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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

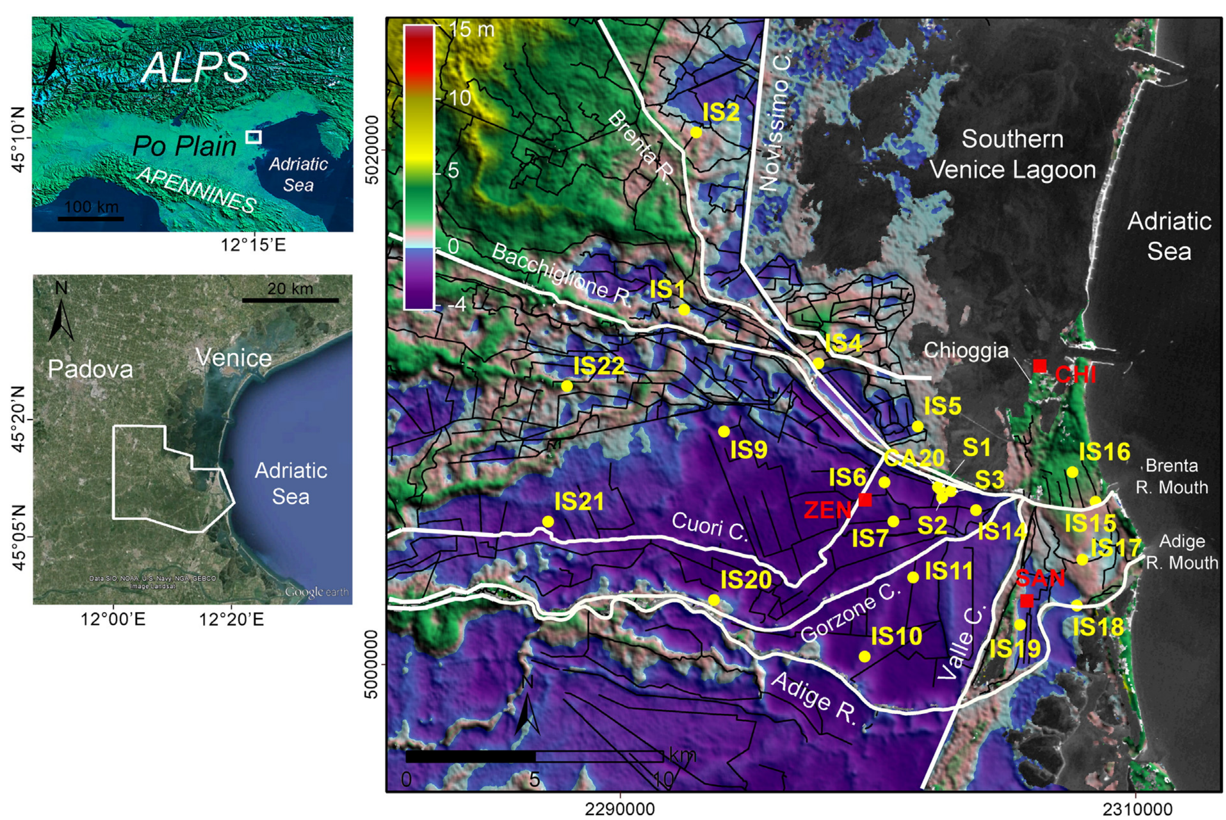


**Fig. 1.** Distribution of the wells of the groundwater monitoring network (yellow dots) superposed to the Digital Elevation Model of the study area. The sketches of the main rivers and reclamation network are drawn in white and black lines, respectively; and the location of the Chioggia tide gauge (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. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)