Fresh water-salt water interactions in the shallow aquifers of Venice lagoon mainland

Eloisa Di Sipio (1), Viviana Re (2), Nicoletta Cavaleri(2), Antonio Galgaro (3)
(1) CNR-Institute for Geosciences and Earth Resources, (2) University Ca' Foscari of Venice, (3) University of Padua
eloisa.disipio@igg.cnr.it, re@unive.it, n.cavaleri@gmail.com, antonio.galgaro@unipd.it

In loving memory of Prof. Giovanni Maria Zuppi

I. Introduction

Salt-water contamination of groundwater systems is a widespread phenomenon typical of coastal areas. This process often leads to a deterioration of the quality of fresh groundwater resources and of building materials in urban settlements. Coastal zones are usually densely populated and progressively modified under the pressure of urban, industrial, agricultural and tourist development [1-2]. The increasing water withdrawal to support drinking, industrial and agricultural uses may result in the overexploitation of aquifers, drawing salt water from the sea and leading to salt-water encroachment and soil salinization [3]. Along the northern Italian coast of the Adriatic Sea, between Ravenna and Venice, large areas of the inland are reclaimed land, affected by subsidence and drainage. The presence of paleorivers, lagoon paleochannels, rivers suspended above the surrounding land and the disappearance of coastal dunes contributes to the intrusion of brackish and saline water towards the mainland. Therefore, in these zones freshwater hosted in unconfined aquifers consists mainly of low salinity water lenses floating above the salt-water wedge [4-5-6-7-8]. In the Venice area, investigations performed between the seventieth and the nineteenths promoted by research institutes (e.g. University Ca' Foscari of Venice, University of Padua, Institute of Marine Science) and local authorities (e.g. Venice Province Authority, Land Reclamation Syndacate, River Basin Authorities), stated the occurrence of salt water intrusion in the unconfined aquifers of the Venice Lagoon mainland [9-10-11-12-13-14-15].
In the venetian coastal plains several elements contribute to the extent of the salt-water contamination: the close vicinity of both sea and lagoon, the hydraulic gradient, low lying areas, the land use, the geological characteristics of the subsoil, the topography and morphology of the area and the occurrence of subsidence phenomena.
In 2004 the scientific cooperation between the University Ca' Foscari of Venice and the University of Padua (PRIN Project "The deep aquifers of the Po Valley as regional resource: aquitard in hydrodynamics, generating of water chemically and thermally anomalous, a suitable place for the CO_2 atmospheric trapping"), led to improvements of the local knowledge of this phenomenon. In particular, the use of duly integrated geophysical and geochemical approaches confers a multidisciplinary character to the research, allowing a more comprehensive identification and circumscription of salt contamination and a better understanding of the process dynamics. An overview of the major achievements in recent years obtained from hydrogeological studies coordinated by Prof. G.M. Zuppi across the coastal Venetian province is here presented.

II. Geological and geomorphological background

The Venetian geological system belongs to the Veneto Plain, delimited by the alpine range, the lessino-berico-euganeo ridge and the coastline between the Po and the Isonzo estuary.
This work presents the results of researches focused mainly into three areas of the eastern Po Plain mainland (Fig.1). The northern sector, 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, includes the territory located between

Piave and Sile rivers, an area with a total extension of about 157 km^2. The central area, called "*Prima Zona Industriale*"(First Industrial Area) or "*Area Nord*" (Northern Area), belongs to the industrial site of Porto Marghera (west of the historic centre) and consists in a triangular shaped peninsula of about 120 hectares, limited by two industrial channels of 10-12 metres depth, the Brentella channel on the east side and the North Industrial channel on the west side. The southern sector, limited by the Venice Lagoon to the north, the Adriatic Sea to the east and the Adige River to the south, extends about 20 km inside the coastal plain and is crossed by two important rivers, Brenta and Bacchiglione, flowing NW-SE.
An agricultural economy prevails in the northern and southern area, while a dominant industrial asset characterizes the central one. The territories, constituted mainly by reclaimed land, often below mean sea level, are subject to severe pumping rates and mechanical reclamation guarantees the free drainage. A dense network of drainage channels conveys the waters to artificial pumping, able to raise excess water and return it to the lagoon. Subsidence, due to human activities and natural processes, affect the areas (mainly the northern and southern one) and contributes to increase the hydraulic risk [16-17-18].

