

Isotopic characterization of saline intrusion into the aquifers of a coastal zone: case study of the southern Venice Lagoon, Italy

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Abstract This study deals with the geochemical characterization of salinization in the semi-confined aquifer of the southern part of the Venice Lagoon, Italy. Twelve boreholes reaching the aquifer were sampled for stable isotopes ($\delta^{18}\text{O}$ and δD). Electrical conductivity (EC) displays a large range of variation (0.7–40 mS/cm). The more saline groundwaters are located at up to 2 km from the lagoon and Adriatic Sea shorelines. In the $\delta^{18}\text{O}$ vs δD diagram, the more saline groundwaters plot along a well-defined mixing line, passing through a continental and a seawater end-member. The brackish and fresh groundwaters do not have a clear spatial distribution. Heterogeneous $\delta^{18}\text{O}$ and EC compositions of brackish and fresh groundwater reflect complex exchanges between deep groundwater, surface and/or rain waters. Characterization of the continental end-member(s) in the mixing is not straightforward, revealing a complex hydrodynamic behaviour in this aquifer.

Key words salinization; coastal groundwaters; stable isotopes; Venice Lagoon

INTRODUCTION

Coastal zones, globally, are highly impacted by the consequences of increasing population. Numerous studies have been recently undertaken to evaluate various impacts of the anthropogenic influence on these fragile ecosystems, and to assess policies for management. Coastal aquifers are especially vulnerable to enhanced pumping for water supply, as this leads to saline water intrusions into the freshwater aquifers and in some cases to land subsidence in coastal flatlands (Andreasen & Fleck, 1997; Barbecot *et al.*, 2000; Capaccioni *et al.*, 2005). In addition, particular attention to saline intrusion is also required given the prospect of sea level rise induced by the expected global warming. The inland areas surrounding the Venice Lagoon represent a dramatic example of these negative effects. In this paper, we focus on the salinization process in the shallow, partially unconfined aquifer in the southern part of the Venice Lagoon. Although substantial extraction of groundwater has not occurred for many years (it has been forbidden by law since the late 1970s), land subsidence has continued in this area driven by natural mechanisms, such as the compaction of surface sediments and oxidation of organic carbon in soils (peat land) (Gambolati, 2003;

Brambati *et al.*, 2004). Saltwater intrusion has been previously documented in this zone using geophysical methods (Carbognin *et al.*, 2003; Di Sipio *et al.*, 2006). Our study aims in particular to characterize the saline intrusion and the exchanges between groundwater and surface waters in this area by using chemical and isotopic tracers. We present here initial results obtained from groundwater samples taken from the partially unconfined aquifer.

STUDY AREA

The study area is situated in the lower Venetian plain, in the coastal flatland of the southern part of the Venice Lagoon (Fig. 1). It extends 20 km east to west and 10 km north to south, delimited by the Venice Lagoon itself on the northeast, the Adriatic Sea on the southeast and the Adige River on the south. One important characteristic of this sector is that the ground level lies mostly below sea level (down to 4 m b.s.l.). The present-day surface water system is artificially regulated by a complex network of pumping plants and canals, which aim to introduce freshwater for irrigation, and to drain the phreatic aquifer. The canal network takes water upstream from the Brenta, Adige, and Bacchiglione rivers, the three main rivers of the area which rise in the Alps and the pre-Alps (Piedmont). In the area, the so-called “Venetian Aquifer system” is mostly composed of sand and silt of the coastal (Holocene) and continental (late Pleistocene) deposits, which cover the Quaternary basement at 230 m b.s.l. The aquifer contains intermittent clay lenses and peat layers (Brambati *et al.*, 2003; Bassan *et al.*, 1994). Despite the overall heterogeneity, six successive confined aquifers have been described between 50 m and 300 m b.s.l. (Carbognin & Tosi, 2003; Dal Prà *et al.*, 2000). The upper 50 m are the phreatic and semi-confined aquifer, and will be referred as A0.

