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Saltwater contamination in the managed low-lying farmland of the Venice coast, Italy: An assessment of vulnerability

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HIGHLIGHTS

- Land reclamation shapes the present saltwater contamination in the Venice coastland.
- Natural and anthropogenic forcings drive the seawater flow in shallow aquifers.
- Hydro-geophysical–geochemical investigations highlight the groundwater origin.
- The vulnerability of the farmland to salt contamination extents up to 20 km inland.
- Usual hydro-geophysical monitoring in managed low-lying farmlands is challenging.

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ABSTRACT

The original morphology and hydrogeology of many low-lying coastlands worldwide have been significantly modified over the last century through river diversion, embankment built-up, and large-scale land reclamation projects. This led to a progressive shifting of the groundwater–surficial water exchanges from naturally to anthropogenically driven. In this human-influenced hydrologic landscape, the saltwater contamination usually jeopardizes the soil productivity. In the coastland south of Venice (Italy), several well log measurements, chemical and isotope analyses have been performed over the last decade to characterize the occurrence of the salt contamination. The processing of this huge dataset highlights a permanent variously-shaped saline contamination up to 20 km inland, with different conditions in relation with the various geomorphological features of the area. The results point out the important role of the land reclamation in shaping the present-day salt contamination and reveal the contribution of precipitation, river discharge, lagoon and sea water to the shallow groundwater in the various coastal sectors. Moreover, an original vulnerability map to salt contamination in relation to the farmland productivity has been developed taking into account the electrical conductivity of the upper aquifer in the worst condition, the ground elevation, and the distance from salt and fresh surface water sources. Finally, the study allows highlighting the limit of traditional investigations in monitoring saltwater contamination at the regional scale in managed Holocene coastal environments. Possible improvements are outlined.

1. Introduction

Throughout history, many coastal swamps, tidally influenced wetlands and lagoons have been reclaimed to meet human needs and converted into farmlands, fishing farms, and urbanized areas (e.g., Jiang et al., 2011). Land reclamation is generally carried out by the construction of hydraulic infrastructures, such as large networks of drainage channels, embankments and dykes. In addition, in flood-prone lowlands, pumping stations are used to keep water table below the ground surface and control the water level according to the different land uses and climate conditions. Usually high levels are maintained in summer for suitable moisture in agriculture and low levels in winter to prevent flooding.

Land reclamation has provided valuable lands and played an important role in the economic development of many coastlands. However, the shifting from undisturbed to managed ecosystems has induced significant environmental changes that modified the continental–marine water interaction over the long–term (Sudha Rani et al., 2015). Therefore in the new man-made areas, the drainage to prevent or reduce

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waterlogging and provide new land for agriculture makes the surficial and groundwater hydrology to be anthropogenically controlled.

While fresh groundwater reserves in coastlands are vital for the community and ecosystems, they are vulnerable to salinization. In particular, in view of the expected climate changes, coastal fresh aquifers are becoming strategically important for water supply (e.g. Pousa et al., 2007; Post et al., 2013; Tosi et al., 2013). Due to relative sea level rise, precipitation decreasing, and groundwater withdrawal, a noteworthy saltwater intrusion in shallow aquifers with low hydraulic gradients has recorded over the last decades along many worldwide coastal plains, for instance, from Maine to Florida along the Atlantic coast (Barlow, 2003), in the lower Burdekin delta, Australia (Narayan et al., 2003), along the Ravenna coast in Italy (Giambastiani et al., 2007), in Jakarta, Indonesia (Abidin et al., 2011), and in the Laizhou Bay, China (Qi and Qiu, 2011).

Understanding the mixing between salt/fresh surficial water and groundwater in coastlands is an issue of paramount importance considering the ecological, cultural, and socio-economic relevance of the coastal plains. The coastland surrounding the Venice Lagoon (Italy) (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, 2009).

The first investigation on the saltwater contamination in the Venice area started in the '70s (Benvenuti et al., 1973). However, only from the end of the '90s the contaminant plume has been systematically monitored. The comprehensive image by Carbognin and Tosi (2003) pointed out that saltwater intrusion extended inshore up to 20 km and deepened from the near ground surface down to some tens of meters. During the last decade, recurring measurements were undertaken to control the salt contamination of the shallow aquifers and to analyze the process in specific sites. De Franco et al. (2009) pointed out the seasonal freshwater–saltwater relationship in an experimental site at the southern lagoon margin. Gattacceca et al. (2009) provided the isotopic and geochemical characterization of the saline waters in the shallow aquifers. Viezzoli et al. (2010), Teatini et al. (2011) and Tosi et al. (2011) analyzed the exchanges between lagoon water and groundwater using airborne electromagnetic and marine continuous electrical resistivity tomography surveys. Rapaglia et al. (2010) analyzed the exchange of groundwater through a highly permeable paleo-inlet along the barrier beach that separates the northern Venice Lagoon from the Adriatic Sea. Rapaglia (2005), Ferrarin et al. (2008), Gattacceca et al. (2011) estimated the submarine groundwater discharge into the lagoon.

The studies mentioned above provided new findings on the relationship among surficial waters, groundwater, continental waters and marine waters, but most of them focused on specific sites. Hence, a thorough and large-scale investigation, which considers the role of the various components controlling the saline intrusion in the Venice coastal plain, whose hydrologic and hydraulic settings were significantly modified over the centuries by anthropogenic interventions, has not yet been performed. This study aims to fill this gap for a 130-km^2 portion of the reclaimed farmlands south of the Venice Lagoon. Specifically, it

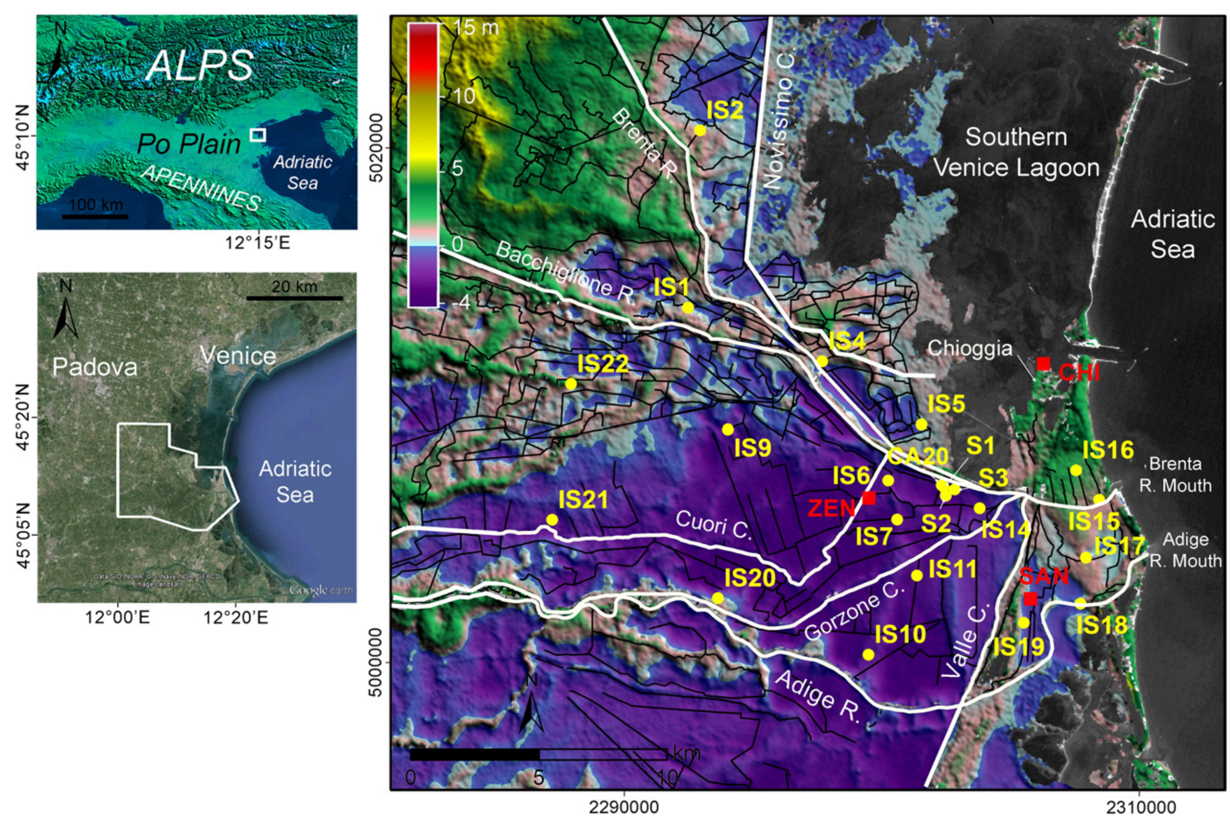

Fig. 1. Distribution of the wells of the groundwater monitoring network (yellow dots) superposed to the Digital Elevation Model of the study area. The sketches of the main rivers and reclamation network are drawn in white and black lines, respectively; and the location of the Chioggia tide gauge (CHI) and the two pluviometers (ZEN and SAN) are shown in red squares. The background is a Landsat image (2011) obtained from the US Geological Survey and Earth Resources Observation and Science (EROS) Center. Coordinate system: Gauss Boaga. The two map-insets show the position of the study area with respect to the Northern Adriatic Sea and Venice.
The background is from Google Earth, data source: SIO, NOAA, U.S. Navy, NGA, GEBCO, Image Landsat.

focuses on characterizing the magnitude and dynamics of the salt contamination and their relation with the natural and anthropogenic forcing factors based on hydrogeological surveys, chemical data, and geophysical investigations recently acquired and collected in previous studies.