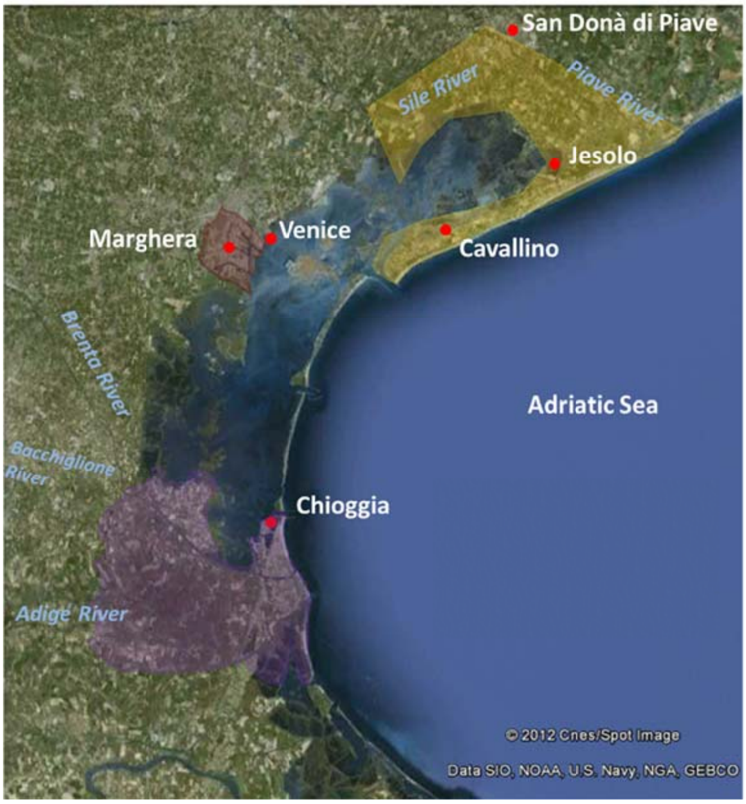

Figure 1 – Venice Lagoon and its mainland. Location of the study area: the northern, central and southern sector (Modified from Google Earth, 2012)

By the geomorphological and sedimentological point of view, the dominant morphologies and deposits belongs to alluvial, deltaic and littoral environment. The alluvial plain consists mainly of silty/clayey layers, sand and peat deposits of marine, continental and marshy origin not homogeneously distributed within the territory. The erosion and deposition events derived by climatic variations and changes in the fluvial regime occurred during the Quaternary have built the present stratigraphic structure. The cyclic marine transgressions and regressions, which created lacustrine and marshy environments followed by dominant continental ones, built a stratigraphic sequence with remarkable lateral variability [19-20].
Therefore, the territory can be subdivided in subsectors following the main morphologies identified within the selected investigation areas. In particular, three subareas are identified in the northern sector: the plain on the left bank of Sile where the river flows parallel to the lagoon, characterised by low-lying areas and clay deposits; the area between the Sile and Piave rivers, characterised by the presence of paleochannels and paelorivers; and the coastal zone, characterized by dunes parallel to the shore line. The southern zone presents sand dunes and old barrier beach in the coastal belt. Inland paleorivers and former lagoon

channels are suspended above the surrounding land. The central area owes his nature not only to lagoon and fluvial processes but also to anthropic actions. As a matter of fact, the material brought here in the past for land reclamation determines the current settlement of the area.

III. Methodology

This research aims at assessing the present degree of subsoil salinization, at determining the extent of saline contamination inland and at identifying critical conditions in relation to the economic activities, mainly of agricultural and tourist type. The combined use of adequately validated geophysical and geochemical tools led to the improvement of the knowledge of the different factors contributing to the salt-water intrusion phenomenon.

During the main sampling campaigns - involving measuring points as piezometers driven in shallow unconfined aquifers, irrigation channels, and river - chemical-physical parameters as water table level, Electrical Conductivity (EC), pH, temperature and dissolved oxygen were measured in the field, while major and trace elements have been determined in laboratory together with isotopic composition. Electrical tomography (ERT) and Vertical Electrical Soundings (VES) have been performed all over the areas and compared, when possible, with selected existing geophysical data dating back to the seventieths to verify possible saline contamination changes in time. The collected resistivity data have been calibrated according to the available geological, geomorphological and stratigraphic information and to the ground water electrical conductivity (EC) values measured in the nearby piezometers.

