Salt water contamination on Venice Lagoon mainland: new evaluation of origin, extension and dynamics

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Abstract The Venice Lagoon mainland is affected by salt water contamination in coastal and circum lagoonal aquifers due to the close vicinity of both the sea and lagoon. The territory, characterized lithologically by alternating layers of silt, clay and sand which have marine, continental and/or marsh origins, is characterized by several critical conditions. These include the existence of paleorivers, lagoonal paleochannels, and rivers which are artificially suspended above the surrounding land by dikes. All of these conditions contribute to an increase in groundwater salinization. Areas with high permeability seem to constitute a preferential way of movement for salt water from the sea or lagoon towards the mainland. Old fossil water seems to be able to reach the surface and contribute to an increase in the process of salt pollution. In fact, during the 1970s, several studies had detected, throughout the territory, the existence of a deep salt water aquifer storing fossil saline water. This aquifer lies at a depth of about 300 450 m in the southern part of the study area and of more than 600 m in the northern part of the Venice mainland. Salt water contamination of subsoil could cause ground salinization and, consequently, desertification of the area, with great economical consequences. These include damaging the large agricultural development of the territory as well as having adverse impacts on the tourist industry.

The combined use of adequately validated geophysical and geochemical tools confers a multidisciplinary character to the research and allows for the definition of the phenomenon's superficial extension .

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Geophysical analysis based on Vertical Electrical Sounding (VES) and conductivity logs have been performed together with water table measurements and geochemical analysis on samples collected from selected wells. Moreover, a critical review of old geophysical data allowed for the verification of possible saline contamination changes in time.

Interesting results have been obtained within the northern sector of the Venice lagoon mainland, specifically within territory of Jesolo. In this case, considering the influence of the Piave and Sile rivers and the presence of a coastal sand dune, it is possible to create a map of salt water contamination to evaluate the agricultural use of superficial water.

Therefore, the aim of this research is to define the effective origin of salt water found in the aquifers of the northern lagoon mainland, its distribution, extension and its preferential way of movement within the territory. Thereby, relating all the information acquired to the geological, geomorphological and stratigraphic characteristics of the area.

Index Terms geology, geophysical measurements, sea coast, water

I. INTRODUCTION

Salt water contamination in unconfined aquifers is a widespread phenomenon that is important for both the lagoon and marine environment. This research, focused on northern sector of Venice Lagoon mainland, between the Piave and Sile rivers, is a new attempt to assess the present degree of subsoil salinization, by means of geophysical and geochemical tools. It also allows for the determination of the superficial extent of salt water contamination within mainland [1].

The northern sector of the Venice Lagoon mainland, part of the eastern Po Plain, is bordered by the Venice Lagoon to the West, by the Adriatic Sea to the South and by the Piave river until San Donà di Piave to the East. It includes the territory located between Piave and Sile rivers encompassing the cities of Portegrandi, Jesolo, and

Cavallino (Fig.1), an area with a total extension of about 157 km^2 [2]

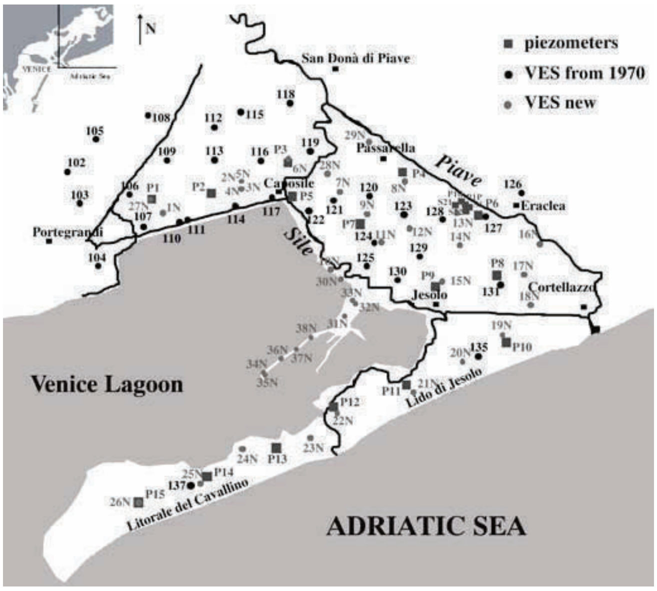


Fig. 1. Location of measurement points within the investigated area: P piezometers (grey squares); VES conducted byPadua University in the 1970 (black dots); new VES site (grey dots)

The geomorphology of the area is characterized by reclaimed land, which is subjected to artificial pumping and has a ground surface elevation lower than that of sea level (-1,-2 m), paleorivers, and former lagoon channels. Each of these are suspended above the surrounding land. Sand dunes and an old barrier beach are present in the coastal belt. The Piave and Sile are the major rivers. The former is an alpine water course and flows in the NW-SE direction; the latter, which is fed by a spring, flows parallel to the lagoon margin from Portegrandi to Caposile and then parallel to the Piave [3]-[4]. Subsidence, due to human activities and natural processes, is a phenomenon present in the area and contributes to increase the hydraulic risk condition for the territory.

Conductivity logs and Vertical Electrical Soundings (VES) have been performed all over the area, detecting groundwater, irrigation channels, and rivers. The obtained results have been compared with pre-existing data to evaluate contamination conditions.

