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# Carbonate Aquifers in Apulia and Seawater Intrusion

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ABSTRACT. The predisposing factors and the determining factors of seawater intrusion in wide carbonate aquifers of Apulia (Southern Italy) are characterized. Main predisposing factors prove the sedimentation environment, the tectonic-karstic evolution, the geometry of the aquifers in relation to the coastline, the depth of the aquifers, the existence of underground outflows and their chemical nature. The effect of salinity pollution and its trend was characterized using data from a regional monitoring network, considering logs time series, and also from well loggings. The intensive and widespread use has led to a progressive deterioration in water quality, particularly in the Salento area, right where the aquifer is most susceptible to seawater intrusion.

*Key terms:* Karstic aquifer, Seawater intrusion, Groundwater degradation

## Premise

The main cause of saline pollution in Italy is seawater intrusion. A particularly interesting case study is that of Apulian seawater intrusion (FIG. 1). Local groundwater resources, which are the main regional water source, given the lack of a meaningful hydrographic network over most of the area, are deteriorating rapidly and dramatically. This is mainly due to saline pollution by seawater intrusion (COTECCHIA, 1981; COTECCHIA & TADOLINI, 1993; COTECCHIA *et alii*, 1981; GRASSI 1974a, 1974b; GRASSI & TADOLINI, 1985a, 1985b; FIDELIBUS & TULIPANO, 1996; POLEMIO & LIMONI, 2001).

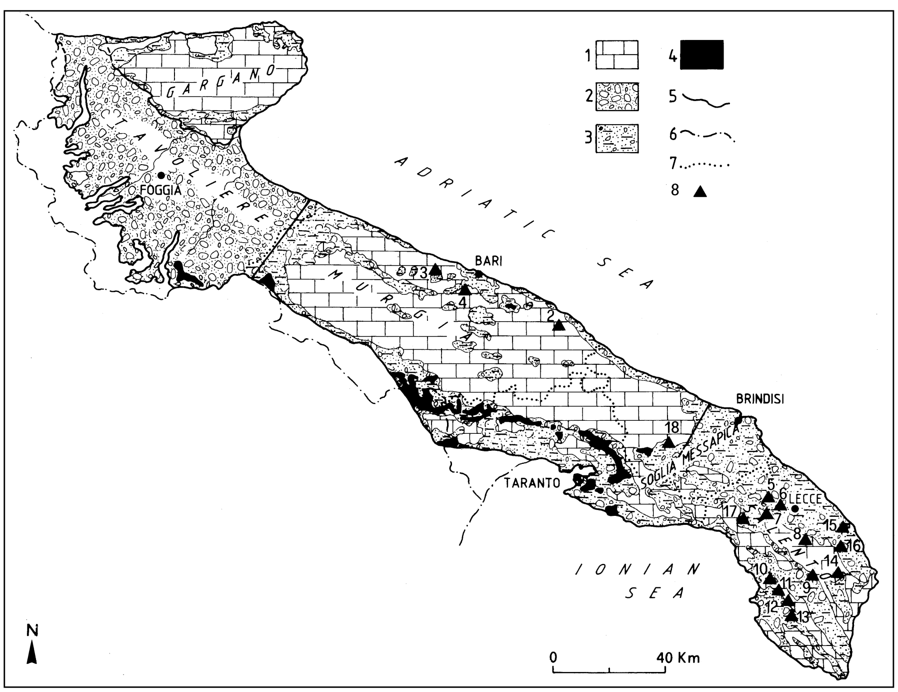


FIG. 1. Apulian hydrogeological units and structures (COTECCHIA & POLEMIO, 1999, POLEMIO & LIMONI, 2001). LEGEND:1) Carbonate rock outcrops of Gargano, Murgia and Salento; 2) Tavoliere unit, mainly conglomerate and sands; 3) shallow aquifers and permeable lithotypes, calcarenites, clayey sands, sands, gravel, or conglomerates; 4) low permeable lithotypes, blue marly clays; 5) hydrogeological unit boundary, dashed where uncertain; 6) regional boundary; 7) provincial boundary; 8) chlorine content monitoring well.

The present paper analyzes the predisposing factors causing this phenomenon, such as the role played by tectonics, karst phenomena and the special geometric and geographic configurations of the aquifers (FIG. 1) (GRASSI, 1983, GRASSI & SIMEONE, 2002 and 2003; GRASSI *et alii*, 2003).

The Apulian regional area has an 800 km long coastline and is, at the same time, the site of the largest coastal karst aquifers in Italy. These aquifers are made up of Mesozoic rocks found in the Gargano area in the north, in the Murgia area in the center and in the Salento area in the south. The Murgia and Salento areas actually make up the Apula shelf which forms a geological and groundwater continuum whose main distinguishing feature is a striking lithological uniformity (unlike in the Gargano area) (GRASSI, 1973). For this reason, however different the Murgia and Salento areas are from a physiographic point of view, in reality they form one major water body.

The Tavoliere separates the Gargano from the Apula shelf, in that the Mesozoic is buried under thousands of meters of Tertiary-Quaternary soil. There are easily discernable hydrogeological differences which make it easy to distinguish the Murgia from the Salento within the Apula shelf. To oversimplify, the Salento is the site of a much more permeable carbonate hydrogeological system than that of the Murgia area; the Murgia is a major feed of the north-west section of the Salentine aquifer. A morphological-structural element called the "Soglia Messapica" straddles the two hydrogeological systems, covering an area which extends from one sea to sea, about 10 km wide, with hydrogeological features which are transitional between the Murgia and Salento areas.

One of the most important determining factors in this situation is the ongoing excessive overexploitation of Apulian groundwater resources (COTECCHIA & POLEMIO, 1995). Depending upon the various configurations and combinations of these elements, there is an observable strong differentiation in terms of the effects of seawater intrusion on main carbonate aquifers: the Gargano area, the Murgia and the Salento. In particular, what makes Apulia a special case is that the vulnerability of Apulian aquifers to seawater intrusion varies widely; this is quite an unusual circumstance within the overall context of the karst coastline. For example, spontaneous saline contamination of the Gargano groundwater is due in part to the fact that it is mixed with very old waters which are nearly still, very hot and very saline, to be found at great depths in the Tavoliere area.

Studies lasting decades have been carried out employing geological, hydrogeological and geochemical surveys, making use of the most advanced technology; these studies have clearly shown that, even irrespective of human activities, the extent of seawater intrusion is substantially different in the area of the Gargano, of the Murgia and of the Salento, so much so that any and all extrapolations of data pertaining to one area are not applicable to another.

## Geological and Hydrodynamic Features

Apulia has a series of calcareous dolomite outcroppings dating back to the Mesozoic era, making up the mountainous areas of Apulia (the Gargano) and the hilly areas of the region (the Murgia and the Salento); it also has a detrital organogenic series which can be attributed to the Tertiary and Quaternary periods, to be found in the topographic troughs and which partially overlaps the above-mentioned series (FIG. 1) (COTECCHIA & MAGRI, 1966; GRASSI, 1973, 1974; 1983).

