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Characterization of the Coastal Phreatic Aquifer of the Cervia Area (NE Italy)

Caratterizzazione dell'acquifero freatico costiero del Comune di Cervia

ULAZZI E. (*), ANTONELLINI M. (**), GABBIANELLI G. (*)

ABSTRACT - The Cervia shoreline area and adjacent landward belt represents a coastal flat zone characterized by a strong subsidence rate. Subsidence is mostly related to uncontrolled winning of gas and groundwater that started at the mid of past century. Massive land development exploded in 1950 bringing to a current 50% urbanization of the territory.

The phreatic aquifer is located on the coastal sand dune, which was deposited during the last marine transgression (5.000-6.000 years old). The marine transgression reached inland as much as 2 km in the north and 1 km in the south. A marsh area developed inland, to the west, where later the romans built the Cervia saltworks.

The stratigraphic reconstruction of the phreatic aquifer was made using 24 borehole records and high quality static penetration tests, chosen on the base of their reliability.

The aquifer is mostly made up of medium to very fine grained sand (1-4 φ) with the medium-fine fraction well represented in proximity to the coast and a fine-very fine fraction represented inland. The sand contains some silty and loamy levels that are more abundant in the central part of the study area.

The aquifer hydraulic conductivity has been measured from piezometric hydraulic tests using the tidal variation in sea level along the coast. We also obtained hydraulic conductivity estimates by using borehole lithologic records and static penetration tests and assigning to every granulometric class the relative average hydraulic conductivity value. The local horizontal and vertical hydraulic conductivity values have been interpolated in order to create maps of the distribution of these parameters. The horizontal hydraulic conductivity is usually one order of magnitude larger than the vertical one. The maps show a core of sediments with a high hydraulic conductivity both in the vertical and horizontal directions that is located in the central part of the study area between highway 16 and the railroad. The values tend to decrease seawards. The effective porosity of the aquifer is 0.15; while the transmissivity medium values is 3.9×10^{-5} (m^2/s).

We also constructed maps of water table depth and aquifer surface and deep salinity. The piezometric level maps show that water table is usually located a few centimetres below the mean sea level. The only areas where water table is above sea level are placed along the coastline and the canals. Most of the aquifer, therefore, does not have a hydraulic head able to stop the marine saltwater intrusion. As a result, most of the aquifer is salty; fresh water is present only in the form of bubbles floating over the salt water along the coastline and the drainage canals.

KEY WORDS: Phreatic Aquifer, Coast, Petrophysics, Salt-Water Intrusion.

RIASSUNTO - Il territorio di Cervia rappresenta una zona di piana costiera ed è caratterizzato da un forte tasso di subsidenza, attribuibile alle spesso incontrollate estrazioni di gas e acque sotterranee profonde e freatiche. La crescente urbanizzazione dell'area, esplosa negli anni '50, ha portato ad un territorio urbano che occupa il 50% dell'area costiera. Oggi tale urbanizzazione è ancora spinta dall'attività turistico - alberghiera.

L'acquifero si sviluppa sul cordone litoraneo sabbioso deposto durante la trasgressione marina avvenuta 5.000-6.000 anni fa: la massima trasgressione raggiunse posizioni distanti dall'attuale linea di costa da 2 km a 1 km, procedendo da nord a sud. A monte di questa, si formò l'area lagunare su cui poi furono costruite le Saline di Cervia.

La ricostruzione della lito-stratigrafia dell'acquifero freatico è stata effettuata utilizzando 24 sondaggi geognostici e prove penetrometriche statiche scelte sulla base della loro attendibilità. Le descrizioni litologiche sono state normalizzate utilizzando la scala granulometrica di Udden - Wenthworth.

L'acquifero è costituito prevalentemente da sabbie da medie a molto fini (1-4 φ), con la componente media nella zona più prossima a costa e la componente fine prevalente-

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mente nella zona retrostante. Si tratta comunque di sabbia con presenza di livelli limosi e/o limoso-argillosi, particolarmente abbondanti nella zona centrale dell'area considerata. Per ricavare i parametri di conduttività idraulica dell'acquifero, abbiamo usato prove di pozzo basate sull'escursione di marea integrate con i dati litologici sopra menzionati attribuendo ad ogni classe granulometrica il relativo valore medio di conduttività idraulica; sono stati poi calcolati i valori medi puntuali su ogni singola colonna, successivamente interpolati per creare mappe di distribuzione della conduttività idraulica orizzontale e verticale. Le mappe evidenziano un valore di conduttività idraulica orizzontale generalmente maggiore di un ordine di grandezza rispetto a quella verticale, con un nucleo di materiale a più elevata conduttività idraulica (orizzontale e verticale) nell'area centrale. I valori tendono poi a diminuire gradatamente verso mare. La porosità efficace media dell'acquifero è di 0.15, mentre la trasmissività idraulica presenta un valore medio di $3.9x10^{-5}$ (m^2/s).

La ricostruzione di una banca dati relativa al periodo di monitoraggio (giugno 2003 - maggio 2004) ha permesso l'elaborazione di mappe delle isofreatiche, della salinità superficiale e profonda. Le mappe hanno evidenziato che le quote freatiche sono raramente e di pochi cm sopra il livello del mare, se non lungo la linea di costa, nelle zone dunari e in altre zone circoscritte e solo durante i mesi invernali, caratterizzati da una maggior ricarica. Ne deriva quindi che, per la legge di Ghyben-Herzberg, l'acquifero non presenta un carico idraulico in grado di ostacolare l'entrata diretta dell'acqua di mare al fondo. Esso si presenta per lo più salato, con nuclei di acqua dolce superficiali e confinati, localizzati lungo la fascia costiera e in adiacenza ai canali di scolo, che determinano ricarica di acqua dolce durante i mesi più piovosi, mentre nei periodi di maggior siccità, a causa della risalita di acqua salata dal mare, determinano intrusione di acqua salata.

PAROLE CHIAVE: Acquifero freatico, Costa, Petrofisica, Cuneo salino.

1. - INTRODUCTION

The characterization of the coastal phreatic aquifer in the Cervia area has been carried out as part of a study concerned with saltwater intrusion along the coast (ULAZZI, 2004).

Coastal aquifers represent a precious water resource especially in densely populated areas such as California, Florida, Hawaii, The Netherlands, Thailand and the northern Adriatic Italian coast (BEAR *et alii*, 1999; SEGOL & PINDER, 1976; SONENSHEIN, 1995; SOUZA & VOSS, 1987). These aquifers are sensitive to changes in coast morphology. Coast morphology is related to the natural evolution of the shore environment, which is in a state of continuous change (CARTER, 1988), and to the human intervention on the territory and on land use.