II. Geophysical Investigation

A. *Sampling and analytical techniques*

Fifteen fully screened piezometers in the province of Venice, at a depth of about 5 m, tapping the unconfined aquifer have been used as references for the present work. Soil and water stratigraphy allowed for the calibration of geophysical results. In the field both geophysical and hydrogeochemical analyses have been completed. Conductivity logs, temperature and water level data have been collected from every well, in April, May and August 2005 (Fig.1). Groundwater levels reveal fluctuations of less than one meter, water temperature varies around 1° C, pH values, which are slightly basic, range between 7.4 and 8, whereas Electrical Conductivity values change significantly in depth and in areal distribution. Looking at the EC log values, only five piezometers located near the Sile river and in the costal dune display an adequately low level of water salinity especially during spring time (values < 1 mS/cm, P5) (Fig.2a), whereas waters collected in the other wells show high EC values ranging from 3,5 to 12,8 mS/cm (P2-P7-P1) (Fig.2b-c-d).

38 new Vertical Electrical Soundings (VES) have been executed to better define the extension of salt water intrusion. Ground Electrical Resistivity is strictly dependent on the water bearing saturation level of the sediments and on quality and quantity of solution ions present in the aquifer itself. The new VES data (Fig.1) duly calibrated with ground water EC and compared with selected existing data (36 measurements) taken by the University of Padua [1-5] describe the changes of ground water salinization. Five resistivity classes have been identified and are explained in Fig.6. The geophysical sounding allows for an investigation of the first 30 m of subsoil and, when combined with geomorphological and stratigraphic information, can determine the existence of preferential pathways for saline water displacement and higher hydraulic conductivity zones such as paleorivers, old lagoonal channels and dunes [3]-[5].

III. Results and discussion

To assess the presence of salt water into the territory, electrical conductivity analyses (EC logs) of both the superficial hydrography (rivers and channels) and the groundwater have been performed. Originally, periodical measurements of conductivity values were collected from August 2004 to May 2005 from the bottom and the top of superficial channels, characterized by bathymetry less than 2 m, as well as from the principal rivers. The chemical characteristics of water and the measured saline content (mS/cm), are needed to determine the utility of using the water to irrigate land, and allow for the characterization of three sectors, which exhibit different behaviours: a) the sector along the left bank of the Sile, between Portegrandi and Caposile, is characterized by conductivity values lower than 2 mS/cm. The low TDS and high water quality are fine for agricultural purposes; b) the sector, between Piave and Sile rivers, shows EC values of ground waters ranging from 2 to 15 mS/cm, indicating a significant decline in water quality due to the presence of salt below cultivable soils; c) the third sector along the Piave river and Adriatic sea coast reveals saline content of more than 25 mS/cm, identifying water not suitable for agricultural purpose (Tab.1, Fig.3)

[6].

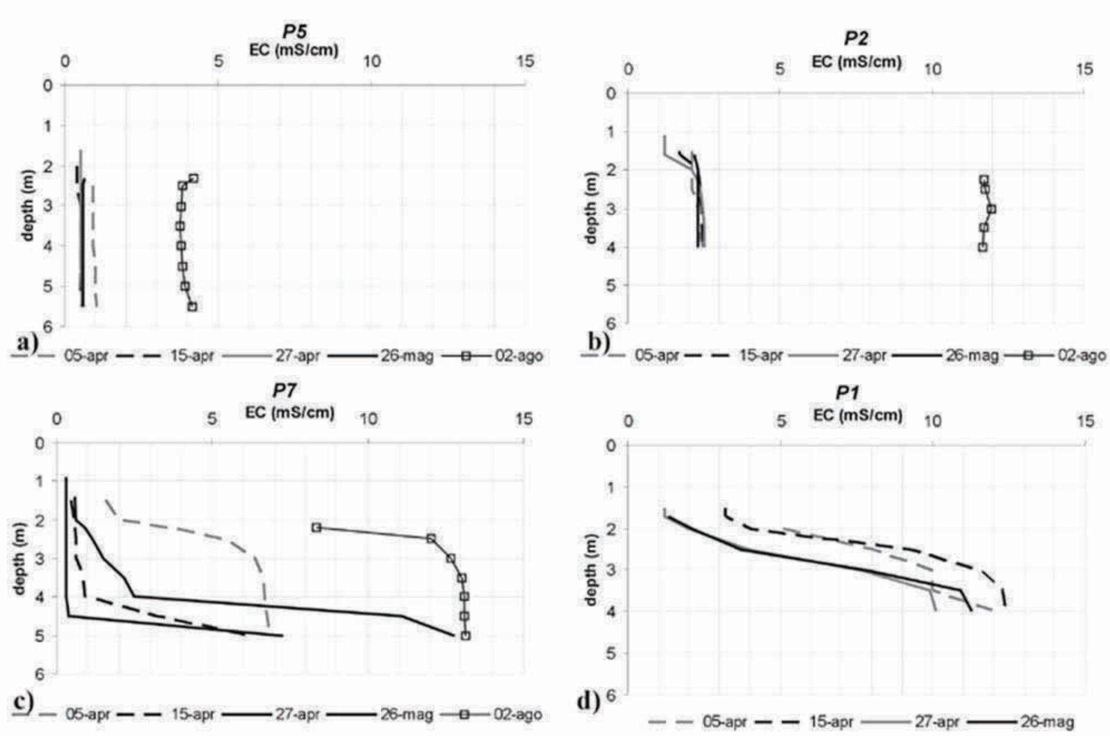


Fig. 2. Conductivity logs showing the electrical conductivity trend for wells characterized by low salinity (P5) and high EC values ranging from 3,5 to 12,8 mS/cm (P2-P7-P1)

