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Coastal processes and environmental hazards: the Buenos Aires (Argentina) and Venetian (Italy) littorals

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Abstract The Buenos Aires (Argentina) and Venice (Italy) coastlands have experienced significant saltwater contamination of the phreatic aquifer, coastal erosion, hydrodynamic changes and relative sea level rise processes due to natural and man-induced factors. These factors expose coastal areas to morpho-hydro-geological hazards, such as soil desertification, frequency and degree of flooding, littoral erosion, and the silting of river mouths and channels. Man-made interventions and actions, such as beach mining, construction of coastal structures and exploitation of aquifers without an adequate knowledge of the hydrology setting and an adequate management program, worsen these natural hazards. Uncontrolled human activity induces environmental damage to the overall coastal plains. The coastal plains play an important role in the social/economic development of the two regions based on land use, such as agriculture, horticulture, breeding, and tourism, as well as industry. Results of investigations on saltwater contamination, sea level rise and morphological changes recently performed in these two coastal areas are presented here.

Introduction

The Buenos Aires (Argentina) and the Venice (Italy) coastal zones are two environments with a high risk of hydrogeological hazards. Although these two regions have their own distinct features, they both are seriously affected by coastal erosion, saltwater encroachment in the phreatic aquifer and sea level rise. These phenomena, worsened by human action, have increased the risk of land degradation.

The eastern coast of the Province of Buenos Aires is composed of a sandy beach-dune system that extends for about 180 km between Punta Rasa and Mar del Plata (Fig. 1). As part of the coastal plain of the Pampas, it shows evidence of Pleistocene and Holocene high sea levels (Schnack et al. 1998, 2004). At a regional scale, this sandy coastline prograded in the last 6,000 years when a maximum sea level stand of

Fig. 1 The study area between Punta Rasa and Mar del Plata. LANDSAT images from CONAE data base

about 3.5 m occurred. For all its progradation characteristics, it undergoes severe erosion aggravated by human action (Schnack et al. 1998; Schnack 2004). The area of interest may be divided into two well-defined sectors: the eastern sandy barrier, extending for about 150 km between Punta Rasa and Mar Chiquita, and the 30 km coast stretch characterized by low cliffs from Mar Chiquita to Mar del Plata. At the northern end (Punta Rasa), the sandy barrier is interrupted by a low energy embayment, transitionally related to the Rio de la Plata estuary. Storm surges are the most important agent for natural coastal erosion on the eastern coast of Buenos Aires Province (Schnack and Pousa 2004).

The Venetian case study focuses on part of the coastal area between the Chioggia littoral and Brenta-Bacchiglione and Adige river mouths (Fig. 2). With gently sloping sandy beaches and a 550 km^2 lagoon, it is characterized by Holocene deposits with different geomorphological features: the coastal stretch, the lagoon margin and the inland. In the Chioggia littoral, where a complex system of sandy dune ridges is preserved, ground elevation ranges from 0 to 2 m above sea level; whereas the inland coastal zone frequently lies below mean sea level and is characterized by the presence of ancient fluvial ridges, paleo-riverbeds and paleo-coastlines. Sandy and silty soils characterize the remnants of ancient fluvial and beach ridges. Clayey silts, often rich in organic matter, fill the inter-distributary lowlands. Bogs with peat layers occur in the reclaimed marshy areas (Rizzetto et al. 2003). The present morphology is the result of the coastline progradation which occurred during the last 6,000 years and the impact of human action during the past few centuries. The coastal plain was completely reclaimed at the beginning of the last century and is now mechanically drained for agricultural purposes.
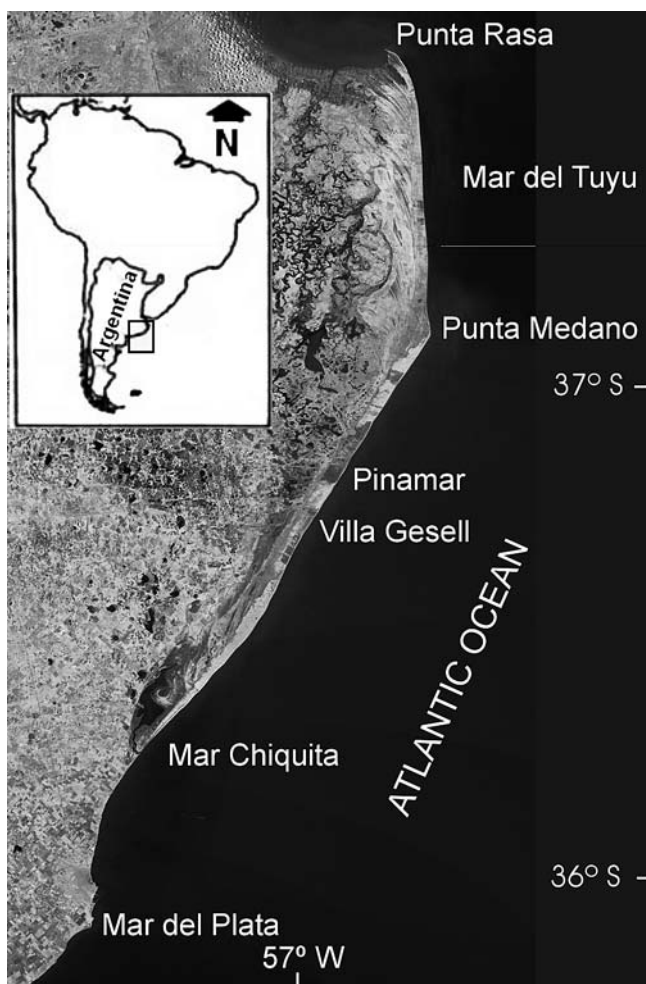
Materials and methods