Lastly, to provide a comprehensive analysis of the salt contamination problem in the study area, and considering that this portion of the Venice coastal plain is mainly devoted to crop production, the available information has been processed to derive and map a vulnerability index to salt contamination in relation to the farmland productivity. Hydrogeologists have failed to reach a general consensus concerning the definitions for groundwater vulnerability assessment (e.g., Gogu and Dassargues, 2000; Ferguson and Gleeson, 2012); however in this study "vulnerability" refers to the relative propensity for salt contamination to occur in the shallow aquifer at a level that can threat the agricultural production. Several indexing methods have been developed for rapidly assessing of the vulnerability of large regions to groundwater contamination, such as the DRASTIC (Aller et al., 1987), GOD (Foster, 1987), or EPIK (Dörfliger and Zwahlen, 1998), which consider key factors that can influence the solute transport process. In this study, we have elected to use the GALDIT approach (Chachadi and Lobo-Ferreira, 2001, 2007), properly adapted to the specific features of a coastland strongly controlled by human infrastructure. A discussion section and conclusions close the paper.

2. Hydrogeological setting of the study area

The investigated area is the coastal plain of Venice between the southern part of lagoon and the Adige River. In this coastland the equilibrium between human needs and natural evolution has always been precarious (Fig. 1). Brenta, Bacchiglione, and Adige rivers, together with Cuori and Gorzone Channels are the main watercourses. Moreover, because the farmlands lie 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 upper 30 m thick subsoil, which is composed of late Pleistocene and Holocene sediments, is the depth of interest for the study aim. The Late Pleistocene sedimentary deposits consist of an aggrading floodplain facies with fluvial channels fills accumulated during the decrease of the sea level, and are 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 paleo-soil, 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 deposits show 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. Abandoned Holocene riverbeds and remnants of littoral ridges are well recognizable by the digital elevation model (DEM), satellites images and aerial photographs (Fig. 1). Human interventions since the 15th century, among all the river diversions and land reclamations, 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 −4 m in the southernmost part of the Venice coastal plain (Fig. 1) (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. Un-confined, semi-confined, and locally confined aquifers develop down to about 50 m depth while beneath a multi-aquifer confined system is well developed at the regional scale (Da Lio et al., 2013). The saltwater contamination occurs from the near ground surface down to 50 m and locally to 100 m depth and extends inshore up to 20 km (Carbognin and Tosi, 2003) (Fig. S1). In the shallow aquifers, the Caranto unit exhibits an important hydrogeologic function and often precludes the downward propagation of seawaters (Teatini et al., 2011), thus the salinity degree significantly reduces below 30 m depth, at least in some portions of the study area. The saltwater intrusion in the shallow aquifers is generally connected to a land elevation below the mean sea level, the presence of several sandy paleochannels, which enhance the groundwater flow from the lagoon to the farmland, and the seawater encroachment into the river mouths. Saline waters involve also aquifers at depths varying from 400 m to more than 1000 m because the presence of brine waters (Agip, 1994; Bixio et al., 1999; Brambati et al., 2003; Di Sipio et al., 2006).

3. Methods

Electrical conductivity (EC) logs in wells and surficial waterbodies, temperature and water level records, rainfalls, and tides measurements acquired in different seasons since 2001 have been used to investigate the saltwater contamination and its dynamics in relation to the changes of the main forcing factors. In addition, chemical analyses on 19 new water samples collected from monitoring wells recently installed, have been processed with data after Di Sipio et al. (2006) and Gattacceca et al. (2009), in particular ion ratios Na^+/Cl^-, $\delta^{18}O/\delta^2H$, $\delta^{18}O/Cl^-$ and deuterium excess, to define the origin of salinity.

Because EC represents a practical and expeditious measure for the estimate of water salinity (e.g., Miller et al., 1988), the available dataset of new and previously acquired chemical measurements has been statistically analyzed to obtain an EC–Cl^- relationship for the study area.

Salty water is seriously affecting the soil productivity in the Venice coastland. For this reason, we elect to mark the limit between freshwater and saltwater values in relation to tolerance bounds for crop growth. 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 water quality: 1) salty if EC exceeds 5 mS/cm; 2) brackish if EC ranges between 2 and 5 mS/cm with salt concentration higher than 1 g/L; 3) fresh when EC is less than 2 mS/cm and the water is suitable for irrigation purposes.

The EC measurements have been acquired in the ISES (the Italian acronym for Saltwater Intrusion and Subsidence) monitoring networks established in 2000 (Carbognin and Tosi, 2003; Carbognin et al., 2005) and integrated with new measuring points established in 2006 (de Franco et al., 2009) and 2011 (Teatini et al., 2012). The monitoring network includes about 150 measuring points in watercourses and 150 piezometers/wells spanning a depth range from a few meters to about 30 m depth. A number of 25 piezometers are screened along the entire length and hence suitable for the detection of vertical EC profiles. A few measure campaigns have been carried out since 2011 at selected sites of the monitoring network representative of the different hydrologic and geomorphologic conditions characterizing the study areas (Fig. 2).

The sea level and rainfall have been recorded in the monitoring stations located in the nearby of Chioggia: the Chioggia Vigo tide gauge (www.venezia.isprambiente.it) and the Sant'Anna and Zennare pluviometers (www.adigeuganeo.it), respectively (Fig. 1). In particular in the analyses here presented we have considered the monthly average value of the tide level and the monthly cumulated rainfall calculated for

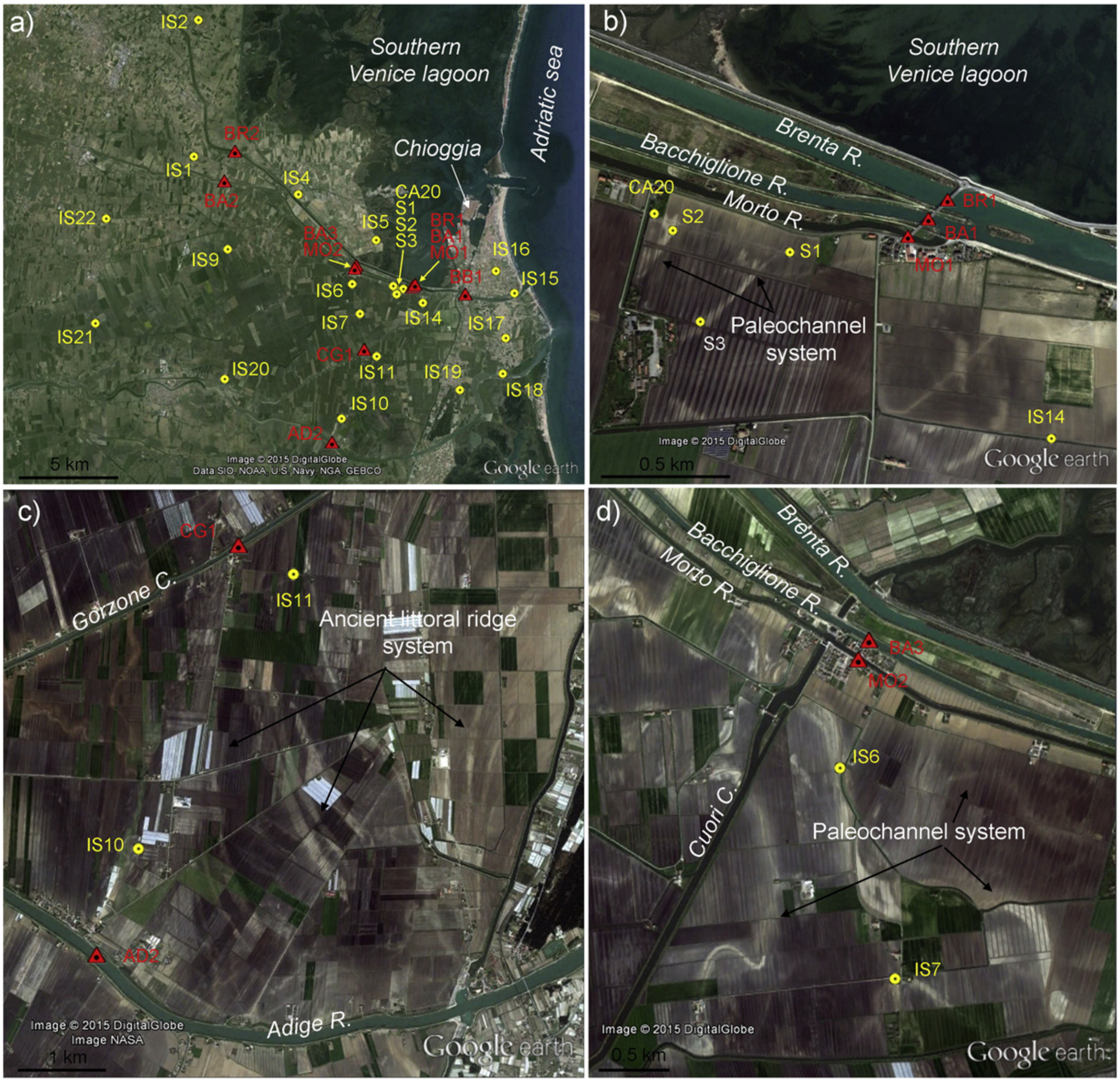

Fig. 2. a) Location of the monitoring sites: groundwater (yellow dots) and surface water (red triangles). b), c), and d) detail the positions of the monitoring sites with respect to the geomorphological structures (white features indicated by the black arrows) and the watercourses.
The backgrounds are from Google Earth, data source: SIO, NOAA, U.S. Navy, NGA, GEBCO, Digital Globe, Image NASA.

the month preceding EC sampling instant. Available information suggests that a time interval from one to a few months is representative for investigating the correlation between surface and subsurface hydrologic parameters in shallow aquifers of flat areas (e.g., Giudici et al., 2003; de Franco et al., 2009).

The morphologic setting of the study area has been obtained by a digital elevation model with 20-m resolution (Gasparetto-Stori et al., 2012) from which the ground elevation profiles have been extracted.

