# Portrait of a Coastal Karst Aquifer: the City of Bari

**Vincenzo Cotecchia, Massimiliano Scuro**

**Abstract:** The region of Puglia in southeast Italy is noted for its extensive groundwater circulation which, at the very least, runs from the River Ofanto in the north to the southernmost end of the Salento Peninsula in the region's Mesozoic carbonatic platform. The latter contains in the subsoil the region's most important water resources. In particular, the so-called "deep karst aquifer" flows seaward almost everywhere, reaching the Adriatic in the northeast and the Ionian Sea in the southwest. Given the high permeability of the rocks comprising the aquifer, almost everywhere there is salt water intrusion. The groundwater thus floats on marine water intrusion until it reaches the sea. Starting from the results obtained following an intensive campaign of hydrogeological surveys carried out to design and construct some major underground works in the city of Bari, this paper focuses on the hydraulic characterisation of the carbonatic aquifer along the coast, whose considerable permeability due to the aquifer's tectonic fracturing and karstification, is circumstance characterising large areas of the whole Puglia. Thus the hydro-dynamic behaviour of the aquifer is analysed. In particular, we explore the difficult equilibrium between the freshwater aquifer and the underlying saltwater intrusion, in an area of particular interest, especially due to the very gentle hydraulic gradient along which the freshwater reaches its coastal outlet.

**Keywords:** coastal aquifer, sea water intrusion, porous media equivalent, transition zone, karst idrogeology

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**Riassunto:** *La regione Puglia è caratterizzata dalla presenza di una circolazione idrica sotterranea, che, quantomeno dal F. Ofanto a Nord all'estremità meridionale della Penisola Salentina, con continuità interessa la piattaforma carbonatica mesozoica della regione. Così estesa, quest'ultima contiene nel sottosuolo la più importante risorsa idrica regionale. In particolare la cosiddetta "falda profonda carsica" defluisce quasi ovunque verso il mare, trovando da ambo i lati -a Nord-Est e a sud-Ovest- nel Mare Adriatico e nel Mare Ionio, il suo recapito finale. Il riversamento a mare avviene ove con continuità, lungo il perimetro costiero di questa terra per gran parte peninsulare, ove con versamenti concentrati in sorgenti costiere, assecondando modalità idrogeologiche che sono funzione delle locali caratteristiche geostrutturali dell'acquifero. Stante la elevata permeabilità pressochè generalizzata delle rocce costituenti detto acquifero, l'acqua di mare risulta quasi ovunque intrusa nel continente, andando a costituire il livello di base dell'acqua dolce; le acque di falda galleggiano quindi sull'acqua di intrusione marina, fino al recapito finale a mare.*

*La presente nota, partendo dai risultati conseguiti a seguito di una vasta e densa campagna di indagini idrogeologiche eseguite per la progettazione e costruzione di alcune importanti opere sotterranee nella città di Bari, si sofferma particolarmente sulla caratterizzazione idraulica dell'acquifero carbonatico lungo costa, la cui notevole permeabilità per fratturazione tettonica e carsismo insita nell'acquifero, sono circostanze caratterizzanti estese aree dell'intera Regione. Cosicchè viene analizzato il comportamento idrodinamico della falda idrica e, in particolare, il difficile equilibrio che regge i rapporti fra la falda di acqua dolce e l'acqua di intrusione marina sottostante, in un'area che mostra a tal riguardo singolare interesse, soprattutto in ragione della ridottissima cadente piezometrica con la quale l'acqua dolce si dirige verso il recapito marino costiero.*

*La ricostruzione della superficie piezometrica della falda, la determinazione dell'andamento nello spazio delle caratteristiche chimico-fisiche delle acque di falda, funzione del rapporto fra l'acqua dolce e l'intrusione marina, e la ricostruzione dello stato di fratturazione della roccia, cui conseguono le circostanze predette, hanno consentito di verificare la possibilità di assimilare l'acquifero carbonatico in argomento, permeabile per fratturazione e carsismo, ad un mezzo poroso equivalente agevolando la interpretazione su base quantitativa del comportamento idrodinamico della falda e, in particolare, gli stretti legami esistenti tra le oscillazioni del livello mare e le variazioni dei livelli di falda nel continente.*

*Attraverso lo studio della propagazione delle onde di marea sui livelli di falda è stato possibile, in particolare, stimare il coefficiente di permeabilità medio afferente a diverse porzioni dell'acquifero.*

*L'esecuzione di misure di velocità di filtrazione nel corpo della falda idrica hanno infine consentito di determinare le singolari condizioni di moto afferenti alla zona di transizione individuata fra la falda di acqua dolce e la sottostante acqua marina di base.*

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## Introduction

The hydrogeological surveys carried out to design and construct major underground works in the city of Bari, represent an important opportunity to characterise the aquifer in the fractured, karstified Cretaceous limestone in the city's subsoil. The hydrodynamic behaviour of the water table was thus documented in detail, on the basis of input essentially derived from the density of the hydrogeological surveys conducted in situ.

Leaving aside the problems tied to the design and construction of such works in a medium with very high permeability coefficients (see Cotecchia et al., 2007; Cotecchia and Tafuni, 2007), this paper starts from the results obtained from hydrogeological surveys carried out for their design and construction, and reports the hydraulic characterisation of the permeable coastal limestone aquifer and the study of the hydrodynamic behaviour of the circulating groundwater. Special attention was paid to analysing the difficult equilibrium between the freshwater aquifer flowing with a very low hydraulic gradient towards the coast, and the underlying seawater. These surveys were conducted prior to the building of multi-storey underground car parks, namely that of Piazza Cesare Battisti in Figure 1, now nearing completion, and that of Corso Cavour, still in the design phase, both 7-10 metres below the water table.

## Geological and hydrogeological context

The geological, structural and morphological features of Puglia have led to the formation of conspicuous groundwater bodies, basically contained in mesozoic limestone successions. Indeed, Puglia is characterised by important groundwater circulation which affects the whole Mesozoic limestone platform, comprising the region's most important water resource. In particular, the so-called *deep karst aquifer* flows seaward almost everywhere. There is saline intrusion onshore, with the freshwater aquifer floating on a saline water base. The way in which the groundwater flows into the sea and the relative effects on groundwater circulation on *terra firma* vary in relation to local hydrogeological conditions.