The new VES (length ranging between 130 and 200 m) were performed using a geo-resistivity probe GMR 1000 Astier and a prototype of the Geosciences Department of the University of Padua, with a 12V battery and a dc–ac converter (output of 310 V ac). The ERT has been performed using a geo-resistivimeter IRIS Syscal Pro 72 provided with three multipolars cables of 24 electrodes, corresponding to a total of 72 electrodes (Fig.2). Two meters inter-distance was used between electrodes, in order to cover a total distance of 142 m. Three different acquisition geometries have been performed: Wenner, dipole-dipole (at 200 V and 400 V) and pole-dipole (remote pole positioned 300 m away northwards from electrode n° 1). Apparent resistivity data have been processed by DCInv, TomoLab and ErtLab software. The different depths of investigation and the different resolutions depend on the electrode arrays adopted during the investigation. For instance, the investigated depth with the Wenner and VES arrays is about 17% of the geometry lengths, while with the pole-dipole configuration can be about 35%. On the contrary, the dipole-dipole configuration results in a less deep profile, but with a higher resolution [21].

The geochemical analyses of the collected groundwater samples were performed by the Environmental Science Department of the University of Venice in cooperation with the Geosciences and Earth Resources Institute, National Research Council (IGG-CNR), Pisa, Italy. A total number of 61 piezometers, distributed 21 in the northern sector, 14 in the central one and 25 in the southern, driven at depth ranging between 6 and 25 m, were used during several field surveys performed between 2003 and 2008 in different times of the year.

Anions (Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-) were detected by ion chromatography by means of a Dionex series 100 ion chromatograph using a AS14 column. Cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and trace elements (F^-, Br^-) were quantified by atomic absorption, ion chromatography, and inductively coupled plasma source-atomic emission spectroscopy (ICPS-AES, Perkin Elmer). Moreover, chloride on samples with highest concentration values have been determined by titration with AgNO3 0,1N (Methrom Ag 9100 or E536 Herisau potenziometer) [22-23]. Stable isotopes have been analysed to study the different groundwater origins and to point out possible mixing processes. Isotopic analyses were carried out for $\delta^{2}H$ and $\delta^{18}O$ for the whole sample set by a Finnigan™ MAT 250 Mass Spectrometer at ISO4 s.n.c., Turin, Italy. The results, expressed as part per thousands with respect to the Vienna Standard Mean Ocean Water (V-SMOW) were obtained by water reduction over metallic zinc for $\delta^{2}H$ and by water–CO_2 equilibration at 25°C for $\delta^{18}O$ [24-25-26]. The analytical errors are ±1 and ±0.1‰ for hydrogen and oxygen isotope respectively.

IV. Results and discussion

To assess the presence of salt water in the territory, electrical conductivity analyses (EC logs) of both the superficial hydrography (rivers and channels) and groundwater have been performed. These values can initially be used to classify water according to its use for agricultural-horticultural purposes, based on the EC limits tolerated by the main crops [12].
However, the integration of all the information collected by the different methods allows a better characterization of the salt water contamination extent. As a matter of fact, the geophysical soundings allow for an investigation of extensive areas and, generally, of the first 30 m of subsoil, according to the adopted array length. When combined with geomorphological and stratigraphic information, these can determine the existence of preferential pathways for saline water displacement and higher hydraulic conductivity zones such as paleorivers, old lagoonal channels and dunes. However, one of the main problems interpreting the electrical resistivity data is that the clayey silty layers of the subsoil present an electrostratigraphic answer similar to that of aquifers saturated with saline water. Therefore, the validation of resistivity sections and maps requires the quantification of the chloride content of groundwater samples as a discriminating factor [27-28]. The following classification criteria have been selected in the Venice area to reveal the presence of salinization process:

- *salt water*: waters with EC values ≥ 5 mS/cm; electrical resistivity of subsoil ≤ 3-4.5 ohm*m; Cl^- content of water samples ≥ 10000 mg/l (Cl > 283 meq/l).
- *brackish water*: waters with EC values ranging between 2 and 5 mS/cm; electrical resistivity of subsoil ranging between 3-4.5 and 15 ohm*m; Cl^- of water samples between 300 and 10000 mg/l (8.46 < Cl <283 meq/l)
- *fresh water*: waters with EC values ≤ 2 mS/cm; electrical resistivity of subsoil ≥ 15 ohm*m; Cl^- of water samples ≤ 300 mg/l (Cl < 8.46 meq/l)

