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Monitoring and methods to analyse the groundwater quality degradation risk in coastal karstic aquifers (Apulia, Southern Italy)

M. Polemio, V. Dragone, P.P. Limoni

CNR-IRPI, Italy, Via Amendola 122/i, 70126 Bari, Italy,

m.polemio@ba.irpi.cnr.it, telephone +39 080 5929584 fax +39 080 5929610

Abstract

A multi-methodological approach based on monitoring and spatio-temporal analysis of groundwater quality changes is proposed. The presented tools are simple, quick and cost-effective in order to be give service to all sorts of users.

The chief and simplest purpose of the monitoring network is the detection of the piezometric or potenziometric level in the aquifer. The spatial and multi-temporal analysis of usual chemical and physical data provides both an assessment of the spatial vulnerability of the aquifer to seawater intrusion, defining a salinity threshold between fresh groundwater and brackish groundwater, and of the water quality trend in terms of salinity. The evaluation of the salinity trend or of salinity-correlated parameters highlights the effects of groundwater mismanagement. The multiparameter logging provides a rapid groundwater quality classification for each well. The whole approach allows evaluating the effects of current management criteria and designing more appropriate management targets.

The Apulian karstic coastal aquifers have been selected as a case study (southern Italy). Three types of aquifer zones can be distinguished: i) areas with low vulnerability to seawater intrusion, ii) areas with high vulnerability, and iii) areas with variable vulnerability in which the salt degradation largely depends on the ability to manage the well discharge. The water quality degradation caused by seawater intrusion appears to be a combined effect of an anomalous succession of drought periods observed from about 1980 onwards and increased groundwater pumping, particularly during drought periods. A management criterion based on aquifer zones is proposed.

Keywords: karstic aquifer, groundwater degradation, seawater intrusion, monitoring

1. Introduction

Karstic aquifer and environment are highly vulnerable to contamination and to anthropogenic modifications.

Karstic aquifers are well known for their specific vulnerability to contamination, due to their particular characteristics such as thin soils, point recharge in dolines and swallow holes and hydraulic conductivity (COST 2003). The residence time of groundwater in these aquifers is generally short and consequently contamination propagates and occurs in a much faster way than in non-karstic aquifers (Kaçaroglu 1999). Therefore, groundwater sampling in karst should be more frequent, especially in the wake of storms, rainy periods or snowmelts, rather than being carried out on a regular monthly or seasonal basis (Vrba 1988).

In Apulia (Southern Italy) the anthropogenic modifications are mainly caused by two types of activity: in addition to the direct pollution from agricultural activities, farming improvements can provoke other negative impacts. Forest and stone clearing due to the advent of machinery have been widely carried out to provide land suitable for farming. Quarrying destroys the epikarst and very often causes the destruction of caves. Other detrimental effects can be related to the wrong management of water resources or of flood risk. The drawdown of the water table and the use of sinkholes for the evacuation of flood waters can trigger the formation of sinkholes (Burri et al. 1999; Parise and Pascali 2003; Selleri et al. 2003). Groundwater vulnerability generally increases as the top soil protection is removed and, in quarry areas, as water depth is reduced. The effects on groundwater availability and quality are complex and generally negative.

In many European countries, 50 % of the drinking water supply comes from karstic aquifers and in many areas like in the Apulian region it is the only available source of fresh water (COST 2003). Runoff yield is generally ten times greater than groundwater flow (UNESCO 2004) except in karstic areas, where the latter prevails. This is the case of the Apulian karstic areas, particularly the Murgia plateau and the Salento lowlands, where the modifications of coastal karstic groundwater discharge may have severe effects on the hydrological and ecological equilibrium of the sea and of coastal wetlands (UNESCO 2004).

Coastal karstic aquifers are also vulnerable to salinization caused by seawater intrusion, including upconing effects. This is a common problem in the Mediterranean coasts and in other coastal areas around the world (COST 2005). The main factor that determines the relative position and movement of fresh groundwater and saline seawater is the density difference. In porous aquifers the seawater intrusion forms a saline wedge below a transition zone, mainly due to the dispersion effect on fresh groundwater (Fleury et al. 2007). The Ghyben-Herzberg traditional approach provides the simplest analytical description of this phenomenon: given that fresh and saline waters are immiscible fluids under hydrostatic conditions in a porous aquifer, the depth of the net interface from sea level is a simple function of both water densities and of the piezometric head (Fleury et al. 2007). A dynamic and more realistic approach would also take into account the effect of the freshwater discharge (Glover 1959). Many case studies of karstic coastal aquifers have shown that fresh groundwater can circulate below sea level, and that intruded seawater can rise above this level when mixed with fresh groundwater (COST 2005). This means that the relationship between fresh/saline groundwater is generally more complex in coastal karstic aquifers than in other types of aquifers (COST 2005; Fleury et al. 2007).

The per capita consumption of fresh water is increasing worldwide while coastal areas are attracting growing numbers of people. These circumstances together with the effects of climate change and groundwater contamination are putting an increasing stress on water resources (Pos 2005), especially in terms of the degradation risk to coastal and karstic groundwater. The heterogeneity and anisotropy of karst aquifers, the diffuse and intense discharge of water through wells and the huge complexity of the different quality degradation phenomena, pose limits to groundwater flow modelling on a regional scale, for management purposes. Monitoring the groundwater in karstic and coastal aquifers is essential in order to determine groundwater degradation and to define management criteria. If the focus is on the effects of seawater intrusion, monitoring may consist of both indirect and direct methods (Melloul and Goldenberg 1997). Indirect methods are mainly based on geophysical approaches, such as geoelectromagnetics and, more specifically, the time domain electromagnetic method (TDEM) used for coastal and karstic aquifers in Israel (Kafri and Goldman 2005). Direct methods include measuring groundwater salinity profiles or logs and groundwater sampling from wells. The former methods are extremely interesting but demand costly equipment and highly trained staff. These are the reasons why they are unlikely to be used for periodic, long-lasting and widespread assessment of salinization and seawater intrusion trends.

The latter methods are more suitable for managing a sustainable exploitation of karstic groundwater. A multi-methodological approach based on direct measurements is presented. It is based on simple and cost-efficient measurements and analyses that can be clearly grasped not only by scientists or qualified staff of private companies, but also by public institutions, associations and professionals. The proposed approach consists of: (1) a hydrogeological monitoring network; (2) spatial and multi-temporal analysis; (3) analysis of salinity or of salinity-correlated parameter; (4) multiparameter logging for rapid groundwater quality classification. The Apulian karst (southern Italy) is proposed as a case study in which piezometric head, salinity, chloride concentration, specific electrical conductivity, temperature, pH, Eh and dissolved oxygen constitute the data analysed.

2. Methods

Subaerial springs would be the most convenient monitoring points in the lowlands of coastal karst aquifers. Surface streams, swallow holes, sinkholes, monitoring boreholes, piezometers and wells may integrate the monitoring network in the upland part of karst regions (Vrba 1988; Kaçaroglu 1999). Due to unavailability or inaccessibility of water, as is typical of karstic territories, monitoring should be continuous or regular in boreholes and springs and irregular at the other locations. The proposed methodologies may be applied to all these sites in order to define monitoring points for the observation of groundwater.

The salinity of water (mg/L) can be determined through a number of methods. These include in increasing order of complexity (Jousma 2006):

- measuring both the specific electrical conductivity (SEC) and the temperature (T), extrapolating salinity with a statistical correlation or through calibration curves defined on the basis of the specific chemical groundwater composition;

- determining the amount of total dissolved solids (TDS or salinity);
- determining the concentration of major ions by means of chemical analysis and calculating the weight of salts.

The first method may be applied on site and in wells. The second and third methods are typical laboratory methods.