TABLE I. THE CHEMICAL CHARACTERISTICS OF WATER AND THE MEASURED SALINE CONTENT (MS/CM) ALLOW TO DETERMINE THE UTILITY OF USING THE WATER TO IRRIGATE LAND (FROM L.CARBOGNIN ET AL., 2003, MODIFIED)

Conductivity (mS/cm)		Water quality	Degree of water use for agriculture purpose
Range	Classification		
0.2-1	low-medium	*good*	All plants
1.001-2	medium-high	*tolerable*	Plants less tolerant salinity
2.001-3	high	*doubtful*	Plants
3.001-5	Very high	*Not usable*	Not suitable

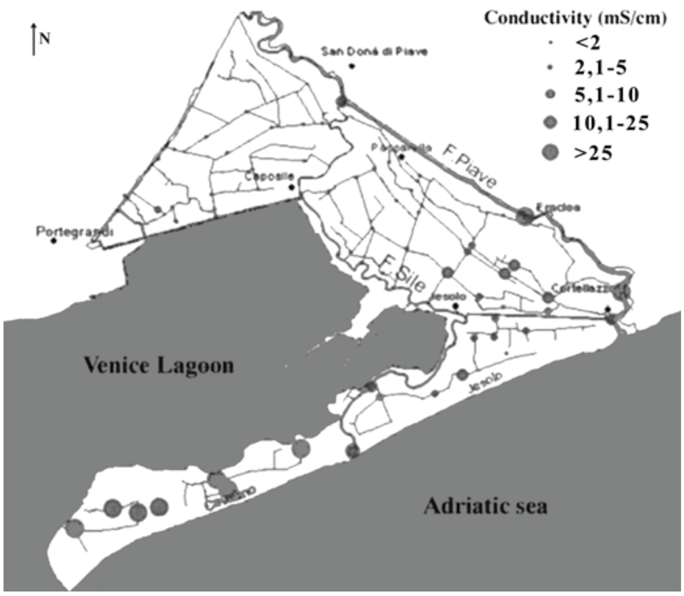


Fig. 3. Conductivity values (EC logs) of the superficial hydrography (rivers and channels) in order to determine the utility of using their water to irrigate the land. This also allow for the determination of increasing

Moreover, EC measured in time [7] along the Piave and Sile rivers indicate that salt is moving progressively from the sea to the mainland and allow for the identification of the extension of salt water intrusion in riverbeds. The EC measured at the surface and at the bottom of rivers highlight the different behaviours of the two rivers. The Piave river near its mouth (Cortellazzo) always reveals the presence of high salinity both at the surface and at the bottom: > 20 e > 40 mS/cm, respectively; at Eraclea, about 8 km inland, the EC values are still high, remaining in the range typically found in sea water, whereas EC values obtained at San Donà di Piave (about 19 km inland from the sea) gently decrease, varying from more than 10 mS/cm on bottom to more than 4 mS/cm at the surface [8]. Here a salt water wedge can be found on the Piave riverbed for about 20 km, aided by the presence, at Eraclea, of a topographic depression (reverse slope), due to Holocene morphology (alternation of dune and lowlands) and anthropic intervention. In fact when, in the past centuries, the Venice republic redirected the Piave flow and created the new river bed by choosing lowlands, this allowed for the present salt water propagation and dispersion into the surrounding mainland (Fig.4).

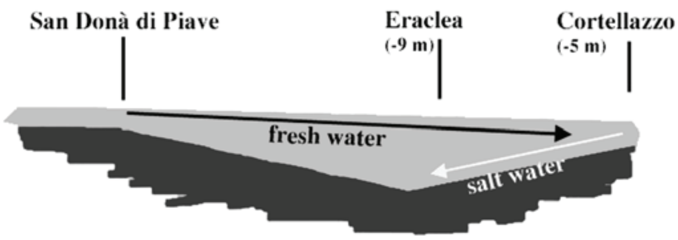


Fig. 4. the Piave riverbed topographic depression near Eraclea favours salt water propagation and dispersion into
the surrounding mainland

On the contrary, in the Sile, high EC values are measured only in the proximity of river mouth: at the Cavallino dock for instance, EC is greater than 15 mS/cm at the bottom and about 4 mS/cm at surface, whereas at Jesolo (about 10 km inland) and Caposile (about 20 km inland) the water is in both cases characteristic of fresh water, with values lower than 1 mS/cm. Anthropic interference of the surface network took place on highlands. So, the absence of salt water intrusion along Sile riverbed is in agreement with local Holocene morphology. At the present time, Sile waters present a fair quality for irrigation purposes (Fig.5).

The VES profiles obtained by direct and indirect modelling of resistivity curves [9]-[10] show the presence of a conductive layer on the surface of the soil. In particular, behind the Sile, where the river flows parallel to the lagoon, the conductive electrolayer is clearly detected and corresponds to an old lagoon channel [3]-[4] in the proximity of P1 (Fig.6a). This is in agreement with EC logs and water chemical analyses. Otherwise, far inland, salinization is absent or related to silty soils saturated by salt water (Fig.6a').