The ERT profiles performed within "Prima Zona Industriale" (central sector) clearly show the existence of salt water intrusion in groundwater aquifers (Fig.2). The Wenner, pole-dipole and dipole-dipole geometries performed over a total lenght of 142 m results in different depths of investigations (about 24 m, 50 m and 15 m respectively) and different levels of resolution. The Wenner geometry exhibits a high vertical resolution in a horizontally layered media. The pole-dipole array allows higher depths of investigation compared to Wenner array, but with a lower resolution of the shallower layers. Finally, the dipole-dipole configuration, because of its high sensitivity, is suitable for resistivity profiles. All the three sections show an electrolayer with very low resistivity (resistivity < 1.5 ohm*m) between 4.5-5 m and 16-17 m depth from the ground surface, typical of a sandy/clayey medium saturated with salt water [29]. Below 20 m depth both the Wenner and the pole-dipole configurations show the presence of a less conductive layer (6.7 ohm*m, Fig.2a-b), overlying another stratum reaching resistivity of 73.5 ohm*m, typical of sand, sand with fresh water, clay, silt (Fig.2c). According to the resistivity measurements, the physical-geochemical analyses of groundwater samples collected in this area highlight the presence of brackish and saline waters characterized by EC values ranging between 0.60 and 25 mS/cm, and Cl concentration ranging between 2.45 and 430.83 meq/l. Moreover, from an isotopic point of view, most of the water samples are distributed between the meteoric and the dilution lines, pointing out the occurrence of mixing processes between fresh and salt water [29].
All over the Venice territory, in the unconfined aquifers, the geochemical and isotopic analyses performed on selected samples identify three different hydrofacies: a) chloride –alkaline waters, enriched in Cl^- and Na^+, defined mainly as brackish or salt water according to the chloride content, typical of lagoon and marine water; b) bicarbonate-alkaline waters, with high levels of Ca^{2+} and HCO_3^-, belonging to the groundwater flow or to fresh continental waters (e.g. rivers); c) mixing waters deriving from the previous ones [30-31]. The relationship between the two stable isotopes $\delta^{18}O$ and $\delta^{2}H$ show samples aligned along the global (GMWL) or the local meteoric water lines (LMWL) – GMWL: $\delta^{2}H=8\cdot\delta^{18}O+10$ [32]; LMWL: $\delta^{2}H=7,6\cdot\delta^{18}O+7,5$ [33]. However a little deviation can be observed, suggesting the occurrence of processes as evaporation or mixing processes with waters characterized by different composition [34].