2.1 Hydrogeological monitoring network

Hydrogeological monitoring by means of a permanent network control points in boreholes and springs is the basis for all activities pertaining to the management and the safeguarding of groundwater resources (WMO 1994; UNESCO 1998). In the case of coastal karstic aquifers, a modern and affordable solution could be to make use of springs and boreholes, the diameter of which should be as narrow as possible in order to minimize the effect of density gradient on the measurements. Electric probes should be used to measure the piezometric level, water temperature and SEC, which should be regarded as the basic group of parameters. A minimum of one to four daily measurements should be recorded. It should also be possible to download data using hand-held units or data could be accessed by means of a telemetry system, based on phone, radio or satellite communications (WMO 1994). Piezometric measurements enable to determine the variable effects of recharge and well discharge on both groundwater availability and on groundwater outflow into the sea. This is highly relevant as any drop in availability and/or outflow increases the risk of negative seawater intrusion effects (Glover 1959). Salinity could be roughly determined by measuring SEC and temperature, taking into account several depths or water levels, mainly in order to determine the depth and thickness of the transition zone, along with the salinity and the potenziometric level of the fresh and saline groundwater. The determination of salinity and temperature enables the water density and the potenziometric level to be calculated.

The underwater equipment should be designed considering the specific chemical characteristics of the saline groundwater. The materials and technologies selected should be as durable as possible. In order to keep low the cost of each monitoring location or to increase their density, public, private and abandoned wells could be used. In this case the frequency of measurement could be limited to discharge periods. Furthermore, a detailed financial plan for the long-term maintenance and management of the network should be included. In any event, setting up and running a protracted, affordable and efficient management of the quality monitoring network is not an easy task, mainly because of the high cost of each measuring point, whether it will need to be bored to become part of the network, and the on-going maintenance of the network as a whole (USEPA 1989; Jousma 2006). Possible consequences are a dearth of regional network monitoring points, which is a huge problem for coastal karstic aquifers which require higher-density measurements than non-karstic aquifers, insufficient measuring frequency and/or a brief monitoring period.

New or recently set up quality networks leave no time for seawater-intrusion monitoring, for plotting its effects, trends and/or quality degradation risks because the monitoring periods are too short while long time series are needed. These difficulties can be overcome by integrating methods which use historical data taken from monitoring points and private or public pumping wells as in the case of the two proposed tools that follow. These methods can improve the data set also if the density of monitoring points and the time frame for measurement are not a huge problem. In both cases, the proposed approach should obtain the highest local spatial density of data points and the longest measuring period as possible. The quality of historical data and network monitoring data should be carefully evaluated (WMO 1994; Jousma 2006). Location, diameter, depth and screen position of wells, type and date of sampling and the method of parameter measurement all need to be considered as part of the validation process. After the validation process has been completed, low quality data should be obviated.

2.2 Multitemporal spatial analysis of the groundwater salinity

The spatial and temporal analysis of seawater intrusion effects on groundwater quality is made easier when a simple criterion to define the effect existence can be established. The criterion is based on a threshold approach or on the determination of a value discriminating between fresh or seawater-contaminated groundwater. The threshold must be determined considering the local hydrogeological conditions, the specific chemical-physical characteristics of rainfall and of dry deposition (deposition of particulate from the atmosphere onto the ground surface in the absence of rainfall), the geochemical nature of rocks, and any local natural factor that might determine the variability of fresh groundwater salinity. If one takes a hypothetical and simplified coastal karstic aquifer and focuses on water salinity modifications from rain water to groundwater outflow, water salinity tends to increase the closer it gets to the sea. The salinity of rain water generally increases slightly when it begins to infiltrate and flow through the topsoil, where there is a natural accumulation of salts, also due to dry deposition typical of coastal areas. Once this water arrives in the saturated zone, its salinity generally increases very slightly along the flow path, mainly because it mixes with older groundwater and because of water/rock interaction processes. There is only a significant increase in salinity where the groundwater flow approaches the sea and fresh and saline groundwaters mix due to seawater intrusion. The salinity threshold value should be defined in order to differentiate fresh groundwater from the rest. The 75 percentile or the mean plus a standard deviation of salinity of pure fresh groundwater could constitute reliable choices.

Multitemporal spatial analysis of salinity is a method based on the spatial determination of the salinity threshold obtained by plotting the contour line of the salinity threshold value. The threshold contour line (TCL) at time t divides the aquifer into two portions, which change as t varies: The upper one, including the recharge areas, where pure fresh groundwater flows, and the lower portion, bounded by the coast, where groundwater flowing towards the sea becomes progressively contaminated by seawater. Spatial analysis tools are essentially based on traditional geostatistical methods such as kriging, which uses georeferenced point values (Deutsch and Journel 1992). The simplest way to highlight the advancement or the regression of seawater intrusion effects on groundwater is to determine the threshold contour line and to compare the distribution of the TCL taking into account a number of multi-temporal determinations.

A sound analysis of the salinity trend requires regular and long-lasting measurements. In the absence of reliable salinity time series, the tool considers that a very high linear correlation should exist between some parameters, such as SEC or the concentration of some ions, and the salinity of groundwater affected by seawater intrusion. A very simple schematisation of the salinity variations of groundwater flowing in a coastal aquifer with homogenous hydrogeological and geochemical conditions might be: roughly, for SEC<700 µS/cm at 25 ºC, the groundwater may be considered fresh and the major ions determining the salinity are chloride and bicarbonate; for SEC>700 µS/cm at 25 ºC, chloride alone is usually sufficient to estimate the salinity of the water (Jousma 2006). Chloride concentration and SEC, expressed at a reference temperature, are two reliable parameters often used to estimate salinity or to assess seawater intrusion effects (Spechler 1994; Larabi et al. 1999; Maimone 2002; Barrocu et al. 2005).

The concentration of some ions is traditionally determined by private parties for various reasons. In many countries it has been compulsory for decades to determine the concentration of ions, sometimes on a daily basis, when groundwater is supplied for drinking purposes. The best parameter for assessing variations in salinity should be selected, case by case, considering the advantages and disadvantages from a geochemical and statistical point of view. Once reliable time series are obtained, the salinity trend and its local variability can be determined.

2.3 Multiparameter logging for classifying the groundwater quality

The use of a down-hole probe equipped with temperature, electrical conductivity and pressure (P) sensors is quite an attractive proposition for use in any kind of monitoring point and in many hydrogeological conditions; this type of logging is quick, relatively inexpensive and the results are available in real time. It also provides various kinds of information, such as the effectiveness of well purging, the rate of groundwater movement, the locations of transmissive fractures and the stratification of salinity (Cotecchia 1977; Michalski 1989; Tulipano and Fidelibus 1989; Keys 1990; Cotecchia et al. 2005). P or the water depth, T and SEC should be considered the minimum number of parameters in the case of multiparameter logging in coastal aquifers. Where the transition zone is observed, the multi-parameter logging provides useful information on the depth and thickness of the transition zone, which are commonly variable for karstic coastal aquifers (Cotecchia 1977). It has been observed that fluctuations of the transition zone are almost negligible near the coast and increase by tens of meters as the distance from the coast increases. Far from discharging wells or point affected by anthropic alterations, fluctuations are closely related to alternating periods of recharge and depletion of the aquifer.

Multi-parameter probes with a large number of sensors can be used nowadays with no appreciable increase in probe diameter or cost related to the technology upgrade. Van Meir et al. (2005) experimented the use of T, SEC, pH and dissolved oxygen (DO) logging in a test site made up of 6 boreholes, each having a 101 mm diameter in a coastal limestone aquifer. Cotecchia et al. (1999) used multi-parameter logs in hundreds of wells, simultaneously measuring P, T, SEC, DO, pH and Eh of groundwater. They operated in four adjacent hydrogeological structures in the Apulian region, three of which are of karstic coastal type. They proved that it is possible to recognise (specific and typical) vertical trends of the selected parameters for each natural hydrogeological condition of an aquifer, in the portion bored by the well. When, after an initial detailed survey, a certain type of trend is recognised for a portion of the aquifer it then becomes easy to determine a simple method for monitoring and classifying that groundwater. Commonly, each typical trend is almost recurrent in space and time in that portion of the aquifer as long as the natural conditions are not modified by anthropogenic activities. These types permit the preliminary detection of hydrogeological conditions in new bored wells; thus the question of whether the groundwater quality is natural or has been modified by seawater intrusion or anthropogenic pollution can be inferred, and a preliminary and qualitative evaluation of the quality degradation level can be made. This may be particularly useful for periodic monitoring purposes, since these surveys are simple, quick and cheap to carry out when the relevant boreholes have already been made for other purposes. In this case, a minimum of one to four annual loggings should be carried out for each point.