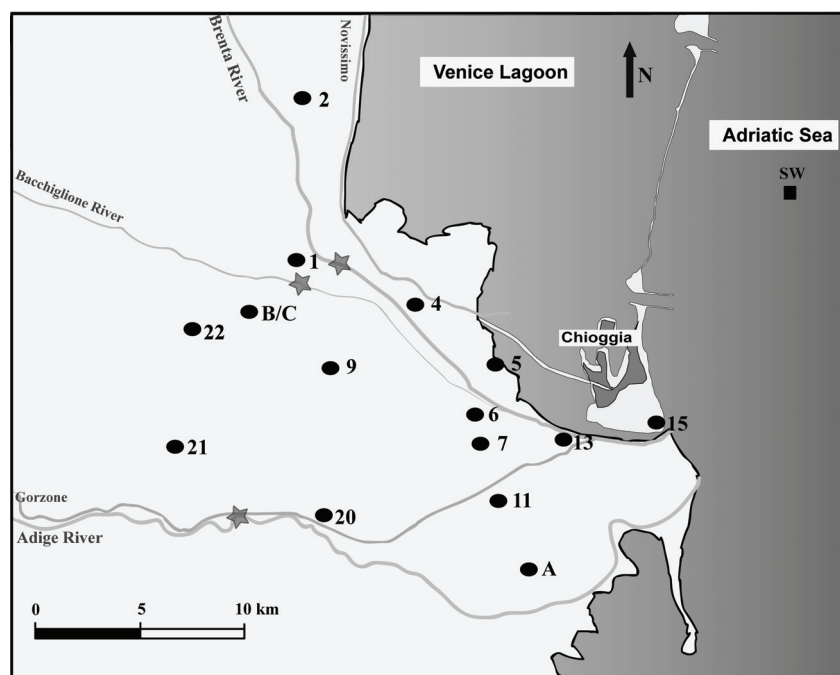


Fig. 1 Study area and water samples location. Circles stand for ISES boreholes; square point stands for seawater; stars stand for river waters.

Samples and analytical techniques

Sample collection was carried out during four field trips in September 2004, February, April and October 2005. Figure 1 displays the location of the boreholes used for this study, which are part of a monitoring network set up in 1999 for a project on salinization and subsidence (ISES). Eleven shallow boreholes screened down to 20 m b.s.l. and one screened between 32 and 53 m b.s.l. (C) were used to sample the groundwater in A0. Samples are identified with ISES boreholes numbers. Samples of groundwater from the first confined aquifers (A1) were taken from two artesian deeper boreholes screened at 76–94 m b.s.l. (A) and at 61–85 m b.s.l. (B). Vertical profiles of electric conductivity (EC) were obtained *in situ* before and after purging water in most boreholes (Fig. 2). In all cases, an immersion pump was set at 1 m above the borehole's bottom and water samples were collected after a stable EC of the pumped water was reached. Surface waters were also collected in the main rivers of the area (Adige, Brenta and Bacchiglione rivers) and in the coastal seawater. Physical parameters (temperature and EC) were measured in the field. Stable isotope analysis ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) are performed at CEREGE on a Delta Plus MS, by measuring a gas (CO_2 and H_2 successively) equilibrated with water samples. Precisions obtained are 0.05‰ and 1‰ for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively.