The geological and geomorphological features of the two study areas were identified through the Argentine Instituto Geográfico Militar (IGM) and the Italian Istituto Geografico Militare Italiano (IGMI) topographic maps, satellite images (LANDSAT, IKONOS, ASTER for the Venice area, and LANDSAT for the Buenos Aires area), aerial photographs, field surveys and stratigraphic analyses (Rizzetto et al. 2003; Rusconi et al. 2004).

In parallel, the hydrogeological settings were investigated by a census of boreholes, electrical conductivity measures and analyses of water samples from wells, rivers, and channels, piezometric measures and vertical electrical soundings (VES) (Carbognin and Tosi 2003).

Fig. 2 The digital elevation model (DEM) of the Venice region. The *black box* indicates the study area
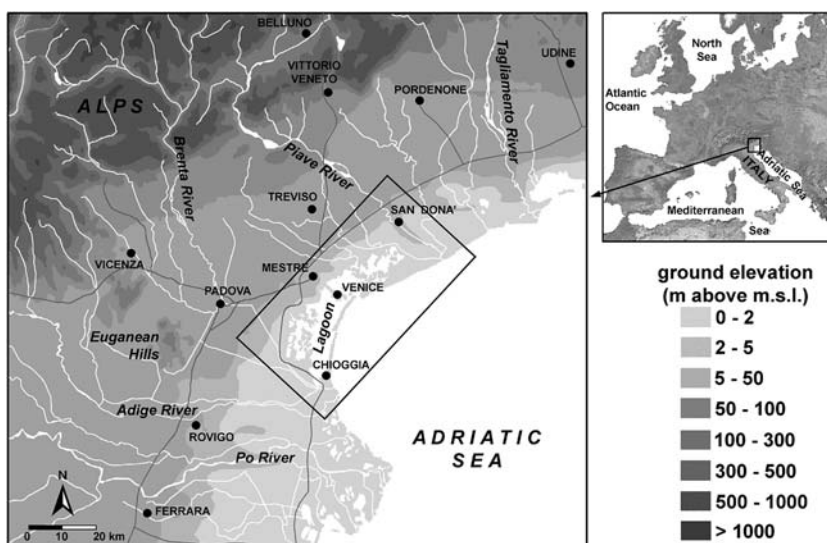
Relative sea level rise trends were calculated using data from the Mar del Plata, Venice and Trieste (Carbognin et al. 2004) tide gauge stations.

Vertical ground movements for the Venice area were analyzed through high precision leveling carried out by the IGMI, the National Research Council (CNR), and the local water authorities, as well as by Differential Interferometric SAR data (Carbognin et al. 1995a, b; Tosi et al. 2000, 2002; Gambolati et al. 2005; Strozzi et al. 2003; Teatini et al. 2005).