Multi-parameter logging based on P, T, SEC, pH, Eh and DO can provide a preliminary description of the chemical-physical characteristics of groundwater over a wide range of hydrogeological and geochemical conditions. Other specific parameters could be added to take into account specific local hydrogeological or anthropogenic conditions. In the absence of sharp changes, the parameters should be determined at maximum measurement interval of 0.5 m, moving downwards from the piezometric surface to the bottom of the hole. Particular attention should be paid to the descent velocity, generally less than 2 m per minute; but in any event as low as necessary to avoid modification of the groundwater quality stratification, as in the case of the transition zone, and to allow the stabilisation of measurements, taking only the permeable and screened portion of the wells into account.

3. Geological and hydrogeological setting of the test area

The Apulian karstic aquifers are made up of Mesozoic rocks of the Apulian foreland (Fig. 1). After the Late Miocene uplift, with the onset of the Pliocene transgression, Apulia started to acquire present shape, particularly during the Pleistocene, when the extensive sedimentation areas which lie between the Gargano, the Murgia and the Apennines and between the Murgia and the Salento were largely filled with clastic deposits (Beneduce et al. 2004).

The Apulian platform emerged at the end of the Cretaceous and became part of the foreland of the South-Apennine chain. It was composed of three structural domains: Gargano, Murgia and Salento. These structural highs were transformed into islands due to subsidence set off during the middle Pliocene. Transgression led to the widespread deposition of Tertiary-Quaternary formations in the Tavoliere, where the platform lies thousands of meters below ground surface, and partially covering the platform carbonate rocks of Murgia and Salento with thin strata of sand, conglomerates, calcarenites, limestones and clays. From the middle Pleistocene onwards, the whole region began to uplift. In the Holocene, the Salento and the southern part of the Murgia were affected by a slow uplift of about 0.08 mm/yr (Beneduce et al. 2004; Lambeck et al. 2004).

The Apulian coastline is 800 km long. This region hosts the largest coastal karstic aquifer in Italy, a country in which seawater intrusion is the main cause of saline quality degradation. The Apulian karstic aquifers have also a high permeability due to dissolution well below the current sea level and intruded seawater underlies fresh groundwater. Confined groundwater is more widespread inland in Gargano and Murgia than in Salento. Groundwater is phreatic everywhere along a narrow coastline strip which surrounds the region. If each area is plotted as a quadrilateral, Gargano and Salento are bounded by the sea along three sides while Murgia is bounded by the sea along one.

Studies carried out during decades using the most advanced technologies and including geological, hydrogeological and geochemical surveys, have clearly shown that vulnerability to seawater intrusion and the accompanying effects are substantially different and lower in the Gargano, than in the Murgia and Salento (Cotecchia et al., 1971; Cotecchia 1977; Cotecchia et al. 1983; Fidelibus and Tulipano 1991; Cotecchia et al. 2005). For this reason, and because of the low density of monitoring wells and the high percentage of data gaps, Gargano has not been studied in detail and attention is focused on Murgia and Salento. The Murgia and Salento Mesozoic rocks form a lithological, geological and groundwater continuum (Cotecchia et al. 2005). The hydrogeological structures are bounded by the coastline and by Pliocene or more recent faults. Some boundaries are clear-cut, such as those between Gargano and Tavoliere, and between the latter and Murgia. However, the boundary between Murgia and Salento is indefinite. They are separated by a morpho-structural element known as the "Messapian Threshold" which covers an area extending from the Adriatic to the Ionian Sea, about 10 km wide. In this area, a gradual shift of hydrogeological features can be observed: the depth to groundwater varies from high to low in the Murgia and from middle to low in the Salento; the piezometric height is above 100 m a.s.l. in the inner Murgia and is lower than 5 m a.s.l. in Salento as a whole, while the hydraulic conductivity varies from middle to low and from high to middle, respectively.

Recharge is exclusively provided by rainfall infiltration.

Polemio and Casarano (2004) assessed that the Apulian mean annual value of rainfall and net rainfall is 644 and 138 mm respectively in the period 1921-2001; in the same period the trend of the net rainfall is equal to a 30% drop of the mean yearly value. This decrease is due to the combined effect of monthly rainfall and temperature modifications, observed in chiefly from 1980 on. The unfavourable recharge conditions observed from 1980 in Southern Italy are caused by frequent periods of drought. The most severe droughts periods after 1980 occurred in 1988-1990 and 1999-2002, and a relevant rainy period was recorded from 1996 to 1997 (Polemio and Casarano 2004, 2008).

About 99.5% of the potable groundwater in the Apulian region is obtained from wells bored in the karstic aquifers. Agriculture is the main use of groundwater. Around 70% of the farmers use groundwater (ISTAT 1999).

4. Results and analyses

4.1 The Apulian hydrogeological monitoring network

The monitoring of the karstic groundwater in Apulia began in the 60's with regular piezometric measurements carried out by the Irrigation Development Agency. The number of wells in the network grew to about 60 in the70's. The piezometric trend was determined analysing 47 monthly piezometric time series (data were published by the Apulia Region Water Protection Plan, realised in 1984, provided by the Irrigation Development Agency and taken from recent surveys carried out by the authors); data are available from 1965 to 2003 with some gaps (Polemio and Casarano 2008). The piezometric trend in 2003, after the serious drought of 1999-2002, was compared with that of 1997 at the end of a rainy period that began in 1996. The trend in both cases was generally negative for each well, even though the 2003 trend was universally worse in terms of quantity degradation.

The minimum values of the piezometric angular coefficient (PAC) of the linear trend or the maximum piezometric decreasing trends were observed in the Murgia wells (Table 1). PAC Salento values are negative but better as the PAC was equal or greater than -0.01 m/month. The overall piezometric trend was generally downward in Murgia and Salento (PAC negative), given the widespread tendency towards a piezometric drop. The piezometric lowering in Salento was slower but extremely worrying, due to the higher vulnerability to seawater intrusion related to its natural low piezometric height above sea level (Cotecchia et al. 1983).

Modernization of the Apulian hydrogeological monitoring network started in 1995. The modern network was designed to provide the real-time information required for the proper management of groundwater resources. Prior to that, the Apulian monitoring network consisted of 120 wells not used for exploitation: 78 piezometric wells, 14 salt-observation wells for measuring fresh-saline water equilibrium, and 28 quality control wells for assessing human-related pollution (Cotecchia & Polemio 1999).

The wells were designed and bored as monitoring points. All kinds of data concerning each well were known with accuracy (depth, diameter, altitude, coordinates, screen length and position). The stratigraphical log for each well was also known, with special detail in about 50% of the wells, which were dug by means of continuous coring. Each type of well was equipped with electric piezometric transducers. The salt observation wells were deliberately located along a coastal strip. They were deep enough to reach the transition zone between the fresh water and the underlying saline water and were equipped with multiple probes for measuring groundwater temperatures and SEC at different depths (fresh groundwater and transition zone). The data was transferred from the wells to databases via radio links and they were ready to be used in a GIS environment for planning and management purposes. The whole network worked quite well for a short period, mainly from 1997 to 1998. Now it is abandoned due to the deterioration of the probes, problems with radio links and the lack of funds to cover the maintenance and operation costs.

The fluctuations of the transition zone could be approximately determined by salt observation wells, in terms of depth and height. However,, only general observations regarding the advantages and limits of these kinds of monitoring wells could be made due to the short time interval of reliable measurements. A representative example of the monitoring achieved using this network is shown in Fig. 2 in the case of well 18 (the well site is in Fig. 3b). The temperature for the three probes was almost constant, like the SEC at the fresh groundwater depth and at the bottom of the transition zone, while the SEC variability at the top of the transition zone appeared to be largely correlated to the piezometric variation measured in the fresh groundwater.

The complex behaviour of the transition zone could not necessarily be wholly evaluated by three fixed depth multiparameter probes alone - despite the fact that the thickness and depth of the transition zone might turn out to be roughly correlated to piezometric height- also where the effect of discharge by nearby wells is negligible. Monitoring of probes located at fixed depths and calibration with multi-parameter logs could enable a highly accurate determination of the fluctuations of the transition zone. Multi-parameter logging should be periodic according to season and/or demanded by relevant variations observed due to the measurements of fixed depth probes. On this basis, the probe depths could be modified and optimised to follow relevant transition zone movements.