The reason for this high vulnerability stems from the process of saltwater intrusion, which results from the ingression of a high-density saltwater wedge underneath lower density freshwater with an inland origin. A diminished freshwater hydraulic head or gradient, due to natural processes or human activities, causes the saltwater intrusion.

The relationship controlling saltwater intrusion is the well-known Ghyben-Herzberg (1889-1901) relationship (FETTER, 2001).

2. - STUDY AREA

The study area includes the coastal phreatic aquifer of the Cervia area (fig. 1); the zone investigated has an extension of 20 km^2.

The territory of Cervia is located in a flat coastal plain and is characterized by a strong subsidence rate (0.42 meters in the period 1950-2004). The subsidence is caused by uncontrolled extraction of gas and groundwater (504 active wells, 232 of which along the coast line). Groundwater winning was particularly intense before 1950, when the city water supply system was not connected to the Romagna Aqueduct.

Starting from the 1950's, the coastal area underwent an intensive urban development that brought to 50% urbanization of the territory (fig. 1). The remaining land consists of farmland and pinewoods. The pinewoods are located in protected areas belonging to the Regional Park of the Po delta.

A dense network of land reclamation drainage canals connected to water scooping machines characterizes the territory. The most important drainage canals are the *Scolo Cupa* and the *Canale Mesola di Montaletto* (fig. 1).

The roman age Cervia's saltworks are located 1.5 km inland (fig. 1): the *Canale del Pino* brings marine water to the saltworks. The city harbour canal and the *Canale del Pino* favour surface saltwater intrusion inland.

3. - GEOMORPHOLOGY

During the last glacial period (75.000-15.000 years ago), the Cervia territory was located within a large alluvial plain made up by marshes and swampy areas extending all along the North Adriatic Sea. The following Holocenic or Flandrian transgression (started about 15.000 years ago), brought back the seawater into the North Adriatic Sea and drowned the continental deposits. The maximum marine transgression (5.000-6.000 years ago during the post-glacial optimum) extended beyond the present coastline (BONDESAN *et alii*, 1978).

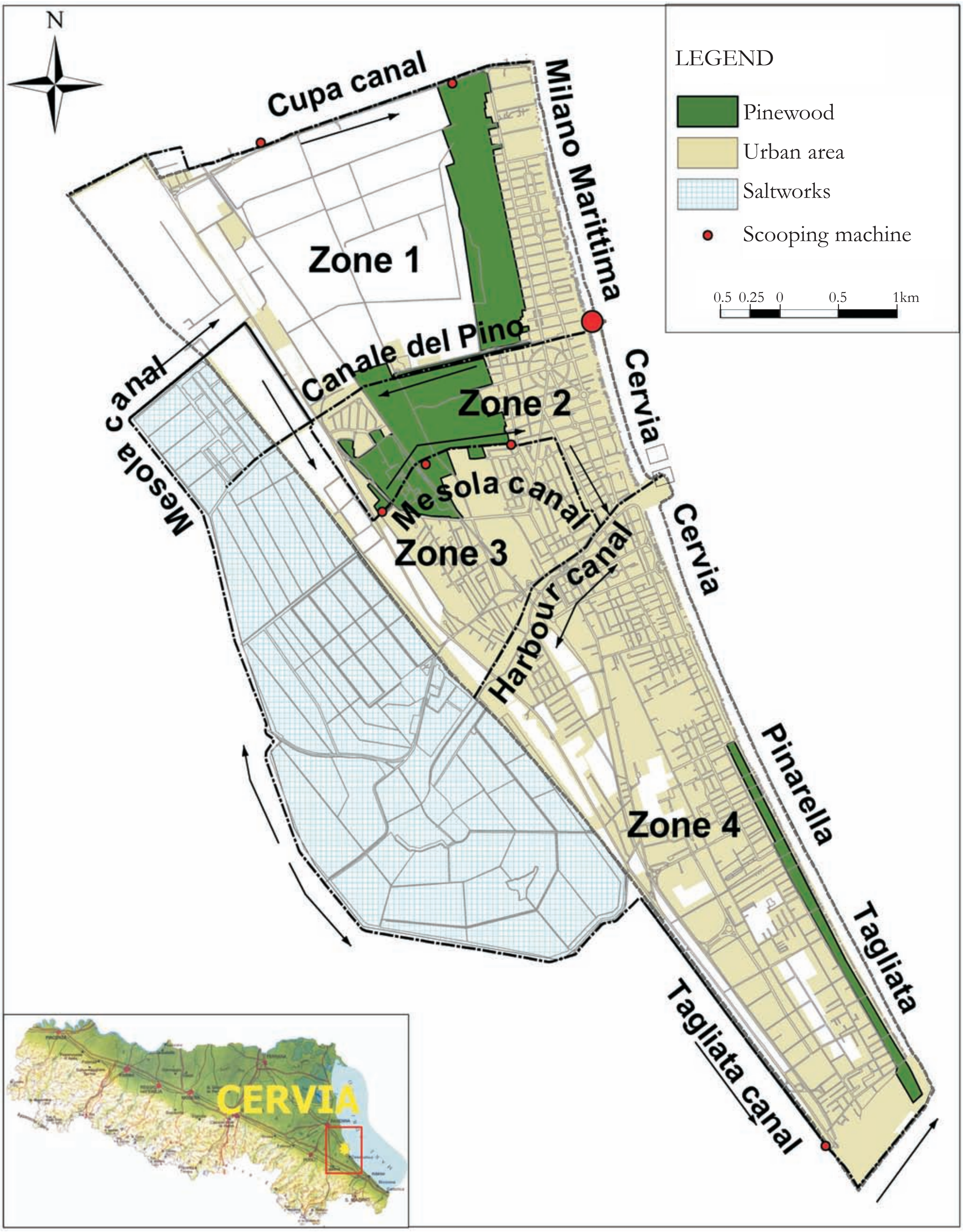

Fig. 1 - Study area.
- *Area di studio.*

During the last 2.000 years, there have been positive/negative sea level fluctuations that combined with local subsidence and tectonic upward movements have brought to local beach progradation and erosional retreat. Beach progradation formed sandy dunes, whereas erosion formed swampy lagoons.

The predominant progradational trend led to the formation of a series of coastal sandy bodies composed by dunes and sandy beaches with intervening marshes and lagoons where peaty silts and clays have been deposited (BONDESAN *et alii*, 1978).

Three morphologic units are recognizable in the Cervia area (fig. 2). The Savio river alluvial plain represents the first unit.

The second unit is characterized by depressions of an ancient lagoon, formed during the last marine transgression. The lagoon formed as a result of compaction driven subsidence of delta sediments (CASTIGLIONI *et alii*, 1990). At present time, the lagoon area has been in part land reclaimed and for the rest is occupied by the Cervia saltworks (VEGGIANI, 1971) and, southward, by the marshes of *Valle Felici*.