The study area (Fig. 2) illustrates the conditions in which the aqui-

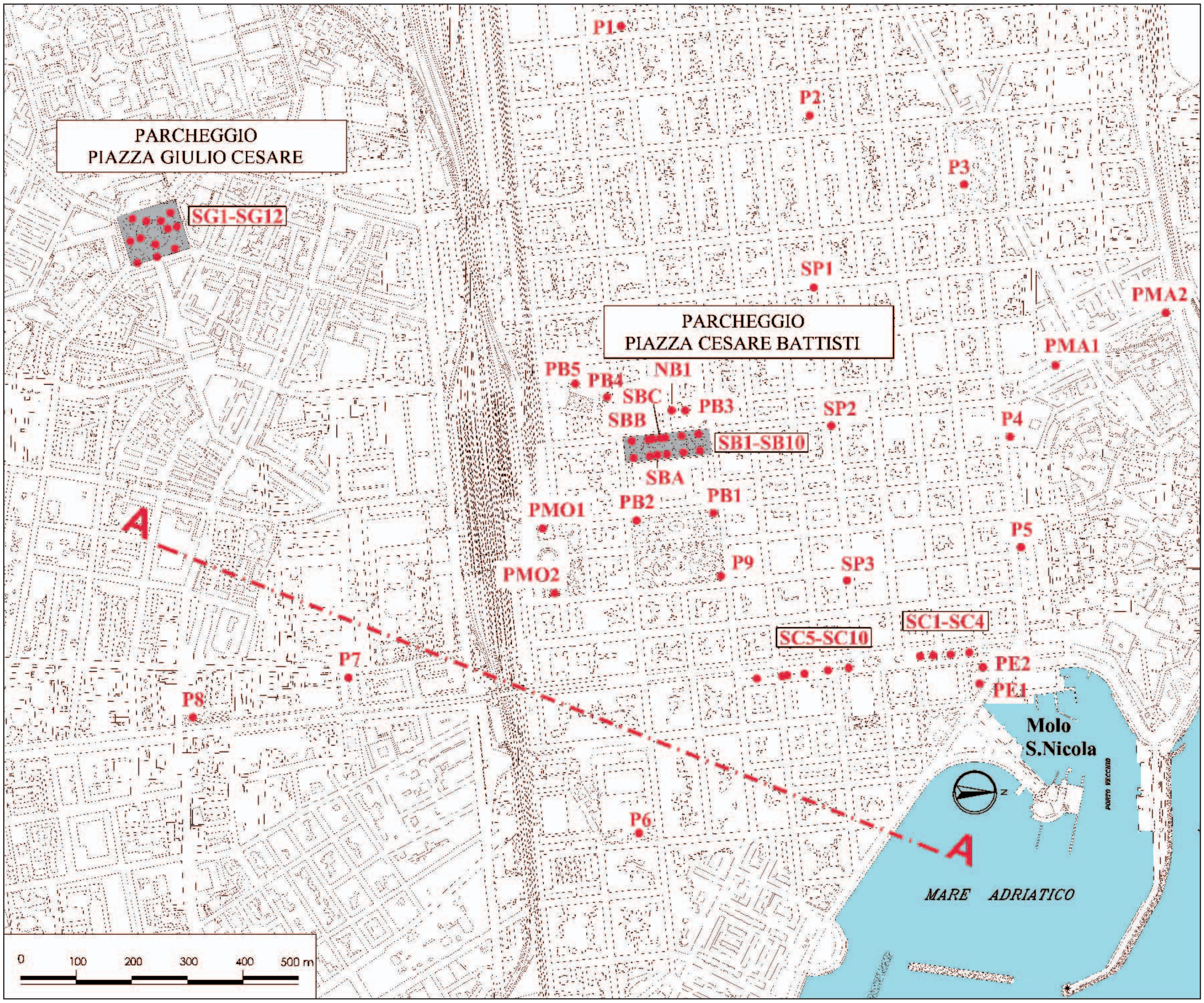

**Fig. 1:** *Map of Bari with indication of the underground parking areas and boreholes.*

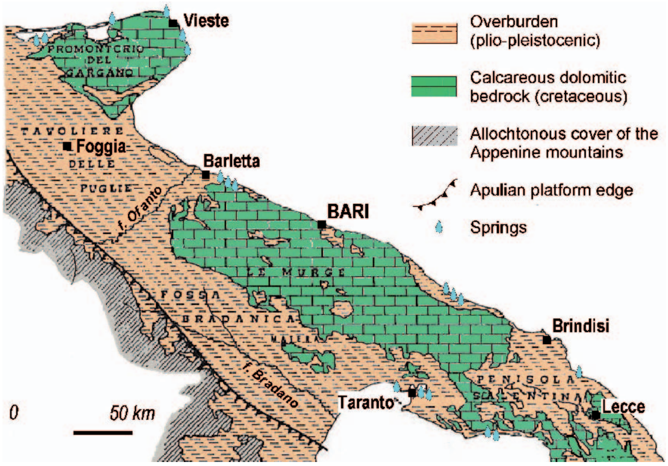

**Fig. 2:** *Simply geological scheme of Apulia Region with the indication of the area of interest.*

fer discharges its waters into the sea. The area in question lies at the foot of the Murgia plateau, where the waters of the deep karst aquifer circulating in the Cretaceous limestone formation, substantially fed at the higher altitudes of the Murgia, flow abundantly seaward, with a hydraulic gradient gradually declining towards the coastline.

The area chosen to study the hydrogeological phenomena covered in this paper is about 2 km$^2$ (Fig. 1), extending about 1.5 km along Bari's coastline, penetrating about 1.3 km inland. At a few metres of depth, Cretaceous limestone is found everywhere, known in the literature as *Calcari di Bari* (Turonian-Barremian). The carbonatic succession comprises limestones, dolomitic limestones and dolomites, which develop for thousands of metres in the subsoil with a thickness of layers varying from a few centimetres to about 70 cm (Fig. 3a) and fairly frequent subhorizontal fractures.

**Fig. 3:** *Lithologic stratigraphy referred to the Cretaceus Formation recognized during the excavation for the multilevel parking in "Cesare Battisti" square - Bari.*

The layered conditions of the carbonatic succession are indeed altered by disturbances of tectonic origin which have produced intense fracturing of the rock formation and have led to the establishment of karstification, which in general occurs with modest cavities, hollows and the presence of *terra rossa*, a particular type of clay from disturbed soils and from the evolution of the insoluble residue of the above limestones (Fig. 3b). The carbonatic formation is thus permeable due to fracturing and karstification (Grassi and Tulipano, 1983; Grassi, 1983; Cotecchia, 1977), so as to present heterogeneous and anisotropic permeability. There is continuous groundwater circulation in the subsoil and generally through intense, widespread fracturing of the rock, such as to be able to consider the aquifer, for the purposes of analysing large-scale problems, generally similar to an equivalent porous medium. From *in situ* measurements of infiltration velocities in Puglia's fractured limestones, the full validity of Darcy's Law also became evident, where there are no large, particularly karstified, preferential flow pathways (Cotecchia et al., 2007).

Due to the considerable permeability of the medium it crosses, the groundwater flows towards the coast with a fairly low hydraulic gradient, generally below 1‰, which further diminishes as it nears the coast, where the final discharge occurs dynamically and by mixing with seawater, directly dependent on the tidal excursion. This matter was illustrated in detail by Cotecchia (1977). The groundwater circulates almost everywhere in phreatic conditions, or it is held slightly under pressure by layers of compacted rock or by fairly impermeable Holocene soils.

## Hydrogeological surveys

Hydrogeological characterisation of the aquifer and the study of hydrodynamic conditions the water table were carried out on the basis of an extensive campaign of *in situ* surveys both to determine the geostructural conditions of the limestone formation, and to study the flow conditions and the physico-chemical stratification of the groundwater and the underlying transition zone between freshwater and saline water intrusion. In this paper we interpret the data obtained from 59 probes distributed in the study area (Fig. 1).