Results and discussion

Morphodynamics

The sandy barrier of the eastern coast of Buenos Aires is composed of a beach–dune system with various types of relationships, mainly dependent upon the uses of the coast. Dune scarps are dominant at the southern tip, closer to Mar Chiquita, while active or unstable dunes predominate towards the north (Isla et al. 1996). The coast is typically microtidal and wave-dominated. Although of variable width, the dune system may reach a width of about 5 km, and is limited to the west by low-lying areas frequently affected by floods. Erosion processes are a common feature all along the coastline, particularly at highly developed localities. The whole coastline under consideration is the most important tourist area in Argentina and includes Mar del Plata, Pinamar and the Partido de la Costa (Mar del Tuyú and other resorts) as the major coastal urban units. The urbanization developed on the dunes and the mining of beach sand for building purposes are the major causes of shore erosion. Also, urbanization and the increase of human activities are causing the exhaustion of

groundwater reserves and a restriction of the recharge areas. Since the harbor at Mar del Plata was constructed at the beginning of the last century, erosion processes started to the north in the direction of net littoral drift (Schnack et al. 1990, 1998). The emplacement of engineering structures (groynes, walls) has been a common practice during the past decades, causing extended damages along the downdrift direction. Beach replenishment was tried at Mar del Plata in 1998.

Storm surges originate in the coastal front of the Province of Buenos Aires as well as in the southernmost area of the Argentine shelf (Schnack and Pousa 2004). Associated with high-energy waves due to strong winds, they are the most important agent for coastal erosion on the eastern coast of Buenos Aires (Schnack et al. 1998). However, in the absence of human intervention, the beach profile tends to re-establish naturally; it is the human action in the form of urbanization, sand mining for building purposes, dune destruction and dune fixation, that establishes an irreversible erosion pattern. Dune scarps are formed during each storm event. Other areas, such as Pinamar, where resort facilities are often founded on the backshore zone, suffer severe erosion with property losses during heavy storms. Although not typically composed of barrier beaches, the coast of Mar del Plata is also subject to extensive erosion and destruction of resort facilities (Schnack et al. 2004).

The southern stretch of the Venice Lagoon between the Chioggia littoral and Brenta River mouth is characterized by a flat sandy beach and a system of dune ridges having the same direction of the present coastline. These features are the consequence of the coastline progradation during the last 2,500 years (Rizzetto et al. 2003). The recent littoral shape is mainly due to human intervention such as the diversion of the Brenta River mouth at the end of the nineteenth century, and the

construction of the lagoon inlets in the sector of Chioggia, between 1911 and 1930 and the wharf, seasonally installed at the Brenta River mouth, to divert the polluted water of the river to the sea. The present morphology of the back-barrier area is completely artificial because of dune leveling and marshland reclamation for agricultural activities.

Figure 3 illustrates the shoreline morphodynamics in the southern part of the Venice Lagoon (Chioggia littoral and Brenta River mouth). The main coastline changes correspond to the Brenta River mouth and the Chioggia inlet. From 1966 to 1997 a prograding trend has been observed (Rusconi et al. 2004). The presence of wharfs, even if seasonally removable, favors the capture of sandy deposits transported by the near-shore circulation. In particular, for the 1987–1997 period, the coastline prograded about 10 m/year on the right side of the Brenta mouth, while it presented slight changes in the distal position with respect to the inlets. During the 1997–1999 period the trend changed because of weather conditions linked to the energy flux from exceptional Bora-Sirocco wind events, having NE and SE direction, respectively. An erosion process of up to 28 m/year was

Fig. 3 Evolution of the Brenta river mouth (modified from Rusconi et al. 2004)

measured on the right side of the Brenta mouth. Only next to the northern wharf a small increase has been observed, probably due to its leeward position. The most recent coastline change (1999–2003) was the progradation that occurred next to the Chioggia inlets.

Groundwater and saltwater intrusion

Fresh groundwater resources are limited in the eastern coastal area of Buenos Aires. The process of saltwater intrusion in the phreatic aquifer of the Buenos Aires coastline is caused by two sources: the marine water and the alluvial water, the latter due to the low velocity of groundwater fluxes and the absence of a developed hydrographic network that enhances the salt content of the groundwater. Sediments of aeolian origin (sand dunes) cover a semiconfined aquifer (Fig. 4) containing saltwater whose salinity ranges between 3 and 15 g/L (González Arzac et al. 1992). The permeability of these sands is greater than 10 m/day, with an effective porosity of 0.15. In this hydrogeological unit, a phreatic aquifer of low salinity (between 400 and 1,000 mg/L), bounded by the sea and the brackish water of both the phreatic continental aquifer and the semiconfined aquifer, are well developed. The characteristics of the surface sediments facilitate infiltration and transmission. Phreatic maps show that groundwater distribution may be divided according to the greatest heights of the coastal ridges into three sectors with a complex interface: the continental water, the dune water, and the sea water (Kruse et al. 2005). Three hydraulic heads are significant at this interface: the local groundwater flow (sand dunes), the regional groundwater flow (continent), and the zero head (the sea). Low-salinity groundwater lenses bounded by brackish water from the sea and the continental plain are the only source of drinking water supply. Dune fresh water reserves are scarce.