The third unit includes the coastal sandy prism

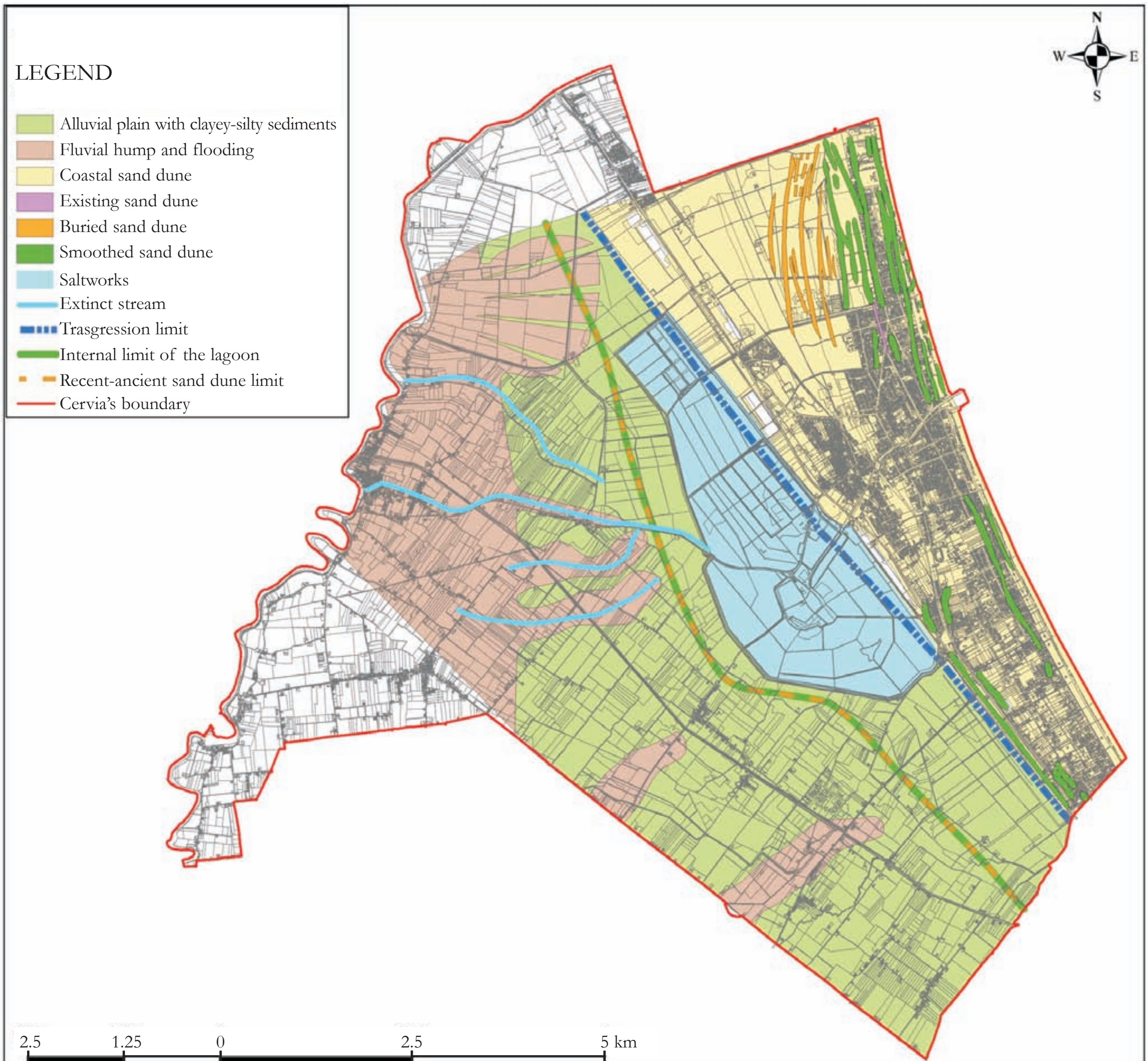

Fig. 2 - Geomorphologic map of the Cervia area (modified from SANTINI, 1992).
- *Carta geomorfologica della zona di Cervia (da SANTINI, 1992, modificata).*

(the phreatic coastal aquifer), placed between the lagoon zone and the shoreline. The sand prism is formed by a series of adjacent sand bodies deposited at various positions of the coastline during the regression period. Regression that started approximately 2.000 years ago. It has a triangular shape in cross section and trapezoid in map view. The width ranges from 4 km in the north to 1 km in the south. The sand prism thickness varies from 18 m in the north to 9 m in the south (SANTINI, 1992). The sand body is bound to the west by the clay of the lower confining layer reaching the surface.

Sub-parallel zones of different topographic elevation are recognizable in this third unit. The easternmost part of the study area includes recent dunes. These can be observed in their pristine state only in the *Milano Marittima* and *Pinarella* pinewoods, because of the strong urbanization that almost completely destroyed their original shapes. The sand beach belongs to the geomorphic third unit. The beach is approximately 100 m wide and edges entirely the eastern border of the study area.

Sand and gravel quarries are located within the inner part of the third unit (VEGGIANI, 1960). The sand and gravel deposits represent southern fluvial sediments formed during the maximum of the marine transgression (ELMI, 1991) due to N-NW oriented along-shore currents.

4. - LITHOSTRATIGRAPHY

We reconstructed the lithostratigraphy of the phreatic aquifer in a way to define the shape and depth of the lower confining layer, as well as to characterize its petrophysical parameters (hydraulic conductivity, permeability, porosity). We studied the lithologic sequence using 24 borehole records and some selected (based on reliability and calibration) high quality static penetration tests.

The lithology reconstruction is restricted to a limited area (see zones 2 and 3 in fig. 1), because of the non-uniform spatial distribution of the borehole data. Given the homogeneous depositional environment in the area and the straightness of the shoreline, we extend the lithology interpretation to zones adjacent to the one with borehole control.

We chose the Udden-Wentworth granulometric scale to make uniform the lithologic descriptions. Figure 3 shows the typical borehole litostratigraphy for the area. Plotting and data representations have been performed using the Rockworks™ software and a Geographic Information system. The software used allows creating a fence diagram that gives a three-dimensional visualization of aquifer litostratigraphy (fig. 4).

The aquifer is made up of medium to very fine grained sand (1-4 phi) with the medium-fine fraction well represented close to coast and the fine-very fine fraction present inland. The sand contains some silty and loamy levels more abundant in the central part of the study area (fig. 4). It is therefore apparent, that the E layer of the aquifer can be considered a rather heterogenous porous media.