A new modernization and repair project has been established. The plan is to increase the number of wells, including the main coastal springs. The new network should start monitoring as soon as possible (2008 or later), resuming activity after a very long gap.

4.2 The spatial and temporal variability of salinity

A data base made up of 500 laboratory analyses of groundwater samples was used (Fig. 4). The altitude or elevation of sampling was known precisely for about 95 % of the samples, some of which came from coastal subaerial springs. The remaining samples were obtained from (discharging) wells. The majority of the points used were wells that were part of the monitoring network, whilst the remainder consisted of springs and discharging wells (Fig. 3a). All the relevant geometrical and hydrogeological details were known for each monitoring point. The sampling was carried out from 1995 to 2003.

Groundwater samples of the hydrochemical facies (water types) Ca^{2+}-HCO_3^-, Ca^{2+}-Mg^{2+}-HCO_3^- and Mg^{2+}-Ca^{2+}-HCO_3^- were considered to be representative of pure fresh groundwater, according to the chemical nature of the rainfall and the characteristics of the karstic aquifer and of the topsoil (Cotecchia et. al. 1971, 1973; Cotecchia 1977; Alaimo et al. 1989; Fidelibus and Tulipano 1991). The variability of the chemical characteristics of the groundwater was mainly determined by mixing of fresh groundwater with seawater in variable amounts and water-rock interaction processes (Fidelibus and Tulipano 1991). The simplest grouping of samples differentiated two groups: pure fresh groundwater (group F) and the remaining samples (group S), made up of pure fresh groundwater mixed with variable percentages of seawater (Fig. 4). All the selected pure fresh groundwater samples were collected in wells located in the inner portion of Murgia and Salento.

Alaimo et al. (1989) distinguished three types of groundwater in the Murgia and Salento areas according to their Na^{+}+K^{+}+Mg^{2+} and HCO_3^{-} concentrations: the first was pure fresh groundwater with variable content in Mg^{2+}, which tends to increase by water-rock interaction processes in dolomite strata, particularly in the Murgia area; the second and the third groups corresponded to fresh groundwater with various Mg^{2+} percentages mixed with varying amounts of seawater. The first type distinguished by Alaimo et al. (1989) on one hand, and the second and third types on the other, roughly correspond to the F and S groups proposed in this work, respectively. Fidelibus and Tulipano (1991) found that the ions with more variable content were Ca^{2+} and Mg^{2+} and that the ratio of $rMg^{2+}/rCa^{2+}>2$ was typical of Murgia and Salento salt groundwater. On the basis of the wider data set used for the proposed grouping, the ratio rMg^{2+}/rCa^{2+} of fresh groundwater was always less than 2.8 and less than 2.0 in 92% of the selected samples.

The TDS of the selected pure fresh groundwater samples ranged from 0.19 to 0.87 g/L. The mean and the standard deviation were, respectively, 0.41 and 0.13 g/L. The 50, 75 and 90 percentiles were 0.38, 0.47, and 0.61 g/L, respectively. Taking into consideration the 75% percentile or the mean value plus a standard deviation, the threshold can be established at 0.5 g/L for the Apulian coastal karstic aquifers, equal to values previously suggested (Cotecchia et al.,1983).

The analysis of the spatial evolution over time was based on low frequency and high density data from which the TCLs of 1981, 1989, 1997 and 2003 were obtained. The 1981 and 1989 data were collected during the survey carried out within the framework of two Regional Plans for the management of water resources; the Water Protection Plan (Apulian Region 1984) and the Aqueduct General Plan (LL.PP. 1989), respectively. In both cases, monitoring points belonging to the regional network, together with private discharging wells, were used. The 1997 and 2003 data were collected using regional network monitoring points and some coastal springs (Fig. 3a). The values used correspond to samples taken immediately below the piezometric level to test the salinity of fresh groundwater.

The seasonal variability of salinity or the SEC of fresh groundwater tends generally to be very low at a distance from discharging wells, as shown by the measurements taken by the shallowest probe in Well 18 (Fig. 2). These values can be considered as representative of the salt observation wells in the monitoring network. In any case, to reduce the effects of seasonal variability to a minimum, data were selected to be as simultaneous as possible. The TCLs were determined using the kriging method (Deutsch and Journel 1992) and their spatial modifications were highlighted by means of GIS applications.

Three types of areas are distinguishable on the basis of the 4 TCLs overlapping TCLs (Fig. 3b). The first type is located where salinity remained permanently below the threshold. This is an inland type of zone. A wide portion of inland Murgia and a narrow strip in the middle of the Salento peninsula have not been contaminated so far. These areas can be considered to have a low vulnerability to degradation due to seawater intrusion. The second type or coastal zone is linked to the areas where salinity is always above the threshold and groundwater saline contamination has been shown to be a long-standing phenomenon (Cotecchia et al. 1983 and 2005). This type can be distinguished in large areas along the Adriatic and Ionian coast in which vulnerability to seawater intrusion is very high. The third type is an intermediate or transitory zone. In each point of these areas, salinity is a function which is highly sensitive climate, water cycle and exploitation variability or, predominantly, by man's ability to manage groundwater resources. For example, from 1981 to 1989, the TCL migrated gradually inland, spanning areas in which the quality of groundwater declined as well. This progressive degradation seems reasonable, given the effects of climate change in terms of net rainfall reduction roughly observed from 1980 onwards. In Southern Italy, the typical response to water emergency situations during droughts is to increase the discharge from existing wells together with creating additional wells: EAAP, the Apulian public water company (now AQP), bored dozens of wells using funds provided by national authorities to discharge more drinking water in response to the 1988-1990 drought. Additionally, many hundreds of wells were privately bored for irrigation purposes. Some years later the TCL inland migration either stopped or was reversed in some parts of Murgia and Salento largely due to the 1996-1997 rainy period.. In this zone there is a very high risk of quality degradation, caused both by the high discharge from single wells and by the total amount of discharge. Another risk factor is the fact that discharge is, to all intents and purposes, unregulated and is not managed in a sustainable way, taking into account the natural recharge variability and the effects of piezometric lowering on seawater intrusion. Sustainable groundwater management in this type of karstic coastal areas requires discharge from wells to be optimized, taking recharge variability into account, and avoiding upconing and the inland lateral migration or intrusion of saline groundwater.

Lengthy time series of salinity are not available for Apulia. The linear correlation coefficient between chloride concentration and TDS is equal to 0.98 (Cotecchia et al. 2005). The concentration of chloride is regularly measured in wells used for pumping drinking water by AQP, following procedures established by national regulations. Thus, the trend analysis of low density and high frequency data is based on time series of chloride concentration. Time series (courtesy of AQP) were selected taking into account several criteria including duration, number of gaps and the overall quality of data. A total of 17 time series of reasonably continuous monthly data has been selected

(Fig. 3b). The linear trend is expressed by the angular coefficient (Table 2; Fig. 5). It is worth noting that the more recent data are subsequent to the 1996-1997 rainy period in the case of the Murgia (1998) and coincide partially with the beginning of the drought in the case of Salento (2000 and secondly 2001). The trend or angular coefficient is, generally, slightly negative in Murgia wells (1, 2 and 3), with a drop in chloride concentration due to favourable rainy conditions. The trend of Well 4, the well with the minimum value of mean annual concentration, would appear to be an exception, but this very low positive trend is the only one not statistically significant at 5%.

If we apply the same criterion used for TDS to chloride concentration to the chemical data set, the threshold value of chloride concentration is equal to 44 mg/L. Murgia Well 3, located a long way from the sea, is the only Murgia well with a 99 percentile of monthly time series lower than the chloride concentration threshold.