Lens-shaped groundwater reservoirs are subjected to intensive exploitation during the summer because of intense tourist activities. Overexploitation of aquifers and the risk of pollution are common in the whole area. Because of over pumping, urbanized areas exhibit depletion of aquifers with consequent intrusion of saltwater. This has forced some pumping wells to be abandoned and the exploitation to be shifted to other areas. Along with urbanization, dune destruction has affected the natural hydrodynamic regime. As a result, the possibility of water infiltration has decreased, thus restricting the recharge areas and the storage of freshwater. Due to the hydraulic behavior of the phreatic aquifer, its high permeability (10 m/day) and the small thickness of the unsaturated zone (between 2 and 4 m), the available fresh water lenses are very vulnerable to pollution. In the present scenario, the risk of contamination of the phreatic
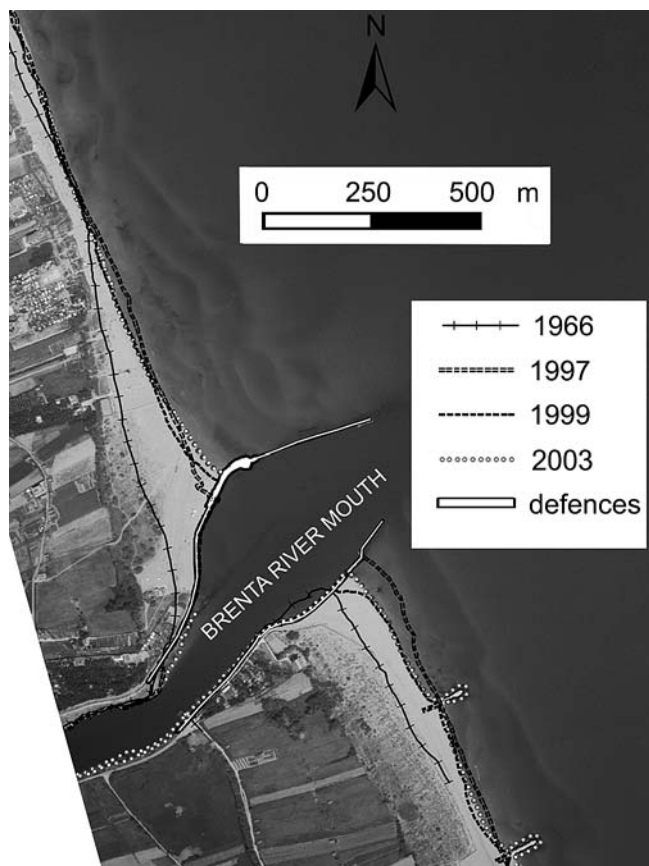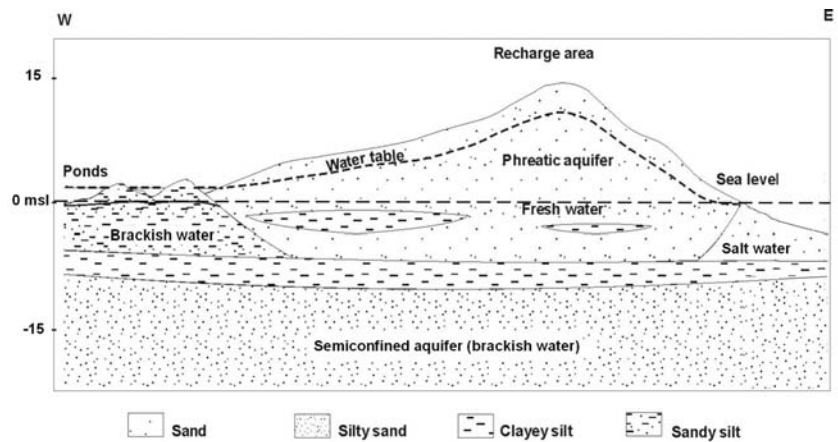
Fig. 4 Fresh groundwater resources in the eastern coastal area of Buenos Aires

aquifer should be related to the infiltration of toxic substances (particularly nitrates) of anthropic origin (urbanization, agricultural activities, sewage and waste deposits).

With respect to the Venetian coastal area, the pattern of saltwater intrusion from the sea and the lagoon into the phreatic aquifer is sketched in Fig. 5 (Rizzetto et al. 2003). Saltwater contamination is due to marine and lagoon water intrusion, river encroachment of tide and its dispersion, and the rise of freshwater/saltwater interface due to maintaining the fresh water table at low levels in reclaimed areas by pumping stations. Paleoriver beds, ancient dunes and littoral ridges, combined with climate changes, contribute to the worsening of this process.

