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The piezometric stress in the coastal aquifers of a karstic region, Apulia, Italy

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Abstract Apulian groundwater is extremely important for the development of local communities, given the extreme scarcity of surface water that is typical for a widespread karstic region. Valuable groundwater from large carbonate coastal aquifers is discharged at increasing rates for domestic, irrigation, and industrial uses. The increase has been particularly relevant during the many recent drought periods, due to paradoxical management. The trend of piezometric head and spring discharge highlights a dramatic decrease in groundwater availability since the 1920s. The remarkable lowering defines a widespread degradation of high quality groundwater resources in each aquifer considered. The lasting "memory effect" shown by each aquifer can reduce and delay, but cannot completely remove the negative effects of long drought periods and increasing well discharge. These effects are more relevant in some inner portions of aquifers. The piezometric lowering in the Salento Peninsula is slow but especially problematic due to the naturally low piezometric head above sea level, which permits seawater intrusion. Salt quality degradation of the Apulian groundwater, due to effects of seawater intrusion, is feared. The decreasing trend of the piezometric head thus defines not only a decrease in groundwater availability, but also a risk of quality degradation.

Key words groundwater depletion; coastal aquifer; hydrological time series

INTRODUCTION

The groundwater in Apulia is a very important resource in terms of regional development, given the extreme scarceness of surface water in the region. Indeed, most historians agree that the availability of groundwater close to the surface was the prime factor behind the founding of major local villages in antiquity, particularly far from the coast, as is the case of the entire Murgia area. Groundwater is often the only available resource for diffuse water-demanding human activities in the area. Salt contamination of the Apulian groundwater, due to seawater intrusion, is a well known and thoroughly investigated phenomenon (Cotecchia, 1977). A strong connection between the current increase in salt contamination and the lowering of piezometric levels, which can be ascribed to groundwater overdraft and/or a natural decrease in groundwater recharge, has been recognised in coastal aquifers. For this reason, a decreasing piezometric trend highlights not only a decrease in groundwater availability, but also a risk of quality degradation.

STUDY AREA

Four hydrogeological structures (HSs) can be distinguished in the Apulian region (Fig. 1). The Tavoliere HS consists of a shallow and large porous aquifer within a conglomerate sandy-silty succession, less than 60 m deep, with a clayey impermeable bottom (Polemio, 2005). It is deep enough to allow seawater intrusion only near the coast. Groundwater is phreatic inland or far from the coast in the recharge area, whereas it is confined in the remaining part of the aquifer; maximum piezometric levels reach 300 m asl. The groundwater quality is not generally high and does not permit drinking use (Polemio *et al*., 2006).

Except for the Tavoliere HS, the Apulian region is characterised by the absence of rivers and the unavailability of surface water resources due to its karstic nature. High-quality groundwater resources are located in large and deep carbonate coastal aquifers, as in the case of the Gargano (which is of secondly interest to this article due to the low data availability), the Murgia and the Salento HSs. The Murgia and Salento areas show some common features (Cotecchia *et al*.; 2005; Polemio, 2005). They consist of large and deep carbonate aquifers, constituted mainly by limestone and dolomite rocks. Carbonate rocks are affected by karstic and fracturing phenomena,