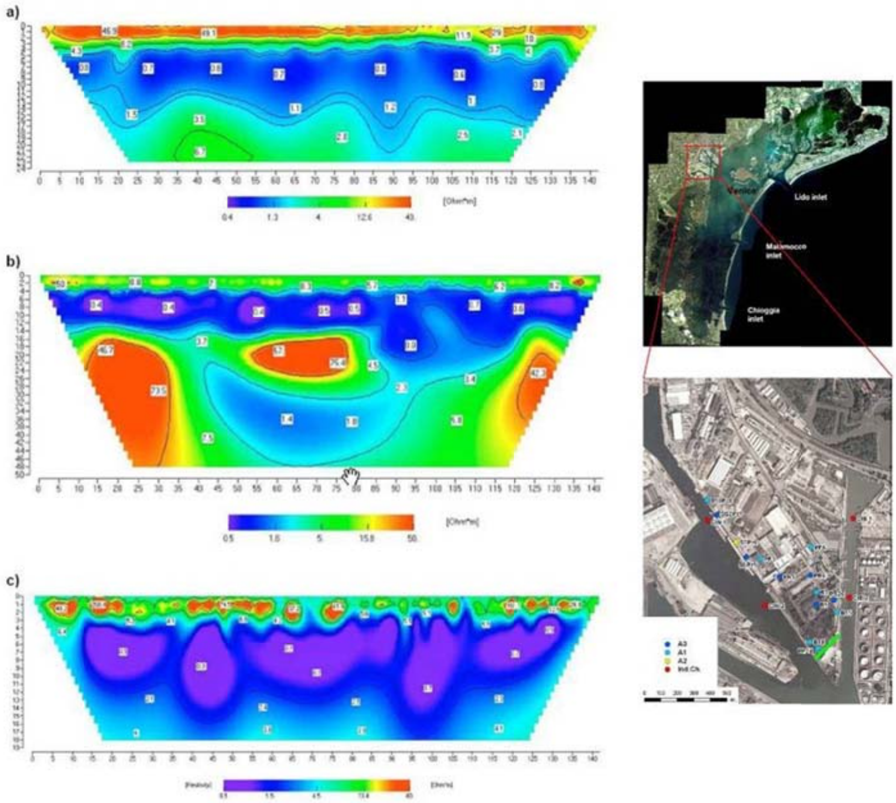

Figure 2 – Porto Marghera, ''Prima Zona Industriale'', geophysical investigation and location of piezometers. ERT apparent resistivity profiles: a) Wenner array, b) pole-dipole array, c) dipole-dipole array (from Cavaleri 2008 modified)

In particular, in the southern sector (Chioggia), the obtained chemical hydrofacies are NaCl for the more mineralised waters and $CaCO_3$ for the less mineralised ones (Fig.3a). The Cl vs Br-Cl correlation suggests the existence of a chemical evolution from continental fresh-water and formation water towards sea water (Fig.3b). The $\delta^{18}O$ vs Cl graphs shows the local mixing process of fresh continental water with marine water and formation waters of the Po Plain (Fig.3c), while the $\delta^{18}O$ vs $\delta^{13}C$ plot supports the existence of three different groups of water: Pliocene formation water, fresh-continental water and sea water (Fig.4c).
In addition, combining EC logs data and VES soundings results validated by geochemical analyses allows to create maps of superficial salinization including the first 25-30 m of subsoil. Interesting results have been obtained specifically within the northern sector (Jesolo). Here, considering the influence of the Piave and Sile rivers and the presence of a coastal sand dune, a map of salt water contamination was created to evaluate the agricultural use of superficial water (Fig.4). The stratigraphic analysis confirms the presence of permeable sand deposits belonging to paleorivers and Piave riverbed, which favour a widespread salinization of the territory and a high salt water content within Piave and the surrounding unconfined aquifers.
The occurrence of strong groundwater salinization can be recognized on coastal areas and between the Piave and Sile rivers. On the contrary the extreme northern sector, characterised by fresh water of continental origin, and small areas located near Sile river and along the dune belt are characterised by low EC values that indicate the occurrence of a low degree of salinisation. Finally, the transition zone connecting the previous ones is characterized by soils saturated with medium-saline waters. The top of the fresh water/ salt water interface is generally located at 2 m depth from the ground surface, but can reach 8 m depth in the coastal zone, where small lenses of fresh water hosted in sand dunes may mitigate the salt water intrusion.

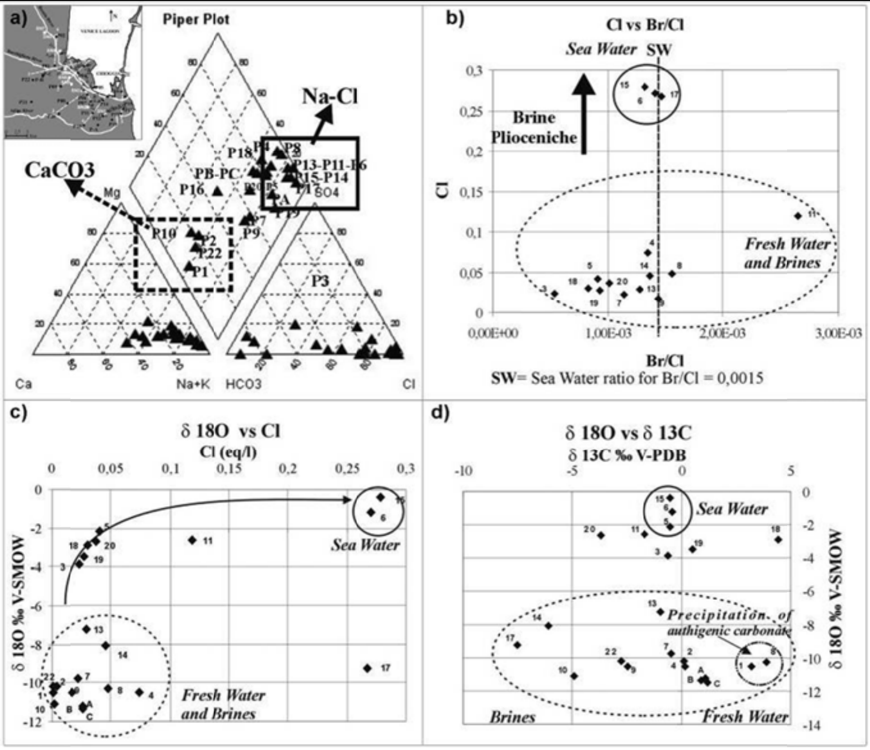

Figure 3 – Southern sector (Chioggia), geochemical and isotopic analyses: Piper diagram (a); Cl vs Br-Cl correlation (b); δ^{18}O vs Cl graphs (c); δ^{18}O vs δ^{13}C (d) (from Di Sipio et al. 2007 modified)