Data and information available from geophysical investigations (e.g., Benvenuti et al., 1973; Galgaro et al., 2000; Carbognin and Tosi, 2003; de Franco et al., 2009; Viezzoli et al., 2010; Teatini et al., 2011; Braga et al., 2012; Deiana et al., 2014), geochemical analyses of waters (e.g., Gattacceca et al., 2009; Di Sipio et al., 2013), geologic, morphogeologic and hydro-stratigraphic characterizations (e.g., Bondesan and Meneghel, 2004; Tosi et al., 2007a; Fabbri et al., 2013) have also been used.

Concerning the vulnerability of the shallow aquifer to saltwater intrusion, we have adapted the GALDIT approach (Chachadi and Lobo-Ferreira, 2001, 2007) to the specific features of a coastland strongly controlled by human infrastructures. Concerning the six factors assumed by GALDIT to directly influence sea encroachment events, namely the aquifer type, aquifer thickness, hydraulic conductivity, level of groundwater above sea level, distance from the shore, and the actual status of the contamination (and its impact), we have elected to:

- remove the first three indices related to the aquifer properties. This is because in a managed coastland as the study one, the properties of the upper aquifer have a negligible impact on the hydrological regime, and consequently on the salt distribution. The dense network of ditches and reclamation channels control the shallowest groundwater flow regime, i.e. in the 2–3 m depth interval, as suggested by the outcome of hydrologic modeling studies (Teatini et al., 2009, 2010);
- substitute the groundwater level with the land surface elevation with respect to the mean sea level. The DEM of the area is known much more in detail, and the pumping stations and reclamation/irrigation network keep the depth to groundwater level at an almost fixed values, ranging between 0.3 to 0.7 m, independently on the climate regime and meteorological conditions (DEM index in the following);
- generalize the index related to the distance from the salt source. In the present case not only the sea, but also the lagoon and the part of the

rivers and canals encroached by the seawater act as salinity distributors (SD index);
- keep the parameter depending on the status of the contamination, as directly provided by the EC measurements (ECw index);
- and introduce a new parameter, that is the distance from the sources of surficial fresh waters. The vulnerability of salt contamination is strongly reduced in the portion of the farmland close to the rivers and canals bringing freshwater from the mainland (FD index).

The parameter values associated with the four controlling factors are converted to "importance" scales, and then aggregated into a GIS environment to produce vulnerability scores using subjective weightings. In detail, each dataset has been interpolated using the Kriging method (Cressie, 1991) on a 100 m regular grid for the same spatial domain, obtaining four thematic layers. Each layer has been classified using a rating value between 0 and 4 which is attributed to each parameter depending on local conditions, stating that high values correspond to high vulnerability for the farmland productivity.

4. Data analysis

EC and chemical data of groundwater and surficial waters have been analyzed to quantify the extent of the saltwater contamination in phreatic and semi-confined aquifers.

A significant correlation ($R^2 = 0.99$) has been found between EC and Cl^- concentration obtained by chemical analyses. The following relationship between the two parameters has been obtained:

$$Cl^- = 10.35\,EC - 14.16 \quad (1)$$

with Cl^- expressed in [meq/L] and EC in [mS/cm]. Eq. (1) provides a simple model to use EC values for the quantification of the groundwater salinity.

4.1. Analysis at regional scale

The available EC dataset, including logs in completely screened piezometres and single-depth EC measurements in partially screened wells, has been used to draw an overall picture of the groundwater contamination in the study area. This has been achieved by a two-step approach. Firstly, EC records representative of the mean condition over the period between 2001 and 2014 at each monitoring site has been selected. It is worth noting that spring 2008 can be reasonably considered for the average EC condition. Log profiles have been sampled at 0.5 m. Then, the selected measurements have been interpolated using the Kriging method (Cressie, 1991) along four sections crossing the study area approximately in the west–east and north–south directions (Fig. 3).

In the littoral of Chioggia (IS16 in Fig. 3a), 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 from both the sea and the lagoon bottom (Fig. 3a). Along the southernmost lagoon margin (IS5–IS14 in Fig. 3a), the marine water infiltrates from the lagoon bottom and intrudes inland, passing underneath the Brenta and Bacchiglione Rivers and the reclamation channels. In the proximity of lagoon margin, EC spans the range from 20 to 40 mS/cm. Toward the mainland, the salt contamination shows different features in the areas to the west and south of the lagoon. In the former, the salinity rapidly decreases (EC values lower

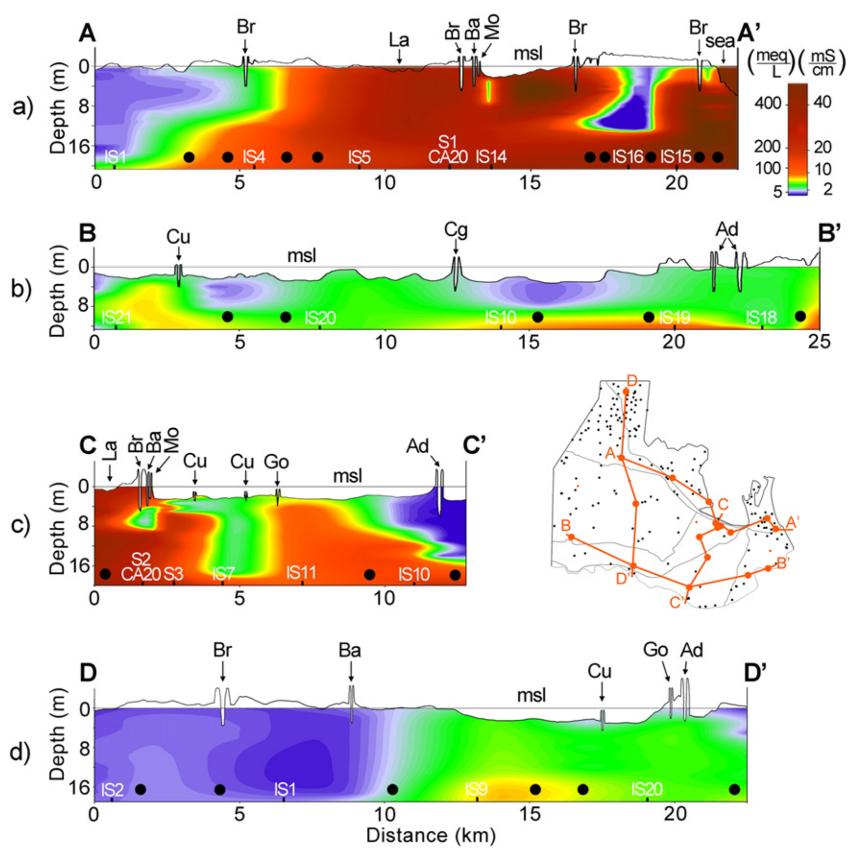

Fig. 3. Profiles of groundwater electrical conductivity obtained interpolating logs (white codes) and punctual data (black dots) representative of the mean condition over the period from 2001 to 2014. In addition, color scale reports Cl^- (meq/L) calculated by (Eq. (1)). Lagoon (La); Brenta River (Br); Bacchiglione River (Ba); Morto Channel (Mo); Cuori Channel (Cu); Gorzone Channel (Go); Adige River (Ad). The map-inset shows the trace of the cross-sections. Well locations are shown in red and black dots if they correspond to logs or punctual data, respectively.

than 10 mS/cm) and to the west of the Brenta River the continental freshwater prevails (IS1 in Fig. 3a).

In the southern farmland (Fig. 3b) there is a general condition of brackish water except in the upper part of the aquifer where fresh conditions, with EC less than 2 mS/cm, have been detected. The recharge of freshwater is mainly supplied by the rainfall. A local contribute to mitigate the groundwater salinity is provided by the freshwater seepage from the irrigation channels and rivers. This is clearly proved by Fig. 4, which points out the origin of salt contamination as derived from the ionic and isotopic relations of the groundwater and surficial water. In particular, the samples from well IS10 show that presence of Adige waters.

In the farmlands between the Brenta and Adige Rivers (Fig. 3c) the salt contamination persists, even though locally variable (EC ranges from 5 to 30 mS/cm). Some brackish groundwater occurrences (EC = 2–5 mS/cm) are found alongside the watercourses. In fact, the Brenta and Bacchiglione Rivers act in different way in the low-lying farmlands: they contaminate the aquifers by the seawater encroachment along the hanging portion closer to the mouth (Fig. S2), while reduce the salinity when river discharges prevail on the tide encroachment.

Different situation is shown in the northern inland sector (Fig. 3d). Freshwater occurs in the nearby of the lagoon margin and brackish water in the southern lowlands. At the northern lagoon margin, saltwater does not extent inland. This is because of the freshwater leakage from the watercourses parallel to the lagoon limit. Isotope and chemical analyses on IS1 and IS2 wells point out the contribution from the Brenta River and Canale Novissimo (Fig. 4). The transition between brackish water and saltwater is located in correspondence of the inland–lowland boundary. In the southernmost part of the profile in Fig. 3d, a local mitigation is given by the freshwater leakage from the Adige River.

4.2. Dynamics of the process at local scale

The analysis has been carried out grouping the wells on the base of the geo-morphologic setting of the study area as follow: littoral strip, lowlands, paleochannels, ancient littoral ridges, and inland sector. The dynamics of the salt contamination has been analyzed at local scale taking into account the EC evolution in time and the corresponding specific climatic and tidal conditions.

4.2.1. Littoral strip

The littoral sector is the 3–5 km wide coastal strip between Chioggia and the Adige River mouth (Fig. 2a).

The northern part of the littoral strip is formed by the Sottomarina spit, which elongates northward between the Adriatic Sea (to the east) and the lagoon (to the west). IS16 well (Fig. 2a) is located in the center of the spit where ground elevation is 2–3 m above msl. The EC profiles are always lower than 2 mS/cm down to about 15 m depth and increase to about 3.5 mS/cm at the bottom of the well (Fig. 5).