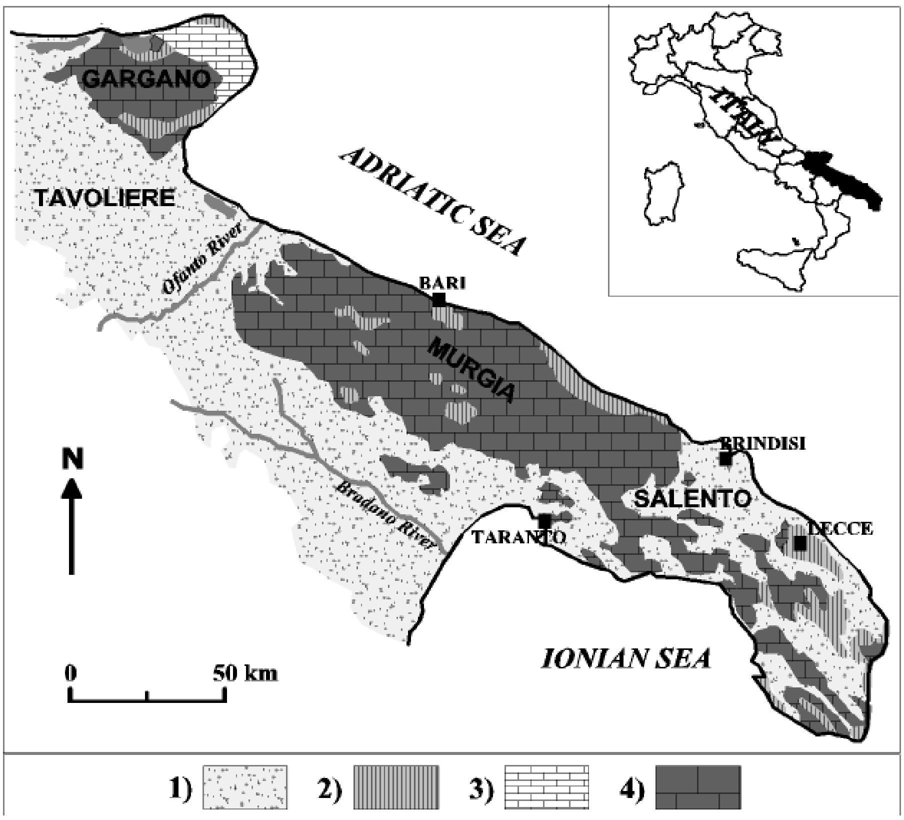

Fig. 1 Geological scheme of the Apulian region; Legend: (1) Recent clastic cover (Pliocene-Pleistocene); (2) Bioclastic carbonate rocks (Paleogene) and calcarenites (Miocene); (3) Scarp and basin chert-carbonate rocks (Upper Jurassic-Cretaceous); (4) Carbonate platform rocks (Upper Jurassic-Cretaceous).

which occur also well below sea level, whereas intruded seawater underlies fresh groundwater owing to a difference in density. Confined groundwater is more widespread inland; groundwater is phreatic everywhere along a narrow strip of coastline. The maximum piezometric head is about 200 m asl in the Murgia area and 6 m asl in the Salento.

ANALYSIS OF WELL TIME SERIES

This study is based on an analysis of monthly time series, mainly piezometric data, although rainfall data and temperature measurements are also included (Polemio *et al.*, 2005). The data come from networks of piezometric, temperature and rainfall gauges managed by different public institutions, controlled by regional institutions in the last years (Hydrological Service, Public works and Civil Protection of Regione Puglia). Recent data mainly come from surveys directly conducted by IRPI in 2003. Thirty wells, or piezometric stations or gauges, were selected from a group of 63 wells considered by Polemio & Dragone (2004) (Fig. 2).

Data are available from 1965 to 2008, with many gaps for various reasons (Table 1); the data for the period from 1973 to 1978 show the maximum density and the minimum number of lags.

The data sets regarding the Tavoliere wells are available for a minimum of 17 years and a maximum of 55 years, in two periods, 1929–1994 and 2001–2002. These data have been extensively discussed in other articles (Polemio *et al*. 1999, 2005).

For a better understanding of the behaviour of the other significant variables of the hydrological cycle, monthly time series of rainfall and atmospheric temperature have been considered. The type of rainfall regime was similar throughout the region, with only a single low in July or August and a single peak between November and February. The same holds true for