Carbonate sedimentation occurred in the area of the cliffs in the Gargano, and in the shelf area in the Murgia and the Salento. In the Gargano area, the distribution of the facies shows that in the Middle Jurassic period there was a typical reef environment which later evolved into two distinct separate environments, the frontal reef (in the eastern part of the Gargano) and the back reef in the period from the Upper Jurassic to the Cretaceous.

An extensive plain known as the Tavoliere lies between the Gargano and the Mesozoic carbonate shelf arising in the Murgia and Salento areas. The "Soglia Messapica" is situated in the midst of the morphological-structural units of the Murgia and the Salento; it is part of the same shelf subjected to subsidence due to neotectonics (FIG. 1).

Periods of sedimentation interspersed with stratigraphic gaps occurred over time after the emergence of Mesozoic deposits. This is the stage during which the Paleogene deposition outcroppings were created along the eastern coastal rim, as were the depositions of Miocene and Plio-Pleistocene transgressive-regressive cycles, which were widespread throughout the area and most particularly in the Salento.

After the upheavals of the Late Miocene period and with the onset of Pliocene transgression, Apulia slowly began assuming the shape it has now, particularly during the Pleistocene, when the extensive areas of sedimentation which lie between the Gargano, the Murgia and the Appennines and between the Murgia and the Salento became filled up with clastic depositions.

The Gargano is a horst which is stretched out on a NE-SW axis, in the shape of a promontory extending out into the Adriatic Sea in a northeasterly direction. Since there are several fault systems, the Gargano rises suddenly from the lowlands of the Tavoliere (50 to 80 m above sea level), and its peak is in the center (1000 to 1055 m above sea level) (GRASSI, 2002; GRASSI & GRIMALDI, 2002a, 2002b; GUERRICCHIO, 1983). The Gargano promontory can be divided into two quite separate and distinct parts in terms of types of carbonate rocks. These two types are very different, even taking into consideration the rocks forming the Murgia and the Salento areas. The eastern sector is made up of frontal reef depositions and transition depositions, then there is a central-western sector where reef facies dominate and subsist in a narrow central strip, and the back reef depositions.

The depositions of the open sea are made up of limestone and marly limestone in thin layers with abundant stripes or nodes of flint stone. The transition depositions are mainly made up of dolomite and dolomite with abundant flint stones. These sediment outcroppings account for about 30% of the Gargano area and are so deep that they thrust underground several hundred meters below sea level.

The reef depositions are massive, made up essentially of organogenic limestone and, to a lesser degree, of crystalline dolomite. Finally, back reef depositions, which make up 58% of the Gargano area, are to be found in beds and/or strata and are made up mainly of compact microcrystalline limestone, occasionally interspersed with dolomite and limestone dolomite.

The Tavoliere completely surrounds the Gargano and separates the promontory from the outcrops of the Mesozoic carbonate shelf to be found north of the Murgia (FIG. 1). Mesozoic carbonate rocks can be found several hundred meters below the surface in the Tavoliere, under many successive strata of Tertiary-Quaternary sediment of various types, though they are mainly pelitic. The uppermost section of this succession of strata is made up mainly of conglomerate and sand, in the form of outcroppings in the north-western part, hidden under a few meters of pelitic soil in the central-eastern portion.

South of the Tavoliere area, Apulia is made up of Mesozoic carbonate shelf rocks (FIG. 1). This is a large undifferentiated lithological unit, several thousand meters thick, which is highly stratified and characterized by an unchanging series of very pure detritic, micritic and biostromal limestone, often dolomitized to a certain extent, interspersed at times with dolomites. Usually, stratification is subhorizontal or at least with a very slight inclination (15° - 20° at most). The morphology is usually tabular in nature, particularly in the Murgia area, and is interrupted by a highly visible karst landscape. Fissuring is at times rare and uneven, at times quite intense. It varies widely.

The shelf is only in isolated sections covered by residual tracts of mainly Plio-Pleistocene sediment.

The area is made up of two morphological-structural units: the Murgia plateau and the Salento lowlands, through which runs the "Soglia Messapica". The Murgia plateau (maximum height 680 m above sea level) is a large asymmetric horst, caged in by two direct fault systems (NW-SE and NE-SW), due to neotectonics. Because of these faults, the morphological structure dips down towards the Adriatic Sea and towards the adjoining regions of the Salento by means of a succession of ledges in the shape of steps, bounded by slight fault throws.

In the Salento area, the shelf itself is a sort of lowland (maximum height 150-180 m above sea level), bounded by two seas, the Adriatic Sea and the Ionian Sea. The covering terrains there are relatively more widespread, though not very continuous.

## *Common hydrodynamic features and main differences*

Apulia, with 800 km of coastline along two seas, is the site of the Gargano hydrogeological unit, of the Tavoliere hydrogeological unit and of the hydrogeological structures of the Murgia and of the Salento. All of these areas are carbonate in nature, except for the Tavoliere. Taken as one unit, they constitute coastal aquifers, and are therefore exposed to contact with the sea; their groundwaters are also affected in a different way by saline pollution, mainly due to natural causes but also to man-made ones.

The Tavoliere hydrogeological unit is characterized by a porous shallow aquifer whose groundwater flow is limited by a clay bottom a few hundred meters thick; the water flow occurs under phreatic conditions upward, far from the sea, and is confined downward, down to the coast. The piezometric surface of the shallow aquifer can be measured at a maximum altitude of about 300 m above sea level inland. It is only along the coast that the aquifer is deep enough to allow seawater intrusion. In the Tavoliere area, salinization is an entirely negligible phenomenon, both from a scientific and from a practical point of view.

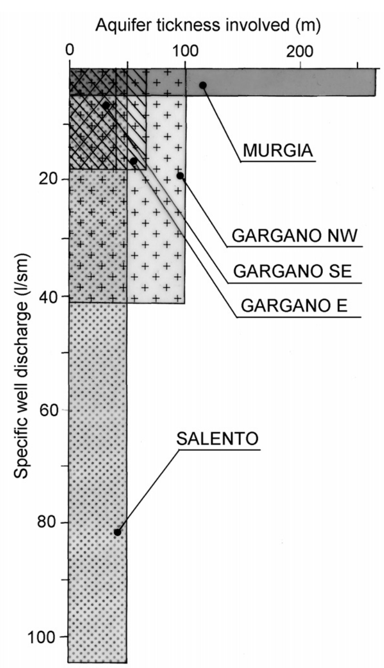


FIG. 2. Schematic comparison between aquifer thickness involved by tapping wells and specific discharge or well yield for main carbonate aquifers.

Carbonate aquifers share a number of common features (COTECCHIA & MAGRI, 1966; GRASSI, 1983; POLEMIO, 2000). They are relatively large and deep, made up of Mesozoic calcareous rock and/or calcareous-dolomite rock. They are influenced by karst phenomena, with varying degrees of three-dimensional fracturing, with permeability from below to above, and in some places, widespread in the

Salento area, with a very high degree indeed of permeability.

