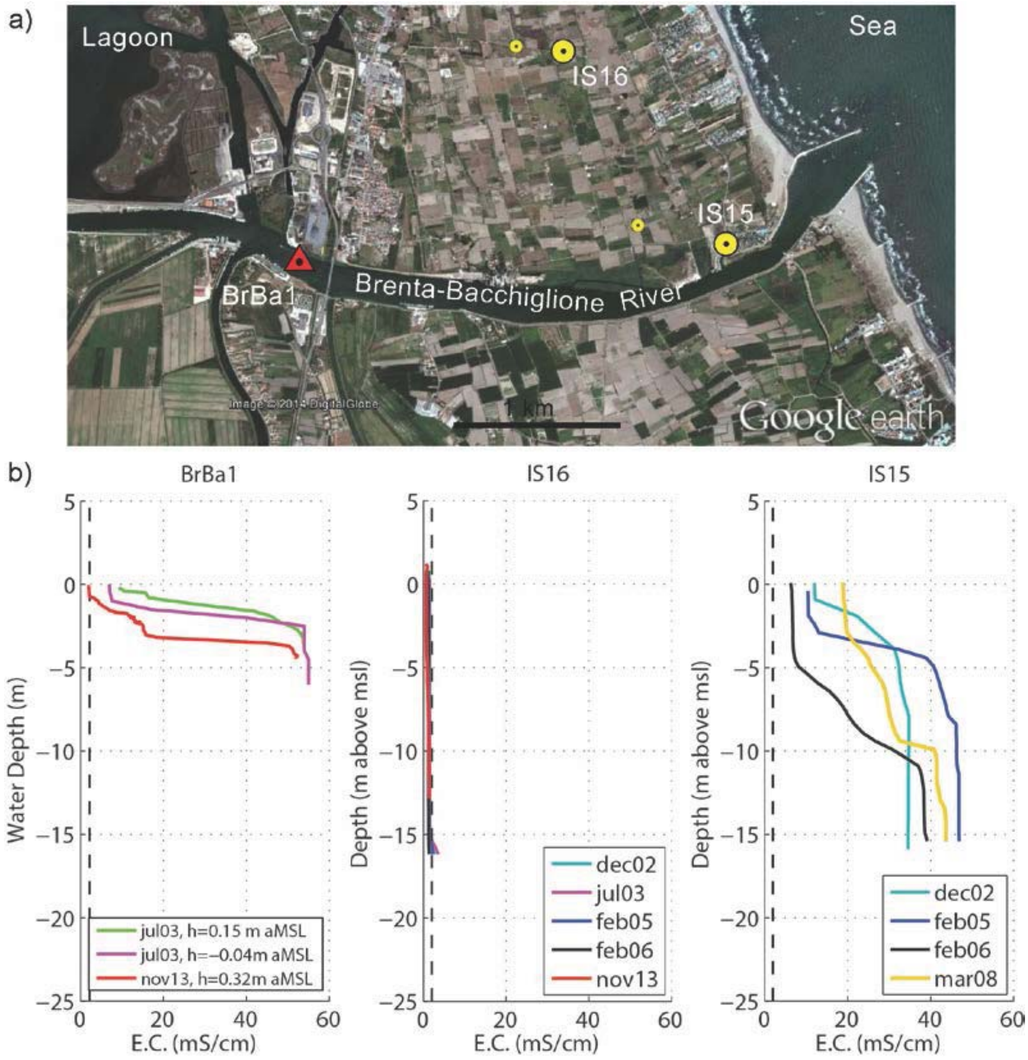

Figure 3 – Freshwater-saltwater dynamics in the sandy littoral ridge. (a) Location of the groundwater (yellow dot) and surface water (red triangle) monitoring sites. The satellite image is from Google Earth, data source: Digital Globe. (b) Electrical Conductivity logs. Dashed line: maximum EC for irrigation use.

In the lowlands surrounding the southern lagoon margin, the fresh-saltwater dynamics is strictly connected to the medium-term (seasonal) changes of the lagoon level, the seawater encroachment along the rivers and river discharge conditions. Close to lagoon margin, EC recorded in S1 (Fig. 4) and IS5 wells (Fig. 5) clearly show that the saltwater contamination is permanent. The presence of freshwater in the main watercourses when river discharges prevail on the tide encroachment, do not sufficiently mitigate the salinization of the aquifers by river leakage, as shown in the BrBa1, Br1, Ba1, Mo1, monitoring points (Figs. 3, 4, 5). The dynamics of the groundwater salinity forced by tide conditions, mostly at seasonal term, is shown in the data recorded at IS5 well (Fig. 5) while minor variations are shown in S1 well (Fig. 4). The rainfall mitigate the saline contamination, but their effect vanish fairly quickly due to the maintenance of low levels of groundwater by pumping stations in order to prevent flooding. For instance EC of 15 and 30 mS/cm have been detected after a total monthly rainfall of 110 mm and 5 mm, respectively.