Here, water table rapidly responds to precipitations. Water chemistry is characterized by low Cl^- values and Na^+/Cl^- ratio equal to 1.1 (Fig. 4a). These numbers point out the occurrence of a permanent freshwater lens in the shallow aquifer recharged by rainfalls. This is also supported by δ^2H vs $\delta^{18}O$, which is close to the meteoric line (Fig. 4b). However the relations $\delta^{18}O$ vs Cl^- and deuterium excess (Fig. 4c, d) highlight a slight tendency toward saltwater contamination.

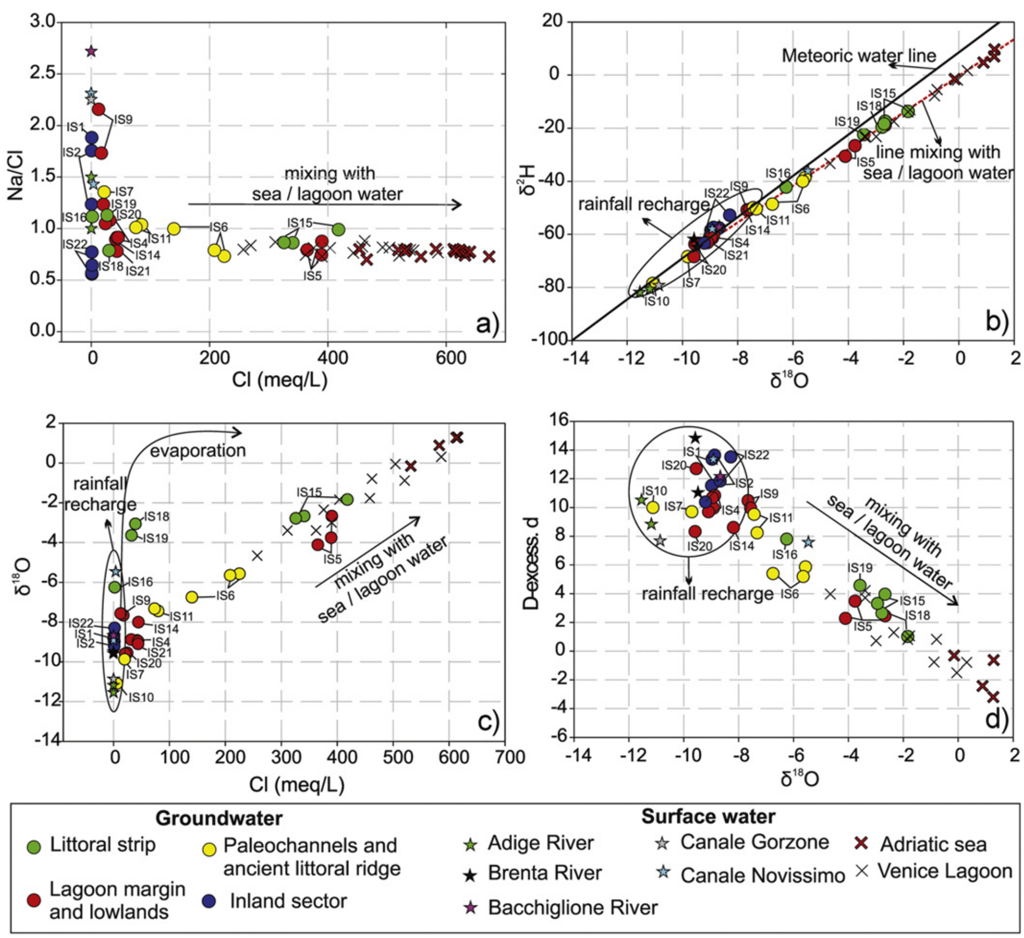

Fig. 4. Ionic and isotopic relations of the groundwater and surficial water. Data from Di Sipio et al. (2006) and Gattacceca et al. (2009) have been integrated. Littoral strip wells: IS15, IS16, IS18, and IS19; lagoon margin and lowland wells: IS4, IS5, IS9, IS14, IS20, and IS21; paleochannels and ancient littoral ridge wells: IS6, IS7, IS10, and IS11; and inland sector wells: IS1, IS2, and IS22.

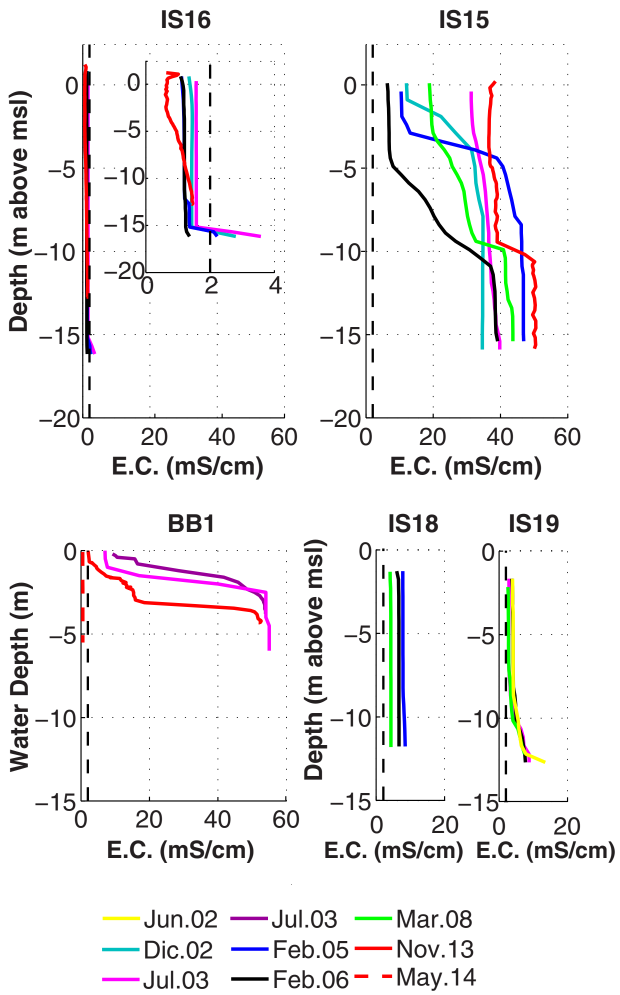

Fig. 5. Electrical conductivity logs showing the freshwater–saltwater dynamics in the sandy littoral strip. The dashed line represents the maximum EC value for irrigation use. The location of the wells and surface waters is shown in Fig. 2a.

The freshwater lens does not seem to be significantly affected by saltwater intrusion in relation to water table and climate changes. For instance, EC = 0.6 mS/cm and EC = 1.6 mS/cm have been measured in correspondence with a monthly rainfall of 72.5 mm (November 2013, wet season) and 9 mm (July 2003, dry season), respectively.

The ground level of the spit decreases to 0.5-1 m above msl close to the Brenta River. IS15 well (Fig. 2a) shows a high variability of the EC: at the top it spans from 6 mS/cm to 19 mS/cm and at the bottom between 34 mS/cm and 45 mS/cm (Fig. 5). The sea level significantly influences the water table but not the groundwater salinity: lower and higher tide levels are not always in relation with lower and higher EC. River discharge and tide encroachment superpose to the effect of tides in the changes of the EC values of groundwater. The Cl^- content ranges between 330 and 420 meq/L and Na^+/Cl^- ratio is between 0.86 and 0.98, which are values slightly higher than that typical of saline intrusion (0.80) from the sea or lagoon (Fig. 4a). In the relationship between δ^2H vs $\delta^{18}O$, IS15 sample shows a clear influence of the sea and lagoon waters positioning on the mixing line (Fig. 4b). Fig. 4c and d (deuterium excess and $\delta^{18}O$ vs Cl^-) show that high chloride content is associated with sea water mixing. For instance, in July 2003 and February 2006, with similar tide levels (+0.47 m above msl and +0.37 m above msl), EC values >31 mS/cm and >6 mS/cm have been detected, respectively. To note that these two periods are characterized by almost the same local monthly rainfalls, but precipitations at regional scale and climate season are different. In this case, the EC differences are likely ascribed to the negligible river discharge occurred in the very dry summer 2003, which caused a huge sea encroachment along the Brenta and Bacchiglione river system (monitoring site BB1 in Fig. 2a) as confirmed by the very high EC values shown in Fig. 5. In general local rainfalls partially influence EC. For example, the two EC profiles acquired in the two extreme climate years, i.e. the very dry 2003, and the wet 2013, are quite similar and point out a very high salinity, between 30 mS/cm and 50 mS/cm, irrespective of the monthly rainfall of 9 mm and 72.5 mm, respectively. Conversely, high local rainfalls amounting to 72.3 mm in December 2002 and 28 mm in February 2005 seem to affect EC, with low values (10 and 8 mS/cm, respectively) recorded in these dates. The EC profile acquired in March 2008, after a 47.3 mm monthly rainfall corresponding to an average decadal value and with a +0.35 m tide level, varies between 20 mS/cm to 45 mS/cm from the top to the well bottom, which represents an average EC condition.

The southern part of the littoral strip, between the Brenta and Adige river mouths, is limited westward by the Canale di Valle. IS18 well (Fig. 2a) is located 2–3 km from the sea, at the foot of the Adige River embankment where the ground elevation of the nearby farmland is below msl. The recorded EC logs are characterize by a constant profile vs depth, with relatively small variability in time ranging between 5 and 10 mS/cm (Fig. 5). These variations are likely related with the river discharge, and consequently with the regional climate conditions: higher EC values have been detected in dry season, e.g. February 2005 with a mean monthly rainfall equal to 24.6 mm, and lower values in wetter season, for example March 2008 characterized by a mean monthly rainfall of 47.3 mm. Cl^- content is equal to 30 meq/L with $Na^+/Cl^- = 0.78$. The records are located on the mixing line of sea–lagoon water in the graphs of isotopic ratios, deuterium excess, and δ^2H vs $\delta^{18}O$ (Fig. 4b, d). However, the observed isotopic enrichment of Cl^- is due to the evaporation process of rainfall, as highlighted in the $\delta^{18}O$ vs Cl^- plot (Fig. 4c).