Well data can be described considering two parameters: the specific discharge or well yield Qsp (discharge per unit drawdown expressed in l/(s m)) and aquifer thickness involved in a well L (m), as a function of the real well penetration in the aquifer. These data spread out along the coast of the Gargano showing very wide intervals: in the SE area (Manfredonia), Qsp varies from 0.3 to 18 l/(s m) with L from 1 to 40 m; in the NW area (Lesina) from 0.13 to 41 l/(s m) and L from 1 to 100 m; to the east (Vieste) from 9.3 to 18 l/(s m) and L from 10 to 70 m (GRASSI & TADOLINI, 1991, 1985a, 1985b; GRASSI & SIMEONE, 2002, 2003; GRASSI *et alii*, 2003b). It should be noted that the Salento area is associated with an interval of 30-100 l/(s m), with an involved aquifer thickness of 0.5-50 m, the “Soglia Messapica” is associated with intermediate values of Qsp, 4-30 l/(s m), with L from 1 to 150 m, whereas in the Murgia area the Qsp is usually low, between 0.01 and 4 l/(s m) with L varying from a few meters to a few hundred meters (FIG. 2).

The Gargano and Murgia areas share a number of hydrogeological characteristics. The groundwater flow in the Gargano and in the Murgia is generally confined, except along a narrow coastal strip. Faults govern the major preferential flow paths and seawater intrusion; they also govern the deep and complex groundwater exchanges along the major hydrogeological boundaries, such as between the Gargano and the Tavoliere. At times, faults also play a role as barriers sharply dividing the downstream hydrogeological environment from the upstream one. Maximum piezometric heights are very high, never less than about 50 m above sea level (FIG. 3).

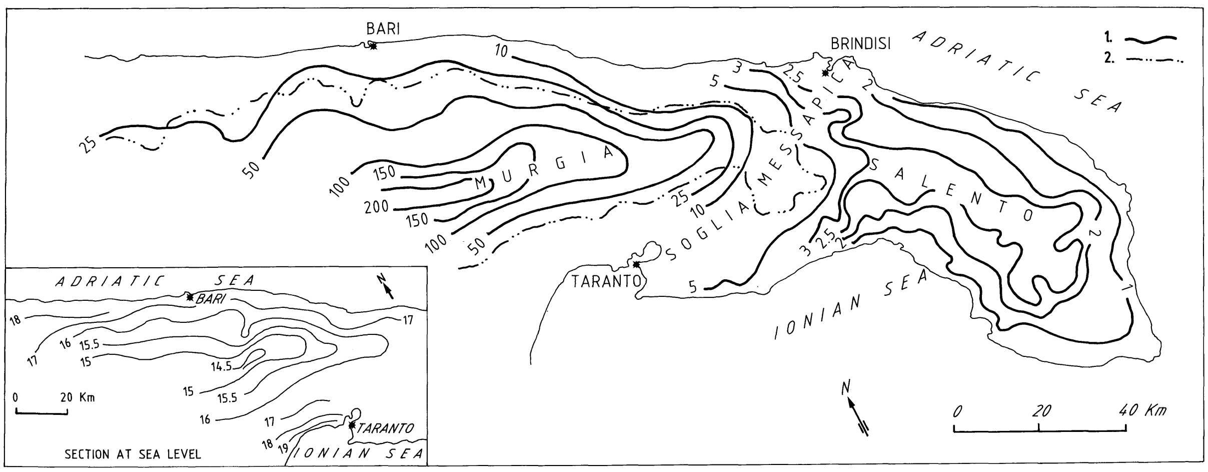


FIG. 3. Piezometric map, salinity and groundwater temperature (GRASSI, 1983; modified). LEGEND: 1) Piezometric contour line (m asl); 2) 0.5 g/l salinity contour line, salinity is higher than 0.5 g/l in the dashed area. On the bottom left, the temperature groundwater map is drawn to sea level.

The hydrogeological structure of the Salento is quite different from the that of the Murgia, though both of them are part of the carbonate shelf (FIG. 1). There is a gradual change from one hydrogeological structure to the other, and it occurs at the “Soglia Messapica”. The deep groundwater of the Salento reaches piezometric heights of only a few meters above sea level (4-5 m above sea level at most, FIG. 3).

Among the main differences between the Murgia and the Salento are:

a) in the Murgia area, the groundwater flow is usually confined and is almost always below sea level, sometimes hundreds of meters, and thus with very high depth to groundwater; in the Salento, groundwater flows mainly under phreatic conditions and the depth to groundwater is quite low.
b) The maximum piezometric height in the Salento are 4-5 m above sea level (FIG. 3) and the altitudes are even two orders of magnitude lower than those of the Murgia.
c) If groundwater floats inland on seawater, the fresh groundwater thickness of Murgia is ten times that of the Salento thickness.
d) In the Murgia, the specific well discharges are 100-300 times lower and, generally speaking, the permeability is lower as well (FIG. 2).
e) The Murgia, unlike the Salento, has groundwater with very low mobility; the isotopic contents of groundwater and velocity data supplied by tracers show that the residence times of the Murgia waters are much longer (GRASSI & TADOLINI 1988, 1991).
f) Groundwater in the Murgia and the Salento show gradual cut off points in piezometric terms as they cross the “Soglia Messapica” (FIG. 3). Some of the Murgia groundwater feeds the Salentine aquifer: this underground outflow is part of a considerable piezometric height loss occurring in the “Soglia Messapica”.

g) In the Salento, groundwater flow is diverged by a watershed ranged along the SE-NW axes, in parallel with the Ionian and Adriatic coastlines, with a piezometric gradient of 0.2-0.3%; in the Murgia area the flow is mainly towards the Adriatic coastline and towards the Salento, with an overall greater piezometric gradient (1-10%) (FIG. 3), secondarily towards the Gulf of Taranto in the Ionian Sea.

h) Given the Salento area's geographical shape, the karst groundwater is lenticular in shape, following a section which is vertical to and perpendicular to the Adriatic and Ionian coastlines; this influences piezometric height, keeps maximum values low and therefore limits the maximum thickness possible for fresh groundwater. In the Murgia, the karst aquifer's main feature is an irregular geometric shape with an impermeable roof (which might actually be a few meters above sea level or might be, not too far away, hundreds of meters below sea level). The bed has an irregular shape as well, though its true shape is not well known.

The Murgia and the Salento are quite different, which would lead to the conclusion that even in the same karst district, where there have been differentiated tectonic-karst events, there might be several complex hydrogeological units, each one so individual that, given these features, it might be impossible to extrapolate with any degree of certainty the effects of seawater intrusion, also given the different boundary conditions.

In essence, the hydrogeological features of the Murgia are similar to those of the Salento only in a very narrow coastal strip, whereas elsewhere they might be more comparable to those of the Gargano. It is also true that the Salento - given its high permeability, its low depth to groundwater, its low piezometric heights and the fact that it is surrounded by sea on three sides - is therefore highly vulnerable both to seawater intrusion and to any type of pollution coming from the ground surface.

The Gargano, the Murgia and the Salento are three different clear-cut examples of the effects of seawater intrusion in karst aquifers, given their different hydrogeological natures, the different effects of the boundary conditions because of coastline differences and the different rates of use of groundwater.