An electrolayer with very low resistivity values is widespread in the area between the Piave and Sile river courses. It reveals the presence of unconfined salty water bodies (aquifers) as well as high salinization of the subsoil, from 15 to 35 m depth (Fig.6b). The high saline content is caused by several conditions including proximity to the lagoon, a ground surface elevation beneath mean sea level, dispersion of salt water from the Piave riverbed, which is suspended above the surrounding territory, as well as during high tides and dry seasons. In fact, the Piave riverbed is formed by sediments which are more transmissive, as a Piave "paleochannel", clearly identified along the E-W direction . These are the preferential modes of salt water movement toward the mainland (Fig.6b). Moreover, a deep conductive layer (fossile brines) is found at 400 m depth and can reach a depth of 800 m around Eraclea.

In the coastal area, which is constituted mainly by sand, the conductive layers show that salinization processes of ground waters take place until a depth of about 25-35 m. Sometimes, above the conductive layer, resistivity values of 15-50 Ωm are recorded, corresponding to fresh water stored in dunes (Fig.6c).

Finally, the combination of EC Logs data and VES soundings help to create a map of superficial salinization (Fig.7), including the first 25-30 m of subsoil: in fact, the stratigraphic analysis confirms the presence of paleoriverbeds and the existence of a relationship between the Piave and phreatic water favoured by sand deposits. Those conditions determine a widespread territory salinization and an high salt water content within the Piave and surrounding unconfined aquifers. Two sectors with high saline ground waters can be recognized on figure 9: the coastal zone, and the area between the Piave and Sile rivers.

The areas with low salinity ground waters correspond to the extreme northern sector which are affected by fresh water of a continental origin [11]. In addition, there are small areas inside the high salinization zone, near the Sile river and along the dune belt, where fresh water with the lowest EC values have been recorded. Moreover, a transition zone connecting the previous ones, is characterized by soils saturated with medium-saline waters. Therefore, this transition area requires a more complete geophysical and geochemical definition of the salt wedge, in order to highlight, in detail, the hydrodynamic conditions controlling the salinization of the northern Venice Lagoon mainland.

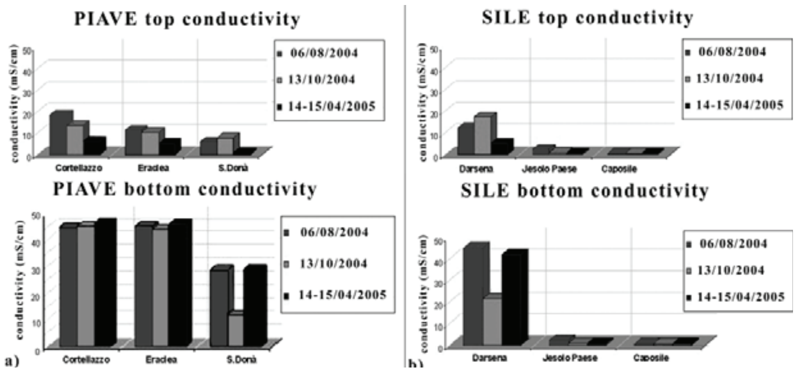
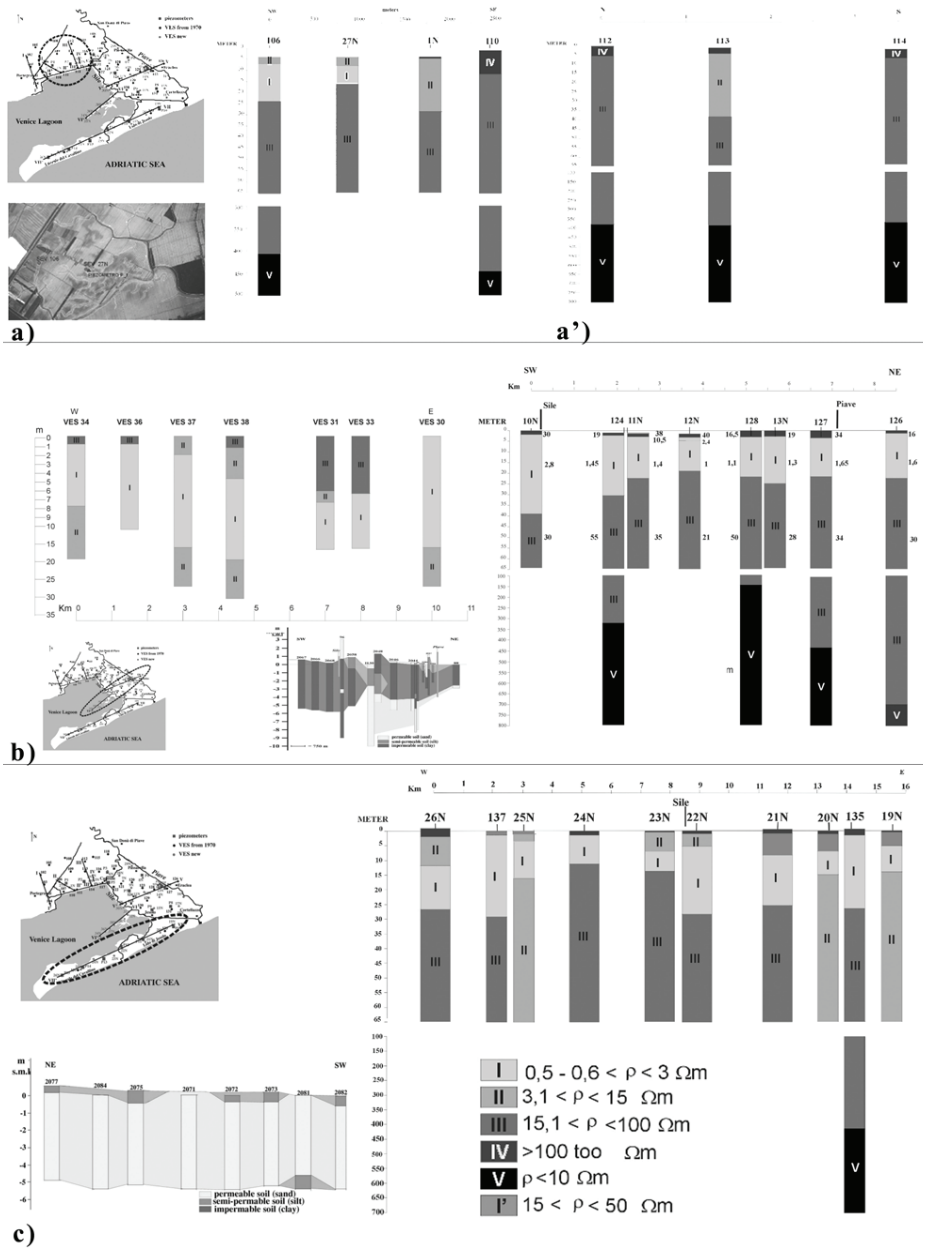