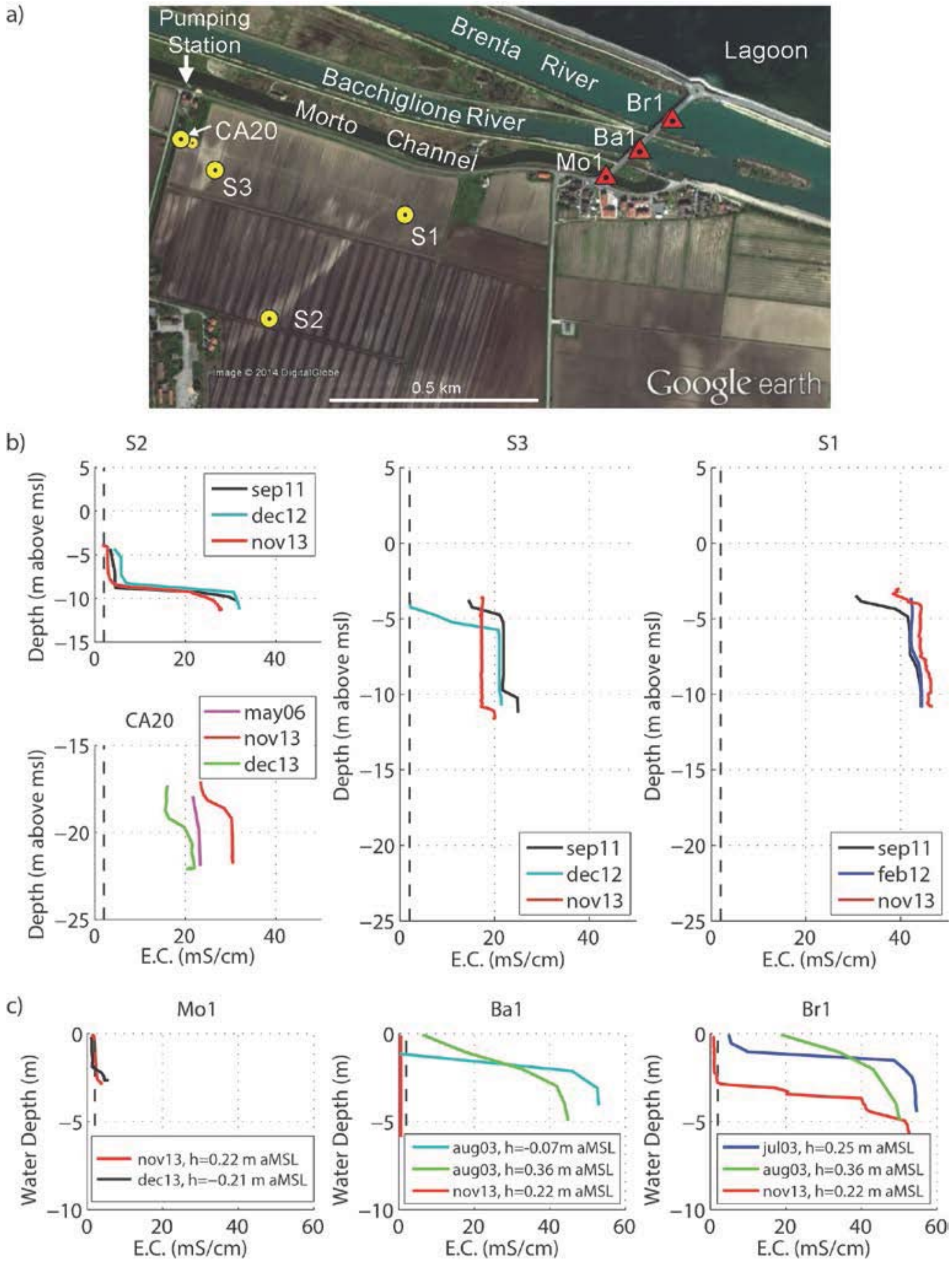

Figure 4 – Freshwater-saltwater dynamics in lowlands and paleochannels. (a) Location of the groundwater (yellow dot) and surface water (red triangle) monitoring sites. The satellite image is from Google Earth, data source: Digital Globe. Electrical Conductivity logs in (b) wells and (c) watercourses. Dashed line: maximum EC for irrigation use.