The time series analysis, using a higher time resolution, is consistent with the TCL analysis, which has a higher spatial density of information. Similar results are observed for the Salento time series. The figure for quality degradation due to seawater intrusion is different and more serious in the case of Salento at the end of 2000, where the trend is mainly positive and the angular coefficient ranges from 0.06 to 5.72 mg/L yr^{-1}. The only exceptions are Wells 12 and 17 located in the Messapian Threshold, where a major groundwater flow path guarantees the recharge of the Salentine portion of the aquifer from the Murgia recharge area. One point to bear in mind is that, when salinity increases too much in a vulnerable zone, wells become abandoned, causing a local discharge decrease and a local quality improvement. These situations complicate salinity trend analysis, especially where the salinity is quite high, as in the case of Wells 12 and 17, in which the maximum annual concentration of chloride is observed. Seawater intrusion in Salento affects larger areas than in Murgia, as shown by TCLs analysis, and it causes a more serious quality degradation trend in Salento, as shown by the trend analysis.

4.3 Multiparameter logging for rapid groundwater quality classification

Multi-parameter logs were carried out along the water column of wells by means of probes equipped with sensors for measuring P, T, SEC, pH, DO and Eh. This method was tested on wells belonging to the regional monitoring network located in the whole Apulian region over one year, with three-monthly surveys.

Six typical multi-parameter log trends were defined for the whole Apulian region (Cotecchia et al. 1999). Three types were distinguished in the study areas where the anthropogenic effect on quality was negligible: A) the inner or recharge area, B) the salt polluted area and C) the transition zone between Murgia and Salento (Figs. 6 and 7).

The logs of type A reveal very low temperature variability along each log, with temperature generally less than 17 ºC but increasing towards the coast. The salinity is low, commonly below 0.5 g/L and with no appreciable increase with depth. The pH ranges between 6.5 and 7.5 and DO is relatively high, with maximum values between 5 and 8 mg/L, and a generally positive Eh (Fig. 7). In addition, some parameters generally remained more or less constant along the vertical axis of the wells, such as temperature, TDS and pH, whereas DO and Eh were higher at some depth, quite often where intensely fractured and/or karstified strata were observed and where groundwater flow was relatively higher.

The B-type logs were typical of wells affected by seawater-intrusion, mostly located along the coast. They were characterised by an increase in temperature of 1-1.5°C and salinity, from a variable minimum, generally less than 2 g/L, to about 40 g/L at the bottom of some wells, as depth increased (Fig. 7). The pH, with average values of 7.5, tended to fall slightly in the saline portion of the aquifer. The DO concentration was generally higher in the portion of fresh groundwater, decreasing and becoming null where intruded sea-water, which has generally a poor or null mobility, was reached. The Eh also tended to decline with depth. This trend, which was more clear-cut compared to that of dissolved oxygen, showed positive values for fresh groundwater and negative values in the remaining portion of the aquifer, characterised by saline groundwater. Moreover, the transition zone between fresh and saline water, the depth of which differs from well to well, showed a sharp change in the salinity values within a few meters, from 3-5 g/L or lower to about 40 g/L.

The C-type logs were typical of the transition zone between Murgia and Salento, where groundwater flows from the former hydrogeological structure into the latter. This type of log was quite similar to A-type logs in terms of parameter range, but displayed greater variability at specific ranges of depths, especially in regard to Eh or DO. Higher Eh values were recorded in some well. The chemical and physical characteristics appeared to be strongly influenced by the effects of the major groundwater flow path lines between the Murgia recharge zone and the Salento coastal outflow areas. This flow appeared to be stratified, as is typical in karstic aquifers.

These typical trends are consistent with the local and natural hydrogeological conditions. These types, which are recurrent in space and time, can be used as a reference for comparison. If a different trend is observed in a specific well, the occurrence of human-related effects is extremely probable. In any case, the multi-parameter log provides a preliminary description of the groundwater quality and an evaluation of the potential effects of possible quality remedial measures.

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5. Conclusions

In karstic coastal aquifers, groundwater flow determines the development of human communities and the ecological equilibrium of coastal wetlands and surface water bodies. Monitoring is essential to detect and assess groundwater degradation in these highly vulnerable aquifers and to design and apply sustainable management strategies.

The multi-methodological approach proposed in this paper for analysing the effects and risks of seawater intrusion is based on simple, quick and cost-effective tools. The boring costs can be reduced substantially using existing boreholes and public, private and abandoned wells.

The use of hydrogeological monitoring networks is a good option and should be pursued in any karstic and coastal area. This type of monitoring tool is very useful for describing quality degradation risk due to seawater intrusion, but requires record periods of a few decades. The piezometric monitoring of the Apulian groundwater shows a significant downward trend in the whole aquifer, quantitatively greater in Murgia, but more worrying in Salento, due to the low piezometric height which characterizes this area.

Multi-temporal salinity spatial analysis, trend analysis of the salinity time series or of simple salinity-correlated parameters and multi-parameter logging can complement the activity of the hydrogeological monitoring network providing a more detailed analysis.

The spatial TCL trends of the Murgia and Salento karstic coastal aquifers highlights three different types of zones: the inland zone, with low vulnerability to seawater intrusion, in which the salinity is always below the threshold; the coastal zone, with high vulnerability to seawater intrusion, in which the salinity is always above the threshold, and the intermediate zone, with variable vulnerability, in which the degradation due to seawater intrusion mainly depends on the ability to manage the discharge as a function of the natural recharge variation.

The time series analysis of monthly chloride concentrations shows the effects of the generalised rising saline contamination in the Salento, while the TCL analysis shows that the inland zone is quite narrow there. The analyses of salinity and chloride concentration suggest that the observed quality degradation is closely related to dry years and to increasing discharge by wells. The phenomenon became relevant after several dry years in the late 80s that resulted in reduced recharge and in increased artificial groundwater discharge.

The typical trends shown by multi-parameter logs provide a reference for comparison. If a different trend is observed in a specific well, the multi-parameter can highlight the effects of human-related pollution or seawater intrusion, together with a preliminary and qualitative evaluation of the level of degradation.

On the basis of the results, some management criteria for groundwater resources can be proposed. Discharge for drinking purposes could be increased in the inland zone considering the annual recharge and operating on the basis of both the yearly true values and of statistical analysis of low values. The effects of the increased discharge should be assessed in detail in the intermediate zone. The discharge in the intermediate zone should be restricted or reduced to a value at which the total discharge of the inland and intermediate zones is lower than the annual recharge. In any case, the discharge in the intermediate zone should be authorised defining a protection strip between the inland zone and the TCL. The discharge in the costal zone should be authorised only for specific uses for which brackish or saline water are acceptable, as long as they do not cause negative economic or environmental effects. Saline water discharge should be encouraged if it entails positive effects on the groundwater resources. In both cases, the effects of discharge in terms of degradation risks should assessed in detail. The discharge plan should be defined taking into account different discharge and recharge scenarios. In the intermediate and coastal zones, the discharge wells (number, location, geometry and construction techniques) should be optimised on the basis of local hydrogeological characteristics. If these goals can be achieved, the high quality of fresh drinking groundwater in the inland zone will be permanently maintained and will remain free from the effects of seawater intrusion.

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Tables

Table 1. Piezometric trend and data availability (MPAC, minimum piezometric angular coefficient as m/month).

Hydrogeological structure and number of time series	Data from	to	MPAC	Trend at 2003
Murgia (30)	1965	2003	-0.02	High decrease
Salento (17)	1965	2003	-0.01	Decrease

Table 2. Statistics of annual concentration of chloride time series (mg/L; well location in Fig. 3b). HS) Hydrogeological structure, M) Murgia, S) Salento, 75) 75 percentile, SD) Standard deviation, IY) Initial year of measurement and LY) Last year, ND) Number of annual data, AC) Angular coefficient of linear regression (mg/L yr^{-1}).