## Seawater Intrusion

There are very strong differences in terms of the effects produced by seawater intrusion on the three main karst districts (COTECCHIA, 1981; GRASSI *et alii* 2003a), as can be seen below, in descriptions ranging from a general overview narrowing down to finer details.

### *Quality assessment by means of regional monitoring*

Traditionally, the quality and quantity of groundwater in Apulia has been studied by taking a regional or unitary approach based upon data from a network of measurement stations of wells and springs. Recently, tests have been carried out using a monitoring network capable of automatically recording parameters indicating the quality and quantity of groundwater. It was agreed that GIS and relational data bases shall process data from the network itself. The monitoring network is made up of over 100 wells (COTECCHIA & POLEMIO, 1999; POLEMIO, 2000) (FIG. 4).

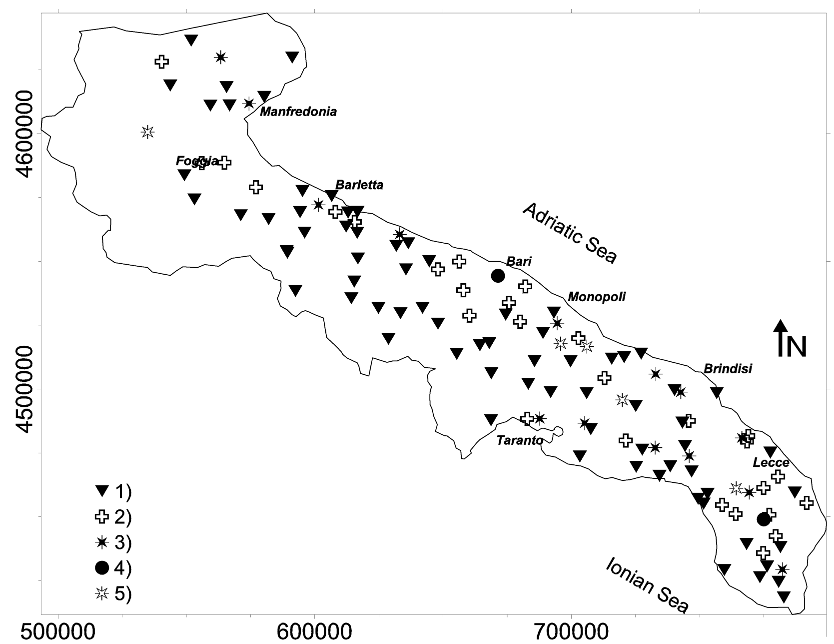


FIG. 4. Apulian hydrogeological monitoring network. LEGEND: 1) Piezometric wells; 2) Quality control wells; 3) Seawater intrusion observation wells; 4) Wells of type 2 and 3, 5) radio link.

The monitoring system is based upon three different types of control: the first type checks piezometric variations and involves all stations; the second, called quality control, measures the main chemical and physical parameters of groundwater (temperature, specific electric conductivity, salinity, pH, dissolved oxygen, reduction-oxidation potential) of wells located in three particularly significant areas (the recharging area, the watershed, and downstream from inhabited areas, or areas at risk due to specific production activities); the third type, involving salinity checks and therefore controlling how the phenomenon of seawater intrusion evolves, concerns wells situated along the coastline.

Salinity stations are equipped with thermometric and electrical conductivity probes situated at three depths along the well water column. The installation levels of the three probes are set so that any changes over time in the width of the transition zone will be recorded. All wells are also used to take water samplings and for carrying out lab tests on a number of parameters.

Groundwater has different saline levels and therefore different density ratios, which cause intense salinity stratification, increasing with depth in all wells subject to the phenomenon of seawater intrusion. Saline stratification is also correlated to greater stratification of water quality, irrespective of use, as can be seen in the examples given in FIGS 5 and 6.

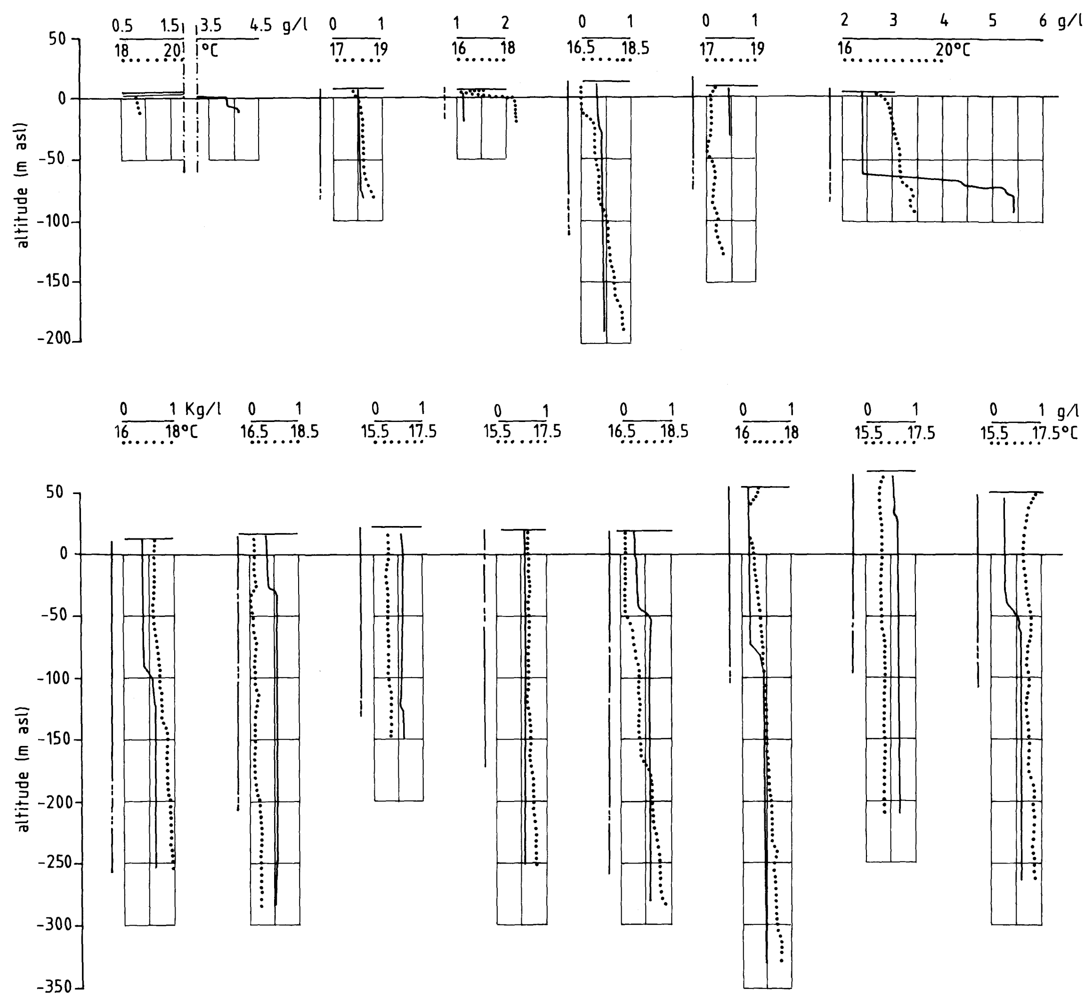


FIG. 5. Some examples of most representative thermometric and saline logs of coastal and inner areas of Murgia.