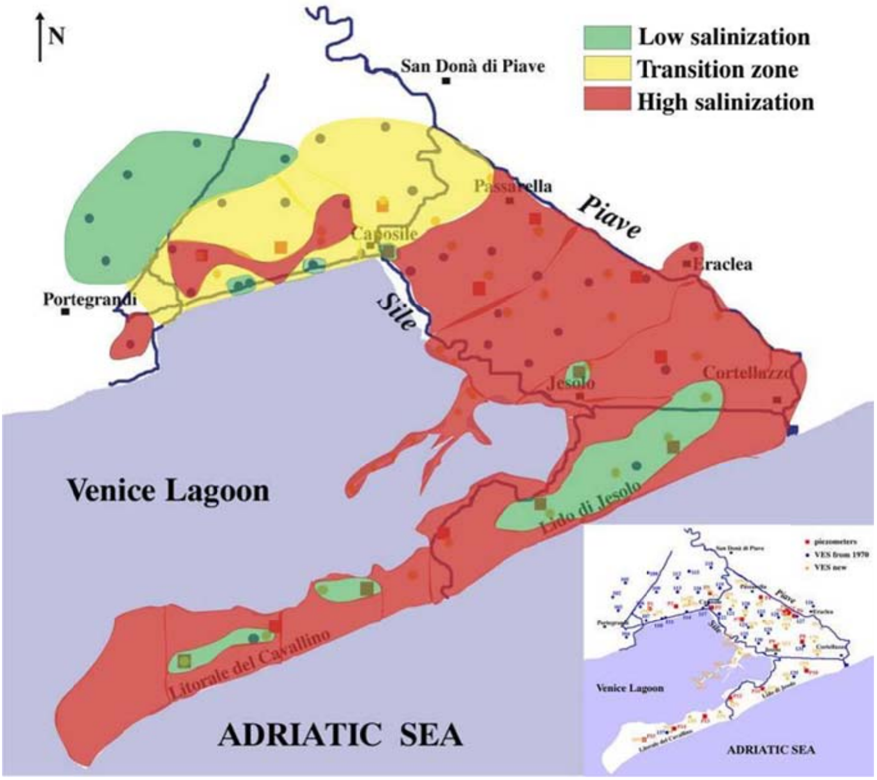

Figure 4 – Northern sector (Jesolo). Map of the superficial salinization of the northern sector of the Venice lagoon mainland obtained by a combination of electrical conductivity (EC) logs data and VES soundings (from Di Sipio et al. 2008 modified)

V. Conclusion

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. Even if the salt water intrusion was identified in the early 1970s, the problem remains and an adequate 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 study and allows the definition of the superficial extension of the phenomenon. Geophysical analysis (ERT, VES) and conductivity logs performed together with water table elevation measurements, geochemical and isotopic analyses on groundwater samples, allows the definition of the salinization distribution and the elaboration of a groundwater discharge model within the territory. The salt water intrusion from both the sea and the lagoon is widespread throughout the territory and determines an increasing of Cl and $\delta^{18}O/\delta^{2}H$ values near the coastal zone. On one hand, the electrical conductivity and the content of chloride and sodium underline the presence of fresh, brackish or saltwater. On the other hand, the ratio between the analyzed elements may indicate the occurrence of mixing phenomena with both the sea and superficial water. Afterwards, the application of stable isotopes allows to clarify the different origins of the groundwater and to point out further mixing phenomena.

Riverbed, paleorivers and old lagoonal channels, all characterized by high hydraulic conductivity values, are the preferential pathways of salt water intrusion towards the mainland. This phenomenon becomes more important in conditions of low flow rivers and sea high tide, when the continental water outflow is not able to contrast the salt water intrusion. Moreover, the isotopic analyses of water samples collected within the Venice region confirms the chemical evolution of groundwater from continental to brackish water moving from inland towards the sea. It is possible to distinguish fresh water of alpine origin in deep artesian well, fresh water affected by rainfalls and rivers and mixing water characterized by marine and lagoon values.