Fig. 5. EC measurements along the Piave (a) and Sile (b) rivers highlight the different behaviours of the two water courses: a salt water wedge can be found on the Piave riverbed for about 20 km, aided by the presence, at Eraclea, of a topographic depression, whereas in the Sile river, the contamination is effectively diminished with fresh water dispersion from the system of springs



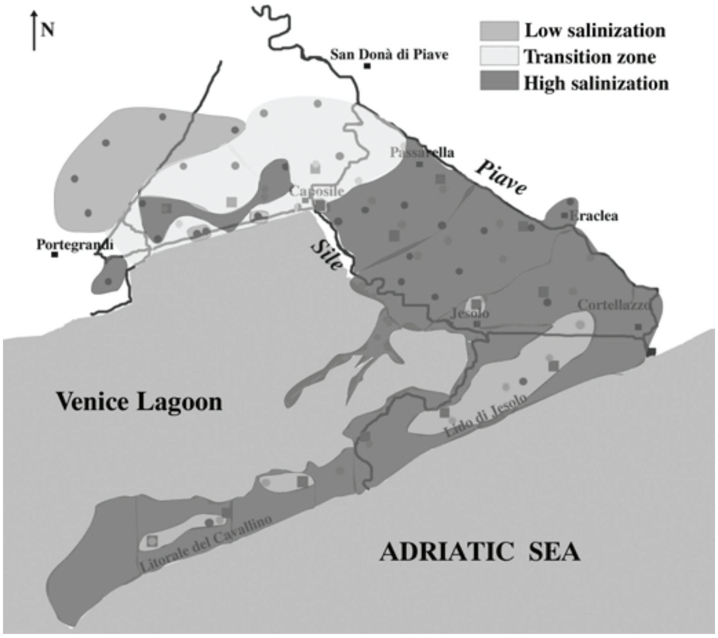


Fig. 7. Map of the superficial salinization of the northern sector of the Venice lagoon mainland obtained by a combination of EC Logs data and VES soundings

IV. Geochemical and Isotopic Investigation

A .Sampling and analytical techniques

Hydrogeochemical analyses have been performed on water samples collected over the entire study area to highlight the chemical characterization of water and to assess the presence of dilution and mixing processes. Electrical Conductivity and pH were measured in situ. Samples were filtered at 0.45 µm and collected in pre-cleaned bottles. A sample aliquot was acidified to 1% HNO_3 for the analysis of cations. Field analyses were repeated for control in laboratory. Chemical analyses were performed by the Environmental Science Department, University of Venice. Anions were determined by ion chromatography, whilst cations and trace elements were determined by atomic absorption, ion chromatography and inductively coupled plasma source-atomic emission spectroscopy (ICPS-AES). All reported values have an ionic balance within 7.5%. Isotopic analyses have been carried out for δ^2H and $\delta\ ^{18}O$ for the whole sample set. Samples were collected according to the procedures described by Clark and Fritz [12]. Hydrogen isotope composition was measured by water reduction over metallic zinc [13], while $\delta^{18}O$ was analyzed by water-CO_2 equilibration at 25 C [14], both results are expressed in V-SMOW [15]-[16]. The analytical errors are ±1 and ±0.1 ‰ respectively. All gases were analyzed on a Finnigan MAT 250 Mass Spectrometer at ISO4 s.s., Torino, Italy.