The thickness of the freshwater layer varies and generally becomes much thinner from the central part of the littoral to the sea and the lagoon margin (Carbognin and Tosi 2002, 2003; Carbognin et al. 2005a). The maximum thickness fluctuates seasonally between 15 and 20 m and depends on the amount of precipitation, which is the main recharge to the phreatic aquifer.

Along the lagoon margin the saltwater/freshwater interface is 3–5 m deep, but it can rise up seasonally to 1–2 m below the ground surface. The land surface below mean sea level (up to −2.5 m) and the encroachment of the sea water along the Brenta and Bacchiglione rivers during high tides increase the landward intrusion of saltwater (Carbognin and Tosi 2003; Carbognin et al. 2005c). In the mainland, characterized by a different geomorphologic setting with ground level varying between 4 m below and 4 m above mean sea level, frequent changes in soil characteristics and different hydraulic conditions are responsible for saltwater contamination in soil and groundwater at different depths. The freshwater/saltwater interface lies at depths between 0 and 10 m, varying with hydraulic and weather conditions and extending up to 20 km mainland. The bottom of salt contamination reaches a depth of 100 m (Carbognin and Tosi 2003; Carbognin et al. 2005a, c).

Land subsidence

There are clear evidences of Pleistocene and Holocene transgressive events in the Argentina study area (Schnack et al. 2004). These events, which can be particularly correlated at regional and global scales with relatively stable areas, were due to changes in ocean volume in response to glacial and interglacial cycles. So far, there is no conclusive evidence that support any significant tectonic influence in the development of coastal environments in the study area, at least during the last 120,000 years (Schnack et al. 2005).

In the Venice area, on the contrary, land subsidence, mainly due to groundwater withdrawal, has represented one of the most serious environmental problems (Carbognin et al. 1977, 1995a, b; Teatini et al. 1995). Once the cause-and-effect relationship was defined and countermeasures taken, the induced subsidence at Venice stopped. A recent study shows a general stability of the Historical Center (Carbognin and Tosi 2002, 2003; Tosi et al. 2002; Carbognin et al. 2004). However, wider areas outside the lagoon are still affected by serious sinking because of the geological history of the region and human activities (Fig. 6). In particular, subsidence is related to the more compressible recent Holocene sediments located in the southern and northern sectors of the lagoon hinterland (Carbognin et al. 2004, 2005a, b; Teatini et al. 2005). These sediments are responsible for natural settlement rates greater than elsewhere (about 2 mm/year). Organic soil oxidation in reclaimed southern areas has also led to an overall local settlement of about 1.5 m during the last 50 years, and has induced sinking rates of up to 3 cm/year (Tosi et al. 2000; Gambolati et al. 2005). Tectonics and saltwater intrusion are also responsible for