RESULTS AND DISCUSSION

EC Data

The electrical conductivity of Adriatic seawater is 58 mS/cm. Brenta, Adige and Bacchiglione rivers were sampled in April and October of 2005. The mean EC for these three rivers is 0.44 mS/cm, 0.33 mS/cm, and 0.74 mS/cm respectively. The electrical conductivity in the groundwater samples of A0 is highly variable (0.7 to 40 mS/cm). Vertical profiles of EC, performed in 10 boreholes tapping A0 are shown on Fig. 2. Fresh groundwaters (I1, I2, I22) display EC values that vary between 0.7 to 1.3 mS/cm. The EC vertical profiles in boreholes ISES2 and ISES22 show a constant EC below 2 mS/cm without any vertical stratification. These groundwaters are found in the northwestern area, where the ground level lies slightly above sea level. They are located upstream of the general groundwater circulation. In this area, brackish to saline groundwaters (I4, I5, I7, I11, I13, I15, I20, I21) display highly variable salinity, with EC ranging from 3.5 to 40 mS/cm. In contrast to fresh groundwaters, EC vertical profiles show a vertical stratification with a sudden increase of EC, locally between 5 and 13 m depth. The upper parts of all profiles converge towards low salinity values, between 2 and 8 mS/cm. The more saline groundwaters (I5, I6, I13 and I15) are found in the boreholes closest to the seawater and the lagoon, within 2 km of the shorelines. Farther inland, neither the EC nor the transition level in brackish waters show a clear spatial distribution. This is likely to be due to the spatial heterogeneity of the aquifer conductive layers. By contrast, in the underlying confined aquifer, the groundwater keeps a constant salinity level, with the EC ranging between 3.4 and 3.7 mS/cm.

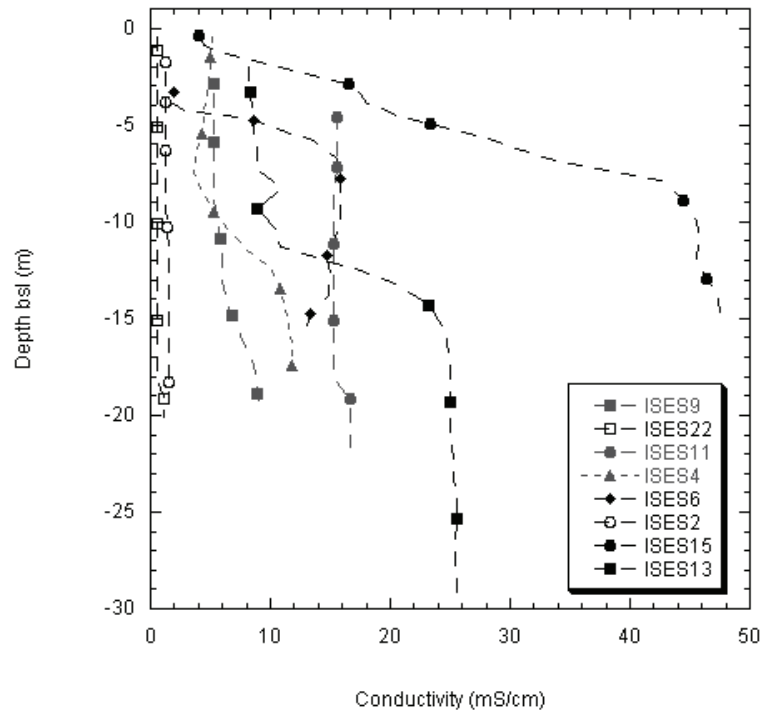


Fig. 2 Vertical EC profiles in ISES boreholes. Black, grey and white dots represent saline, brackish and fresh groundwaters, respectively.