V. Results

The highest concentration values for the whole set of samples correspond primarily to sodium and chloride and secondly to calcium and bicarbonates. The Electrical Conductivity (EC) is strictly correlated with the results of chemical analysis, therefore water samples have been used to calibrate information obtained by EC logs, well stratigraphy and VES. The chemical hydrofacies identified are: calcium bicarbonate waters (P5-P9), directly related to the Sile river drainage; magnesium sulphate waters typical of perched aquifers in sand dunes as well as phreatic aquifers along the left (change to direction) bank of the Sile river (P2-P7-P11-P15); mixing water (P3-P6-P8-P13) with Cl contents ranging from 7 to 14 mg/l in piezometers located along the right (change to cardinal direction) bank of the Piave river; alkaline chloride waters (P1-P10-P14-P1d-P1P-S1-S21-S22) and alkaline bicarbonate waters (P4) with Cl and Na greater than 50 mg/l (Fig.8). Generally it is possible to recognize a progressive enrichment in Cl content near Piave river, in connection with old lagoon channel (P1) and paleochannel, as well as in the coastal zone away from sand dunes, where the effects of fresh water lenses is not efficient.

Cl and $\delta\ ^{18}O$ content of ground waters collected along the subterranean flow direction allow for the clarification of the influence of the Piave (Fig.9a). Geochemical analysis are in agreement with the geophysical data and point to the existence of widespread salinization in the territory between the two major river courses, influenced by the lagoon, Adriatic sea and marine water raising the course of the Piave.

The hydrographic profile of the Piave in the N-S direction compared to local altimetry and to electrostratigraphy must be considered. Because the Piave bed is suspended above the surrounding territory, hydrometric level correspond to locally higher equipotential lines, so the river can continuously recharge the unconfined aquifers toward the west (lagoon). This process is favoured by the permeable riverbed formed mainly by sand deposits.

So, water tables are affected by mixing processes of different ratios with salt water, as indicated by water chemistry. Moreover, considering an E-W cross-section it is possible to observe the greater hydrodynamic energy of the Piave compared to that of the Sile and the specificity of the adjacent neighbourhood areas (Fig.9b). The groundwater discharge is direct from E to W and the high salinization of subsoil pointed out by VES analyses is due also to the dispersion of salty groundwater by the Piave towards the lagoon.

On the contrary, the groundwater discharge, supplied by the fresh water suspended in dunes, moves essentially towards Adriatic sea (eastward).

The Cl content is very high in the proximity of the Piave river and diminishes progressively westward. Groundwater with the lower Cl content are present near the Sile river (P9). Oxygen isotopic values confirm the mixing process between continental and marine waters.

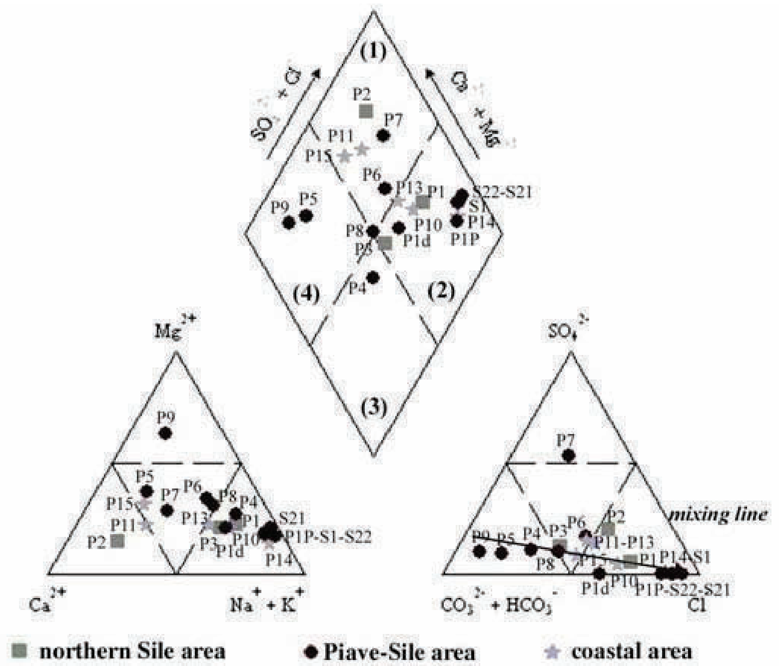


Fig. 8. The chemical hydrofacies for the samples collected from the unconfined aquifers: generally it is possible to recognize a progressive enrichment in Cl content
near the Piave river, in connection with an old lagoon channel and paleochannel, as well as in the coastal zone away from sand dunes, where the effects of fresh water lenses is not able to contrast the salinization effects