Along all the verticals, piezometric readings were made under various tidal conditions, which allowed us to determine the surface oscillations of the aquifer according to sea level oscillations. Some probes with such depths as to penetrate salt water intruding into the mainland were analysed with multiparametric Logs and dilution tests with a tracer in individual boreholes. In particular, pH, electrical conductivity, temperature, dissolved oxygen and oxidation-reduction potential were plotted against depth. These surveys were fundamental in gaining specific knowledge of the variations in the physico-chemical properties of water circulating in the city's subsoil, in relation to that of transition at the base. The dilution tests with a tracer in individual boreholes allowed us to determine the possible presence of vertical currents in the borehole, as well as the groundwater filtration velocity at various depths, until the intruding saline water layer was reached.

Of considerable importance were some hydrographic surveys conducted at various distances from the coast. Such tests consisted in determining, with a usually less than hourly frequency, the groundwater level within some piezometers and in measuring sea level, with the same frequency and in the same brief time interval, so as to study the propagation mode of tidal waves on the water

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table levels. In probe NB1 we also continuously detected electrical conductivity and groundwater temperature at various depths.

In this respect it should be pointed out that as the hydraulic gradient of the aquifer was extremely low, it was necessary to refer to a high-precision topographical survey to measure the height of all probes, insofar as errors in determining this quantity, even of the order of a centimetre, would invalidate the reconstruction of the piezometric surface. As mean sea level varies in time, all the depths, including that of sea level, refer to zero IGM, so as to allow determination of the actual hydraulic load of the water table compared with sea level in the same time interval.

## Groundwater physico-chemical properties

Determination of groundwater physico-chemical properties was fundamentally important to understand the flow of fresh groundwater and the equilibrium between the latter and the underlying saline water. The multiparametric Logs (Fig. 4b) showed the presence, in the study area, of the freshwater aquifer of thickness varying between 20-25 m. The thickness of the freshwater aquifer throughout the study area declines, albeit by only a few metres, as the coast draws near (Fig. 5) and has variable salinity due to varied mixing with sea water. In the study area, the aquifer's salinity varies with depth.

In the first 5-7 m of depth measured against the groundwater level, little salinity was found (less than 1g/l). Starting from depths of about 10m, salinity already increased significantly, reaching values around 3 g/l. At such depths where the groundwater still experiences filtration flow towards the coast (Fig. 4c-d), as shown by the filtration velocity measurements, the groundwater is greatly mixed with saline water due to hydrodynamic dispersion. Indeed, Schoeller's diagrams drawn on the basis of the results obtained by chemical analyses of groundwater and saline water samples show the sodium chloride facies of such water even at depths less than those where intrusive saline water was found (Fig. 6). The freshwater-saltwater transition occurs in a zone about 6 m thick where salinity undergoes a sharp increase (Fig.4b). Moreover, within the transition zone the groundwater filtration velocity sharply diminishes until it is zeroed in saline water (Fig. 4d). This is also confirmed by the measurement of dissolved oxygen (Fig. 4c), which drops to zero in seawater due to the absence of movement.

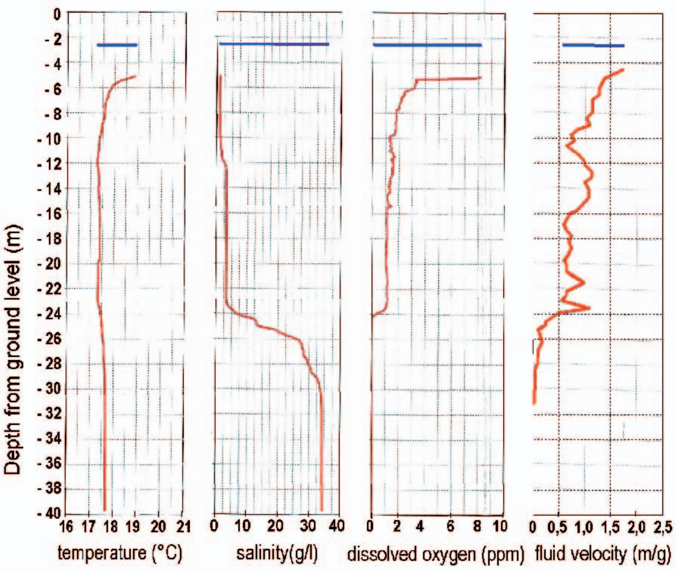

**Fig. 4:** *Multiparametric logs carried out 20/07/2005 in the borehole P9 - Umbero I square - Bari.*

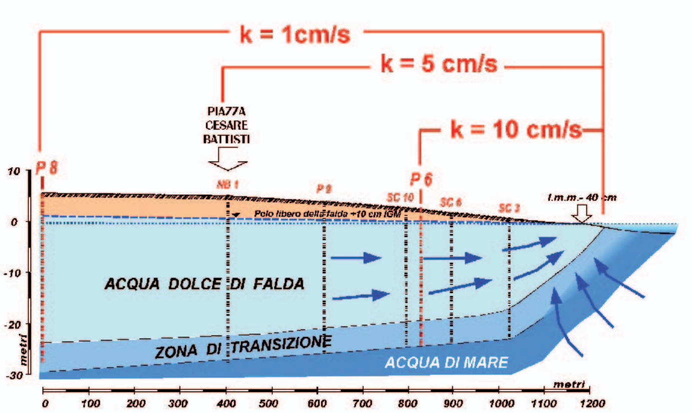

**Fig. 5:** *Hydrogeological section with indication of permeability coefficient drawn out from interpolation of data obtained from water level recorder.*

The depth at which saline water was found in the study area was significantly higher than that obtained by applying the law of Gyben–Herzberg, according to which the depth of the interface of separation between two fluids measured against the piezometric surface of the water table, determined under the hypotheses of hydrostatic equilibrium and immiscibility between the same, is equal to:

$$h = \frac{t}{1 - \frac{\gamma_d}{\gamma_s}} \qquad (1)$$

where $t$ is the piezometric head of the groundwater compared to the sea, and $\gamma_d$ and $\gamma_s$ respectively the density of freshwater from the aquifer and saline water.

The piezometric head in the study area, measured against the actual sea level, as will be illustrated in detail below, is about 10 cm in the sections closest to the coast (probe SC3 in Figures 1 and 5), and reaches peak values of 80 cm in the parts farthest from the coast (probe P8 in Figures 1 and 5). Such a piezometric head would correspond, under the Gyben-Herzberg hypothesis, and assuming $\gamma_s$ = 1030.7 g/l and as a first approximation for freshwater $\gamma_d$ = 1000 g/l, to a depth at which salt water was found of $h$ = 3.3 m in proximity to probe SC3 and $h$ = 16.5 m close to P8. As inferred from figures 4 and 5, the saline waters are actually found in the study area at appreciably greater depths than such values, even if we wish to refer to the ceiling of the transition zone. This circumstance, already evidenced close to

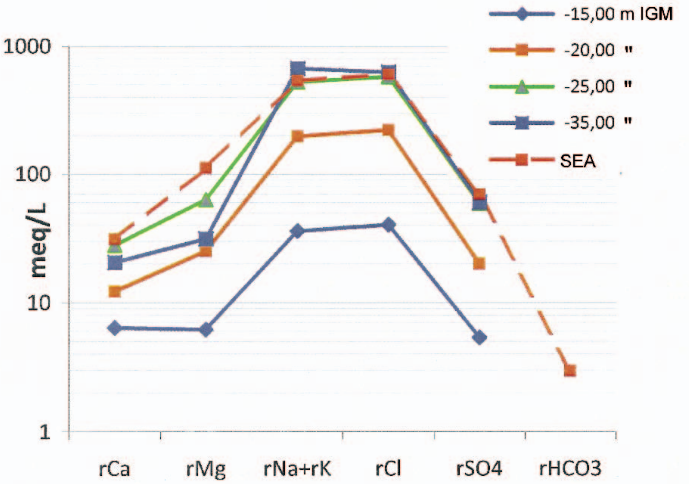

**Fig. 6:** *Comparison of the ground water chemical characteristics obtained from borehole P9 with those of seawater.*

the coast at other sites in Puglia (Cotecchia, 1977), may be attributed both to the increase in density that the groundwater undergoes with depth, which reduces the denominator of 1), and to three-dimensional effects occurring close to the coast, due to the non-negligible vertical component of filtration velocities (Bear, 1979).