In general the sandy paleochannels contain saltwater, nevertheless they allow the rainfall storage in the upper water table for a limited time. Specifically, IS6 well (Fig. 5) points out that the paleochannels permanently contains saltwater while S2 well (Fig. 4) shows the freshwater recharge in the upper layer by rainfalls. In this latter, EC varies from 2 to from 5 mS/cm as result of 110 and 80 mm of monthly rainfalls, respectively. Different behavior is show by the S3 well, which is located in a paleochannel having constantly fresh-brackish water in upper part of the aquifer.

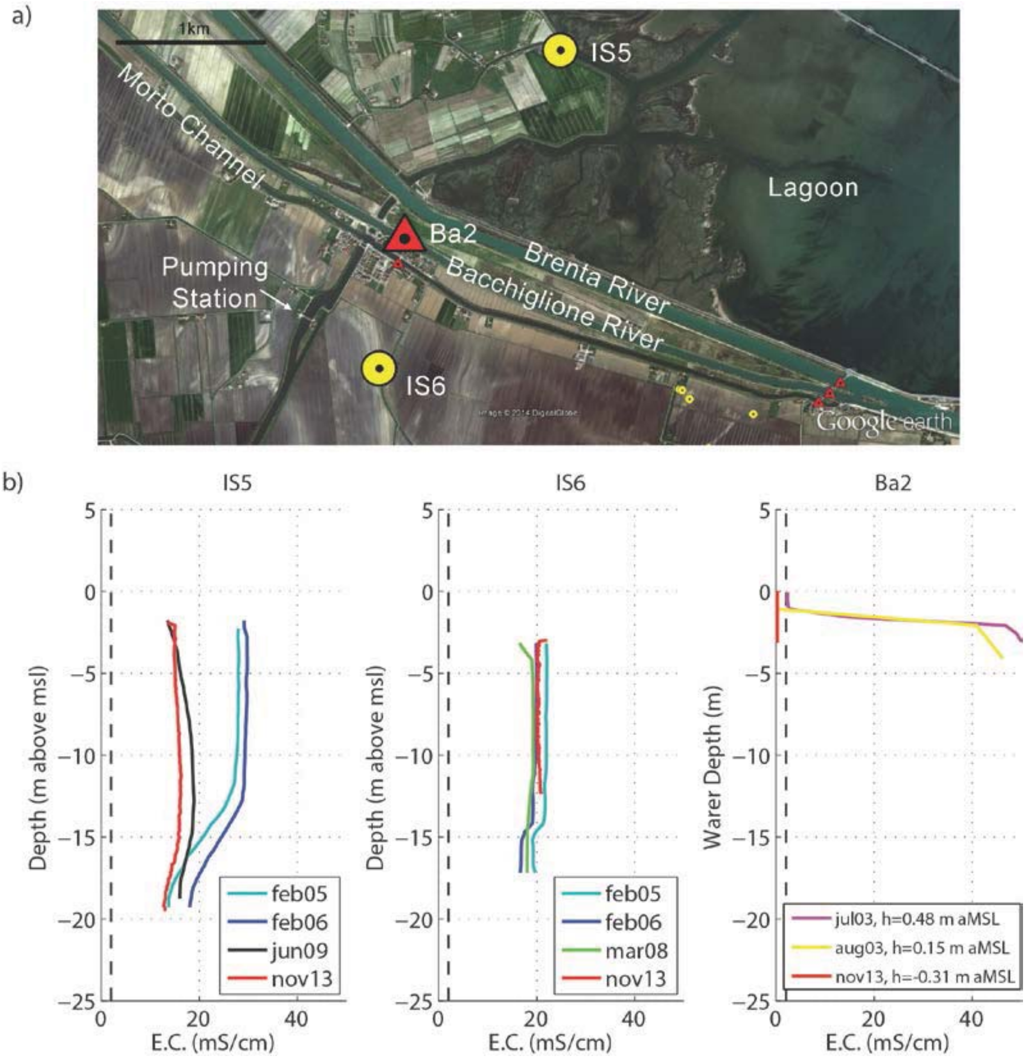

Figure 5 – Freshwater-saltwater dynamics in lowlands and paleochannels. (a) Location of the groundwater (yellow dot) and surface water (red triangle) monitoring sites. The satellite image is from Google Earth, data source: Digital Globe. (b) Electrical Conductivity logs. Dashed line: maximum EC for irrigation use.