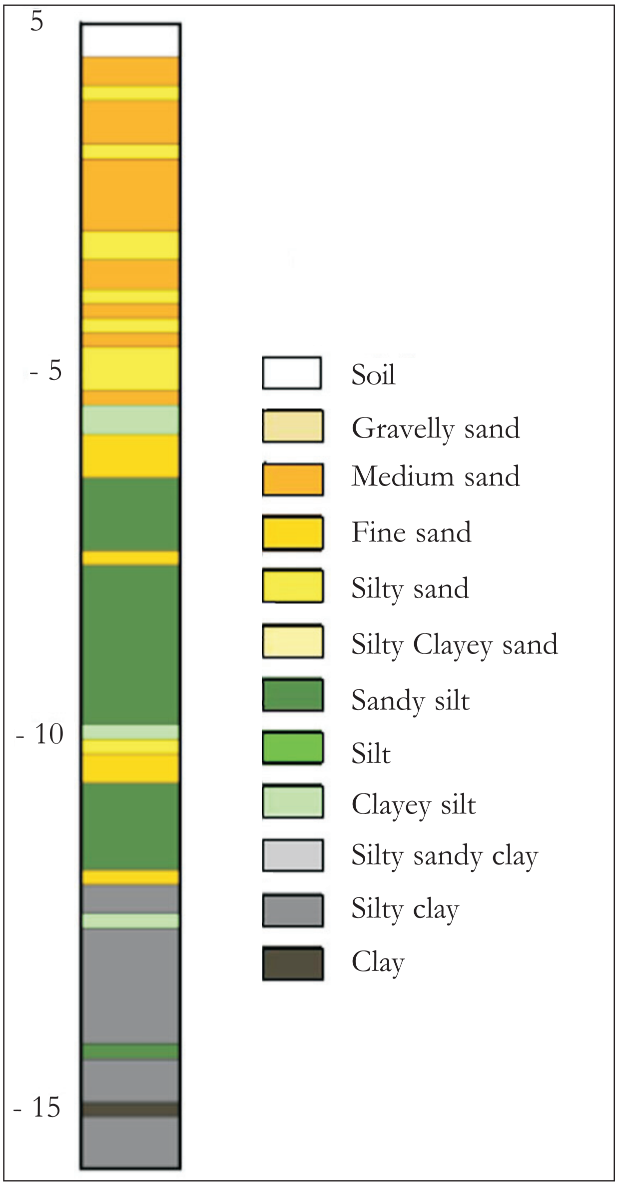

Fig. 3 - Typical borehole litostratigraphy of the area.
- *Tipico profilo litostratigrafico per la zona di studio.*

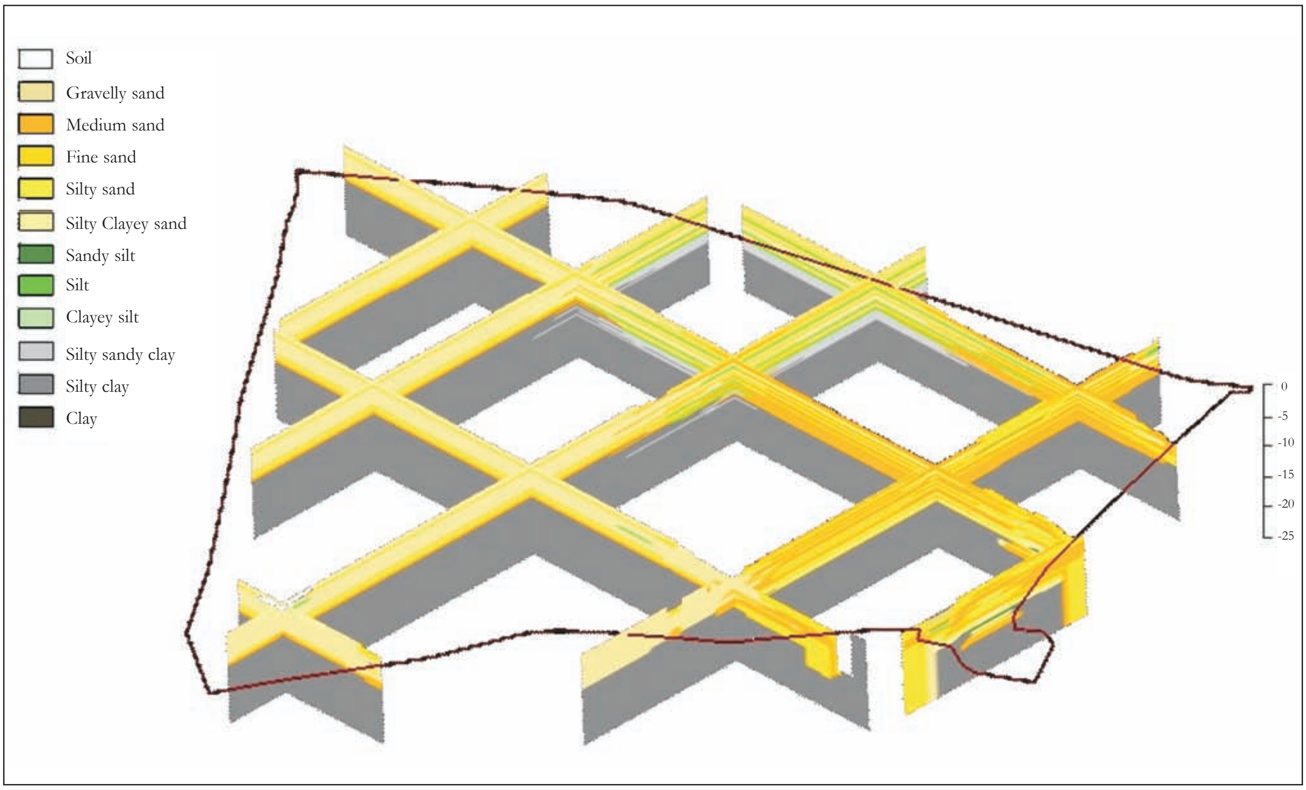

Fig. 4 - 3-D fence diagram of the lithostratigraphic sequence in the phreatic aquifer.
- Diagramma 3-D a steccato rappresentante la sequenza litostratigrafica dell'acquifero freatico.