Of considerable interest are also the determinations carried out with thermo–conductimetric probes placed at various depths at NB1, placed at about 700 m from the coastline (Figs. 1 and 5). The surveys enabled us to highlight the variations in salinity experienced by the groundwater caused by variations in the piezometric head of the groundwater measured with respect to the actual sea level and following climatic events.

The time course of daily average levels of groundwater and sea level measured with respect to the IGM zero are shown in figure 7, along with that of the water table level measured at sea level and electric conductivity of groundwater measured at -3.35 m IGM and the waters belonging to the transition zone measured at -20.35 m IGM. The measurements show variations in electrical conductivity measured in the transition zone, which cannot be correlated with the variations in the absolute piezometric head of the aquifer. However, if the electrical conductivity measured in the transition zone is compared with the piezometric head of the groundwater, measured with respect to the actual sea level, we may note a close correspondence between the two magnitudes: a lowering of the hydraulic head of the aquifer with respect to the sea level is matched by an increase in electrical conductivity, and vice versa. Yet if we analyse the time course of electrical conductivity measured at -3.35 m IGM, this correspondence is lost and we note instead a variation in electrical conductivity tied to weather conditions. The rapid response of the upper parts of the groundwater to external climatic variations is also confirmed with the temperature trend with depth (Fig. 4a), which in summer shows higher values on the surface than in depth, due to the higher temperature of water sources.

Figures 8 and 9 show the trends in electrical conductivity and temperature detected in the same multiparametric probes as figure 7, but with an observation interval of about 13 months. The measurements made at -20.35 m IGM allowed us to ascertain that groundwater temperature in the transition zone is independent of variations in external temperature (Fig. 8). Instead, electrical conductivity experiences variations which are linked to the hydraulic head of the aquifer compared with the sea. By contrast, the measurements carried out at -3.35 m IGM show a strict dependence of the groundwater temperature upon external temperature (Fig. 9). Indeed, there is a temperature increase in the transition from spring to summer, as well as an increase in the transition from autumn to winter. Groundwater temperature in the upper parts of the water table also experiences variations during rainfall events, represented in figure 9 by sharp variations. In particular, we note a temperature increase during rainy days in summer and a decrease, instead, on rainy days in winter.

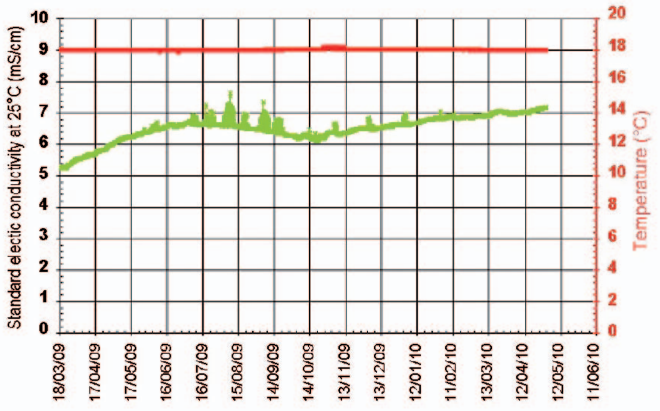

**Fig. 8:** *Fluctuations of temperature and hydraulics conductivity recorded in the piezometer NB1 at -20.35 m from sea level, between 18/03/2009 and 30/04/2010.*

Of particular interest are the tests carried out in a borehole close to the city's law courts (Cotecchia et al., 1993) with continuous core-drilling to a depth of 250 m (borehole 2 in Fig. 10). The trend of salinity with depth shows that at depths of around 15 m from the soil surface, the transition zone begins, about 10 m thick, beyond which we find sea water. However, the logs of salinity carried out in the above borehole show that for depths above 70 m the salinity undergoes a further increase, reaching at the bottom of the borehole a decidedly higher concentration than that of sea water. This circumstance is probably related to the long residence times of deeper sea water, older than that in direct contact with the groundwater.

The surveys carried out thus show that the saline stratification of groundwater in the city of Bari is the result of a set of phenomena, in part tied to variations in sea level variations, in part to the hydraulic head of the water table and the conditions of the sources of the latter.

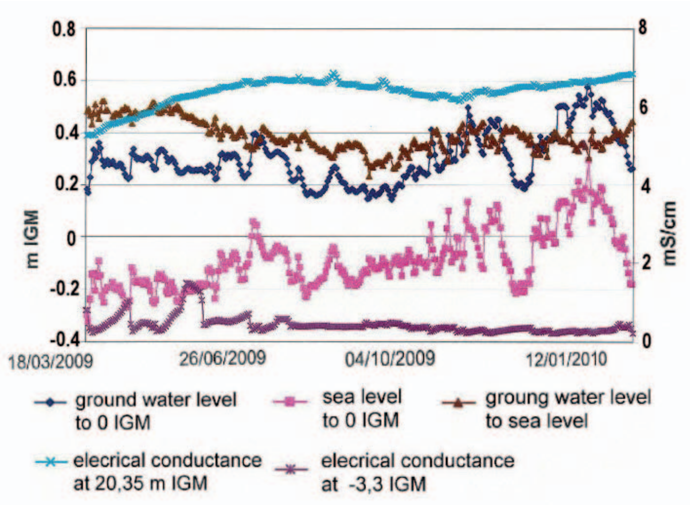

**Fig. 7:** *Fluctuations of groundwater level, of sea level (daily average values) and of ground water electric conductibility gauged at different depth.*

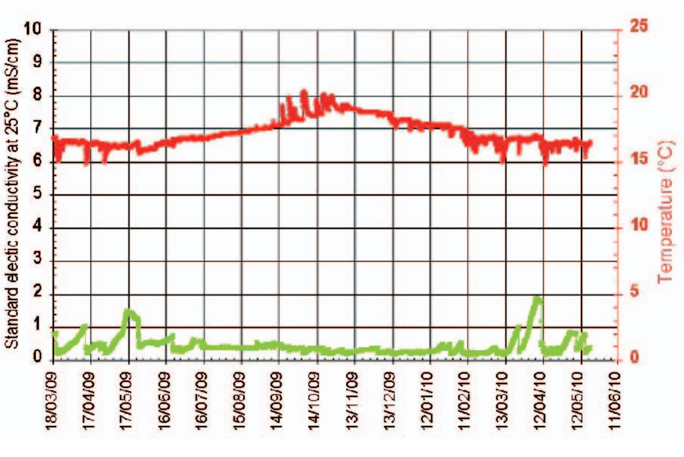

**Fig. 9:** *Fluctuations of temperature and hydraulics conductivity recorded in the piezometer NB1 at -3.35 m from sea level, between 18/03/2009 and 12/05/2010.*

## Cretaceous limestone aquifer permeability along coastal section of Bari

The possibility of likening a rocky medium which is permeable due to fracturing and karstification to a porous medium of equivalent permeability (EPM) is linked to the existence of a representative elementary volume (REV), whose dimensions indicate the scale within which such equivalence may be considered valid (Bear, 1979; Long et al., 1982). This was made possible in our case through the hydrogeological surveys, using indirect indicators of the geometry of the rock fracturing and flow conditions (Bradbury et al., 1991).