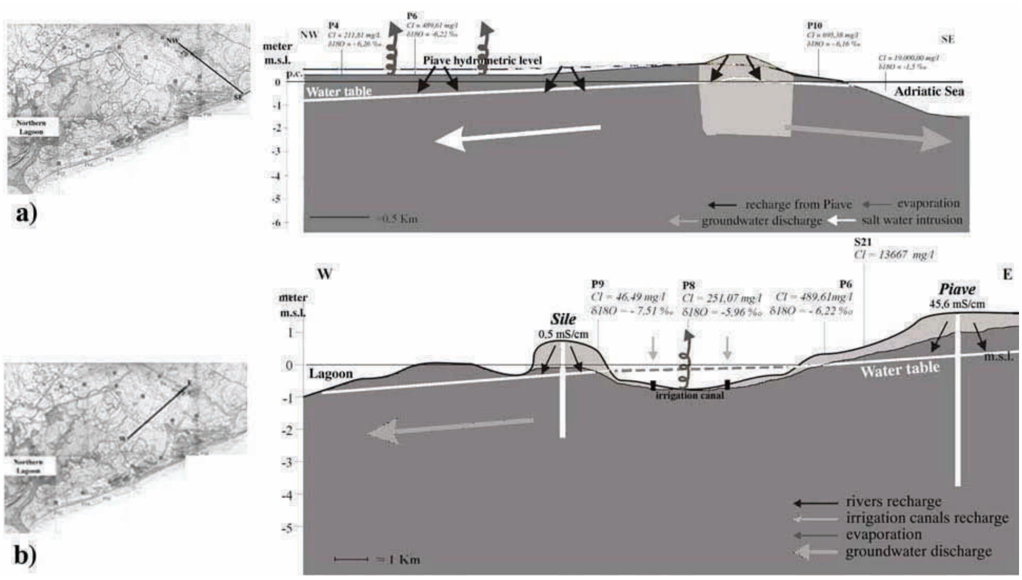


Fig. 9. The hydrographic profile of the Piave and Sile rivers compared to local altimetry and to electrostratigraphy and associated with Cl and $\delta^{18}O$ content of ground waters shows that a) in the N-S direction the Piave, suspended above the surrounding territory, can continuously recharge the unconfined aquifers toward the west (lagoon). This process favoured by the permeable riverbed formed mainly by sand deposits; and b) when considering an E-W cross-section, the groundwater discharge is direct from E to W (from the Piave to Sile) and the high salinization of the subsoil pointed out by VES analyses isdue also to the dispersion of salty groundwater by the Piave towards the lagoon

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lagoon. This takes takes place in sandy sediments of the holocenic Piave. Moreover, irrigation channels and evapotranspiration processes in lowland complete this scenario.

Within the mainland of the Venice lagoon's northern sector, water points generally fall on the sea water dilution line. Therefore some water points show a Br enrichment (Tab.2), due to a contribution of bromine [17]-[18]-[19], showing the effects of human pressures on natural processes, owing to the large use of methyl bromide in controlling of pests, fungi and weeds [20]- [21].

The Cl/SO_4, Br/SO_4, NO_3/Br and NO_3/Cl plots confirm groundwater supplied from agricultural activities. We can hypothesize that ground waters in phreatic aquifers result by mixing between seawater and surface water in different proportions. In particular, the percentage of seawater compared with surface less saline waters increase with depth, as indicated by the samples lying along hypothetical mixing lines.

The average $\delta^{18}O$ values of water taken from deep artesian wells (-10‰ ± 1‰) are similar to those of water collected in the entire (geological, hydrological and hydrogeological) northern Adriatic region [22]-[23]-[24]. The data (Fig.10-11) point out different recharge conditions than the present [23]. These waters are free of modern carbon, indicating the Last Glacial Maximum (20 ka BP) and the early Holocene (8Ka BP) as recharge periods [25]-[23]-[22].

Waters (GW) from the alpine basins (Piave) or from the so called "raw spring" (Sile) prove a quite constant isotopic composition ($\delta^{18}O$ = -8.0‰ ± 1‰) (Fig.10). The average $\delta^{18}O$ values of the plain aquifers are similar to the isotopic composition of the rivers, which participate in the aquifer recharge. Fresh waters (MW) collected in dug wells are enriched in $\delta^{18}O$ by about 2‰ with respect to river waters. Their isotopic composition suggests that there is a mixing between river waters and Adriatic sea water. The dissolved inorganic carbon of these waters shows a ^{14}C content of about 80 pmc, suggesting a very fast underground circulation and a short residence time.

Saline waters collected in dug wells and in through benthic chambers (LW) inside the lagoon [26] are similar or enriched in $\delta^{18}O$ with respect to present lagoon waters. The isotopic composition suggests a mixing between fresh continental waters (ground as well as surface) and Adriatic sea water. Even in this case, the dissolved inorganic carbon shows a ^{14}C content of about 80 pmc, confirming their very short underground residence time.

The relationship between chloride and oxygen isotopes (1/Cl vs $\delta^{18}O$) highlights the mixing and dilution trend of water in the northern sector of the Venice Lagoon territory. Considering also data in the confined aquifer waters located in Venice and in some lagoon islands (S.Erasmo, Treporti) it is easy to recognize three different mixing lines related respectively to the Sile water (spring raw) with fresh continental water values, to the Piave river, a typical alpine system water interested on the river mouth by salt water intrusion (found in the majority of analyzed samples) and to palaeowaters. (Fig.11).

VI. Conclusions

The salt water intrusion from the sea and the lagoon, which was determined by means of geophysical and geochemical tools, is widespread throughout the territory, apart from some coastal areas. Here the effect is mitigate by fresh water lenses suspended within dune. In addition, near the Sile river the contamination is effectively contrasted with fresh water dispersion from the spring raw system. Geophysics, geochemical and isotopic analyses allow to identify as principle sources of salinization the sea, the lagoon and the Piave river, whose water, through the geomorphological characteristics of territory, such as old lagoon channels, paleorivers, and reclaimed land lower than m.s.l., could penetrates far inland.

Increasing withdrawals of groundwater from the Venice coastal aquifers for agricultural and urban uses induce sea-water intrusion into the unconfined aquifers, which consequently results in a decline in water quality. Though salt water intrusion was recognized as early as the 1970s [5] the problem remains and a new knowledge of the real extension of the phenomenon is necessary to understand the several processes controlling the groundwater evolution.