Fig. 5 The pattern of saltwater intrusion in the Venetian coastal area (modified by from Rizzetto et al. 2003)
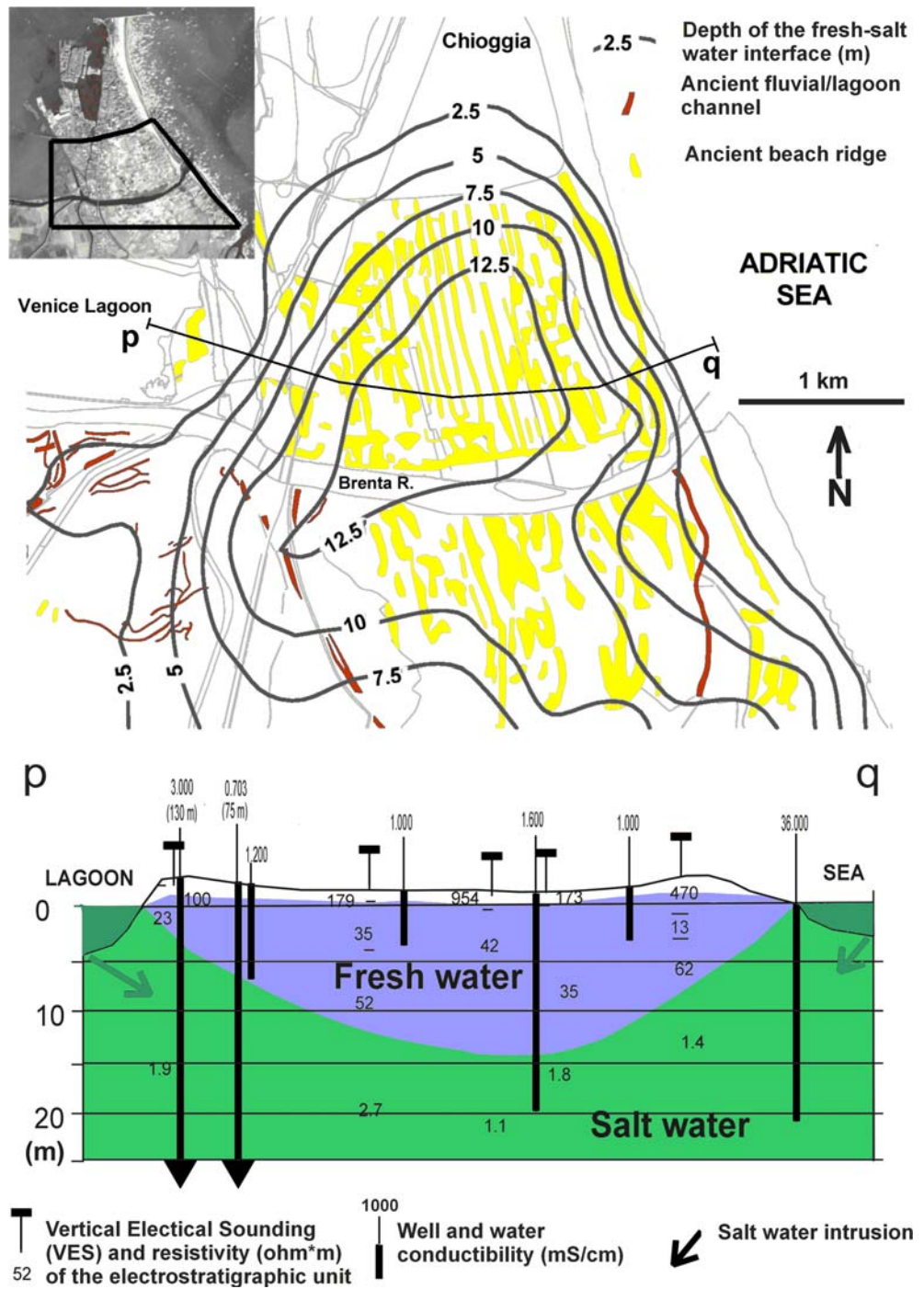
land subsidence (Carbognin et al. 2005a; Teatini et al. 2005).

Sea level rise

Hourly sea level measurements from the Mar del Plata (Argentina) tide gauge station for the period 1954–2002 have been used as the basic data to calculate a filtered series of absolute annual mean sea levels. The linear regression analysis of this series shows a trend of 1.4 ± 0.01 mm/year (D'Onofrio EE, Fiore MME, Servicio de Hidrografía Naval, Armada Argentina, unpublished data, 2005) (Fig. 7). This value is consistent with the global trend of 1–2 mm/year for the last century as indicated by the IPCC (2001). Even if the forecast of