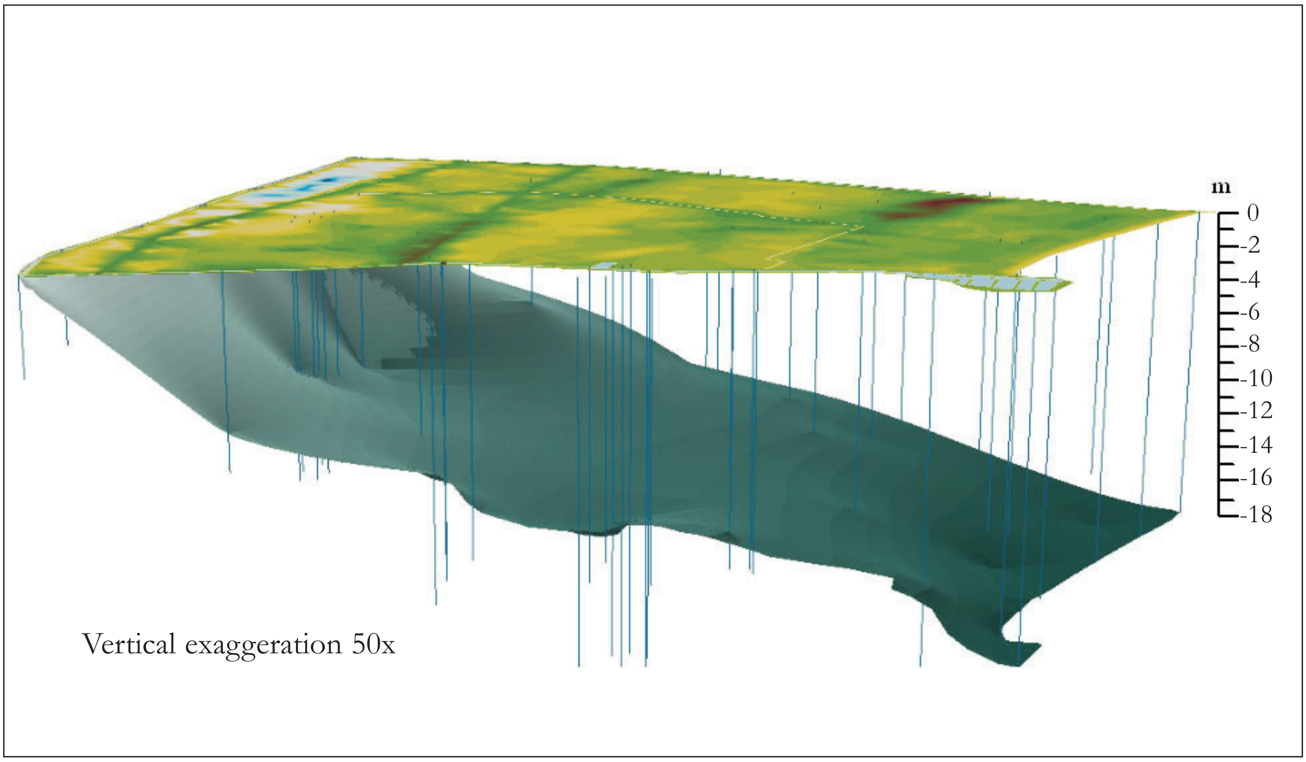

Fig. 5 - 3-D shape of the lower clayey confining layer of the aquifer.
- Forma in 3D dello strato argilloso alla base dell'acquifero confinato.

The lower confining layer of the aquifer is a consolidated clay layer (fig. 5): its depth increases in an E-W direction, from -18 m m.s.l. near the coastline to 0 m m.s.l. in proximity to the maximum marine ingression line. The clay-confining layer deepens in the N-NW direction, as observed also by other authors (VEGGIANI, 1960; BONDESAN *et alii*, 1978; ELMI, 1991).

5. - PETROPHYSICAL DATA

The major difficulty we encountered in petrophysical properties characterization has been the lack of well tests. We solved this problem by making tidal well tests on piezometers close to the shoreline. The method we used is the one described by FETTER (2001), and by JACOB (1950), which is valid for a confined aquifer but can be extended as a valid approximation to unconfined aquifers, if the range of tidal fluctuations is small compared with the thickness of the saturated aquifer. In our case, the thickness of the aquifer is 18 m and the range in tidal fluctuations is less than 0.8 m. For this reason, we think that the method of the tidal well tests is a valid approximation also in our case.

The governing mono-dimensional flow equation can be used to describe the flow of water into and out of the aquifer as the tide changes. If *Ho* is the amplitude of the tidal change and *to* is the tidal period, at any distance *x*, inland from the coast, the amplitude of the tidal fluctuations *Hx* is given by (JACOB, 1950):

$$H_x = H_0 \exp(-x\sqrt{\pi S_y / t_0 T}) \qquad (1)$$

where *Sy* and *T* are the aquifer gravific water and transmissivity. The time lag, t_τ, between the high tide and the peak of the water level (or low tide and the low point in the water level) is given by

$$t_\tau = x\sqrt{t_0 S_y / 4\pi T} \qquad (2)$$

rearranging the formula above by knowing the saturated aquifer thickness, *b*, we can compute the hydraulic conductivity, *K*,

$$K = \left(\frac{x}{t_\tau}\right)^2 \frac{t_0 S_y}{4\pi b} \qquad (3)$$

The variation of water level in a piezometer located 40 m from the shoreline is given in figure 6,