Stable isotopes

The isotopic data are reported in the conventional δ (‰) notation as a deviation from the V-SMOW in the SMOW-SLAP scale. Precipitation was sampled monthly between October 2004 and September 2005, and had a weighted average composition of $\delta^{18}\text{O} = -6.10\text{‰}$ and $\delta\text{D} = 39.1\text{‰}$, close to the long-term average composition measured in Trieste ($\delta^{18}\text{O} = -6.60\text{‰}$ and $\delta\text{D} = 42.6\text{‰}$, Longinelli & Selmo, 2003). A meteoric water line has been defined for northern Italy from long-term average of several sampling stations (North Italy Meteoric Water Line, NIMWL, $\delta\text{D} = 7.7094 \times \delta^{18}\text{O} + 9.40343$; Longinelli & Selmo, 2003). The measured Adriatic seawater composition is $\delta^{18}\text{O} = 1.29\text{‰}$ and $\delta\text{D} = 8.4\text{‰}$, in agreement with previous studies (Stenni *et al.*, 1995). The isotopic compositions of the three main rivers of the Venice region, Adige, Brenta and Bacchiglione rivers, are $\delta^{18}\text{O} = -11.36\text{‰}$, -9.53‰ , and -8.67‰ , and $\delta\text{D} = -81.2\text{‰}$, -63.3‰ and -57.2‰ , respectively. There is a significant difference between these three rivers, reflecting the different recharge altitudes: the Adige River originates from the Alps, while the Brenta and the Bacchiglione rivers have their sources at lower altitudes. The isotopic composition of groundwater from the A0 aquifer ranges from -10.4‰ to -1.84‰ for $\delta^{18}\text{O}$ and from -61.4‰ to -13.7‰ for δD . Deep groundwater shows a $\delta^{18}\text{O}$ and δD isotopic composition ranging from -10.22‰ to -10.66‰ and from -69.2‰ to -72.3‰ respectively. These values are intermediate between the Brenta and Adige samples and are similar to the most depleted A0 groundwater samples.

In δ space (Fig. 3), freshwater samples cluster along the NIMWL, with a composition intermediate between the Brenta River and local precipitation values.

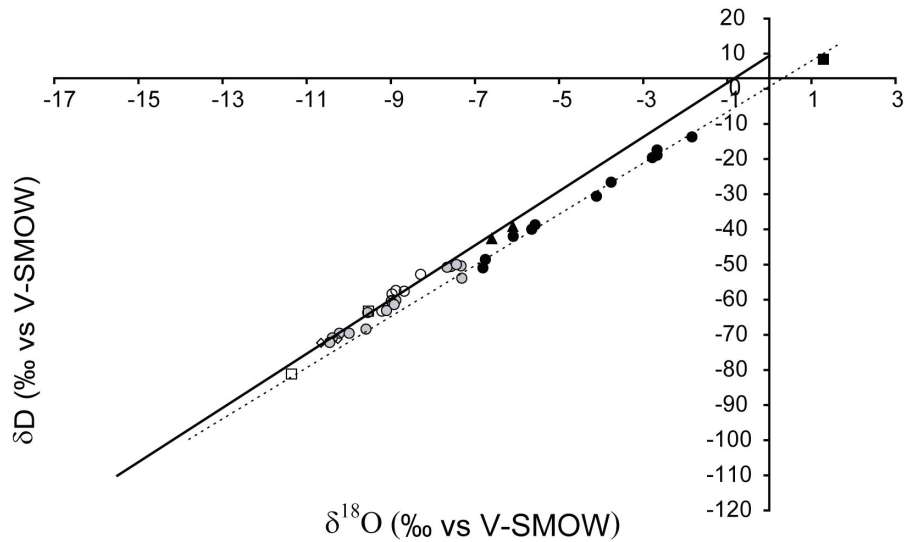


Fig. 3 δD vs $\delta^{18}O$ diagram. Black, grey and white circles stand for saline, brackish and fresh groundwaters from A0 respectively; black square stands for seawater; white squares stand for Adige, Brenta and Bacchiglione rivers, diamond shaped dots stand for deep groundwater, triangle dot stands for rainfall, (—) defines the NIMWL, (---) defines the regression line through the more saline groundwaters from A0.

Brackish samples present a more important range of variation (from $\delta^{18}O = -10.45$ to -7.33‰) and are located along, or slightly lower than, the NIMWL. The saline groundwaters are enriched in stable isotopes compared with the two previous groups, and deviate significantly from the NIMWL (I5, I6, I13, I15). They define a mixing line ($\delta D = 7.27 \times \delta^{18}O + 0.67$; $n = 11$; $r^2 = 0.992$) between the seawater composition and a continental water end-member, isotopically depleted. The isotopic composition of this continental end-member, as estimated by the intercept of the mixing line and the NIMWL, is very sensitive to the slope of the mixing line. By taking into account the saline samples only, its composition could correspond to that of the Adige River (Fig. 3). However, taking brackish groundwater samples into account for the linear regression, in addition to the more saline groundwaters, would lead to a lower slope, and to a higher isotopic composition for the continental end-member.