IS19 well (Fig. 2a) is also located next to the Adige River but in the inner sector of the littoral strip. Also here EC is relatively constant and equal to about 3 mS/cm, increasing to 10 mS/cm at the well bottom, without seasonal variations (Fig. 5). These EC values lower than those at the close IS18 well are due to the mitigation effect exerted by a submerged barrier constructed in the Adige River for preventing the tide encroachment. IS19 chemical data show that a certain recharge from rainfall in the most superficial levels of the aquifer could exist. The vicinity of the sea, the low-lying of the nearby farmland and the maintenance of the water table at low levels by pumping stations allow only a limited aquifer recharge by rainfalls and river leaking. Consequently, even the shallower 10 m thick subsurface is here characterized by a widespread brackish environment.

4.2.2. Lagoon margin and lowlands

The lowlands, i.e. areas characterized by an elevation below the mean sea level, down to 4 m below msl, compose the majority of the study zone (Fig. 1). They are bounded by artificial embankments that separate the cultivated areas from the lagoon basin and keep safe the territory against river flooding. Lowlands are kept dried by a continuous drainage that is performed through a number of artificial channels, a dense network of ditches, and a few pumping stations, which convey the surplus waters into the rivers or the lagoon.

IS4 well (Fig. 2a) is located close to the lagoon margin, in the ancient delta systems of the Brenta and Bacchiglione rivers, which flowed into the lagoon before their last human diversion. In particular, this well was drilled in an abandoned sandy paleochannel which ground surface is higher than the surrounding lowlands. The well (Fig. 6) is characterized by two well-distinct EC values equal to about 6 and 12 mS/cm, in the top 10 m depth interval and in the deeper part, respectively.

The higher EC values at depth are directly related with the seawater intrusion from the lagoon basin, while the mitigation effect of the fresh water leakage from the Brenta River and the Canale Novissimo is clearly distinguishable in the shallow aquifer. These relationships are supported by the water chemical composition, with Cl^- contents close to

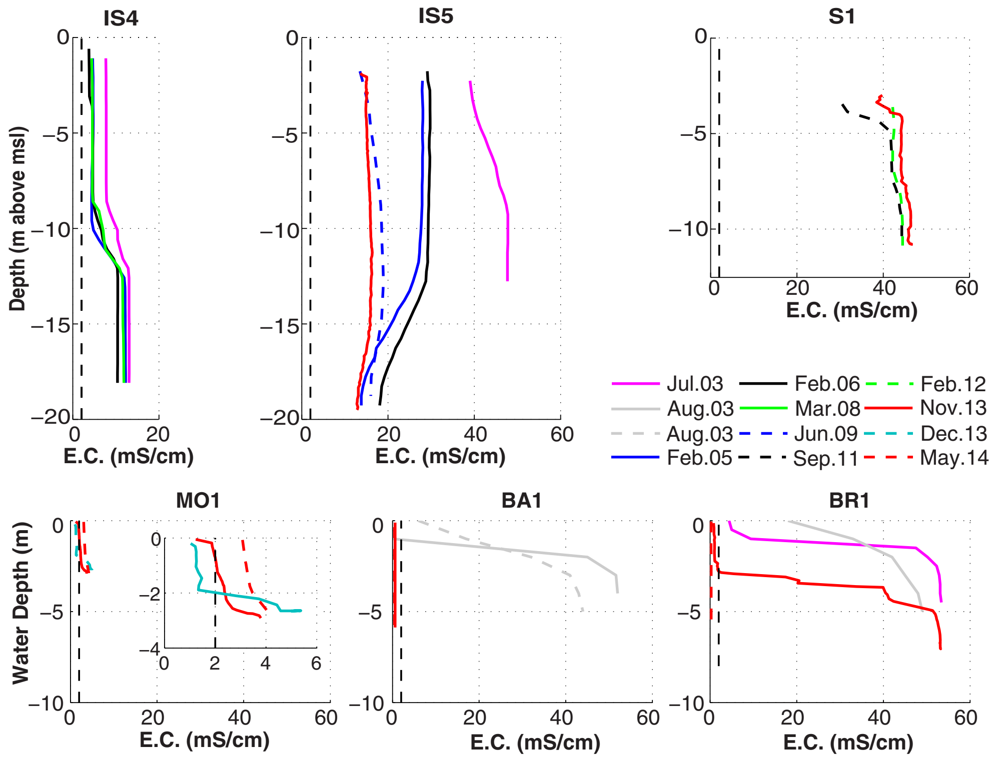

Fig. 6. Electrical conductivity logs showing the freshwater–saltwater dynamics in the lagoon margin and lowlands. The dashed line represents the maximum EC value for irrigation use. The location of the wells and surface waters is shown in Fig. 2a and b.

40 meq/L and the ratio Na^+/Cl^- equal to 0.89 (Fig. 4a). In the graph δ^2H vs $\delta^{18}O$ (Fig. 4b) the groundwater samples are located on the meteoric line similar to the Brenta River and Novissimo Canal isotopic contents; however the deuterium excess and Cl^- values show a slight influence from the lagoon water (Fig. 4c, d). Seasonally, the EC values are almost constant in the shallow part and show a certain variability in the lower portion of the well. To note the increasing salinization during the dry 2003 when the seawater encroached along the Brenta and Bacchiglione rivers for about 20 km and leaked into the aquifer.

Also IS5 and S1 wells (Fig. 2a, b) are located in the lowlands nearby the lagoon margin. Reclamation activity directly controls the water table and water levels of channels on the base of the rainfalls and tide levels. EC values seasonally vary from 15 to 48 mS/cm in IS5 (Fig. 6), and are generally higher than 40 mS/cm in S1 (Fig. 6). Indeed the shallow aquifer is permanently saline. The contamination is directly related to the saltwater from the lagoon basin that intrudes inland beneath rivers and channels. Chemical samples from IS5 clearly show the influence of the lagoon water in the groundwater: Cl^- contents, Na^+/Cl^- values (Fig. 4a), δ^2H vs $\delta^{18}O$ relation (Fig. 4b), deuterium excess and $\delta^{18}O$ vs Cl^- values (Fig. 4c, d) are similar to values typical of the lagoon water. The presence of freshwater in the main watercourses when river discharges prevail on the tide encroachment, as shown in BB1, MO1, BA1, BR1 sites (Fig. 2a, b), are not sufficient to mitigate the salinization of the aquifers by river leakage (Figs. 5 and 6). In general, rainfall strongly decreases the saline degree and its effect vanishes quickly due to the maintenance of low groundwater levels by pumping stations in order to prevent flooding. For example, values of EC between 15 and 30 mS/cm have been detected in IS5 (Fig. 6) after a monthly rainfall of 72.5 mm (November 2013) and 10 mm (February 2006), respectively. During the extremely dry summer 2003 the highest salt contamination (EC = 40–45 mS/cm) occurred. Minor variations are measured in S1 well (Fig. 6).

IS14 well (Fig. 2a, b) is located in the lowland between the Gorzone channel and the Bacchiglione River, a sector particularly affected by the leaching of saltwater from these two watercourses because of the seawater encroachment. Although this well is not so far from the lagoon margin, EC values are relatively small (in the range of 3–5 mS/cm corresponding to brackish water) and almost constant with depth (Fig. 7). These quite low salinity values are likely due to the mitigative effect of a drainage/irrigation channels located near the well. It is interesting to note that EC is not correlated with the climatic season (dry or wet), but it is strongly related with the reclamation level maintained by the pumping stations: low water table in winter and high water table in summer to prevent flooding and allow agriculture, respectively. In a sample with EC of 4.3 mS/cm, the chemical analyses provide 45 meq/L of Cl^- and Na^+/Cl^- equal to 0.9. In Fig. 4b, c, and d the sample values of δ^2H vs $\delta^{18}O$, deuterium excess and $\delta^{18}O$ vs Cl^- are associated with rainfall and drainage/irrigation channels.

IS9 well (Fig. 2a) has been drilled in the lowland just south of the ancient W–E path of the Adige River (Rizzetto et al., 2002) clearly visible in Fig. 1 because of its high elevation. EC profiles show the existence of two main water layers: brackish water with about 5 mS/cm in the shallower part and saltwater with EC = 8 mS/cm in the deeper portion (Fig. 7). Seasonal variations are negligible.

In the South-western sector, the EC measurements carried out in IS20 and IS21 wells (Fig. 2a) show values of 4–6 and 5–8 mS/cm (Fig. 7), respectively, highlighting the presence of salty groundwater also 20 km far from the coastline. They show quite constant EC from the top to the bottom of the wells with very small seasonal variations in relation to the combined effect of rainfalls and drainage activity. For example, IS20 well clearly shows the effect of the dry 2003 in terms of relatively higher EC (5 mS/cm). IS20 well shows EC values lower than IS21 likely because the former is located in a major sandy paleochannel while the latter in the lowland. IS9, IS20, and IS21 groundwater samples have low Cl^- contents with Na^+/Cl^- ratio greater than 1, and in particular greater than 2 for IS9 like detected in Bacchiglione River samples (Fig. 4a). In the graph δ^2H vs $\delta^{18}O$ (Fig. 4b) the values are located on the meteoric line, hence the deuterium excess and Cl^- contents are representative of precipitation recharge (Fig. 4c, d).