Références bibliographiques

[1] Bear J., Cheng AH.-D., Sorek S., Ouazar D., Herrera I., 1999 – Seawater intrusion in coastal aquifers: concepts, methods and practices. Kluwer, Dordrecht, The Netherlands

[2] Kouzana L., Benassi R., Ben Mammou A., Sfar felfoul M., 2010 - Geophysical and hydrochemical study of the seawater intrusion in Mediterranean semi arid zones: case of the Korba coastal aquifer (Cap-Bon, Tunisia). *Journal of African Earth Science, 58, pp. 242–254*

[3] Re, V. & Zuppi, G. M., 2011 - Influence of precipitation and deep saline groundwater on the hydrological systems of Mediterranean coastal plains: a general overview. *Hydrological Science Journal* 56(6), *pp*. 966–980.

[4] Barrocu G., 2003 - Seawater intrusion in coastal aquifers of Italy. *In: Calaferra J (Ed) State of seawater intrusion in coastal aquifers of the Mediterranean Coast. SWIM-SWICA, Alicante, Spain, pp. 207-223*

[5] Antonellini M., Mollema P., Giambastiani B., Bishop K., Caruso L., Minchio A., Pellegrini L., Sabia M., Ulazzi E., Gabbianelli G., 2008 - Salt water intrusion in the coastal aquifer of the southern Po Plain, Italy. *Hydrogeology Journal 16, pp. 1541-1556*

[6] Giambastiani B.M.S., Antonellini M., Oude-Essink G.H.P., Stuurman R.J., 2007 - Saltwater intrusion in the unconfined coastal aquifer of Ravenna (Italy): a numerical model. *Journal of Hydrology 340, pp. 91-104*

[7] Di Sipio E., Galgaro A., Zuppi G.M., 2006 - New geophysical knowledge of groundwater systems in complex estuarine environment. *Estuarine Coastal Shelf Science 66, pp. 6-12*

[8] Rapaglia J., Di Sipio E., Bokuniewicz H., Zuppi G.M., Zaggia L., Galgaro A., Beck. A., 2010 - Groundwater connections under a barrier beach: A case study in theVenice Lagoon. *Continental Shelf Research 30, pp. 119-126*

[9] Benvenuti G., Norinelli A. and Zambrano R., 1973 - Contributo alla conoscenza del sottosuolo dell'area circumlagunare veneta mediante sondaggi elettrici verticali. *Bollettino di geofisica teorica ed applicata, XV/57, pp. 23-38*

[10] Benvenuti G., Norinelli A., 1974 - Studio geofisico di interfaccia acqua dolce- acqua marina nell'area circumlagunare veneta e nella zona delle sorgenti del Chidro (Taranto). Memorie *degli Istituti di Geologia e Mineralogia dell'Università di Padova, 1974, XXXI, pp.1-16*