A linear trend also appears in the relationship between EC and $\delta^{18}O$ for the more saline groundwater samples ($EC = 5.3041 \times \delta^{18}O + 52.43$; $r^2 = 0.88$; Fig. 4). The mixing line crosses the seawater plot, suggesting that the high salinity originates mainly from the mixing with seawater. However, the linear correlation is not robust enough, and it is not possible to identify a unique continental end-member. Freshwater samples compositions reflect a mixing between waters originating from the main rivers, with a potential influence of local rainwater. The situation is more complex for the brackish samples: their position on both sides of the mixing line defined by the saline group may reflect the contribution of surface water, deep groundwater, or/and rainfall. A detailed geochemical study will be necessary to identify the respective contributions of these different waters.

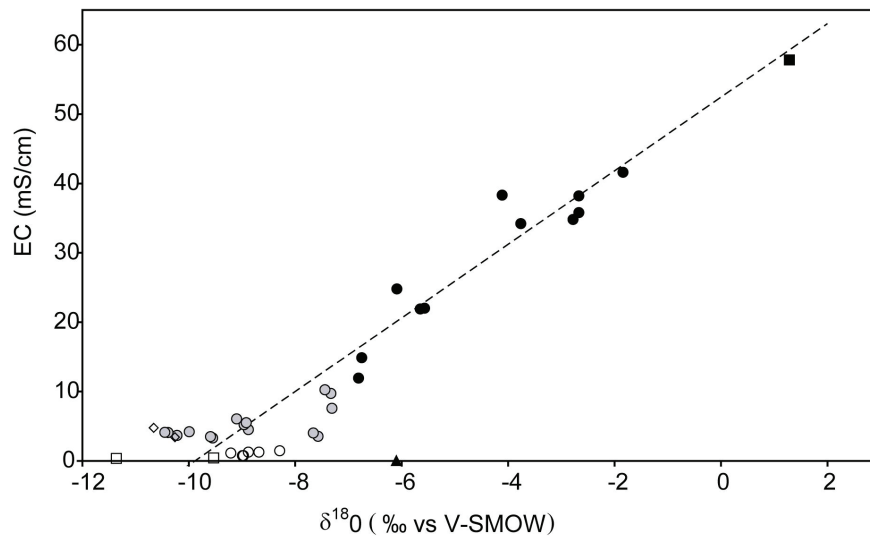


Fig. 4 $\delta^{18}\text{O}$ vs EC (same symbols as in Fig. 3) for the water samples representation. The dotted black line stands for the linear trend between $\delta^{18}\text{O}$ and EC for the saline groundwaters ($\text{EC} = 5.3041 \times \delta^{18}\text{O} + 52.43$; $r^2 = 0.88$).

CONCLUSION

A first investigation of the salinization processes has been carried out by using EC and isotopic tracers in the semi-confined aquifer of the southern Venice Lagoon system. Saline groundwaters are shown to result from a mixing between continental and marine water end-members. However, the dynamic process of saltwater intrusion in the semi-confined aquifer has to be clarified as the salinization may occur via intrusion of seawater, either directly or through the lagoon or the rivers system. Further data are also necessary to characterize the origin of the continental end-member(s) in the mixing process with seawater: surface water, lateral groundwater flow and/or deep groundwater. The presence of fresh to brackish groundwater associated with a water table below the sea level is not compatible with a natural steady-state system. It may be explained by a non-steady state saline intrusion in response to the subsidence, or by the influence of the artificial canal network which induces a permanent renewal of groundwater. Indeed, the isotopic data reveals an important influence of surface water in fresh groundwater samples. Brackish samples have shown an important heterogeneity which was not clearly related to their geographical position, nor to a simple mixing process. The origin of their salts has to be studied further.

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