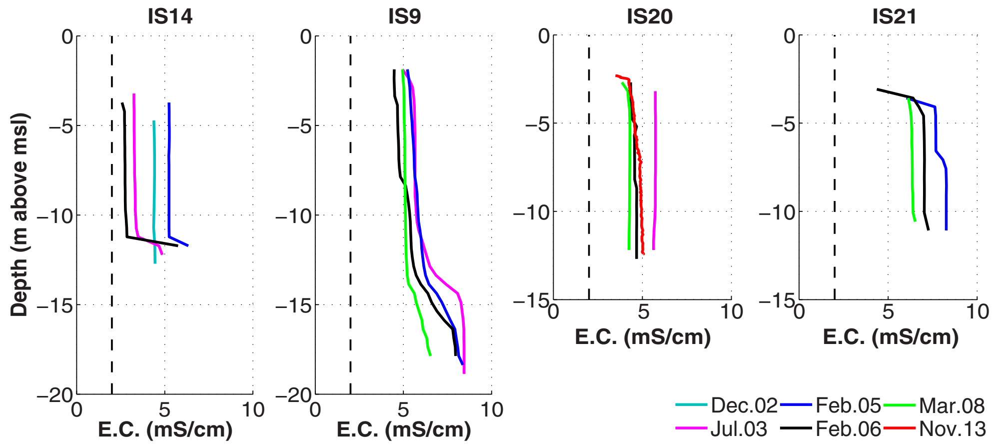

Fig. 7. Electrical conductivity logs showing the freshwater–saltwater dynamics in the lagoon margin and lowlands. The dashed line represents the maximum EC value for irrigation use. The location of the wells and surface waters is shown in Fig. 2a.

4.2.3. Paleochannels and ancient littoral ridge systems

The coastland between the lagoon margin and the Adige River is crossed by a number of geomorphologic structures. Abandoned riverbeds, mainly corresponding to Late Holocene courses of the Brenta River occur in the central and southern catchments, and those of the Adige and Po rivers are located in the southernmost sector. In addition, paleo-beach ridge systems extend in NE–SW direction from the Po Delta to the Venice Lagoon. These features are well visible in the DEM of the area (Fig. 1) because of their ground elevation significantly higher than the nearby landscape.

IS6 and S3 wells (Fig. 2d and b, respectively) are located in two paleochannels close to the southern lagoon margin. They show similar EC profiles, generally in-between of 20 mS/cm. The quite constant values of the EC suggest that the influence of the water table control on the groundwater salinity is negligible (Fig. 8). These paleochannels permanently contains saltwater. Mitigation from BA3 and MO2, mainly freshly due to do the dykes which prevent the saltwater intrusion, does not occur because of the distance. Relatively lower values of EC referable to the temporary occurrence fresh–brackish waters have been found in the shallower part of S3 in concomitance of a heavy rainfall event. Chemical samples from IS6 show the influence of the lagoon water in the groundwater chemistry: Cl^- contents are up to 224 meq/L and Na^+/Cl^- values are close to 0.80 as the lagoon (Fig. 4a). In the δ^2H vs $\delta^{18}O$ relation (Fig. 4b) the samples are located on the mixing line representing lagoon and sea water, in agreement with the deuterium excess (Fig. 4d) and $\delta^{18}O$ vs Cl^- (Fig. 4c).

S2 well (Fig. 2a, b), instead, shows lower salinity content and a certain EC variability, whose values range between 2 and 5 mS/cm at the top and from 28 to 35 mS/cm in the deeper part (Fig. 9). The lower EC values in the shallower part of the aquifer are likely due to the leakage of freshwater from the Morto Channel and the Bacchiglione River that mitigate the saltwater intrusion from the lagoon. The EC variability is probably ascribed to the effect of rainfalls that recharge the sandy paleochannel. In particular lowest and highest EC have been detected in correspondence of 73.5 mm (November 2013) and 19.5 mm (December 2011) monthly rainfalls, respectively.

CA20 well (Fig. 2a, b) is located in a very complex hydrologic contest, i.e. near a pumping station, close to the lagoon margin, reclamation channels, and rivers. It is screwed between 15 and 20 m depth with the purpose to detect a locally confined aquifer. EC profiles point out the occurrence of a stratified saltwater with EC seasonally variable and ranging between 16 and 30 mS/cm (Fig. 9). These high values are related to the marine water intrusion from the lagoon basin.

Conversely, IS7 well (Fig. 2a, d) shows constant EC = 3–4 mS/cm along the whole 18-m depth interval of the borehole (Fig. 9). This brackish water are characterized by low Cl^- contents (22 meq/L) and a Na^+/Cl^- ratio equal to 1.35 (Fig. 4a). Concerning the δ^2H vs $\delta^{18}O$ relationship, the samples are located on the meteoric line (Fig. 4b), showing a significant rainfall recharge as confirmed by the deuterium excess and $\delta^{18}O$ vs Cl^- (Fig. 4c, d). This well shows a lower salinity than the other boreholes drilled in paleochannels. This paleo-structure is locally recharged by the leaching from a close irrigation channel through which freshwater is distributed in summer. However, the effect of the 2003 drought is highlighted by the higher EC values also in this structure.

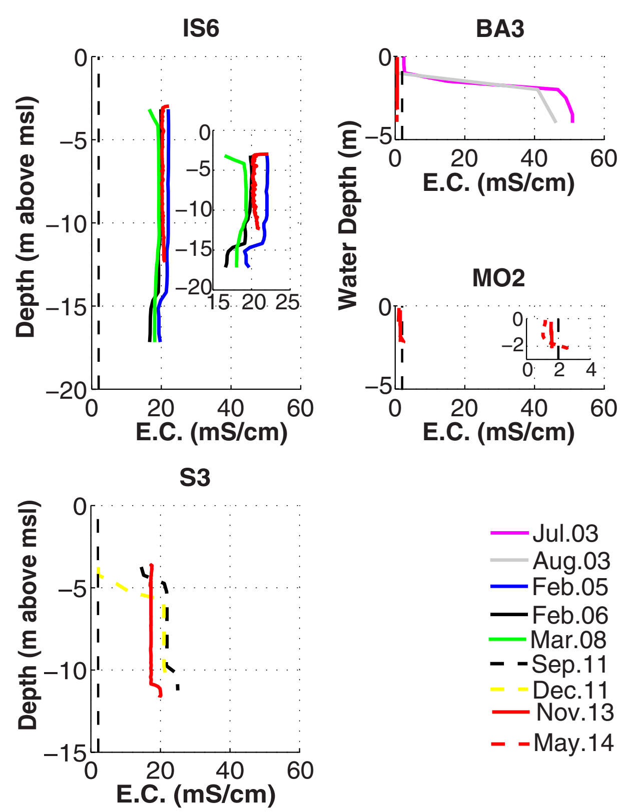

Fig. 8. Electrical conductivity logs showing the freshwater–saltwater dynamics in the paleochannels. The dashed line represents the maximum EC value for irrigation use. The location of the wells and surface waters is shown in Fig. 2a, b, and d.

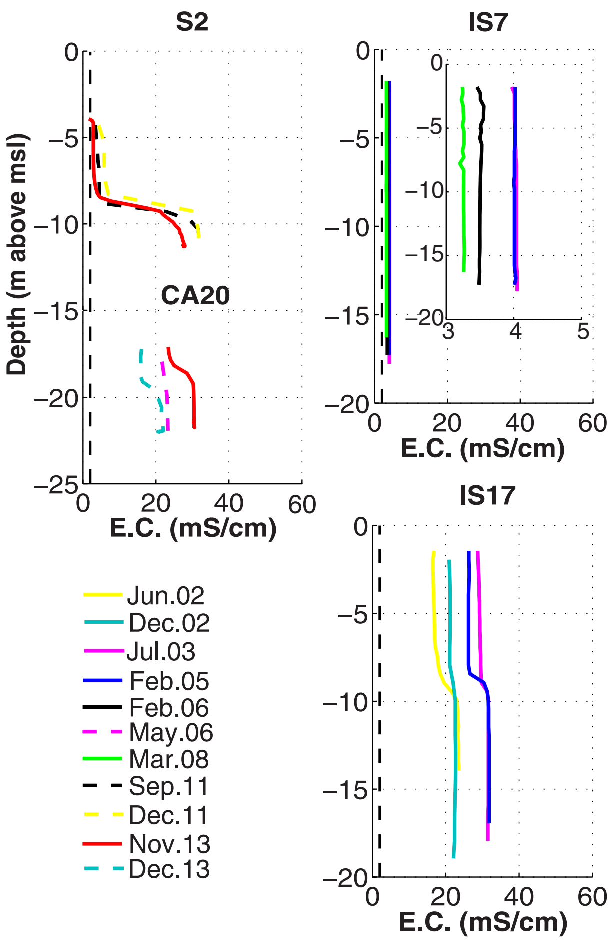

Fig. 9. Electrical conductivity logs showing the freshwater–saltwater dynamics in the paleochannels. The dashed line represents the maximum EC value for irrigation use. The location of the wells and surface waters is shown in Fig. 2a, b, and d.

IS17 well (Fig. 2a) is drilled in the central part of the littoral strip, close to a buried paleochannel of the ancient mouth of the Brenta River. The well shows quite constant EC values with depth. Conversely, a significant seasonal variability between 16 and 30 mS/cm due to the rainfalls has been measured (Fig. 9). The highest EC occurred in the dry 2003 summer, and lowest records in June and December 2002 when 41.5 and 72.6 mm monthly rainfalls occurred, respectively.

