Geomorphic setting and related hydrogeological implications of the coastal plain south of the Venice Lagoon, Italy

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Abstract The contribution of the geological and morphological setting to the worsening or contrast of land subsidence and saltwater intrusion was pointed out in three areas located south of the Venice Lagoon (Italy): the littoral stretch of Chioggia, the southern lagoon margin (Punta Gorzone) and an inland sector of the lagoon drainage basin (the Zennare Basin). The main geological and morphological features were identified by sedimentological and geomorphic investigations. Saltwater intrusion, whose extent was indicated from geophysical investigations and analyses of water samples from wells, rivers, and channels, is related to the presence of sandy paleo-channels and a land elevation significantly below the mean sea level. At present, land subsidence, assessed by geodetic surveys, in situ evidence and topographical map comparison, is mainly caused by the drainage of cultivated peaty areas.

Key words coastal plain; geomorphology; land subsidence; saltwater intrusion; Venice

INTRODUCTION

The area under investigation is part of the coastal plain between the lower stretches of the Brenta and Adige rivers, south of the Venice Lagoon (Italy) (Fig. 1). Three zones, characterized by their different morphological settings and hydrogeological features, were examined: the Chioggia littoral, the Punta Gorzone area close to the southern lagoon margin, and the Zennare Basin, an inland sector of the lagoon drainage basin.

The coastal plain lies almost completely below the mean sea level, with the exception of the eastern zone, where old elevated beach ridges are preserved. Most of these territories, which were completely reclaimed at the beginning of the last century, are mechanically drained by pumping stations to make agricultural activity possible.

The main hydrogeological problems of this part of the Venice area are the advancing of saltwater contamination into the phreatic aquifer, and the settlement of the land surface. These two phenomena have increased the risk of scenarios of soil desertification, the instability of the water course embankments, and the frequency of inundation because of a reduced drainage capability. Geological and geomorphic features can favour or mitigate these processes.
The methodology used to study the saltwater contamination consists of the map of the top of the saltwater wedge and cross-sections drawn by means of vertical electrical soundings (VES) and electrical conductivity measures on water samples from wells, rivers, and channels. Vertical GROUND movements were calculated using high precision levelling carried out by IGMI (Istituto Geografico Militare Italiano), CNR, and local water authorities. Aerial photograph and satellite image (IKONOS, LANDSAT, ASTER) interpretation, field surveys, stratigraphic analyses, and altimetric investigations were used to identify the main geological-geomorphic features.

This study was performed combining results from two researches aimed to study land subsidence and saltwater intrusion processes in the Venetian region: the VOSS Project (Venice Organic Soil Subsidence) and the ISES Project (Land Subsidence and Saltwater Intrusion).

GEOLOGICAL AND GEOMORPHIC SETTING

The study area is characterized by Holocene deposits with different geomorphic features in the eastern coastal stretch, the lagoon margin and the western inland. In the Chioggia littoral, where a complex system of sandy dune ridges is preserved, the ground elevation ranges from 0 to 2 m a.s.l. Punta Gorzone and the Zennare Basin lie...
completely below the mean sea level and are characterized by the presence of ancient fluvial ridges, palaeo-river beds and palaeo-coastlines.

Favero & Serandrei Barbero (1978) identify the inner coastline position, reached during the Flandrian transgression, 5000–6000 years BP, in the north-western part of the study area, along the alignment X in Fig. 1; here marine-lagoon deposits were buried by fluvial sediment supplies which caused a rapid eastward coastline progradation. Outcropping evidence of beach ridges is recognizable inland, about 1–2 km east of the Zennare Basin, along the alignment Y in Fig. 1; the coastline reached this site about 4500 years BP (Bondesan et al., 2001) and remained here for a longer time than in the inner position. During the last 4000 years, several fluvial depositional events of the Brenta, Bacchiglione, Adige and Po rivers filled up the back barrier lagoon and the surrounding swamps, with a consequent eastward coastal migration (Z, W in Fig. 1).

The different depositional environments are responsible for the various lithologies and geological features. Sandy and silty soils characterize the remnants of ancient fluvial and beach ridges, whereas clayey silts, often rich in organic matter, fill the inter-distributary lowlands; bogs with peat layers occur in the reclaimed marshy areas.