[11] Benvenuti G., Galgaro A., Tosi L., 1998 - Indagine geoelettrica per la valutazione dell'intrusione salina negli acquiferi costieri del comprensorio meridionale veneziano. *Technical Report n. 222, ISMAR-CNR, Venezia*
[12] Carbognin L., Tosi L., - 2003 - Il progetto ISES per l'analisi dei processi di intrusione salina e subsidenza nei territori meridionali delle province di Padova e Venezia, *ISMAR – CNR and Venice Province Authority 2003*
[13] Gattacceca J. C., Vallet-Coulomb C., Mayer A., Claude C., Radakovitch O., Conchetto E., Hamelin B., 2009 - Isotopic and geochemical characterization of salinization in the shallow aquifers of a reclaimed subsiding zone: The southern Venice Lagoon coastland. *Journal of Hydrology 378 (1-2), pp 46-61*.
[14] Viezzoli A., Tosi L., Teatini P., Silvestri S. 2010 - Surface water-groundwater exchange in transitional coastal environments by airborne electromagnetics: the Venice Lagoon example. *Geophysical Research Letters, 37, L01402, pp. 1-6*
[15] Rapaglia J., Di Sipio E., Bokuniewicz H., Zuppi G.M., Zaggia L., Galgaro A., Beck A. 2010 - Groundwater connections under a barrier beach: a case study in the Venice Lagoon. *Continental Shelf Research, 30 (2), 119-126*
[16] Tosi L., Teatini P., Carbognin L., Brancolini G., 2009 - Using high resolution data to reveal depth-dependent mechanisms that drive land subsidence: The Venice coast, Italy. *Tectonophysics, 474, pp. 271-284.*
[17] Carbognin L., Teatini P. , Tosi L., 2004 - Eustasy and land subsidence in the Venice Lagoon at the beginning of the new millennium. *Journal of Marine Systems, 51, pp. 345-353*
[18] Brambati A., Carbognin L., Quaia T., Teatini P., Tosi L., 2003 - The Lagoon of Venice: geological setting, evolution and land subsidence. *Episodes, 26(3), 264-268*
[19] Blum MD, Törnqvist TE, 2000 - Fluvial response to climate and sea level change: a review and look forward. *Sedimentology 47(suppl 1), pp. 1–48*
[20] Serandrei Barbero R., Lezziero A., Albani A., Zoppi U. 2001 - Depositi tardo-pleistocenici ed olocenici nel sottosuolo veneziano: paleoambienti e cronologia. *Il Quaternario. Italian Journal of Quateranry Science 14(1), pp. 9–22*
[21] Reynolds J.M. 2001 - An introduction to applied and environmental geophysics, John Wiley & Sons Editors
[22] Haddad P.R., Jackson P.E., 1990 - Ion chromatography: principles and applications. *Journal of Chromatography Library, 46*
[23] Sanz-Medel A., 1991 - Inductively coupled plasma-atomic emission spectrometry: analytical assessment of the technique at the beginning of the 90's. *Journal Microchimica Acta 104 (1-6), pp. 265–275*
[24] Clark I., Fritz P. 1997 - Environmental Isotopes in Hydrogeology, Lewis Publisher, 1997
[25] Gonfiantini R., 1978 - Standards for stable isotope measurements in natural compounds. *Nature 271, 534–536*
[26] Gonfiantini R., Stichler W., Rozanski K., 1995 - Standards and intercomparison materials distributed by International Atomic Energy Agency for stable isotope measurements: reference and intercomparison materials for stable isotopes of light elements. *In: Proceedings of a Consultants Meeting held in Vienna, 1–3 December, 1993, IAEA-TECDOC 825, pp. 13–29*
[27] Oude Essink G.H.P., 2001 - Improving fresh groundwater supply problems and solutions. *Ocean & Coastal Management, 44, 2001, pp. 429-449*
[28] Vandenbohede A., Lebbe L., 2006 - Occurrence of salt water above fresh water in dynamic equilibrium in a coastal groundwater flow system near De Panne, Belgium. *Hydrogeology Journal, 14, 2006, pp. 462-472*
[29] Cavaleri N. 2008 - Groundwater flow and remediation actions in the industrial site of Porto Marghera – Venice, PhD Thesis, University Ca' Foscari of Venice
[30] Di Sipio E., Galgaro A., Zuppi G. M., 2006 - New geophysical knowledge of groundwater systems in Venice estuarine environment. *Estuarine, Coastal and Shelf Science 66, pp. 6-12*
[31] Di Sipio E., Galgaro A.,Rapaglia J., Zuppi G.M., 2008 - Salt water contamination on Venice Lagoon mainland: new evaluation of origin, extension and dynamics. *Proceedings 1st SWIM-SWICA Int. Joint Saltwater Intrusion Conference, , Cagliari-Chia Laguna, Italy, 3ESSE Commerciale, (CA), pp. 195-204*
[32] Craig H., 1961 - Isotopic variations in meteoric waters. *Science 133, pp. 1702-1703*
[33] Zuppi G.M., Sacchi E., 2004 - Dynamic processes in the Venice Region outlined by environmental isotopes. *Isotopes in Environment and Health Studies, 40, pp. 35-44*
[34] Di Sipio E., Galgaro A., Zuppi G.M. and Zangheri P., 2005 - Detecting the origin of salt water contamination in groundwater in a lagoon area by the combined use of geophysical and geochemical tools: the example of the southern Venice Lagoon mainland. Groundwater and saline intrusion. *Proceedings of the 18th Salt Water Intrusion Meeting. Instituto Geológico y Minero de España, Madrid, Spain, Hidrogeología y Aguas Subterráneas Series, 15, pp. 373-384*