Two wells, namely IS10 and IS11 (Fig. 2a, c) are located in the ancient sandy littoral ridge system elongated in the north–south direction from the Brenta and the Adige Rivers. EC is always less than 2 mS/cm in the upper 8–10 m depth interval of IS10, and seasonally increase from 5 to 10 mS/cm at larger depth (Fig. 10). Cl^- content, Na^+/Cl^- ratio and environmental isotopes are similar to those of Adige River. In the plots Na^+/Cl^- vs Cl^- (Fig. 4a) and δ^2H vs $\delta^{18}O$ (Fig. 4b) the IS10 sample lies among the Adige River and on the meteoric line closest to the Adige River samples, as observed in the deuterium excess diagram and $\delta^{18}O$ vs Cl^- plot (Fig. 4c, d). The recharge of freshwater into the upper part of this sandy structure is supplied by the Adige River, whose water is generally fresh in this sector. For example, EC values recorded in the AD2 monitoring site (Fig. 2a, c), where the watercourse intercepts the sandy ridges, are generally less than 1 mS/cm (Fig. 10) owing to the presence of a barrier built next to the river mouth to prevent the seawater encroachment during dry periods with low discharge. Conversely, brackish–salty waters with EC in the range of 6–15 mS/cm are detected in IS11 (Fig. 10). Cl^- concentrations are equal to 80 meq/L with Na^+/Cl^- ratio of 1.0 (Fig. 4a). In the graph δ^2H vs $\delta^{18}O$ (Fig. 4b) the samples are located close to the meteoric line with a slight tendency to the mixing line of lagoon water. Hence, deuterium excess and $\delta^{18}O$ vs Cl^- relation show a slight tendency to salinization (Fig. 4c, d) associated to the leakage of the seawater encroached into the Brenta–Gorzone river system (CG1 in Fig. 10).

4.2.4. Inland sector

IS1, IS2, IS22 wells (Fig. 2a) were drilled in the north-western inland. EC values are less than 2 mS/cm with very slight variability (Fig. 11), hence the aquifers permanently contain freshwater. In this sector the shallow aquifers are recharged by the present and ancient Brenta and Bacchiglione river systems. EC measured in BA2 and BR2 (Fig. 2a) along the two rivers shows typical freshwater values. Only in concomitance of very dry seasons, the tide encroaches from the Brenta mouth and can reach this sector. This sector of the study area represents the limit of the saltwater contamination extent in the shallow aquifers. Chemical data of IS1, IS2, IS22 show low Cl^- contents (less than 2 meq/L) and Na^+/Cl^- values between 0.5 and 2.0 (Fig. 4a). In the graph δ^2H vs $\delta^{18}O$ (Fig. 4b) the samples are located on the meteoric line and the values of the deuterium excess and $\delta^{18}O$ vs Cl^- relations are characteristic of rainfall recharge (Fig. 4c,d).

4.3. Vulnerability assessment

The classification intervals and the classified thematic layers used in the GALDIT approach are shown in Table 1 and Fig. 12, respectively. In

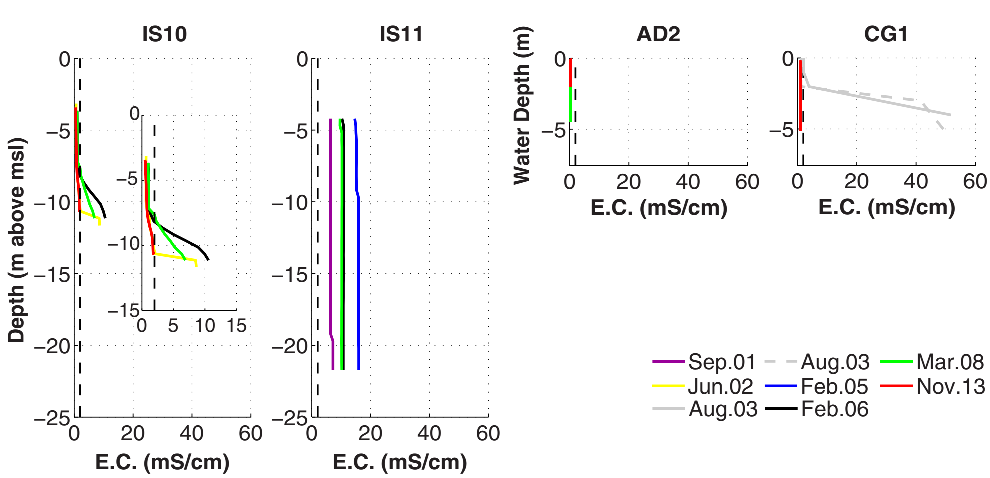

Fig. 10. Electrical conductivity logs showing the freshwater–saltwater dynamics in the ancient littoral ridge systems. The dashed line represents the maximum EC value for irrigation use. The location of the wells and surface waters is shown in Fig. 2a and c.

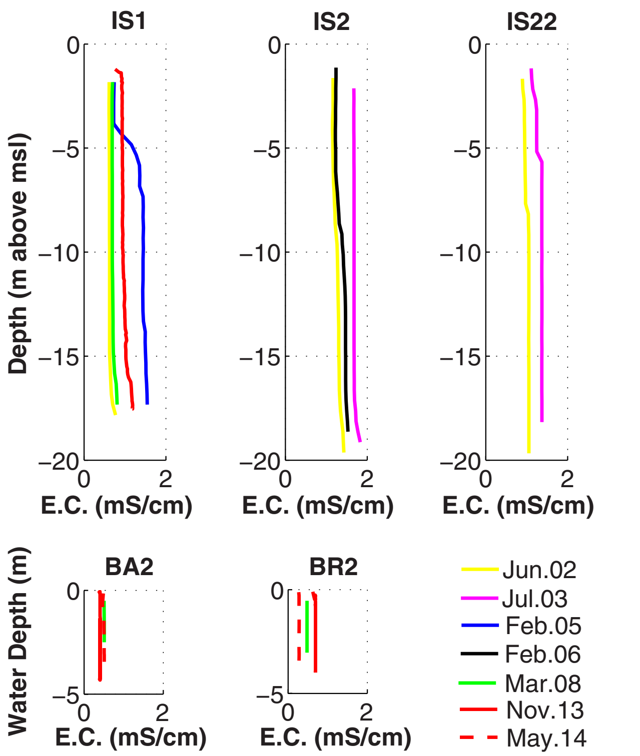

Fig. 11. Electrical conductivity logs showing the freshwater–saltwater dynamics in the inland sector lagoon. The dashed line represents the maximum EC value for irrigation use. The location of the wells and surface waters is shown in Fig. 2a.

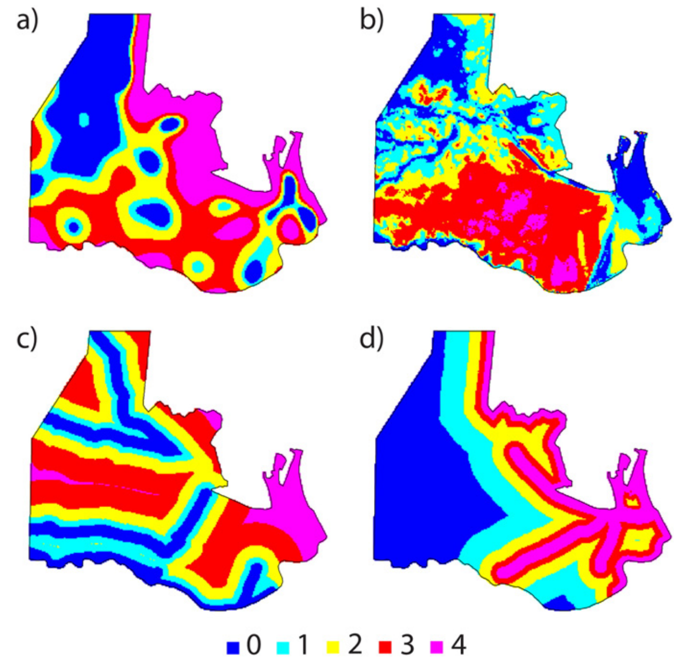

Fig. 12. Classified thematic layers of the four factors influencing the salt contamination at the Venice coastland: a) electrical conductivity (ECw); b) soil elevation with respect to the mean sea level (DEM); c) distance from a fresh water source (FD); d) distance from a salt water source (SD). Classes range from (0), meaning low (or positive) influence for agriculture activities to (4), which means a strongly negative effect.

order to provide the relative importance of each factor, a relative percentage weights is assigned to each classified layers (Table 2).

As ECw is the parameter that directly influences the soil productivity and defines the limit from suitable to unsuitable use of the groundwater for agricultural activities, we assigned it a weight w_{ECw} double than that given to DEM (w_{DEM}), FD (w_{FD}), and SD (w_{SD}). Finally, the four weighted factors have been integrated using a Multi-Criteria Evaluation approach (Carver, 1991), with the vulnerability index V_i for each grid node i obtained as:

$$V_i = w_{ECw} \cdot EC_i + w_{DEM} \cdot DEM_i + w_{FD} \cdot FD_i + w_{SD} \cdot SD_i. \quad (2)$$

The V values thus obtained have finally reclassified into five classes (from negligible to extreme) to produce the map shown in Fig. 13. Reclassification has been carried out through the Jenks optimization method (Jenks, 1967) that reduces the variance within classes and maximize the variance between them.

Fig. 13 highlights a certain local variability of the vulnerability superposed to the regional trend diminishing from the sea to the mainland. The vulnerability map partially agrees with the hydro-morphologic zonation used for the local analysis of the saltwater contamination components. It can be observed that in the littoral strip and lagoon margin are the sectors where V ranges from marginal to extreme for crop production; in the most part of the lowland sector a moderate to critical vulnerability exists. Paleochannels and ancient littoral ridges are preferential pathways both for fresh or salt groundwater flow: in these features the vulnerability varies significantly (from negligible to extreme) depending on the local position with respect to the saltwater or freshwater sources and the ground elevation. The inland sector is generally characterized by a negligible to marginal vulnerability.