In terms of salinity and, more generally speaking, in terms of water quality, it is understood that a great deal depends upon the level at which a recording is made, or a sample taken, since along the same vertical axis very high quality water can give way to unusable water. This is an aspect which clearly shows how important correct and appropriate design and construction of groundwater tapping work is, if the well, is to be used as an instrument for the rational use of water resources, whereas this work up until now has been left in the hands of unskilled technicians.

When carrying out the calculations which led to the mapping presented below, at each specific depth, the mean concentration of each individual parameter chosen was taken into account. Then for each well, the peak mean and the lowest mean concentration recordings were taken, hereinafter, for the sake of simplicity, denominated the best and worst concentration levels for each well.

In order to establish terms of reference for comparison in the definition of the qualitative status of groundwater resources, reference was made to the Italian law D.Lgs. February 2nd, 2001, n. 31) which is a transposition of EU Directive number 1998/83, covering water quality for human consumption. In particular, reference was made to the ‘parameter values’ pertaining to a number of ‘indicator parameters’ for use as potable water, as per the provisions of the law.

In order to assess the drop in quality due to saline pollution, a mapping of the salinity in terms of TDS was carried out, which also shows the marine origin of the salinity; also chlorine ions were mapped, using the kriging technique, on 1996 data (FIGS 7, 8 and 9).

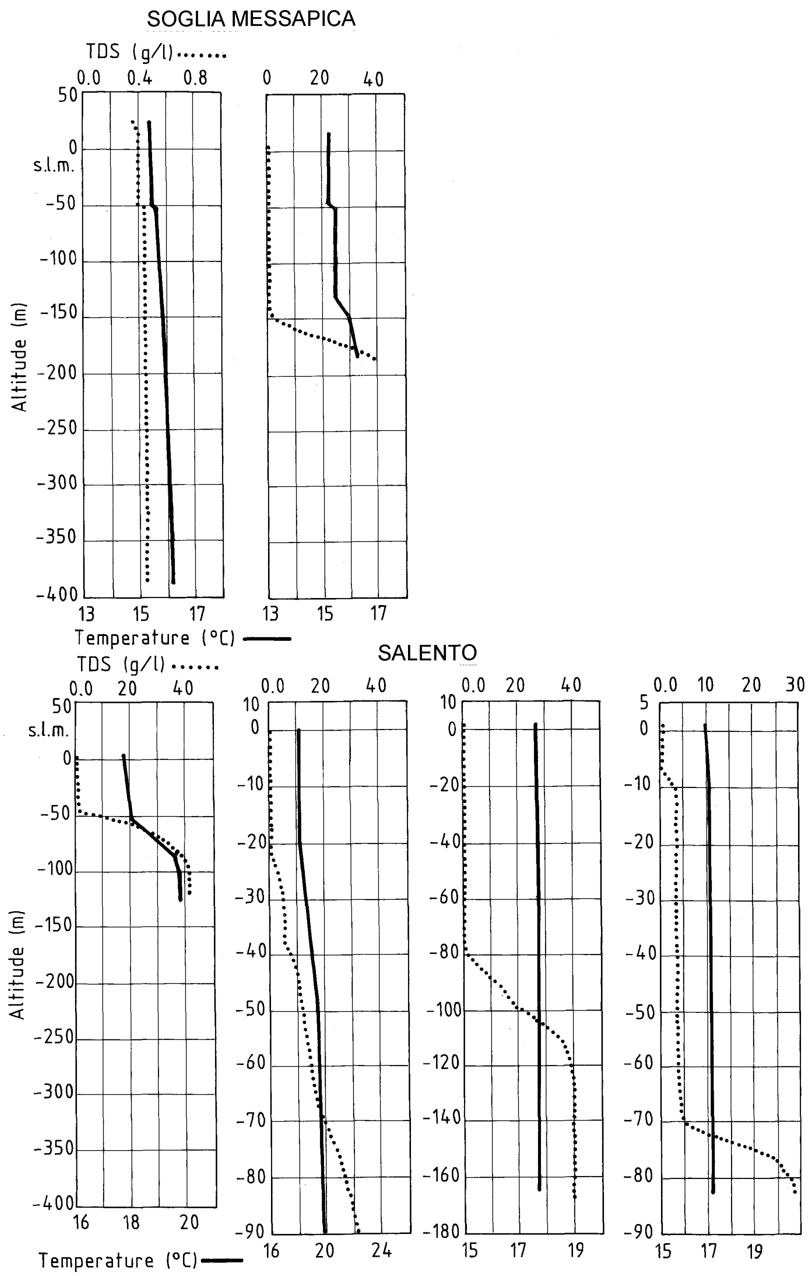


FIG. 6. Some examples of most representative thermometric and saline logs of coastal and inner areas of Soglia Messapica and Salento.

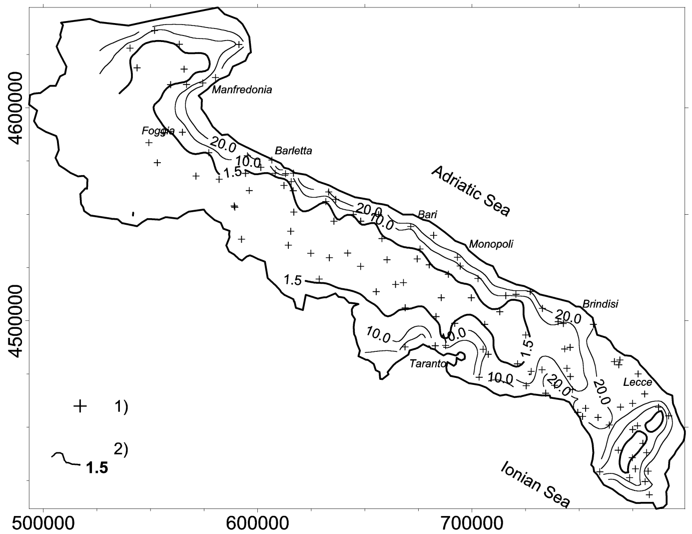


FIG. 7. Salinity map (g/l), peak or the worst concentration along each well (COTECCHIA & POLEMIO, 1999). LEGEND: 1) Well; 2) saline contour line (the line corresponding to the drinking water threshold is thicker).

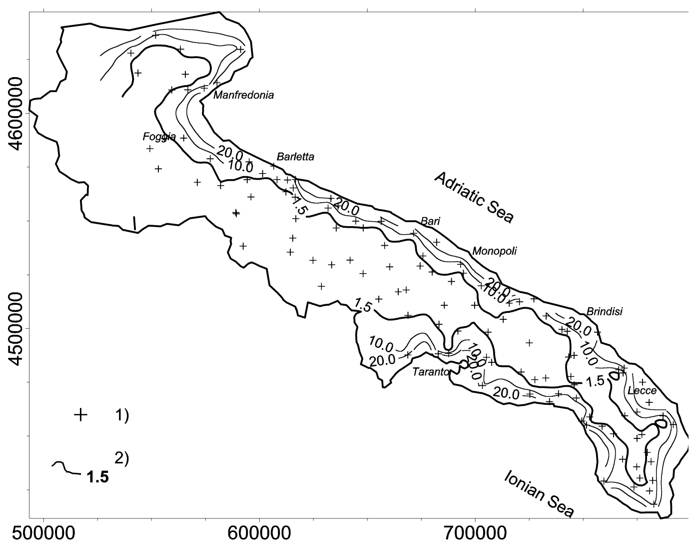


FIG. 8. Salinity map (g/l), minimum or the best concentration along each well (COTECCHIA & POLEMIO, 1999). LEGEND: 1) Well; 2) saline contour line (the line corresponding to the drinking water threshold is thicker).