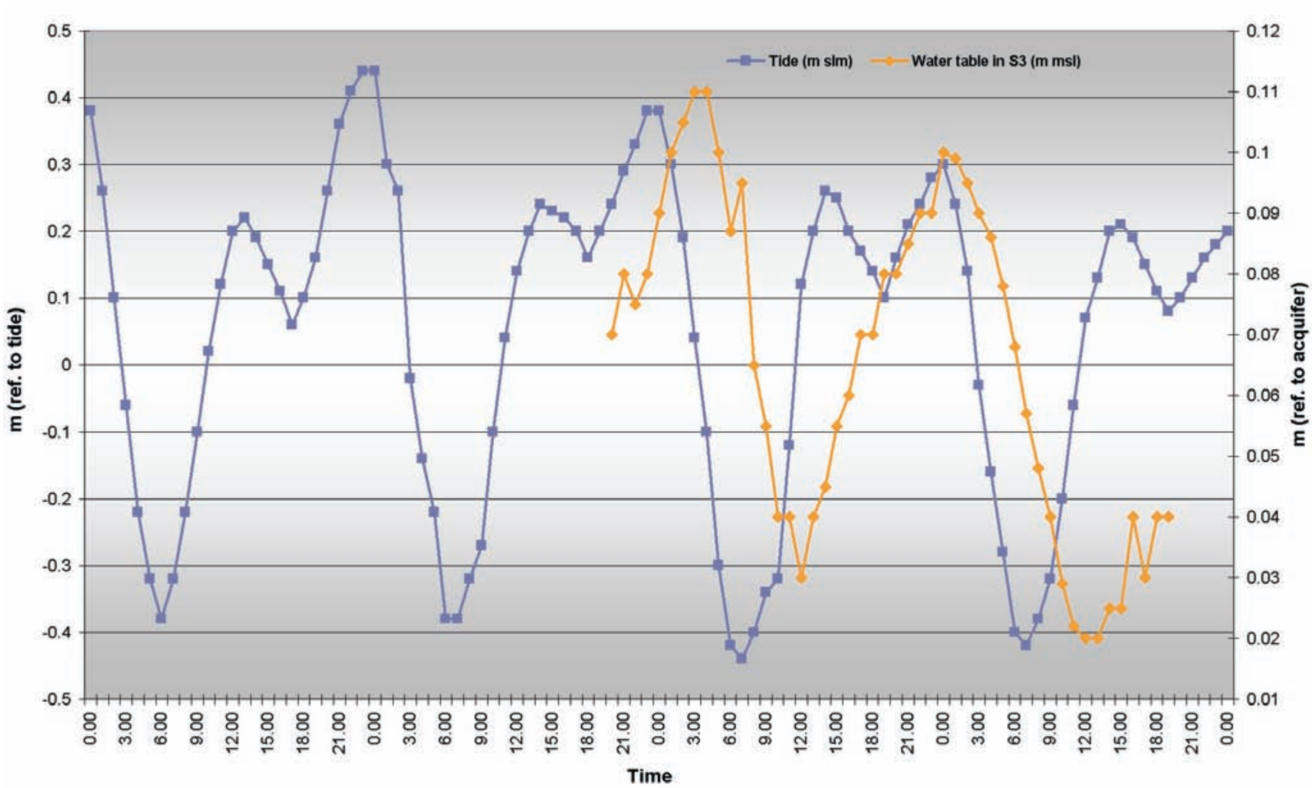

Fig. 6 - Sea tide excursion and variation of water level in a piezometer located 40 m from the shoreline.
- Escursione mareale e variazione della tavola d'acqua in un piezometro a 40 m dalla linea di riva.

where we can also measure the lag time t_T. Table 1 summarizes some of the hydraulic conductivity values that we obtained.

Tab. 1 - *Summary of hydraulic conductivity values obtained.*
- Riassunto dei valori di conduttività idraulica ottenuti.

x (m)	to (h)	t (h)	Sy	b (m)	K (cm/s)
40	16	5	0,2	18	2.4×10^{-2}
40	15	5	0,18	18	2.1×10^{-2}
40	13	6	0,18	18	1.3×10^{-2}

Obviously, these figures represent values for hydraulic conductivity averaged at the scale of tens of meters, which is the scale of the experiment performed, and, therefore, represent the behaviour of the aquifer as a whole in the belt close to the shoreline. These values have been compared and integrated with estimates obtained via empirical formulas (FETTER, 2001) and the lithologic descriptions from the boreholes.

The 12 lithologic classes (fig. 3) observed in the borehole data have been compacted to 5 granulometric classes. For each granulometric class we assigned the relative medium hydraulic conductivity value by using the formula of Hazen as reported in FETTER (2001). The local (at a borehole) average values of horizontal (4) and vertical hydraulic conductivity (5) and of trasmissivity (6) have been calculated using the formulas below:

$$K_h avg = \sum_{m=1}^{n} \frac{K_m b_m}{b} \qquad (4)$$

$$K_v avg = \frac{b}{\sum_{m=1}^{n} \frac{b_m}{K_m}} \qquad (5)$$

$$T = bK \qquad (6)$$

where:
$K_h avg$ = medium horizontal hydraulic conductivity (m/s);
$K_v avg$ = medium vertical hydraulic conductivity (m/s);
K_m = m-level hydraulic conductivity (m/s);
K = medium hydraulic conductivity (m/s);
b_m = m-level thickness (m);
b = aquifer thickness (no clay) (m).
T = transmissivity (m^2/s);

The average values obtained at any borehole have then been interpolated to create maps of the hydraulic conductivity distribution (horizontal and vertical) in the aquifer.

The horizontal hydraulic conductivity is usually one order of magnitude larger than the vertical one. The spatial variability of the hydraulic conductivity is reported in fig. 7: the maps show a core of sediments with an high hydraulic conductivity, both in the vertical and horizontal directions, located in the central part of the study area. The values tend to decrease seawards.

Some estimates of effective porosity for the different lithologic levels in the aquifer have been made making use of data present in the literature. In particular, the values have been extrapolated from the calibration of log-based permeability with core data for the Lower Hibernia Formation publication (WATSON *et alii*, 2000), obtaining an effective porosity value for each lithology-K class considered.

The average effective porosity of the aquifer is about 0.15, whereas the transmissivity has an average value of 3.92 $\times 10^{-5}$ (m^2/s) (tab. 2).

Tab. 2 - *Summary of the aquifer hydraulic characteristics.*
- Riassunto delle caratteristiche idrauliche dell'acquifero.

$K_{h\ Average}$	2.2 E-4 (cm/s)
$K_{v\ Average}$	4.6 E-5 (cm/s)
$k_{ih\ Average}$	2.5 E-9 (cm^2)
$k_{iv\ Average}$	5.3 E-10 (cm^2)
Effective Porosity n_e	0.15
Average Trasmissivity	3.9 E-5 (m^2/s)
S_v	0.15

6. - FIELD MONITORING

A field monitoring campaign aimed to assess the seasonal variability of saltwater intrusion in the phreatic aquifer has taken place from June 2003 to May 2004. The monitoring has been performed on a total of 187 stations (piezometers and canals) and included water table depth, temperature, and electric conductivity. Electric conductivity was converted in salinity values using Lewis e Perkins (1981) equation (UNESCO, 1983).