5. Discussion

Over the historical time, river diversions, channeling, and land reclamation progressively changed the hydrogeologic setting of the Venice coastland. Most of the area between the southern lagoon margin and the Adige River is now below the mean sea level, and the surficial water–groundwater exchanges is now human-driven through a dense reclamation network. Most of the territory is affected by saltwater contamination, which is certainly due to the natural process of seawater intrusion into coastal aquifers. However, the signal of the factors driving the saltwater intrusion, i.e. the morphological setting, rainfall events, and tidal and river regimes, is filtered by the artificial maintenance of the water table at depths suitable for agricultural activities and flood prevention of the lowlands. Therefore, the artificial control of surficial water and groundwater levels plays a significant role in the saltwater–freshwater interaction.

Table 1
Classified thematic layers of the four controlling factors influencing the salt contamination at the Venice coastland. Value (0) means low vulnerability for the farmland productivity, (4) means high vulnerability.

ECw (mS/cm)	DEM (m above msl)	FD (m)	SD (m)	Class
0–2	1–10	0–500	>4000	0
2–3	0–1	500–1000	2000–4000	1
3–6	−1–0	1000–2000	1000–2000	2
6–10	−3–−1	2000–4000	500–1000	3
10–50	−5–−3	>4000	0–500	4

Table 2
Weights assigned to each classified thematic layer.

Factor	Class	Weight
ECw	0–4	0.4
DEM	0–4	0.2
FD	0–4	0.2
SD	0–4	0.2

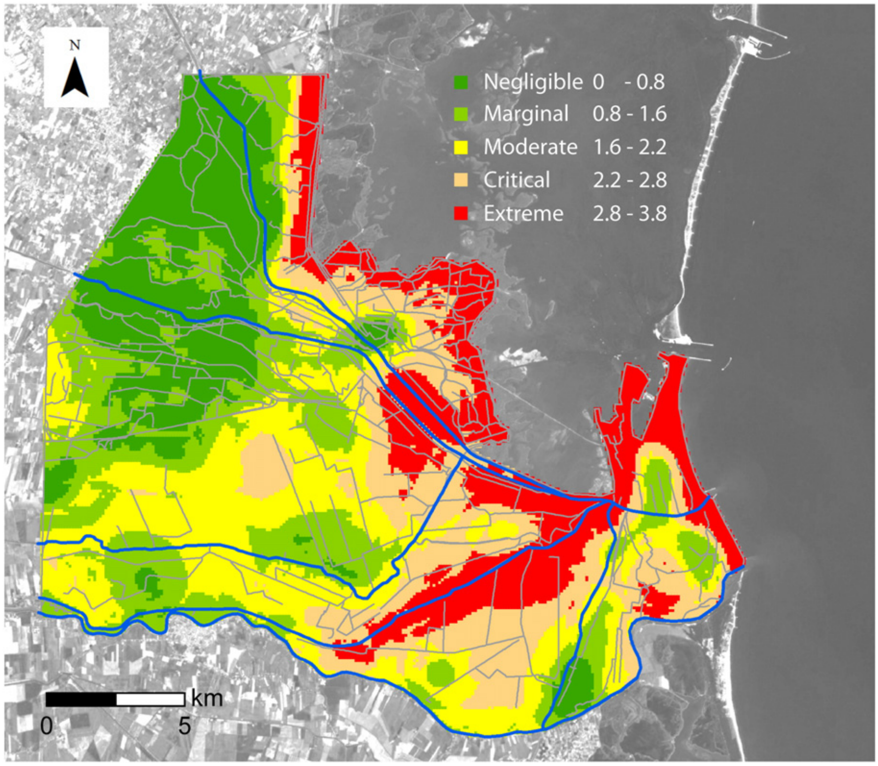

Fig. 13. Map of the index of vulnerability to salt contamination in relation to the farmland productivity, obtained from Eq. (2). The values are classified into five classes from negligible to extreme. The background is a Landsat image (2011) obtained from the US Geological Survey and Earth Resources Observation and Science (EROS) Center.

The origin, extent, and dynamics of the salt contamination, and their relation with the natural and anthropogenic forcing factors, have been analyzed in this complex setting.

In the littoral sector, a ground elevation up to 3 m above msl allows the natural discharge of the surface water into the sea. This morphological setting makes possible the subsurface storage of rainfalls in permanent 15–20 m thick freshwater lenses thinning toward the sea, lagoon, and rivers. The water table varies depending on the climate conditions but with no significant effect on the groundwater salinity. In the mainland, which is mostly lying below the mean sea level, the saltwater contamination significantly affects the shallow aquifers. The maintenance of the water table below the ground surface by pumping stations favors the salt intrusion. In addition, 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, which are located well above the surrounding farmlands. When tides prevail on the river discharge, the seawater located on the deepest layer of the water column (July 2003 and November 2013, BB1, Fig. 5; August 2003, BA1, and July 2003, August 2003, November 2013, BR1, Fig. 6; July and August 2003, BA3, Fig. 8; August 2003, CG1, Figs. 10; and S2) infiltrates through the bed of the watercourses in the nearby lowlands. Conversely, when the river discharges counteract the seawater encroachments (May 2014, BB1, Fig. 5; MO1, November 2013, BA1, and May 2014, BR1, Fig. 6; MO2, November 2013, BA3, Fig. 8; AD2, November 2013 CG1, Fig. 10), the watercourses exert a significant role in mitigating the salt contamination in the aquifers. This is confirmed by the outcome of a local airborne electromagnetic survey crossing the Brenta, Bacchiglione, and Morto watercourses carried out in 2009 (Viezzoli et al., 2010; Teatini et al., 2011). The presence of sandy buried paleochannel systems crossing the farmland, with a main direction from inland to the lagoon boundary, acts as preferential pathways for groundwater flow and solute transport as detected in other similar coastal sites (Wicks and Herman, 1995; Mulligan et al., 2007). These features generally increase the saltwater flow from the lagoon into the low-lying sectors, even though they allow a short-term storage of rainwater in the very shallow subsoil. Conversely, the sandy paleo-ridge systems are capable to contain groundwater with lower salinity than that occurring in the paleochannels, at least in the shallow part. For both paleochannels and paleo-coastal ridges, the water quality is significantly improved by local rainfalls that rapidly supply freshwater.

The measurements carried out over a decade has pointed out that the saltwater contamination in the shallow aquifer of the coastland south of Venice is widespread and permanent. However, no clear long-term trend has been detected. This could be explained, at least in part, by a sort of quiescence in the process evolution or a dynamic time-scale much longer than the decade spanned by the present investigation. On the other hand, although the large processed dataset, clear reference and actual pictures of salt contamination are challenging to be obtain at the regional scale in this kind of coastal environment. The study points out that the outcome of traditional methods of investigation, based on the integration of well/piezometer measurements with local and scattered hydro- geophysical surveys, suffers for the not simultaneously acquisitions (i.e. different meteo-hydrologic conditions), the possible missing of monitoring sites over time, the likely non-representativeness of the monitoring sites in relation to the typical large heterogeneity usually characterizing the Holocene coastal farmlands. This limit could be overcome updating the monitoring network by continuous multi-parameter probes, at least for the EC and water level, integrated by advanced 3-D geophysical characterizations, e.g., using airborne electromagnetic surveys (e.g., Siemon et al., 2009).

Nonetheless, the interpretation of the available information has allowed depicting an original map of the vulnerability to salt contamination in relation to the farmland productivity at the regional scale. Its interpretation is very simple and can provide an easy-to-use tool to support administrative and management decisions. Moreover, it can help detecting the zones at higher risk, where local more detailed investigations must be performed to improve the quantitative knowledge of the ongoing process and develop numerical models for the prediction of the future behavior.

6. Conclusions

This study has characterized the magnitude and the dynamics of the saltwater contamination in the coastal farmland south of Venice Lagoon, a lowlying area whose hydrology is strongly influenced by anthropogenic pressures.

The analysis points out that this process, which is due to the natural intrusion of seawater into shallow aquifer, is controlled by various factors, i.e. ground elevation, the presence of buried geomorphologic structures, a possibly significant tide encroachment along rivers and channels, and land reclamation activities.

The main conclusions can be summarized as follows:

- the depth of the fresh/salt-water interface varies from 1 to 30 m below the ground level and exhibits a certain time variation, which is mainly seasonal or linked to the actual meteorological conditions. The dynamics of the soil salinization process is especially sensitive to changes in river 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, provide a hydraulic connection between freshwater aquifers and sea, possibly facilitating saltwater intrusion landward or, conversely, acting as reservoir of freshwater from precipitation, irrigation, and percolation through river beds;
- a vulnerability map to salt contamination in relation to the farmland productivity clearly outlines that most of the coastland is in moderate to extreme conditions. We are conscious that the approach implemented has the well-known common limitations of index methods, which mainly consist on subjectivity and lack of physically-based underpinnings in converting hydrogeological characteristics into vulnerability to salt contamination. Nonetheless, the method is easy to apply and provide a first-order assessment of vulnerability that is easy to be interpreted. The map provides suitable information to the water authorities for supporting farmers activities, improving the management of the reclamation actions as well as to take appropriate decisions to plan countermeasures for mitigating the saltwater contamination and precluding a further worsening;
- considering that some of the factors controlling the saltwater intrusion are directly or indirectly controlled by eustacy and land subsidence, the expected relative sea level rise may contribute to worse the water salinization condition.

Finally, it is worth noting that the study has revealed a certain weakness in monitoring salt contamination by traditional well logs in the Venice coastland. Because of the complex morpho-hydro-geologic setting of this low-lying human-influenced area, an improved and integrated monitoring approach, for example by coupling continuous in situ-measurements with geophysical large-scale investigations, is required to better understand the surficial water–groundwater exchanges at the regional scale. Following this general outcome, a few most representative piezometers have been selected to be equipped by multi-parameter probe and a regional airborne electromagnetic survey has been planned.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2015.07.013.

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