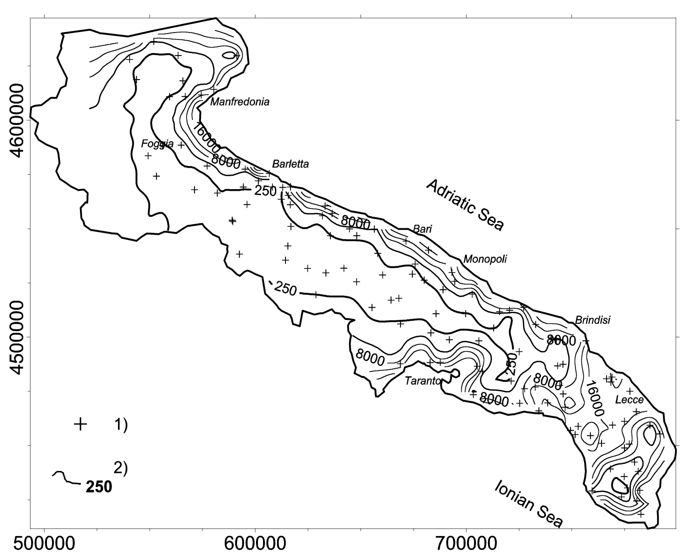


FIG. 9. Chlorine concentration map (mg/l), peak or the worst concentration along each well. LEGEND: 1) Well; 2) chlorine concentration contour line (the line corresponding to the drinking water threshold is thicker).

FIGURES 7 and 9 show that water of quite acceptable quality, bounded by 1.5 g/l of salt contour line and 250 mg/l of chloride contour line, can be found in the Murgia, where the effects of seawater intrusion are felt only along a narrow coastal strip, and in the Gargano. Seawater intrusion has dramatic effects on Salentine groundwater. Much of the Salentine region bears the effects of intense saline pollution, which per se reduces the quality of groundwater to the point at which is it no longer potable. Only moderate improvement is effected when taking into account the findings from data from samples of freshwater waters taken along each vertical axis, as is the case in FIG. 8.

When considering 1.5 g/l of contour line, it is important to note that in FIG. 7, there is a break in the contour line from the Murgia to the Salento; the break disappears in the case given in FIG. 8. Basically, the salinity variation from Murgia to Salento, as evidenced in the so-called "Soglia Messapica", is of great hydrogeological importance. In the former case, the contour line is interrupted at the southern rim of the Murgia; in the latter case, it recedes with regard to both coastlines but does indeed continue, joining the Murgia and Salento areas.

The area circumscribed by the 250 mg/l chlorine contour line extends from the Gargano to the Murgia, where it recedes from the Adriatic coastline, as it does in a few scattered areas of the Salento (FIG. 9).

### *Seawater intrusion in the Gargano*

The main (E-W) axis of the Gargano promontory corresponds more or less to the main watershed for the groundwater flow. The groundwater flows more or less everywhere under pressure, in an aquifer which is at times even more than 100 m under sea level. At the levels in which groundwater flows, there are carbonate rocks which are highly permeable due to fractures and to karst phenomena. Rock permeability may vary from very low to moderately permeable exclusively due to fractures along almost the entire southern coast and up to the easternmost spur. From that point to the northern coastline can be found rocks which are, to all intents and purposes, impermeable. The rest of the coastline has rocks whose degree of permeability ranges from moderate to high.

The fact that the Gargano rocks are of varying degrees of permeability affects seawater intrusion. Saline pollution is detectable only close to the coastline, most particularly along the strip adjacent to the Tavoliere, both in the SW portion (the area around Manfredonia) and in the NW portion (in the Lesina-Varano area), a zone noted for the existence of two very large lagunas. In the inland Gargano up to a few kilometers from the coast, groundwater salt concentrations are generally lower than 0.3-0.5 g/l (GRASSI & TADOLINI, 1996b). Conversely, in the marginal and coastal areas of the promontory, salinity can reach levels of 4-5 g/l. In the SW area, in particular, groundwater salinity is very much influenced by the effects of underground feeds from a very deep aquifer located in the Tavoliere; this groundwater feed contains notable salinity levels abated only due to dilution with fresh Gargano groundwater, which comes from the central Gargano, a recharge area.

It must also be noted that, due to several fault systems near the Gargano-Tavoliere boundary and which therefore use highly complex and deep water paths, the promontory drains the warm saline water (salinity 27-28 g/l) found in the Mesozoic carbonate rocks in the Tavoliere, buried beneath 500-2000 m of Quaternary soils. The deep Tavoliere groundwater flows into the fresh groundwater of the Gargano and mixes with saline water due to marine and/or lake intrusions. Though the deep groundwaters of the Tavoliere are not of recent origin, they are quite similar to the water of the current seawater intrusion.

The main factors affecting saline pollution risks of the Gargano groundwater, which are not factors found in the Murgia and the Salento, are the following:

- the presence of brackish water lagoons close to sizeable springs;
- the feed of saline water from the Tavoliere;
- the two sources of saline pollution - seawater intrusion or lagoon intrusion and underground feeds - affect the entire perimeter of the hydrogeological unit;
- outcropping permeable Mesozoic carbonate rocks located both on the surface and deep underground (accounting for about 25% of the Gargano) are quite common, particularly along one portion of the coastline;
- there are extensive inland areas (about 20%) of the promontory which are very permeable with very frequent karst formations such as sink-holes, swallow-holes and chasms, forming extensive endorheic regions.

Clearly, for both sources of pollution, tectonic features control saline pollution. Moreover, unlike what happens in the Salento and – to a far lesser extent – in the Murgia, the aquifer is almost always below the mean sea level.

In terms of human use, it should be noted that the rate of groundwater use is still low and sustainable in terms of hydrological equilibrium. Samplings from wells are significant only near the coastal areas, since in the hinterland the high altitude, in conjunction with low human density leads to conditions which are not conducive to intense use.

### *Seawater intrusion in the Murgia and the Salento*

Use of groundwater in these cases is quite high and, generally speaking, disproportionate. Water is supplied from several hundreds of thousands of wells, with a mean well density throughout the area of ca. 5-6, at times even 10-12 wells/km$^2$. This is tantamount to intensive exploitation of groundwater, and throughout the region there are cases of what can only be termed overexploitation, which is even more intensive and widespread in the Salentine peninsula.