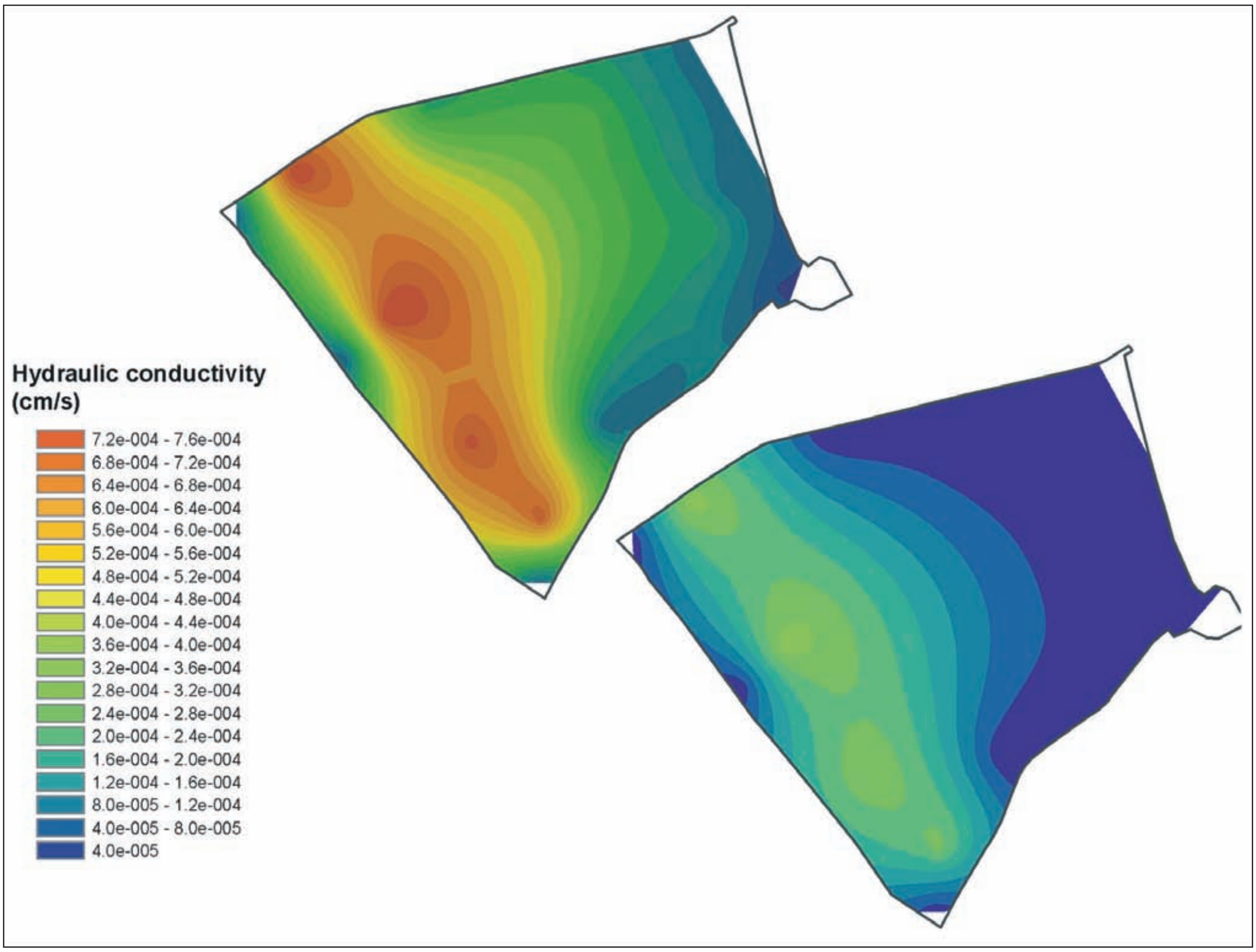

Fig. 7 - Map of hydraulic conductivity: horizontal (above) and vertical (below).
- Carta rappresentante la conduttività idraulica media orizzontale (sopra) e verticale (sotto).

We implemented the data collected in a GIS system (Geographic Information System) using ArcGis 8.2. Using this database, we produced water table maps for zones 2 and 3 (see fig. 1). The seasonal piezometric maps (fig. 8) evidence a water table depth located a few centimeters below mean sea level. The few areas above sea level are located along the coastline and the canals (*Canale del Pino*, harbour canal and *Canale Mesola di Montaletto*). The canals, in fact, are often recharging the phreatic aquifer. The water table depth fluctuates seasonally with an average range of 0.9 m. The maximum-recorded value of 0.82 m (m.s.l.) in winter time and the minimum recorded value in summer time of -1.06 m (m.s.l.). During the fall-winter period the water table depth tends to stay above the mean sea level, thanks to the large precipitations and high water levels in the drainage canals.

On the basis of the water table maps just discussed, it is apparent that most of the aquifer does not have a hydraulic head able to stop the saltwater intrusion at its base. The saltwater - fresh water interface does not reach the bottom of the confining layer and it does not prevent saltwater ingression from the sea, if not in the winter period and in proximity to the drainage canals.

The surface salinity maps (fig. 9) show that the harbour canal and the *Canale del Pino*, as well as the sea outlets of the drainage canals, cause surface saltwater intrusion: the salinity value is about 30-34 g/l (same as the sea value) in the aquifer up to a distance of 250 m normal to the channel axes and inland from the sea up to 2 km. The salinity is also high in proximity to the pinewoods and to the water scooping machines, as a consequence of the saltwater up-coning caused by the pinewoods evapotranspiration and the waterwork systems drainage (Ghyben-Herzberg law). The salinity value is smaller than 2-3 g/l along the coastline.