THE CASE STUDIES

The Chioggia littoral is a gently sloping sandy beach with a system of dune ridges which have the same direction as the present coastline (Fig. 2). These features are the result of the coastal advance that occurred during the last 2500 years (see Fig. 1), while the present littoral shape is mainly due to human intervention, such as the diversion of the Brenta River mouth from the lagoon to the Adriatic Sea at the end of the 19th century, and the construction of the jetties at the Chioggia inlet between 1911 and 1930, which have strongly modified the coastal hydrodynamic and sediment transport regime. In the 1960s this area experienced high subsidence rates, up to 1.4 cm year$^{-1}$, mainly due to groundwater withdrawal. Since the regulation of the groundwater exploitation, a general decrease of subsidence rates has been observed. Present settlement, less than 1.5 mm year$^{-1}$, indicates the relative stability of Chioggia. The pattern of saltwater intrusion from the sea and the lagoon into the phreatic aquifer is sketched in Fig. 3; 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 (see Fig. 2); the maximum thickness, seasonally fluctuating between 15 and 20 m, depends on the amount of precipitation, which is the main recharge to the phreatic aquifer.

The Punta Gorzone area is a part of the coastal plain that lies below the mean sea level, down to −2.5 m; to the north it is bounded by the Brenta-Bacchiglione River, flowing close to the southern edge of the Venice Lagoon (Fig. 4). Many traces of ancient fluvial and lagoon channels and drainage canals, such as the old course of the Canale Vecchio dei Cuori (X in Fig. 4), and paleo-beach ridges (Y in Fig. 4) have been found by means of geomorphic investigations. This area is characterized by a high hydrogeological risk, due to the critical land elevation of the territory and to the water level of rivers and channels, which may be up to 5 m above the surrounding ground surface. Periodic levelling was carried out during the last 50 years along the national network that includes the lagoon margin (Carbognin et al., 1976, 1995; Tosi et al.,
2000). Figure 5 shows the changes in land surface elevation, assuming the 1951 IGMI survey as reference. The highest subsidence rate during the period 1960–1970 was due to a combination of several causes, such as groundwater withdrawal for domestic, industrial, and agricultural use, a natural consolidation rate of about 2 mm year\(^{-1}\), and the oxidation of organic soils induced by their drainage. In situ evidence of the overall settlement occurred in this zone during the last 60 years is shown in Fig. 6(a). Along
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Fluvial/lagoonal channel
Depression (< 2 m)

Fig. 4 Geomorphic features in the southern lagoon margin (Punta Gorzone) and map of the depth below ground surface (m) of the fresh-saltwater interface. (X) Canale Vecchio dei Cuori; (Y) traces of the coastline position 3000 years BP; (Z) erosional trench in the Brenta River bed.

Fig. 5 Ground vertical movement obtained from leveling surveys along the south-western boundary of the Venice Lagoon: (a) IGML/CNR surveys carried out from 1951 to 1993; (b) CNR/1SES from 1993 to 1999. The position of the levelling line is shown in the insert map.

In the southern lagoon margin the salt-freshwater interface is 3 to 5 m deep, but seasonally can rise up to 1–2 m below the ground surface. The land surface below the mean sea level and the encroachment of the sea-lagoon water along the Brenta River and channels during
Fig. 6 (a) An old bridge, located in the Punta Gorzone area and constructed in the twenties, whose foundation protrudes about 150 cm. In the background, the newer bridge, in use today, reveals subsidence of about 50 cm over the last 30 years. (b) An old masonry culvert, in the Zennare Basin, presently above water level and substituted by two lower concrete drainpipes; the upper one is already unusable; a qualitative position of the ditch section in the original configuration is sketched in both figures.

Fig. 7 Map of the major geomorphic features of the Zennare Basin (Rizzetto et al., 2002, modified) and the contour line of the depth below ground surface (m) of the fresh-salt water interface. (X) Ancient branches of the Adige River system; (Y) evidence of the ancient Brenta River; (Z) meanders of the old Canale dei Cuori; (W) ancient branch of the Po River.
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high tides increase the landward intrusion of the saltwater. Moreover the ancient channels and an erosion trench in the Brenta river bed, 8 m lower than the ground surface (Z in Fig. 4), enhance the inland flow of the saltwater from the lagoon.