Irrespective of use, there is a marked change for the worse in terms of susceptibility to saline pollution when going from the Murgia to the Salento (GRASSI, 1974, 1983;

GRASSI *et alii*, 1977; GRASSI & TADOLINI, 1992, 1996; POLEMIO & LIMONI, 2001). Indeed, marine contamination in the Murgia is far and away lower and consistently limited exclusively to a very narrow coastal strip, usually varying in width from 2-3 km at its narrowest to 10-14 km at its widest (FIGS 3, 7 and 8). It should also be noted that upward this strip, saline concentration is consistently low (0.4-0.6 g/l) down to extreme depths, as much as 500-900 m below sea level (FIG. 5). This salinization phenomenon is so widespread throughout the Salento that it is only in very small sections of the hinterland that groundwater is still freshwater, with a degree of salinity not exceeding 0.5 g/l. Throughout the rest of the area, salinity levels are much higher, mainly around 2-5 g/l, even in the hinterland, whereas along the Adriatic and Ionian coastal strips salinity can reach levels of 10 g/l or even higher. This phenomenon leads to an enormous saline stratification, as can be seen even in wells which are only moderately deep (FIGS 6, 7 and 8).

It is to some extent likely that, given current hydrogeological conditions, the salinization of the Salentine groundwater can be considered a permanent one, both in terms of its size and its spread. This can be demonstrated by taking into account the evolution over space and over time of sea contamination (POLEMIO & LIMONI, 2001). It is, therefore, of some use to quantify the speed with which groundwater salinization spreads over the area and/or increases in intensity in the same point.

Once a contour line of 0.5 g/l has been chosen as a reference baseline, since it is a simple threshold value between on the one hand, low salinity water, which is to all intents and purposes free of any significant saline pollution, and is thus freshwater groundwater in the truest sense of the term, and on the other hand the groundwater entering into contact with marine intrusion waters, then one can record the receding, advancing or in some cases even the disappearance of the contour line of 0.5 g/l over the course of about 20 years (FIG. 10). In the Salento, the receding of the 0.5 g/l contour line can occur at a rate of 0.2-0.6 km/year, whereas in the Murgia the speed of recession does not exceed 0.3 km/year.

There is also evidence that an enormous portion of the aquifer has been affected by seawater intrusion (over the course of 20 years of observation), in that salinity has consistently exceeded 0.5 g/l (dotted line area in FIG. 10). This area is a coastal strip of the Murgia. In the Salento area, however, this would cover not only a generally larger coastal strip but would also continue right into the Adriatic and Ionian coasts, except for “islands” in the central-southern section of the Salento area. This occurs where there is a greater susceptibility to seawater intrusion. The distance between the two coasts is very short (about 32 km), whereas the distance from the transfer feed areas from the Murgia is great, the latter occurring in the inland and central-southern areas, where Mesozoic limestone outcroppings occur at altimetric peaks, which correspond to rainfall peaks in the peninsula.

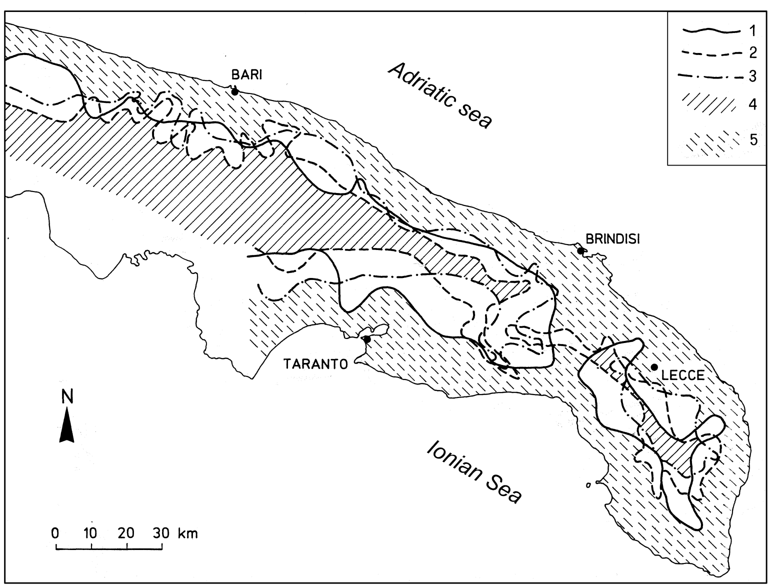


FIG. 10. Map of 0.5 salinity contour line modifications (POLEMIO & LIMONI, 2001). LEGEND: 1) 1997; 2) 1989 and 3) 1981 contour line; 4) salinity always less than 0.5 g/l; 5) salinity always greater than 0.5 g/l.

There is, moreover, a portion of the aquifer which is constantly fed by fresh groundwater, which of course must be protected in the future. In the Salento, this section of the aquifer is directly connected to the main area of direct recharge, which is much smaller than the Murgia area.

Lastly, there is a portion of the aquifer in which the presence of contamination is a function of time. In other words, there is a vast area where the quality of groundwater depends upon our ability to make a balanced and rational use of this natural resource; we must clearly take into account weather variations and the effects of these variations on recharging.

Hundreds of lab tests have yielded the optimum linear correlation between salinity and chlorine ion concentrations (correlation coefficient equal to 0.98). Over the course of about thirty years, data has been collected on chlorine ion concentration, on the basis of the study of 18 working wells for potable water in the Murgia and in the Salento between 1970 and 1998. A range of between 21 and 27 sets of data have been used on a yearly basis for each well (TABLE 1). For each well, a regression line has been established (TABLE 1 and FIG. 11).

Thus, it was possible to establish in quantitative terms what current trends are. The result was obtained by defining the angular coefficient of the regression lines (TABLE 1). It should be noted that the values of this parameter are, in the main, positive; in other words, water salinity is rising everywhere. This trend is practically equal to zero in well 1, which is protected from seawater intrusion, while it reaches peak values for well 2, situated along the coast. Both these wells are in the Murgia.

TAB. 1. Statistics concerning chlorine concentration of monitoring wells (see FIG. 1) (POLEMIO & LIMONI, 2001). LEGEND: AQ) aquifer; M) Murgia; S) Salento; SA) shallow aquifer; minimum, average and maximum chlorine concentration as mg/l; AC) angular coefficient of regression line (mg/l year).

| **WELL** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AQ** | M | M | M | M | S | S | S | S | S | S | S | S | S | S | SA | SA | S | M |
| **Min** | 11 | 11 | 11 | 11 | 14 | 57 | 74 | 71 | 50 | 163 | 156 | 195 | 163 | 50 | 14 | 11 | 103 | 11 |
| **Average** | 29 | 292 | 29 | 38 | 172 | 276 | 107 | 131 | 97 | 207 | 197 | 226 | 196 | 76 | 53 | 35 | 347 | 46 |
| **Max** | 50 | 961 | 53 | 82 | 263 | 398 | 259 | 263 | 142 | 252 | 256 | 270 | 263 | 135 | 213 | 114 | 455 | 156 |
| **AC** | 0.05 | 25.7 | 1.06 | 1.71 | 2.97 | 4.49 | 2.10 | 5.18 | 1.84 | 3.89 | 1.93 | 1.70 | 1.92 | 2.44 | 1.56 | 0.21 | 1.03 | 0.89 |