Fig. 6 Vertical displacements (mm/year): **a** of the Veneto Region coastal area over the period 1992–2002 obtained by SIMS (Teatini et al. 2005) and their "potential" causes, negative values are subsidence (modified from Carbognin et al. 2005b); **b** along the Venetian coastline over the period 1993–2000 obtained by the interpolation of InSAR data (Strozzi et al. 2003)
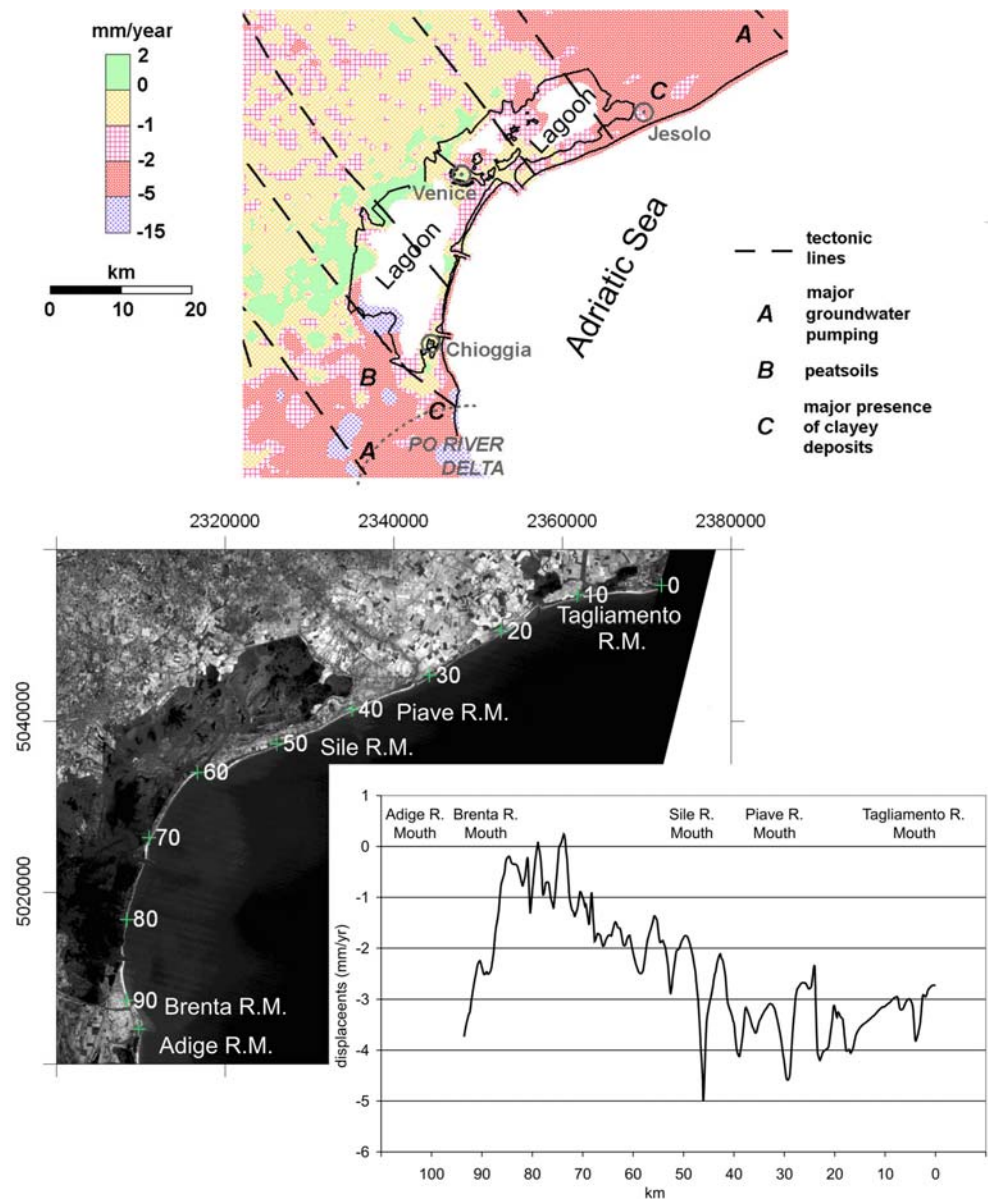
eustasy shows an increasing trend, the ground elevation and the morphology of the back shore should guarantee a certain degree of protection from relative sea level rise for the immediate future.

The case of the northern Adriatic Sea (Italy) was studied through data from two tide gauge stations established at the end of the nineteenth century in Venice and Trieste (Carbognin and Tosi 2002; Carbognin et al. 2004). The average linear rate of 1.13 mm/year is representative for the last century and agrees with the data from other tide gauges in the Mediterranean. Actually, tide gauge measurements clearly show an up-and-down behavior in mean sea level depending upon short-term climatic fluctuations. In particular, the existence of a non-unique secular trend for Venice is statistically verified and due to a temporary influence of anthropogenic subsidence. Differences between tide gauge values recorded at Venice and Trieste for the period 1896–2000 are shown in Fig. 8.