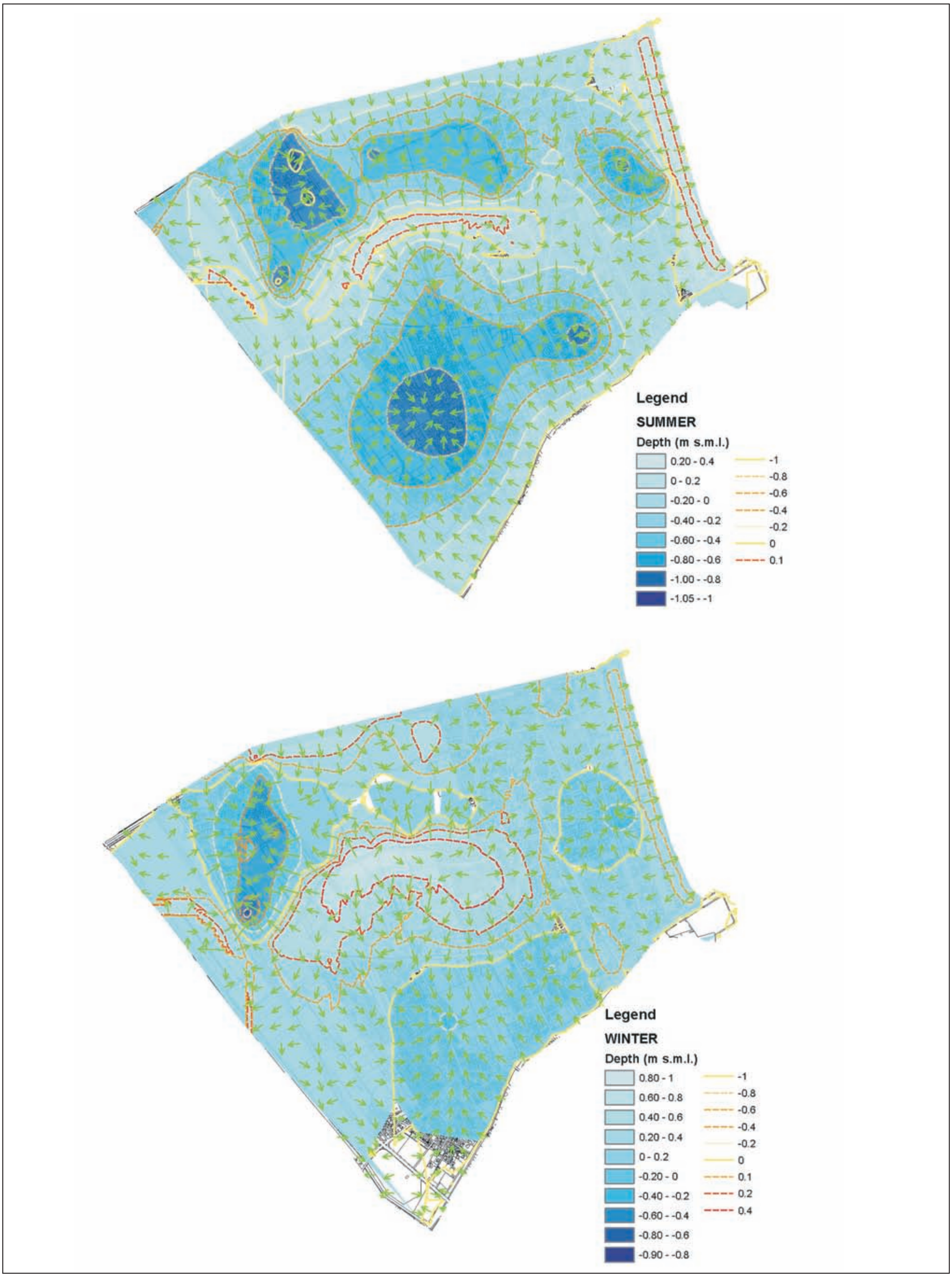

Fig. 8 - Maps of water table depth for the summer and winter periods.
- Carte di profondità della freatica per i periodi invernale ed estivo.

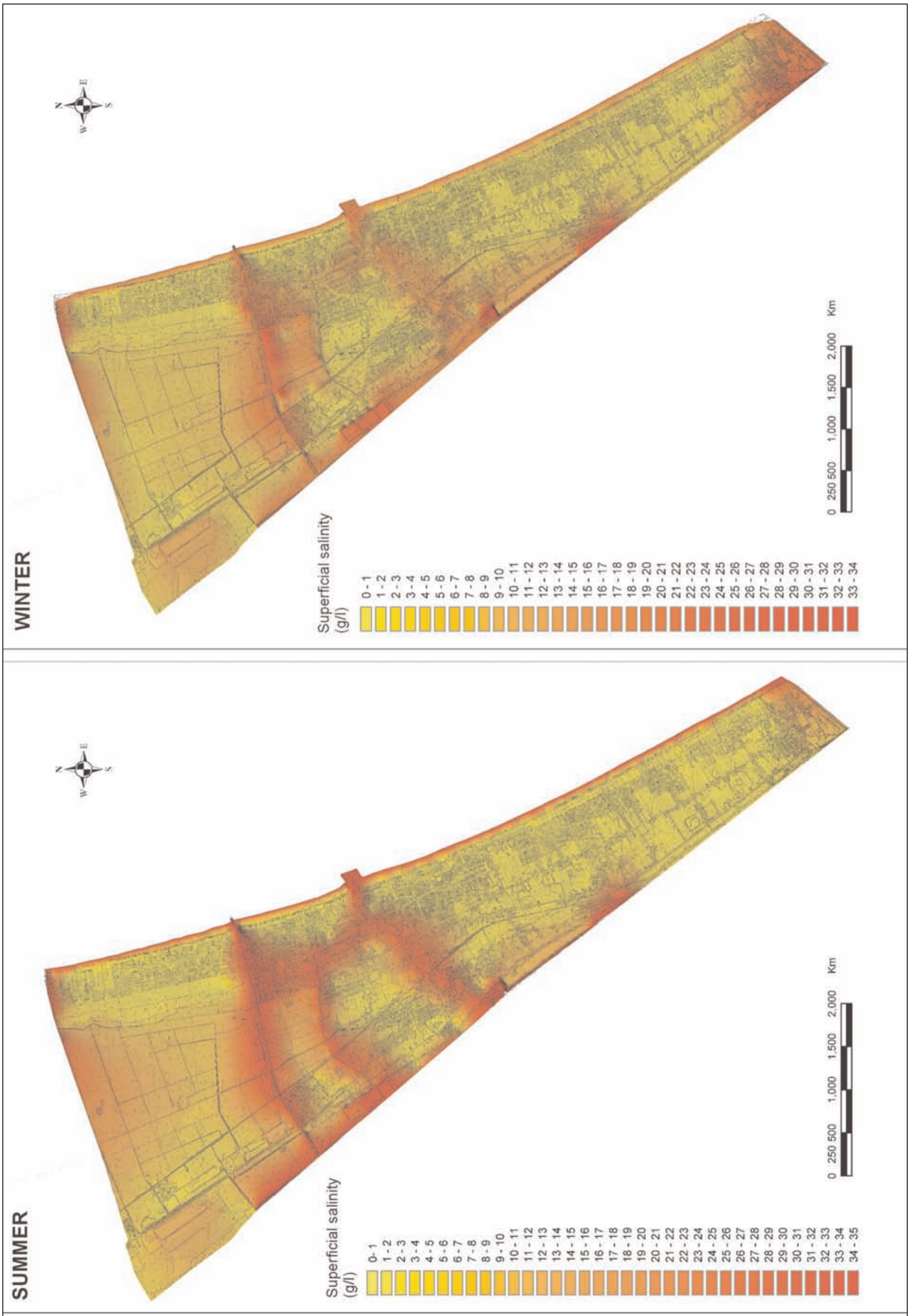

Fig. 9 - Seasonal variation in surface salinity distribution.
- *Variazione stagionale nella distribuzione della salinità superficiale di falda.*

The maps also show the influence of the *Canale Mesola di Montaletto* on the seasonal salinity values: during the fall-winter period, characterized by large precipitations, it recharges the aquifer with fresh water, whereas during the summer period it recharges the aquifer with saltwater.

From the analysis of all maps produced, it is therefore apparent that the phreatic coastal aquifer of *Cervia* is reduced to a few fresh water bubbles floating over the marine saltwater. The thickness of such bubbles changes seasonally as a function of the precipitations and/or of fresh water recharge from the canals.

7. - CONCLUSION

The saltwater intrusion study that we performed, points out the need for an accurate characterization of the aquifer porous media and its petrophysical properties. The hydraulic properties of the aquifer, in fact, control the extent of saltwater intrusion. As it is apparent from the comparison of salinity distribution maps and the lithologic maps of the aquifer, high porosity and hydraulic conductivity sediment bodies promote saltwater intrusion, whereas low porosity and low hydraulic conductivity sediments prevent saltwater intrusion. This is of paramount importance to understand the aquifer's flow dynamic in the different seasons and the causes (subsidence, well pumping, land reclamation, etc.), that brought it to the present disturbed state. In particular the aquifer characterization with the tidal well tests has shown that the sandy layers close to the surface have a very high hydraulic conductivity in the order of $1.2\text{-}3.4\text{x}10^{-2}$ cm/s and they are the most vulnerable to saltwater intrusion. The finer levels in the aquifer contribute to reduce the overall aquifer hydraulic conductivity in the vertical direction by about one order of magnitude, whereas they have not much effect on the aquifer's horizontal permeability.

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