The combined use of adequately validated geophysical and geochemical tools confers a multidisciplinary character to the research and allows the definition of the superficial extension of the phenomenon. Geophysical analysis (VES) and conductivity logs performed together with water table measurements, geochemical and isotopic analyses on samples collected on selected wells, permits to define the salinization diffusion and to elaborate a groundwater discharge model within the territory.

All the data acquired help to define a new groundwater circulation: in the northern sector of the Venice Lagoon mainland the absence of relevant tectonic lineaments allows to paleorivers, old lagoonal channels and actual riverbed of Piave to be the preferential way of movement to circulate again towards the lagoon salt water coming initially along the Piave riverbed. Following the natural groundwater discharge, which is oriented in the NE-SW direction, from the Piave to the Sile, the salt water wedge could reach the San Donà di Piave city and can be again dispersed within the territory and, through permeable lenses, can flow again towards the lagoon where, recent studies, revealed the emersion of salt water directly from the lagoonal bottom.

TABLE II. CHEMICAL AND ISOTOPIC COMPOSITION OF GROUNDWATER SAMPLES

Samples	Cl	SO_4	NO_3	Br	δ^2H	$\delta^{18}H$
P1	1854.71	193.50	7.14	10.09	-40.41	-6.10
P2	483.04	245.61	14.43	0	-52.91	-7.40
P3	370.62	148.82	9.42	1.4	-52.43	-7.18
P4	211.81	106.65	9.71	1.1	-41.91	-6.26
P5	56.53	38.16	10.11	0	-67.88	-9.47
P6	489.61	236.97	3.67	3.2	-41.82	-6.22
P7	179.81	567.54	37.70	1.3	-74.52	-10.54
P8	251.07	86.77	14.81	1.9	-39.21	-5.97
P9	46.49	67.01	26.57	0	-51.07	-7.51
P10	695.38	65.40	0.00	3.6	-42.64	-6.16
P11	256.48	107.64	2.41	0.3	-58.05	-8.32
P13	309.69	113.49	0.00	2.4	-39.99	-6.19
P14	2893.23	20.82	10.22	15.8	-33.04	-4.91
P15	244.28	58.70	168.25	0	-38.46	-5.63
S1	7621.90	25.22	0.00	41.1	-15.11	2.06
S21	13667.46	16.97	51.61	70.2	-17.43	1.15
S22	8225.03	4.42	33.79	25.9	-13	3.75
P1d	848.31	0.43	2.13	4	-21.68	1.18
P1P	7218.63	6.59	30.03	50	-17.09	1.72

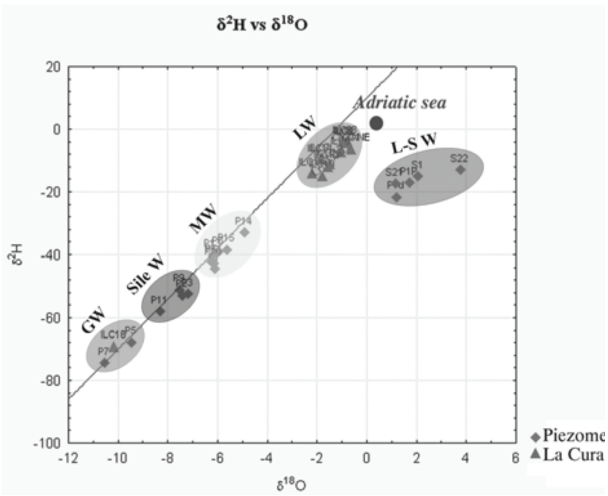

Fig. 10. The isotopic composition of waters collected from the alpine basins (Piave, GW); from the so called "raw spring" (Sile, W), from the fresh waters (MW) collected in dug wells and saline waters collected in dug wells and

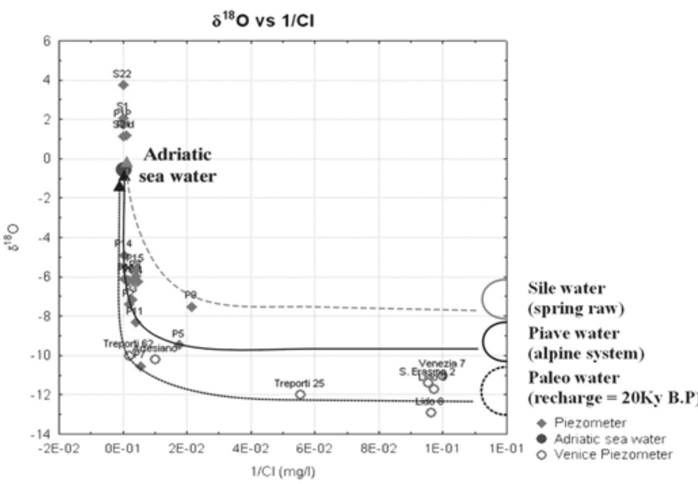

Fig. 11. The relationship between chloride and oxygen isotopes (1/Cl vs $\delta^{18}O$) highlights the mixing and dilution trend of water in the northern sector of the Venice Lagoon territory: three different mixing lines related respectively to the Sile water (spring raw) with fresh continental water values, the Piave river, a

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