In the area nearby to the Adige River, the IS10 well is located in an aquifer formed by sandy deposits of the ancient littoral ridge system (Fig. 6). The measures point out the permanent occurrence of freshwater in the upper part of the aquifer, with EC less than 2 mS/cm up to 8-10 m depth, while saltwater seasonally ranging from 5 to 10 mS/cm at larger depth. The recharge of freshwater is supplied by the rainfalls. In addition, the Adige River provides an efficient mitigation effect by leaking the freshwater discharge in the nearby lowlands. Data recorded in the Ad2 monitoring site point out the permanent presence of freshwater in the river (Fig. 6). EC, generally less than 1 mS/cm, is owing to the presence of a barrier built next to the river mouth to prevent seawater migration upstream during dry periods with low discharge. Conversely, the IS11 well (Fig. 6), which is located in the same system of sandy littoral ridges, shows the presence of brackish-salt waters. The salt variability (EC 5-18 mS/cm) detected in this well is due to the effect of the rainfalls and the tide encroachment from the Gorzone Canal (Cg1) in the nearby lowlands. Moreover, EC of 10 and 15 mS/cm are associated to 47 and 29 mm monthly rainfalls.

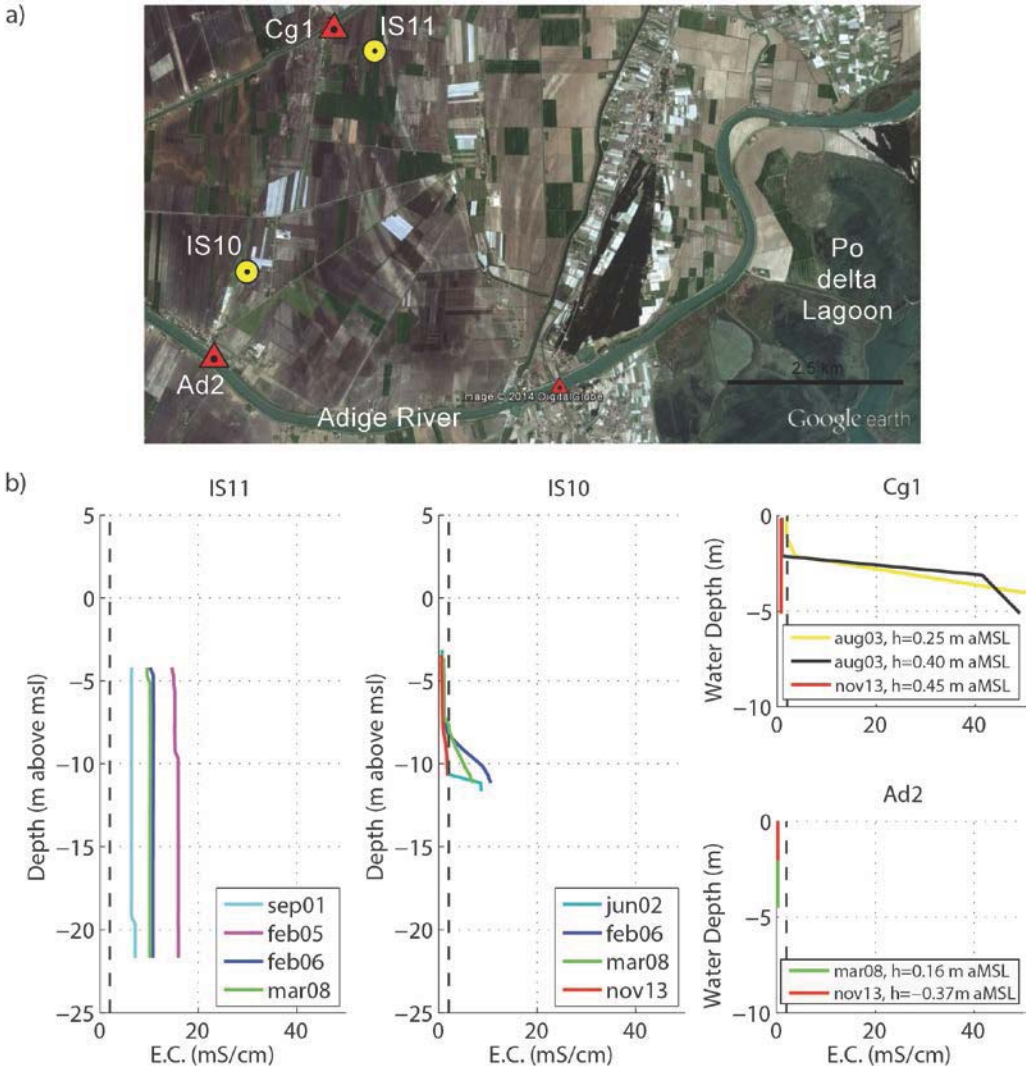

Figure 6 – Freshwater-saltwater dynamics in paleocoastal ridges. (a) Location of the groundwater (yellow dot) and surface water (red triangle) monitoring sites. The satellite image is from Google Earth, data source: Digital Globe. (b) Electrical Conductivity logs. Dashed line shows the maximum EC value of the waters for irrigation use.

5 DISCUSSION AND CONCLUSIONS

Most of the area between the southern lagoon margin and the Adige River is affected by saline contamination, which is certainly due to the intrusion of the seawater in the shallow aquifers. The hydrological regime and consequently the saltwater contamination dynamics are controlled by several natural and anthropogenic factors such as the hydro- geo- morphologic setting, rainfall events, tidal- river- regime, and reclamation activities.

The hydrogeologic setting of the Venice coastland is complicated by the Late Pleistocene-Holocene subsoil architecture. These deposits represent the transition through the fluvial in tide-dominated depositional systems triggered by the sea level changes.

The morphologic setting of the coastal plain plays a significant role in the saltwater-freshwater relationships, both in surficial waters and groundwaters. In the littoral sector, the presence of remnant sandy ridges related to ancient coastlines and sand dunes, which preserve a ground elevation up to 3 m above msl, allows the groundwater storage of rainwater forming freshwater lenses. They seasonally fluctuate to a depth between 15 and 20 m depending on the climate conditions. In the mainland, which is mostly lying below the mean sea level, the saltwater intrusion involves the topsoil. The maintenance of the water table below the ground surface by pumping stations favors the salt contamination.