As will be illustrated below, the surveys highlighted a regular distribution of piezometric head and time variations of the same substantially tied to sea level variations. It was verified that this variation substantially depends on distance from the coast, without particular irregularities. The physico-chemical surveys conducted also showed that, along the various verticals, temperature, electrical conductivity and salinity of the groundwater present substantially the same law of variation with depth. Further, stratigraphies determined by extensive continuous core-drilling showed the very intense presence of fracturing.

What was observed by the surveys nonetheless represents a set of necessary but not sufficient conditions to show the equivalence between the fractured karst medium, like that in the present study, and an equivalent porous medium. However, in our specific case, this equivalence is deemed applicable, insofar as no survey carried out showed groundwater behaviour that could not be interpreted by the hydraulics of porous media (Cotecchia et al., 2007; Cotecchia et al., 2007a).

Having verified the possibility of likening the aquifer to an equivalent porous medium, we then determined the coefficient of permeability, which in this case is considered as a first approximation homogeneous and isotropic, even if predominance of the state of horizontal fracturing implies the existence of anisotropies, which may as a rule always be interpreted in the context of porous medium hydraulics.

The high permeability due to karst phenomena and fracturing of the limestone formation in question made it difficult to carry out direct permeability tests in the study area, given also the need to use huge volumes of water in an intensely urbanised environment. Several pumping tests carried out with flows of 10 l/s in SBA, SBB and SBC probes (Fig. 1) recorded zero hydrodynamic depressions, confirming the very high permeability of the aquifer in question.

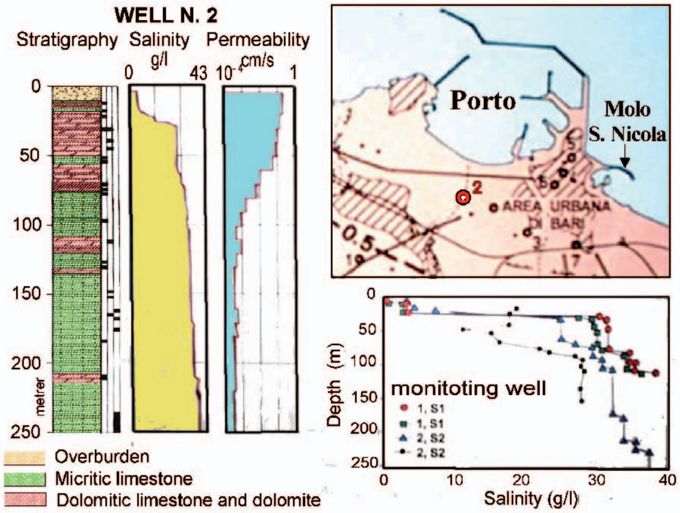

**Fig. 10:** *Stratigraphy, permeability and salinity profiles drawn from some historical wells located in the town of Bari.*

With a view to estimating the coefficient of permeability in the area concerned we took into account of previous permeability tests carried out in historic boreholes located close to the study area. Of particular interest is the above-mentioned borehole drilled close to the Bari Law Courts (Fig. 10). This borehole underwent permeability tests throughout its depth of 250 m. The tests showed a coefficient of permeability of about $1E^{-01}$ cm/s in the upper parts of the aquifer, which gradually diminishes with depth, reaching at the base of the borehole approximately $1E^{-04}$ cm/s, that is 1000 times less than that measured on the surface.

In the study area we were able to obtain an estimate of the permeability coefficient by studying the propagation of sea-level fluctuations on the water table levels. With h(x,t) the oscillation in time of the phreatic surface at a generic point at a distance x from the coast and at time t, under the assumption of a linear stationary hydrogeological system the differential equation of the non-permanent flow of filtering water may be expressed as follows:

$$\frac{\delta^2 h}{\delta x^2} = \frac{1}{D}\frac{\delta h}{\delta t} \qquad (2)$$

where $D$ [$L^2/T$] is the aquifer's diffusivity.

Eqn. 2 holds, in the case of a phreatic aquifer, only when the oscillation h is negligible as regards the thickness of the water table, as occurs in the case in question. The solution of the above differential equation may be determined with the following boundary conditions:

$$\begin{aligned} &h = 0 \text{ for } t = 0; \\ &h = h(0,t) \text{ for } x = 0, \end{aligned} \qquad (3)$$

where h(0,t) represents the law of variation of the sea level.

The solution of (2) with boundary conditions (3) is given by Duhamel's theorem:

$$h(x,t) = \int_0^t h(0,t-\tau)\,p(x,\tau)\,d\tau = \int_0^t h(0,\tau)\,p(x,t-\tau)\,d\tau \qquad (4)$$

where $\tau = n\Delta t$ and $p(t)$ represents the impulse response of aquifer.

Subdividing the law of sea level variation h(0,t) into a series of constant impulses at suitable time intervals $\tau_k - \tau_{k-1}$, and introducing the attenuation parameter of:

$$A = \frac{x}{2}\sqrt{\frac{1}{D}} \qquad (5)$$

we obtain (Magri and Troisi, 1969; Cotecchia, 1977) :

$$h(x,t) = \sum_{k=1}^{l} \frac{h_k}{2}\left(erfc\frac{A}{\sqrt{\tau-\tau_{k-1}}} - erfc\frac{A}{\sqrt{\tau-\tau_k}}\right) + \frac{h_{l+1}}{2}erfc\frac{A}{\sqrt{\tau-\tau_l}} \qquad (6)$$

where:

$$erfc(u) = \frac{2}{\pi}\int_u^{\infty} e^{-\mu^2}\,d\mu \qquad (7)$$

Having fixed a generic point x (points at which hydrographic readings are available) and with known variations in sea level h(0, t), appropriately subdivided into constant impulses $h_k$, we may calculate the different laws of variation governing the groundwater level, one for each value of attenuation A. By comparing the water table oscillations calculated with those measured it is then possible to determine the correct value of attenuation A, hence for eqn. 5, of diffusivity $D$.

Once the diffusivity is known, we may then determine the permeability coefficient of the aquifer from the relation:

$$K = \frac{Dn}{H} \tag{8}$$

where $n$ and $H$ are respectively aquifer porosity and thickness. Aquifer thickness was determined on the basis of the results obtained from the multiparametric logs (Fig. 5), while porosity was assumed at 10% (Cotecchia et al., 2007; Cotecchia and Tafuni, 2007).