Recent measurements at Venice and Trieste indicate that mean sea level has had such an abrupt increase in the last years (3 cm from 1995 to 2000) that the mean rising rate recalculated with a linear trend for the period 1971–2000 was equal to 0.6 mm/year, a significant value considering that between 1971 and 1993 no sea level rise occurred.
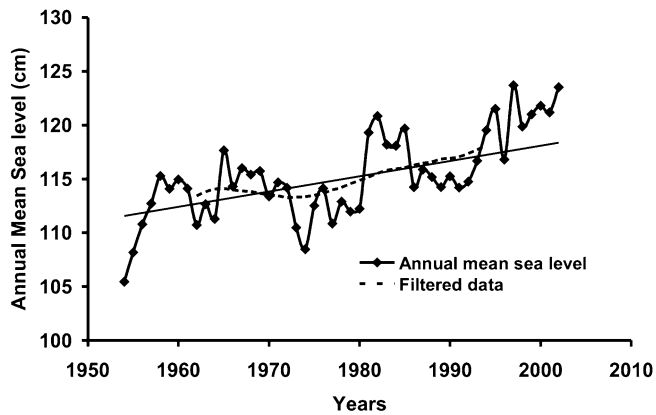
Fig. 7 Linear regression calculated from filtered data of absolute annual mean sea levels at Mar del Plata for the period 1954–2002
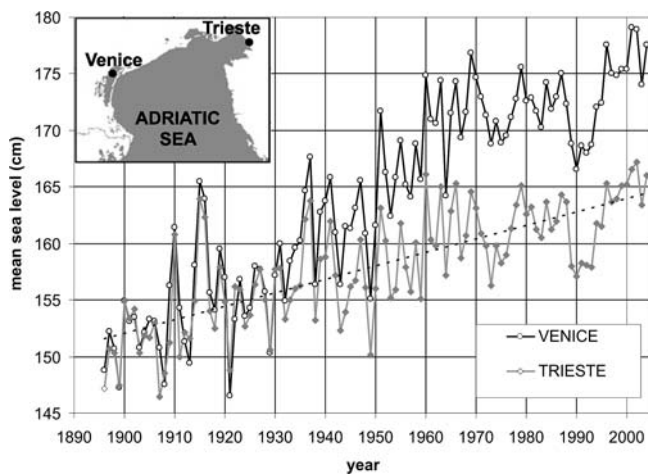

Fig. 8 Differences between tide gauge values recorded at Venice and Trieste for the period 1896–2004 (modified from Carbognin et al. 2004)

Conclusions

Storm surges, saltwater intrusion, land subsidence, eustasy and human activities play different roles in the development of the eastern coastal plain of the Buenos Aires Province and the southern coastal plain of Venice. The eastern coastline of the Province of Buenos Aires undergoes beach erosion and saltwater intrusion. Beach erosion is mainly related to storm surges together with high-energy waves due to the associated strong winds. The coastal configuration suffers dramatic modifications with a pronounced change in the beach profile and the environmental impact is more severe on areas of heavy human intervention (beach sand mining, urbanization, coastal constructions). Conversely, the natural evolution of the littoral tends to re-establish the beach profile after

the storm surges. Saltwater contamination in the phreatic aquifer is caused by the marine intrusion and by the water coming from the alluvial plain aquifer rich in salt content. Although, for the immediate future, the absence of land subsidence, the ground elevation and the morphology of the backshore should guarantee a certain degree of protection from the hazard of flooding events, the increase of the eustacy induces a high risk of the groundwater salt contamination extent. The processes that increase the vulnerability of Venice's south littoral are mainly the saltwater contamination and the relative sea level rise. Saltwater contamination is due to the marine and lagoon water intrusion and is worsened by natural and induced factors, such as the river encroachment of tide and the drainage by pumping stations in the reclaimed areas. The relative sea level rise particularly threatens Venice's south coast where the contributing factors are natural compaction in relation to the deposition of estuarine sectors (2–5 mm/year), the oxidation of organic rich soils (a few cm/year) and the eustatic sea level rise (1.13 mm/year). Nowadays the beach erosion between the Chioggia inlet and Brenta River mouth is reduced to a few meter per year and does not appear to be a serious problem because of an accurate management plan; the increase of relative sea level and adverse climatic conditions could, however, activate the shoreline erosion process. In conclusion, the processes that are triggering the geological hazard in these two study areas are due to different causes and they have a different degree of impact on the coastal environment. In particular, these areas show important sand dune systems and littoral sectors with similar morphology characteristics and land use. The system of sand dune ridges contains an important reservoir of freshwater, in some cases the unique reservoir, which makes agricultural and tourist activities possible. The overexploitation of aquifers induces saltwater intrusion of marine and continental origin, while dispersion of water from sewage contaminates and reduces freshwater reservoirs. Human activities such as beach mining, construction of coastal structures and exploitation of aquifers without an adequate knowledge of the hydrogeological behavior and an accurate management program, induce irreversible environmental damage to the overall coastal plains. The main consequence of the environmental impact of human activities in the two study areas is the modification of the natural processes related to the coastal morphology and hydrodynamics, such as long-shore circulation, seasonal beach nourishment, land subsidence, and fresh groundwater recharge. Although some engineering interventions for the remediation are possible, they should be set off at local scale and with high costs. Presently, the accurate land use planning and the management of the exploitation of natural resources seem to be efficient measures to preserve the coastal environment.

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