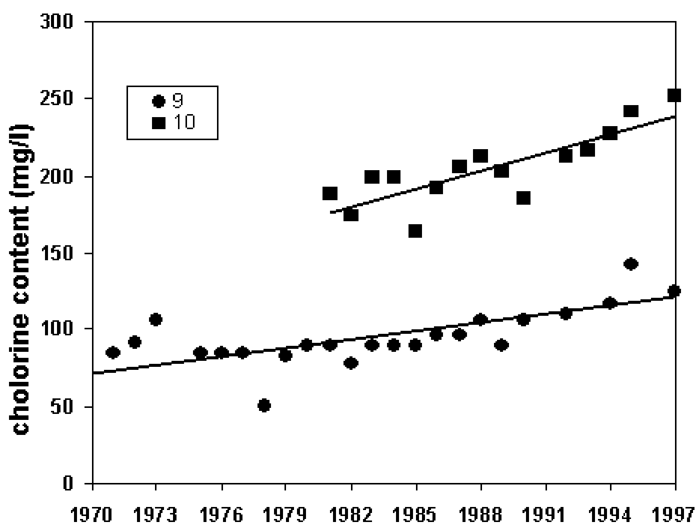


FIG. 11. Chlorine concentration trend of Salentine wells number 9 and 10 (POLEMIO & LIMONI, 2001).

As far as the Murgia is concerned, the chlorine concentration at well 3, situated along the northern coast, has progressively increased, from 10 mg/l to over 50 mg/l during the course of the nineties. All data collected so far confirm that the situation is quite serious in this area, where the ongoing recession of the 0.5 g/l from 1981, together with the progressive increase in chlorine concentrations, suggest that a worrying process of water salinization is underway which cannot be reversed in the short term. Well 4, which is situated on the outskirts of Bari, shows discernible variations of chlorine concentration over time, with a progressive chlorine rise from 1985 to today (TABLE 1). The situation at well 2 is dramatic. From the early 1980s on, the concentration has risen sharply, reaching a peak in 1995 of 1000 mg/l. This case presents a peak angular coefficient of the regression line (TABLE 1). Well 1 is inland and is thus never subject to marine contamination, and so salinization trends are absent or zero.

In the Salento area, chlorine concentration at well 7, which is distant from both seas, remained more or less constant up until 1991. The situation at wells 5 and 6, however, is quite disturbing. At well 5, concentration levels went from ca. 200 to 250 mg/l, with uneven trends during the years from 1975 to 1982, whereas at well 6 there was a marked rise in levels, from an average of 300 mg/l during the seventies to 400 mg/l during the nineties. The three wells are situated in an area where salinity and chlorine content vary widely in terms of time and space, as can be seen by the marked point to point fluctuations of the 0.5 g/l contour lines. This would appear to be mainly due to the widespread tapping of groundwater by wells.

Well 8 is in the central area of the Salento, where the 0.5 g/l levels receded markedly and chlorine concentration went from ca. 100 to 250 mg/l, rising sharply during the nineties. This is the well which established the second value in decreasing order of the trend. There is a similar situation, though less marked, in the area of wells 14 and 9 (FIG. 11). As far as the southern areas of the Salento are concerned, wells 10-13 along the Ionian sector show to varying degrees an ongoing rise in chlorine concentrations (FIG. 11). This fact is consistent with the observations made during the 1989-1997 period, when there was a sharp drop in the 0.5 g/l contour line in the area.

The Salentine groundwater is highly susceptible to saline pollution by its very nature, due to a number of factors, such as the aquifer's high susceptibility, the low piezometric levels, the fact that the fresh groundwater body is not very thick (at most about 100 m thick with a mean thickness of ca. 30 m) and the fact that from a geographical point of view it is a peninsula surrounded on three sides by seas, which influences outflow directions, the groundwater body geometry and distance from the sea (always quite close, at most 20 km).

Taking human activities into account in the Salento, tapping groundwater by wells is quite risky in that, even inland, groundwater may become saline from seawater below it, at a depth which a number of wells may reach, something which does not occur in the Murgia (FIGS 5, 6 and 7). Indeed, a tendency towards the expansion and lifting of the transition zone has been observed, which often precludes a complete salinization of the entire well water vertical axis (Cotecchia *et alii*, 1974).

The isothermal maps (FIG. 3) confirm this picture. In the inland Murgia, groundwater temperature is clear proof that seawater has almost no impact on the groundwater (14.5-16 °C). The 17 °C contour line and the 0.5 g/l contour line taken together clearly show that seawater penetrating into the continental area has a direct physical and chemical impact on groundwater only along a very narrow strip of coastline.

The Murgia groundwater would appear to be less exposed to the risk of degradation due to seawater intrusion for a number of reasons: the piezometric height is greater, the fresh groundwater body is thicker, the aquifer is less permeable, groundwater is less mobile, there is only one side exposed to the sea and the distance from the sea itself is generally greater, at times as much as 50 km and more (FIGS 3, 5, 6 and 2).

The Murgia carbonate shelf has a different degree of permeability, which is important. The permeability is overall lower and not homogenous, with a highly variable vertical axis. Often, permeability is very low for several hundred meters, down to depths below sea level, where often the aquifer proper lies. It is only along a very narrow strip of coastline that permeability rises and can be considered comparable to that of the Salento (FIG. 2). The fact that it is less permeable overall is a contributing factor – together with other factors such as different boundary conditions – towards maintaining elevated piezometric levels. Therefore, the Murgia is less apt to suffer from seawater intrusions; this is clearly due to the different tectonic and karst conditions applying over time to the groundwater network.

The situation is more serious when taking into account man-made factors as opposed to natural phenomena. In the Salento, observations from abstraction wells is indeed easier and more necessary. It is easier and cheaper because wells are less deep, with greater flows and the depth to groundwater is lesscompared to the Murgia. It is more necessary because there are fewer alternatives available for the water supply, given the fact that the main non-local water sources are much further away. It is therefore not surprising to note that there is increasing use being made of groundwater in the Salento, for a number of reasons: the increasing frequency of periods of drought (COTECCHIA *et alii*, 2003; POLEMIO & DRAGONE, 2004), the general downward trend in terms of piezometric levels, the upward migration and expansion of the transition zone, which often leads to the complete salinization of the entire groundwater thickness; high well density, which promotes upconing. All these factors lead to higher risks of deterioration due to saline pollution throughout the entire region.

## Conclusion

These case studies of seawater intrusion in coastal carbonate aquifers in the Apulia region were carried out bearing in mind both the predisposing factors and the determining ones. Amongst the most important predisposing factors are the sedimentation environment, the tectonic-karst evolution, the geometry of the aquifers in relation to the coastline, the depth of the aquifers, the existence of underground outflows, groundwater chemistry and the distribution of piezometric levels.

The aquifers are by their nature susceptible to saline pollution due to seawater intrusion. The effects of intensive use have been studied: it has led to a progressive deterioration in water quality, particularly in the Salento area, precisely where the aquifer is most susceptible to seawater intrusion.

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