The analyses carried out neglect the oscillation in the groundwater level due to changes in the form and position of the transition zone between the fresh groundwater and the underlying sea water. This variation is thus considered small, in the period of time covered by our analysis, namely tens of hours, compared with the oscillation in the groundwater level, caused by the variation in sea level, as confirmed by the results of the analysis.

Equation 6 was solved with the aid of a spreadsheet, subdividing the sea-level fluctuations recorded on the Bari mareograph in time intervals within which the level may be considered constant (Magri and Troisi, 1969; Cotecchia 1969).

Using the data from piezometer P6 at 390 m from the coast (Fig. 11) the sea level trend was compared with that of the groundwater measured in the same period. It was found that sea level oscillations were felt to a lesser degree at the water monitoring point about one hour later. The graph reports the groundwater oscillations calculated, assuming a permeability coefficient of about 10 cm/s. An almost perfect correspondence may be noted between the calculated and measured groundwater oscillations. In the case of piezometer P8, placed about 1.2 km from the coastline (Fig. 12), a delay of about 48 hours is recorded. Calculated oscillations in groundwater are close to those measured in correspondence of a permeability coefficient used in the calculation of about 1 cm/s. It should be pointed out that in figures 11 and 12, for the sake of graphic clarity, we omitted the sea level trend in time intervals prior to those for which groundwater oscillation was calculated. The trend was nevertheless used in the calculation.

The calculations indicate a reduction in the equivalent permeability coefficient with increasing distance from the coast, as indicated in Figure 5, in accordance with what was determined in the borehole drilled close to the Bari Law Courts (Fig. 10).

## Reconstruction of the phreatic surface of the water table and analysis of its hydrodynamic behaviour

The piezometric levels of the water table are influenced by a series of parameters, such as rainfall, atmospheric pressure and sea-level fluctuations (Cotecchia, 1977). Neglecting in the context of this paper the variations in the water table tied to rainfall, our survey enabled important information to be obtained concerning the existing links between barometric oscillations, sea level oscillations and oscillations in the water table at various distances from the coast.

Barometric oscillations affect groundwater levels both directly, and indirectly, due to tidal action. Non-periodic oscillations of sea level, which are transferred to the groundwater levels, are not only of the lunar-solar type but also linked to atmospheric pressure (Fig. 13): a lowering of sea level corresponds to an increase in atmospheric pressure, and vice versa. In the case in question, being the distance from the coast very small, it was not possible to distinguish the direct influence of atmospheric pressure on groundwater levels from indirect influence: the two phenomena substantially overlap. Analysis of seal level oscillations measured from 1998 to 2006 did not allow us to determine mean sea level, as the latter is related to the period in which it is measured. Thus, in order to understand the hydrodynamic behaviour of the water table, one should always refer to the actual sea level in the period of observation, as already highlighted in analysing the variation in time of groundwater salinity.

The water level readings (Figs. 14 and 15) showed a strict correspondence between sea-level oscillations and those of the water table, with a smoothing and delay that increase as distance from the coast increases. This entails the continuous change in shape of the phreatic surface, due to the different oscillations at the various water points in the same instant as distance from the coast varies. The water level readings at the piezometers represented in figure 14, which were very close together and located at about 700 m from the coast, show approximately a three-hour delay between sea-level oscillation and that of the water table. Both the delay and the softening of the effect are similar among the probes, indicating a hydrodynamic behaviour of the groundwater substantially affected by distance from the coast and not by further geostructural accidents, which could invalidate the hypothesis of equivalence between the fractured karstified limestone medium and what is deemed a porous medium under the effects of the aquifer's hydraulics. The water table oscillations

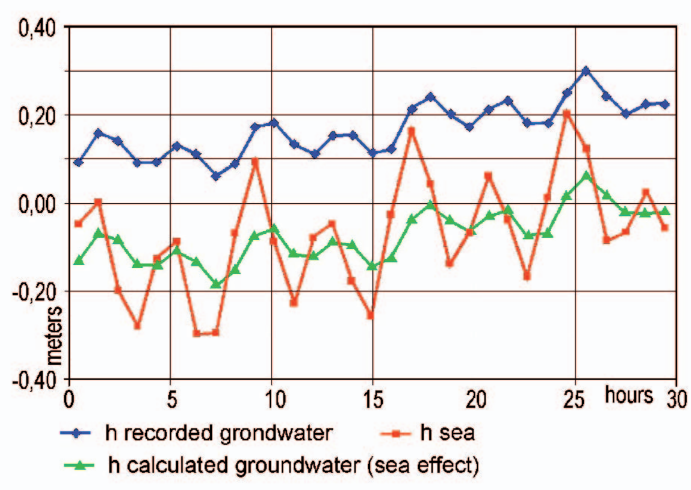

**Fig.11:** *Comparison between sea level fluctuation, recorded groundwater level fluctuation and calculated groundwater level fluctuation for piezometer P6 placed at 390 m from the coastline.*

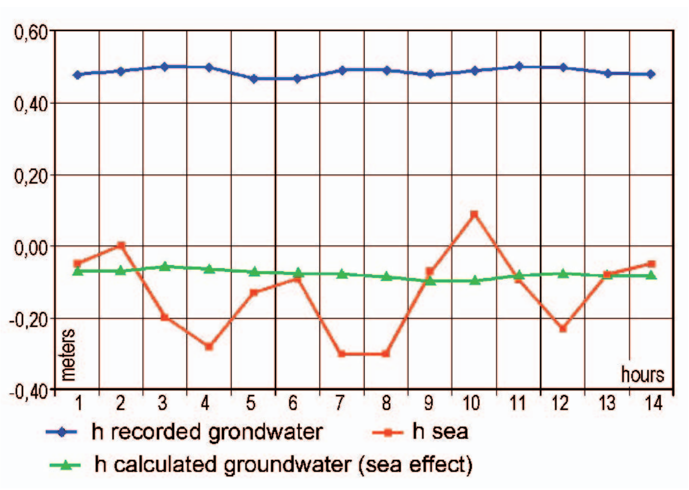

**Fig. 12:** *Comparison between sea level fluctuation, recorded groundwater level fluctuation and calculated groundwater level fluctuation for piezometer P8 placed at 1200 m from the coastline.*

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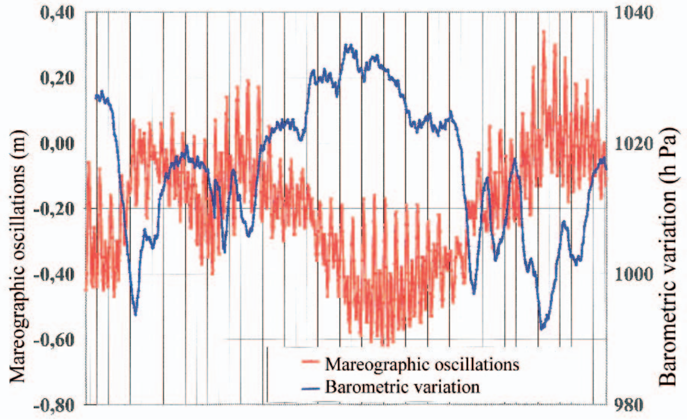