Well	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
HS	M	M	M	M	S	S	S	S	S	S	S	S	S	S	S	S	S
Min	25.7	28.2	18.9	25.5	85.2	237.4	80.5	38.1	56.1	74.5	31.1	134.8	201.4	170.4	138.5	178.7	266.3
Mean	35.6	63.0	32.6	32.3	106.1	314.9	146.6	58.9	90.9	91.1	40.0	189.1	227.4	204.9	193.7	214.4	354.1
75^{th}	37.4	74.5	35.5	35.1	119.8	345.9	192.9	49.7	106.1	99.4	42.1	205.4	238.5	219.4	205.6	223.3	376.3
Max	40.4	80.9	37.8	51.1	141.3	378.4	238.2	67.0	147.1	104.9	65.7	236.1	261.3	244.9	273.4	230.3	390.5
SD	3.05	11.54	7.66	5.59	14.47	34.28	53.05	7.1	25.54	9.29	8.28	26.65	16.20	21.89	24.64	12.95	35.92
IY	1973	1973	1968	1975	1973	1969	1973	1980	1973	1971	1981	1973	1968	1969	1975	1981	1973
LY	1998	1998	1998	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2001	2000	2000
ND	24	23	28	26	25	29	25	19	26	28	20	26	30	29	25	19	26
AC	-0.08	-0.16	-0.56	0.01	1.53	2.19	5.72	3.16	2.56	0.06	0.08	-0.48	0.77	2.04	1.06	1.30	-0.76

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Figures

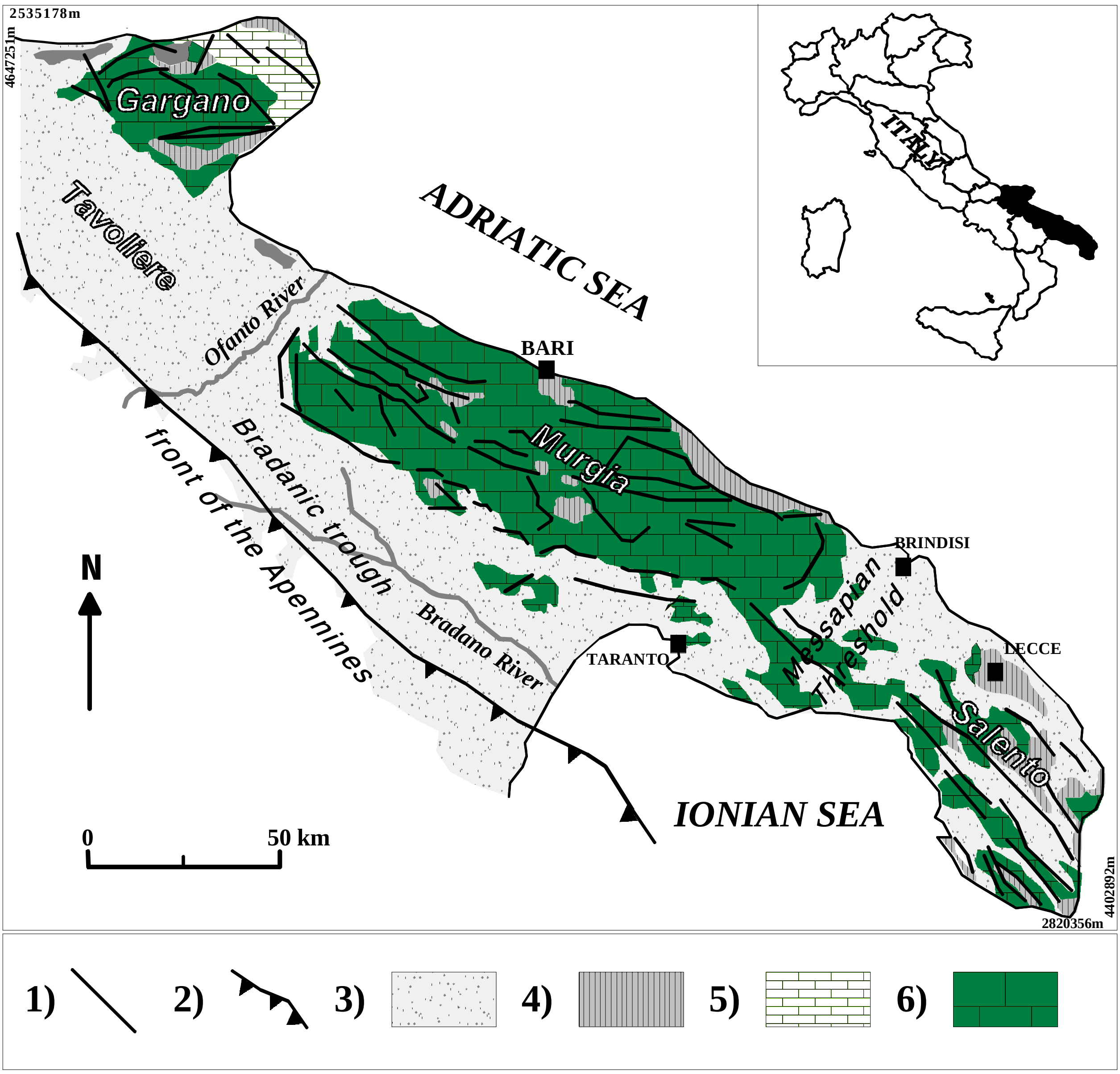

Fig. 1. Geological scheme (modified after Beneduce et al., 2004). 1) Fault, 2) front of the Apennines, 3) recent clastic cover (Pliocene –Pleistocene), 4) bioclastic carbonate rocks (Paleogene) and calcarenites (Miocene), 5) carbonate platform rocks (Upper Jurassic-Cretaceous), 6) chert-carbonate rocks (Upper Jurassic-Cretaceous).

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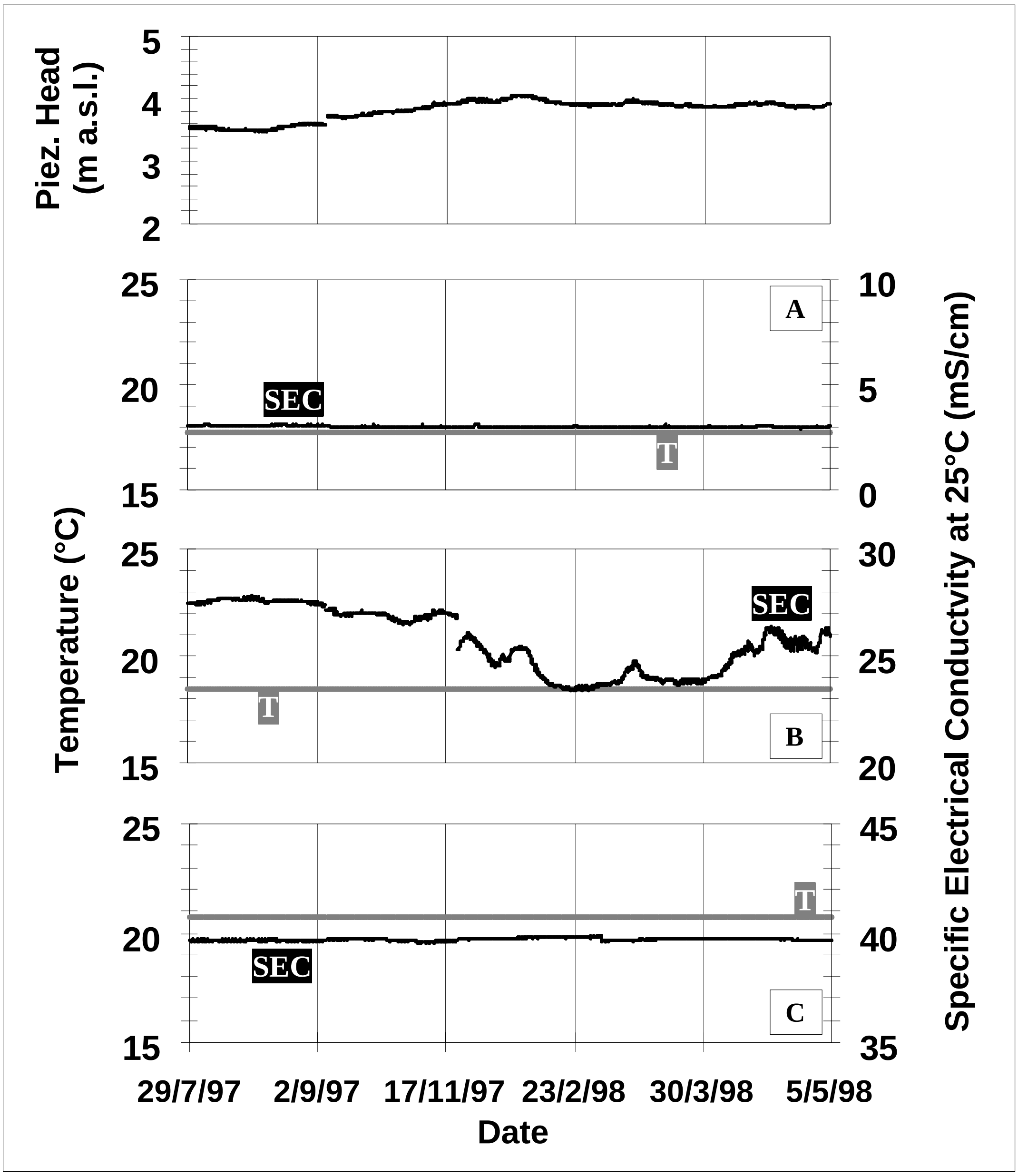

Fig. 2. Results of a salt observation well (well 18 on Fig. 3b) of the monitoring network: The upper chart shows the piezometric head, while the lower threes the temperature (T) and specific electrical conductivity (SEC) measured at -38 (A), -88 (B) and -198 (C) m a.s.l.