An important forcing factor that plays a primary role in the subsoil salinization dynamics is the water leakage from the bed of the major rivers. When tides prevail on the river discharge, seawater infiltrates through the bed of the watercourses in the nearby lowlands. Just as example, the reduced freshwater discharges that occur in the Brenta and Bacchiglione rivers during the dry of summer 2003 allowed the seawater to flow up from the river mouths to 18 km inland. Conversely, when the river discharges contrast the seawater encroachment, the watercourses exert a significant role in mitigating the salt contamination plume. The presence of sandy buried paleo-channel systems crossing the farmland, with a main direction from inland to the lagoon boundary, acts as preferential pathways for groundwater flow and solute transport. These features generally increase the saltwater flow from the lagoon into the low-lying sectors, even though they allow the short term rainwater storage in the very shallow subsoil. The water quality in the shallower subsoil is significantly improved by local rainfalls that rapidly supply freshwater while a decrease of the reclamation water level due to the pumping station activities produces an increase of the salinity concentration in the groundwater.

Finally, a very serious situation has been brought to light in a large portion of the coastal farmland. The fresh/saltwater interface is very close to the ground surface, between 0 to 10 m, with the thickness of the upper freshwater lenses often on the order of 1 m, depending on drainage and weather conditions. Since the high value of the agricultural and horticultural land use, mitigation measures are of paramount importance. As the source of the saltwater intrusion in shallow aquifers is permanent, i.e. the sea/lagoon, the mitigation of salt contamination has to be found by a specific and accurate water management. Some actions have already been successfully tested and implemented, for instance the use of an ad hoc drainage management to maintain the water table as high as possible. This is done by the real-time controls of the pumping stations in order to avoid the excess of lowering of the phreatic level when heavy rainfall is forecasted. Another mitigation measure should be the control of seawater upstream migration from the river mouths by mobile gates. In fact the rivers can act indeed as an effective hydraulic barrier to salt contamination from the lagoon if they contain freshwater or can represent a strong source of salinization if seawater encroaches along the final portion of the watercourses. In addition, since sandy geomorphologic structures, e.g., the paleochannels, seems to play an important role in improving or worsening the subsurface contamination, experiment for understanding their effectiveness in the artificial aquifer recharge should be tested.

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