**Fig. 13:** *Mareographic and barometric oscillations recorded from 04/07/05 to 29/05/05 by the mareograph of Bari.*

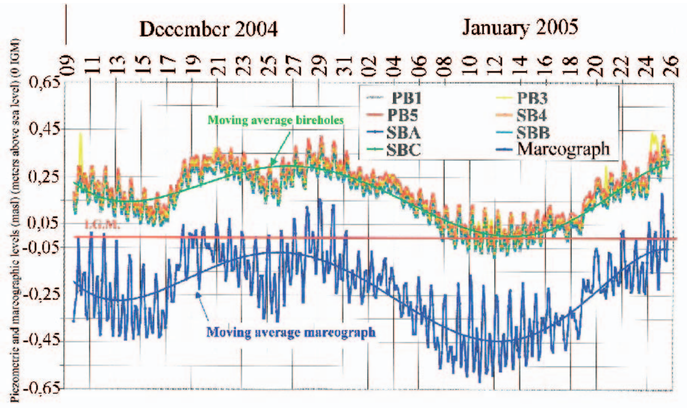

**Fig. 14:** *Comparison between the freshwater level fluctuation (recorded in piezometers PB1, PB3, PB5, SB4, SBA, SBB e SBC) and the sea level fluctuation recorded by the Bari's mareograph from 09/12/2004 to 25/01/2005.*

recorded in piezometer PB5 highlight a greater delay and a diminished effect (Fig. 15), confirming the greater distance of the above piezometer from the coastline (Fig. 1).

Analysis of Figures 14 and 15 shows that on various days during the data acquisition interval the sea level recorded an absolute value ranging from -30 to -40 cm IGM. This resulted in a lowering of the absolute value of the phreatic level, which in boreholes closest to the coast, such as those represented in Figure 14, reached zero or even negative values. In substance the surveys show that in very permeable coastal aquifers, with a low hydraulic gradient and hence phreatic level, it is extremely necessary to refer the groundwater level to the actual sea level so as to capture the piezometric head of the same water table.

In order to reconstruct the piezometric surface of the water table, it was thus necessary to measure the groundwater levels at all the piezometers sited in the study area, with measurements taken in a short period of time, compatible with sea-level oscillation records. A water-table measuring campaign with 58 piezometers was thus launched, with each measurement made over the space of an hour. This enabled us to determine distinct configurations of piezometric surfaces on two different days of the year (9/05/2005 and 11/10/2006), so as to "photograph" the piezometric surface in distinct conditions of tides and seasons.

In Figures 16 and 17 we report the piezometric maps calculated on 11/10/2006 in conditions of high and low tide respectively. Analysis of these piezometric surfaces show what was highlighted above: sea level oscillations cause a variation in the water table, which diminishes with increasing distance from the coast. Moreover, a change in the shape of the piezometric surface is found to correspond also to a variation in the direction of water flow and in hydraulic gradient, which are significant circumstances near the coastline.

On analysing the difference in the piezometric surface recorded in the piezometers on the two different days (Tab. 1) a substantial variation in absolute piezometric head of the water table is noted. This may be correlated both with the different tidal conditions, and in the general rise experienced by the water table during the transition from spring to autumn. The latter circumstance may be observed from the fact that this rise can be observed at any hour of the day.

**Piezometer drilled in the investigation area**

**Measures performed on 9.05.2005 and on 11.10.2006 between the hours 7,00 – 8,00 AM, 12,00 – 1,00 PM and 15,00-16,00 PM**

| Sign | Piezometer location | Altitude Well (I.G.M.) [m] | Δ (difference piezometer measure) Ott. 2006 – Magg. 2005 hours 07.00 - 08.00 [m] | hours 12.00 - 13.00 [m] | hours 15.00 - 16.00 [m] |
|---|---|---|---|---|---|
| PB1 | P.zza Umberto I | 4,52 | 0,08 | 0,09 | 0,01 |
| PB2 | P.zza Umberto I | 5,52 | 0,12 | 0,13 | 0,05 |
| PB3 | Posta | 4,64 | 0,13 | 0,13 | 0,09 |
| PB5 | Via De Rossi | 7,60 | 0,14 | 0,15 | 0,10 |
| SC10 | Corso Cavour | 2,59 | 0,13 | 0,13 | 0,04 |
| P2 | P.zza Risorgimento | 4,35 | 0,12 | 0,12 | 0,05 |
| P3 | P.zza G. Garibaldi | 3,77 | 0,14 | 0,13 | 0,05 |
| P5 | C.so VitT. Emanuele | 4,24 | 0,12 | 0,10 | 0,03 |
| P6 | P.zza Balenzano | 2,94 | 0,12 | 0,11 | 0,05 |
| PMA2 | P.zza G. Massari | 2,37 | 0,15 | 0,09 | 0,03 |
| PM01 | P.zza A. Moro | 6,60 | 0,16 | 0,13 | 0,03 |
| PMO2 | P.zza A. Moro | 5,95 | 0,17 | 0,12 | 0,04 |

**Tab. 1:** *Comparison between piezometric levels measured on 9/05/2005 and on 11/10/2006 at different hours.*

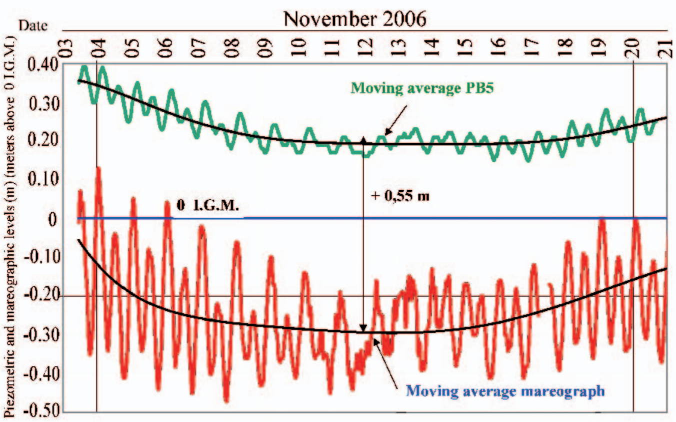

**Fig. 15:** *Comparison between the freshwater level fluctuation (recorded in piezometer PB5) and the sea level fluctuation recorded by the Bari's mareograph from 03/11/2006 to 20/11/2006.*