The last study zone is the Zennare Basin, a subsiding area of the lagoon drainage basin lying down to 4 m below the mean sea level. It was completely reclaimed in the 1930s for agriculture and is characterized by the presence of bogs with outcropping peat layers, presently less than 2 m thick, which provide evidence of ancient swamps. Several traces of paleo-river beds with their main flow direction towards the southern Venice Lagoon margin were found (Fig. 7) (Rizzetto et al., 2002). Two of them, probably related to an ancient water course of the Adige River, cross the Zennare Basin with a SW–NE direction (X in Fig. 7), whereas the ancient southernmost course of the Brenta and Bacchiglione River system (Favero & Serandrei Barbero, 1978) can be observed in the north-eastern sector (Y in Fig. 7). The old course of the Canale dei Cuori is recognizable by the traces of its meanders (Z in Fig. 7), intersecting the new canal (Canale Nuovo dei Cuori) built at the end of the 19th century. Finally, the meanders located close to the north-eastern boundary (W in Fig. 7) represent the northernmost ancient branch of the Po River. A subsidence rate of 2–4 cm year\(^{-1}\) was determined for this area by comparing leveling surveys performed by the local water authorities, and the ground elevation of the 1983 Regional Topographic Map, and by the analysis of the macroscopic evidence of the area’s settlement (Table 1, Fig. 6(b)). The high sinking rates are mainly due to the oxidation of soils rich in organic matter, induced by the drainage and the intensive agricultural activity (Fornasiero et al., 2002), whereas natural sediment consolidation is only responsible for a secondary impact (2–3 mm year\(^{-1}\)) (Gambolati & Teatini, 1998; Tosi et al., 2000). Peaty soils are located in the lowest, i.e. rapidly sinking, areas, whereas sandy-silty deposits, representative of ancient fluvial ridges, are more stable. Concerning the saltwater contamination, the freshwater infiltration through the Canale dei Cuori embankment into the basin and the presence of an aquitard, characterized by thick silt-clayey layers from 5 to 10 m below the ground surface, preclude the salty pollution in the southern area, whereas a paleo-river system favours the saltwater propagation from the lagoon in the northern part. In the central sector another palaeo-river system, containing freshwater, maintains at a lower level the top of the saltwater.

Table 1 Average land subsidence rate in the four sub-basins (a, b, c, d in Fig. 1) (after Tosi et al., 2000).

<table>
<thead>
<tr>
<th>Zone</th>
<th>Levelling survey (year)</th>
<th>Land subsidence rate (cm year(^{-1})) up to 1983</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1935</td>
<td>1.9</td>
</tr>
<tr>
<td>b</td>
<td>1965</td>
<td>2.7</td>
</tr>
<tr>
<td>c</td>
<td>1929</td>
<td>2.6</td>
</tr>
<tr>
<td>d</td>
<td>1941</td>
<td>3.5</td>
</tr>
</tbody>
</table>

CONCLUDING REMARKS

The influence of geological and geomorphic features on the propagation or mitigation of land subsidence and saltwater intrusion is demonstrated in three sectors of the coastal plain located among the southern margin of the Venice Lagoon, the Adriatic Sea and the Adige River. The research has been carried out by means of
sedimentological and geomorphic studies (aerial photograph and satellite image interpretations, altimetry investigations, field surveys, and stratigraphic analyses), geophysical investigations (vertical electrical soundings), and electrical conductivity measurements of water samples from wells, rivers, and channels.

On the Chioggia littoral, the system of sand dune ridges contains a reservoir of freshwater up to 15 m thick and subsidence is no longer a problem. Land sinking and saltwater intrusion processes seriously threaten the hydrogeology of the area adjacent to the southern lagoon margin. In particular, the ground surface below the mean sea level, the pumping to maintain drainage, the tide encroachment along the river mouths and the paleo-river beds, expand landward the saltwater intrusion. In the inland sector, the deposit characteristics are responsible for the significant lowering of the land surface. While the organic soils correspond to the highly sinking areas, sandy-silty deposits, which form fluvial ridges, are more stable. Saltwater contamination shows different behaviour from the south to the north of the Zennare Basin and depends on the leakage of freshwater from the irrigation canal network and the geological features.

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