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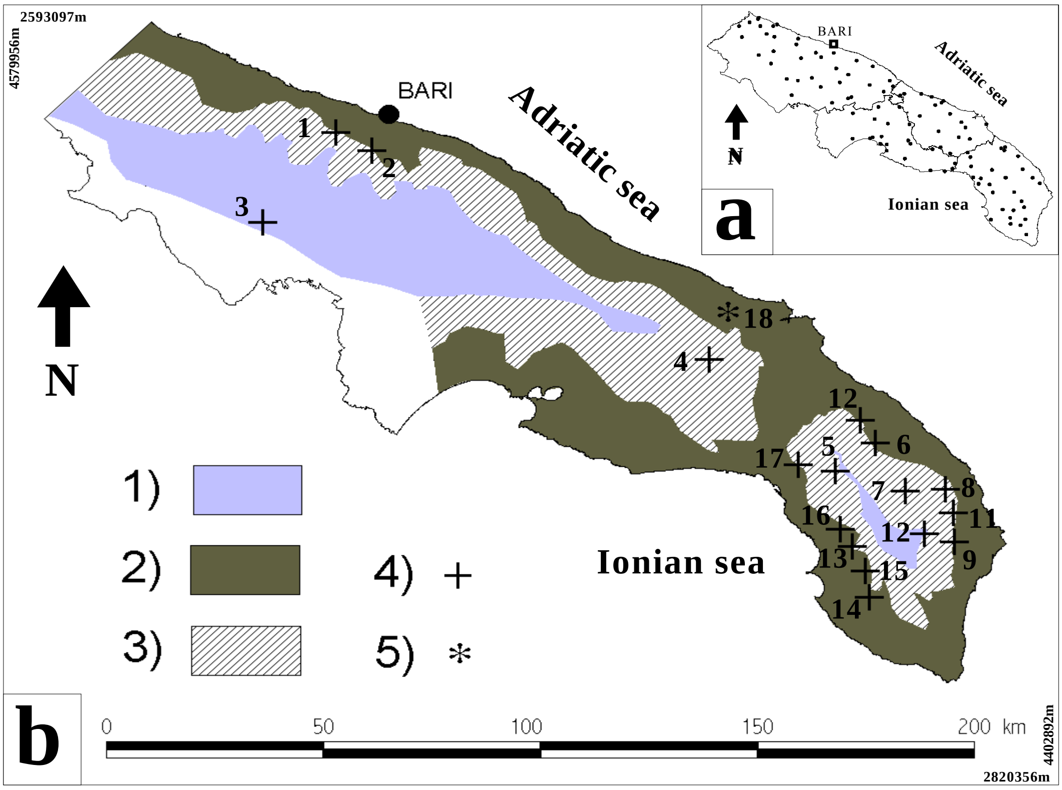

Fig. 3. Sampling points and map of vulnerable areas to seawater intrusion: 3a) Wells of the monitoring network and coastal springs. 3b) Explanation: 1) Inland zone, salinity always less than 0.5 g/L, low vulnerability to seawater intrusion; 2) Coastal zone, salinity always greater than 0.5 g/L, very high vulnerability to seawater intrusion; 3) Intermediate zone, salinity lower or greater than 0.5 g/L from time to time, from middle to high vulnerability to seawater intrusion; 4) chloride time series wells; 5) selected well of the hydrogeological monitoring network (Fig. 2).

Reference to be cited: *Polemio, M., Dragone, V. and Limoni, P.P., 2009. Monitoring and methods to analyse the groundwater quality degradation risk in coastal karstic aquifers (Apulia, Southern Italy). Environmental Geology, 58 (2): 299-312.*

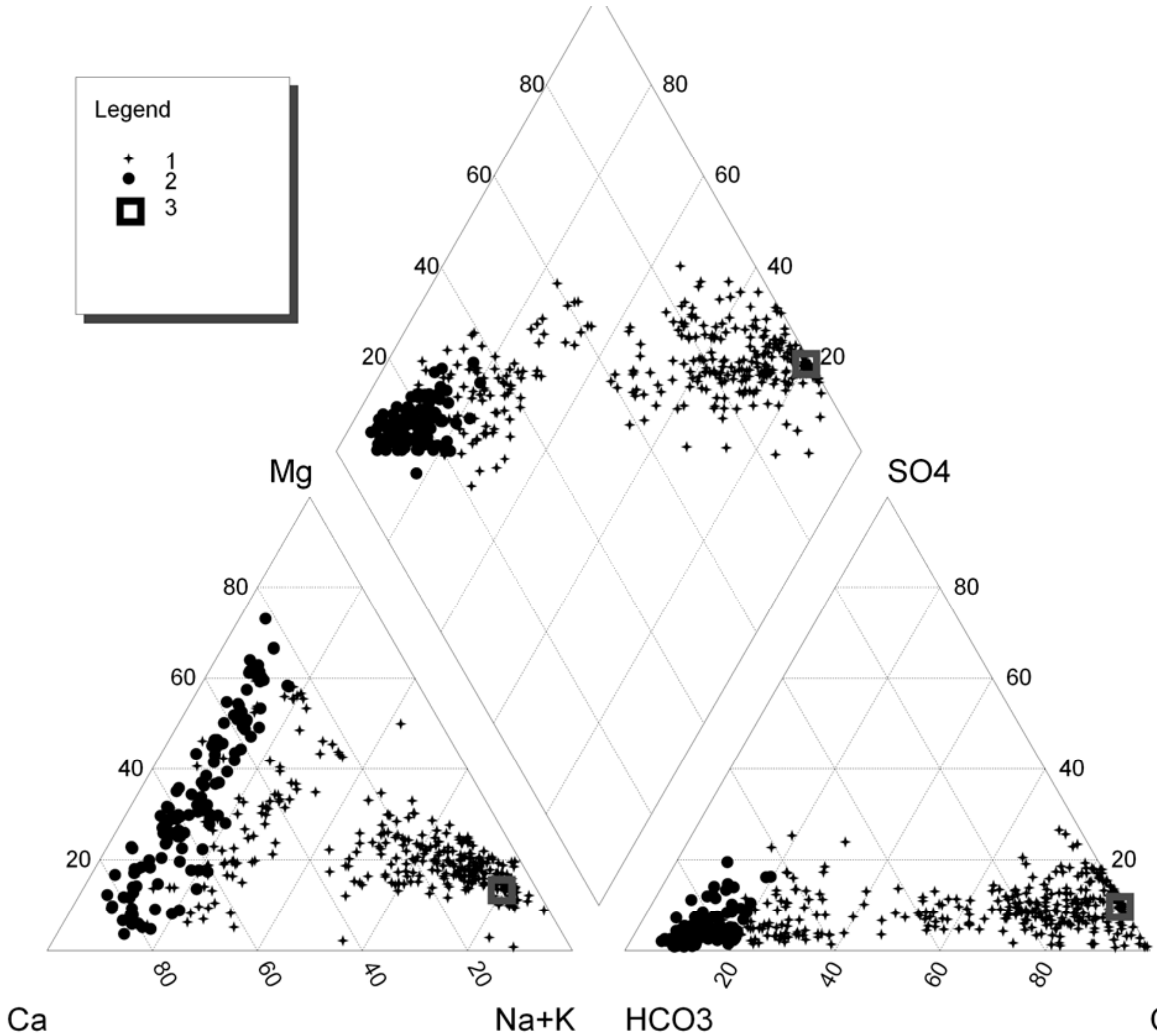

Fig. 4. Piper diagram of the data set. 1) Fresh groundwater mixed with variable percentages of seawater (S group); 2) Pure fresh groundwater (F group); 3) Sea water.