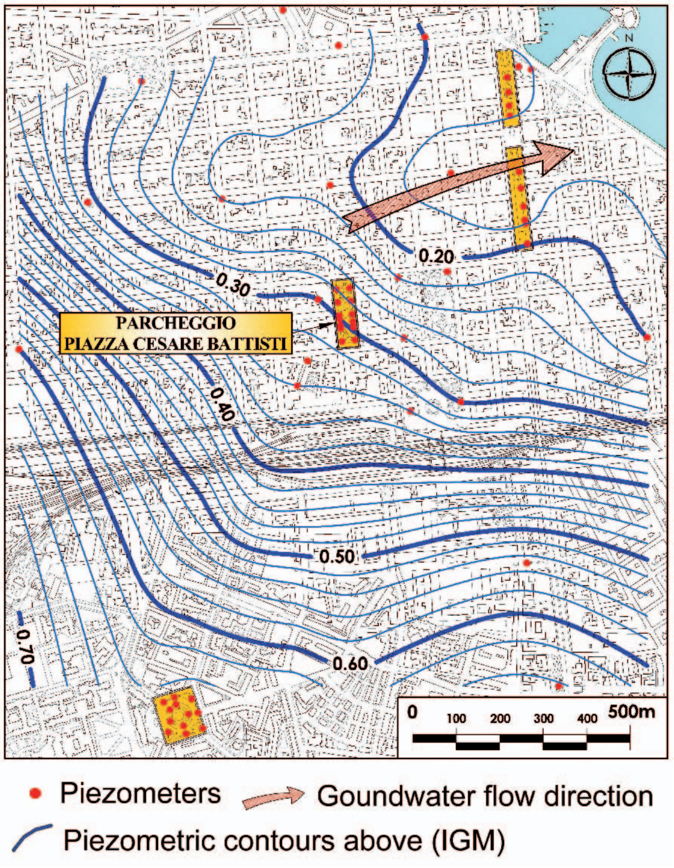

**Fig. 16:** *Piezometric Chart calculated on 11/10/2006 between 7:00 and 8:00 am sea level = - 0.07 IGM (Low tide).*

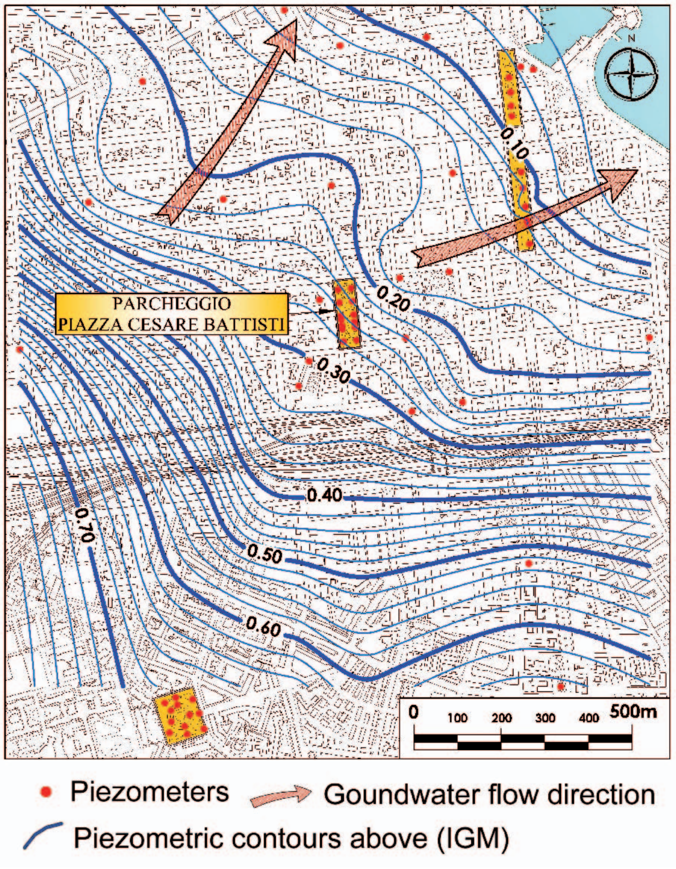

**Fig. 17:** *Piezometric Chart calculated on 11/10/2006 between 7:00 and 8:00 am sea level = - 0.20 IGM (High tide).*

## Conclusions

The extensive campaign of hydrogeological surveys carried out to date, design and construct major underground and aquifer works in the city of Bari represent an important opportunity to characterise the fractured karstified Cretaceous limestone aquifer in the city's subsoil and determine the hydrodynamic behaviour and physico–chemical evolution of the circulating groundwater. The results of the surveys of the geographical area in question specifically depict how the groundwater from the Murge aquifer reaches the sea thanks to both small- and large-scale permeability along much of Puglia's coastline.

Determination of the physico-chemical properties of the groundwater enabled us to highlight, together with the saline stratification of the aquifer close to its discharge into the sea, the reasons for the variability in saline content of the groundwater with depth up to the underlying salt water. In the study area the freshwater aquifer is present to a variable depth of 20-25 m, within which salinity generally increases, up to about 3 g/l. Beyond this depth, there is the transition towards the underlying saline water across a transition zone about 6 m thick. Measurements of filtration velocities carried out along some verticals also showed the absence of the movement of saltwater intrusion into the mainland. The depth at which saltwater was detected at the study area is significantly higher than that obtained from the application of Gyben-Herzberg's Law due both to the motivated increase in density experienced by the groundwater at depth, and to the three-dimensional effects arising close to the coast, due to the non-negligible vertical component of filtration velocity.

Interpretation of the hydrogeological surveys allowed us to liken the limestone aquifer in the study area, permeable due to fractures and karst features, to a porous medium of the same permeability, using indirect concrete indicators of the geometry of the rock's fracturing and the hydraulic groundwater flow conditions. It was thus possible to interpret the oscillations in the water table as arising from sea level fluctuations and then estimate by successive attempts the coefficient of the formation's permeability. The latter varied according to distance from the coast, assuming a permeability of about 10 cm/s in proximity to the coastline and about 1 cm/s at a distance of about 1 km. The latter values were obtained from in situ hydrogeological controls and directly conducted in the area. With continuous measurements of the water table and sea level, it was also ascertained that the water table oscillations are the same order of magnitude as those of the sea level. This circumstance makes it necessary to define the water table level as being at sea level so as to capture the actual hydraulic head of the aquifer, on which its hydrodynamic behaviour depends. Electrical conductivity of the groundwater, continuously measured at different depths, thus varies according to the oscillations in the water table compared with the actual sea level, and not in relation to the absolute load of the same aquifer.

The different effects of sea level oscillations on groundwater levels in relation to distance from the coast and the local hydrogeological parameters entail a continuous change in the morphology of the piezometric surface of the water table. This circumstance was quantified on the basis of the reconstruction of piezometric head carried out at various moments during the day, with measurements of the water table at various survey points (over 50), all carried out in the space of an hour.

The meaningful results of the hydrogeological research before summurized derive from the singular about planar morphology of the karstic area of the calcareous coast illustrated and discussed above. These relevant results have been achieved because of the dense hydrogeological monitoring conducted, that allowed to obtain exhaustive data and parameters in order to characterize the area under analysis. Moreover, the results are still more relevant because it's not easy to find in literature case studies, similiar to the one analized in this paper with refernce to the Piana di Bari, that go so deeper into the matter of hydrogeology and hydraulics of subterranean flows in carbonatic karstic formation through intense in situ experimentations.

About hydrogeological monitoring well performed, specifically referred to coastal areas affected by seawater intrusion, it seems appropriate to mention the brilliant results obtained from the hydrogeological research conducted for 50 years in the Biscayne bay, South of Florida. In this case, in fact, have been conducted excellent in situ real-time observations in order to manage water resources for Miami city. In consequence, the case study of South of Florida and his monitoring data, with particular reference to the Biscayne aquifer, have been analized by the most popular researchers, allowing a detailed analysis of seawater intrusion ever seen before and making then history of hydrogeology (Kohout, 1960; Cooper et al., 1964; Meyer 1989).

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