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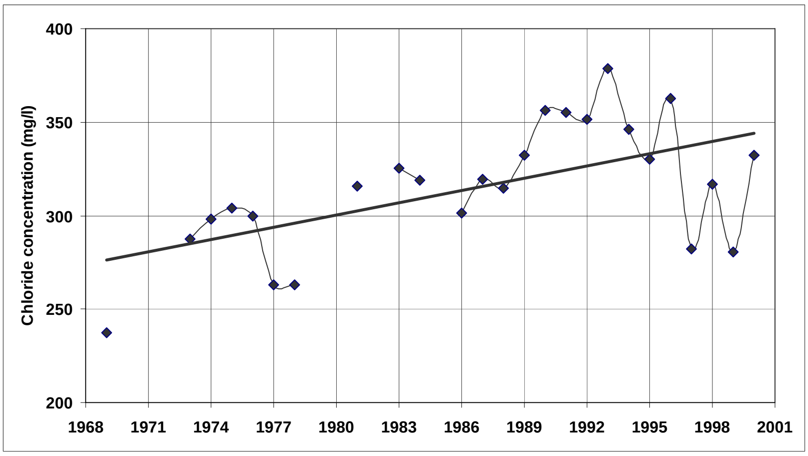

Fig. 5. Time series and trend of annual chloride concentration of well 6 in Salento (Fig. 3b).

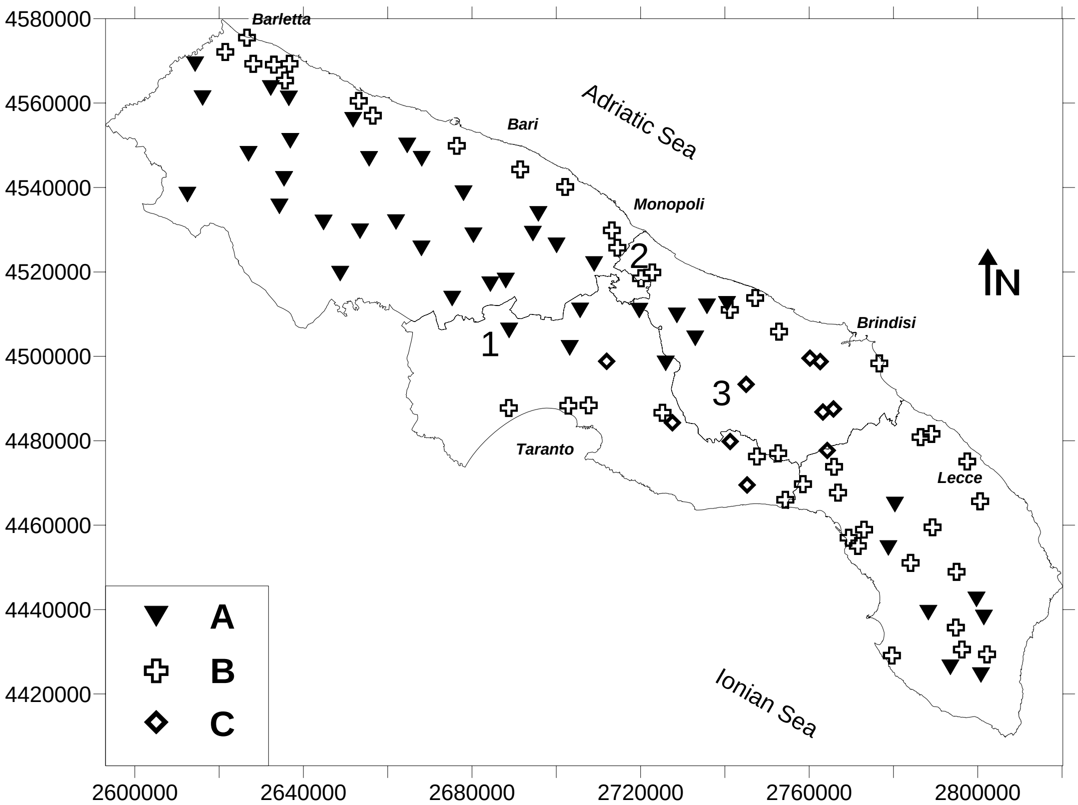

Fig. 6. Logging wells and log types of Murgia and Salento. Legend of log type: A) Inner or recharge area, B) coastal strip or sea water intrusion area and C) transition zone between Murgia and Salento. The typical log of wells 1, 2 and 3 is in Fig. 7.

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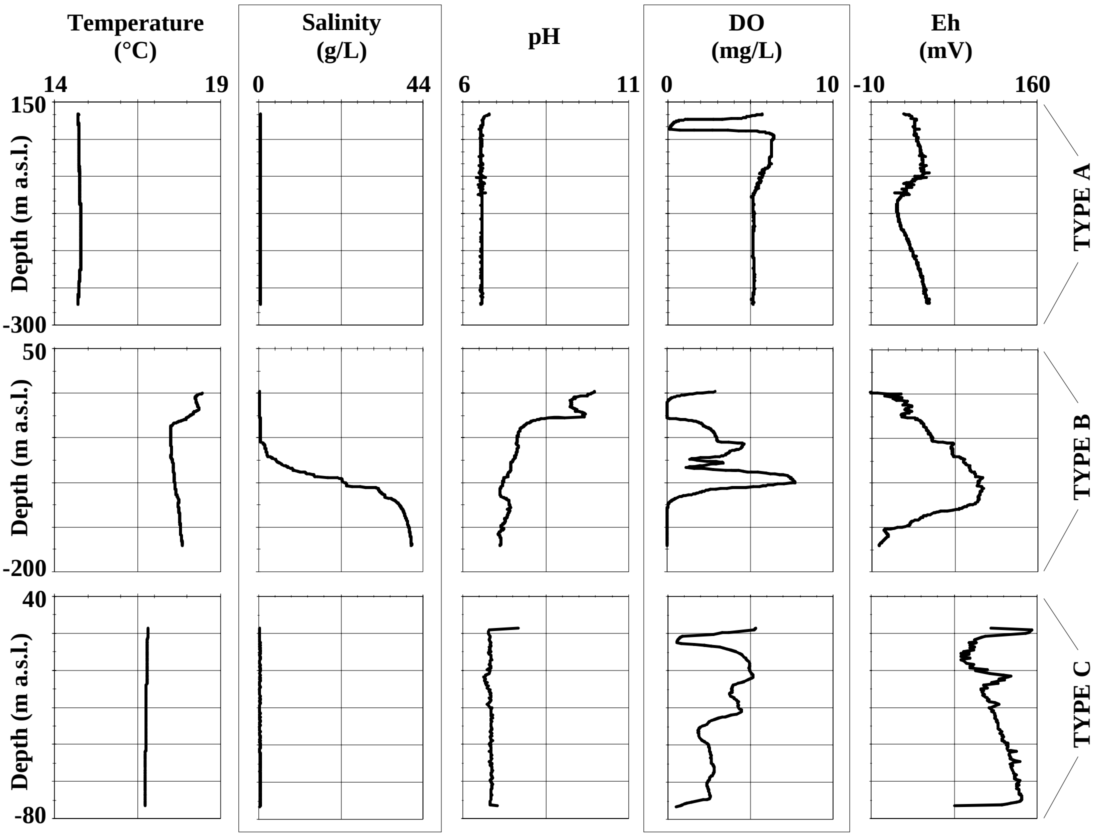

Fig. 7. Typical multi-parameter logs typical examples of logs, spring 1997 (location of plotted logs in Fig. 6, wells 1, 2 and 3). Parameters: 1) temperature (ºC), 2) TDS or salinity (g/L), 3) pH, 4) DO or dissolved oxygen (mg/L), 5) Eh or oxidation-reduction potential (mV).