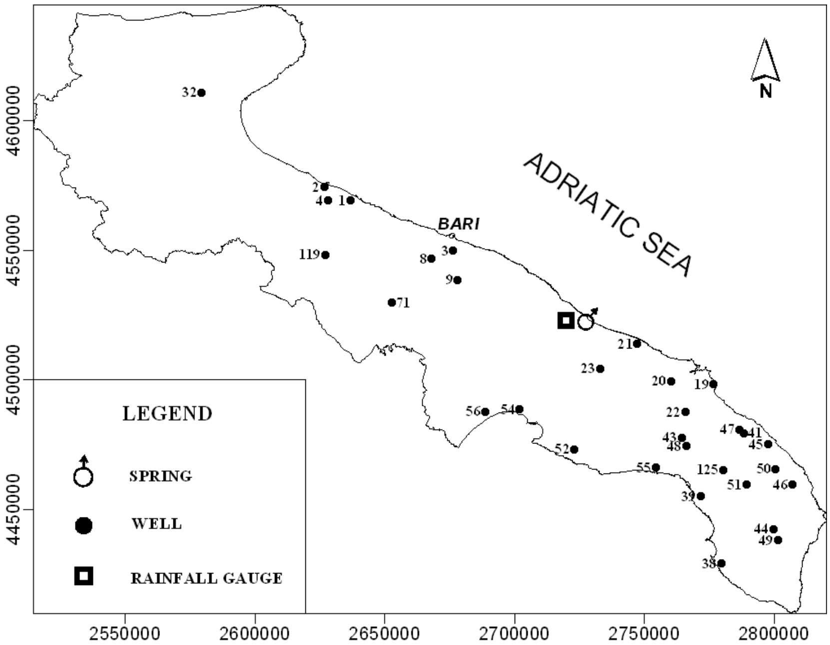

Fig. 2 Gauge location map of selected time series.

Table 1 Statistical values and main dates of the selected piezometric time series. (MM, Number of months with measurements; CA) Angular coefficient of straight line trend.

Well	Measurement period			Piezom. head (m asl)			Statistical (m)		Month of		AC
	From	to	MM	Min.	Mean	Max.	Std.	Range	Min.	Max.	(m/yr)
1	Sep–73	Sep–03	62	0.89	1.48	1.64	0.11	0.75	Sep–03	Sep–73	–0.010
2	Sep–73	Sep–03	69	4.77	6.28	6.58	0.26	1.81	Sep–03	Sep–73	–0.037
3	Dec–65	Sep–03	159	–0.11	0.85	2.02	0.37	2.13	Sep–03	Oct–73	–0.016
4	Jun–75	Sep–03	46	4.95	31.17	63.54	28.22	58.59	Sep–03	Nov–76	–1.879
8	Jun–75	Sep–03	48	42.79	47.12	53.31	2.58	10.52	Sep–95	Nov–76	–0.109
9	May–75	Oct–03	49	34.21	44.76	49.10	3.03	14.89	Sep–95	Apr–77	–0.368
19	Sep–73	Sep–03	58	1.51	1.99	2.20	0.13	0.69	Sep–03	Nov–76	–0.012
20	Oct–73	Sep–03	67	1.95	2.24	2.67	0.14	0.72	Aug–78	Nov–76	0.030
21	Oct–73	Sep–03	64	0.45	1.42	1.79	0.17	1.34	Sep–03	Nov–76	–0.013
22	Sep–73	Sep–03	56	0.99	2.07	2.40	0.19	1.41	Sep–03	Nov–76	–0.019
23	Sep–73	Sep–03	67	24.55	27.45	28.18	0.50	3.63	Feb–95	Jan–77	–0.049
32	Oct–75	Sep–03	44	3.31	5.18	6.89	0.51	3.58	Sep–03	May–97	–0.010
38	Sep–73	Sep–03	62	–0.11	1.68	2.93	0.31	3.04	Nov–96	Jan–95	–0.018
39	Sep–73	Sep–03	61	–0.65	0.43	0.92	0.17	1.57	Sep–03	Feb–96	–0.001
41	Oct–73	Sep–03	60	–6.40	1.49	1.85	1.05	8.25	Oct–96	Jan–77	–0.086
43	Sep–73	Sep–03	96	1.10	2.24	2.94	0.43	1.84	Sep–03	Nov–76	–0.053
44	Sep–73	Sep–03	62	1.44	3.35	3.73	0.32	2.29	Sep–03	Nov–76	–0.059
45	Oct–73	Sep–03	68	1.01	2.17	2.41	0.17	1.40	Sep–03	Nov–76	–0.019
46	Oct–73	Sep–03	56	3.53	4.71	5.17	0.28	1.64	Sep–03	Jan–74	–0.018
47	Jan–78	Sep–03	18	0.18	1.45	1.99	0.34	1.81	Sep–03	Jan–96	–0.013
48	Jul–68	Sep–03	97	1.17	2.68	41.75	3.99	40.58	Sep–03	Oct–96	–0.020
49	Jun–75	Nov–96	46	4.46	4.84	5.58	0.20	1.12	Oct–78	Nov–96	0.023
50	Oct–73	Sep–03	64	2.21	3.21	3.62	0.16	1.41	Sep–03	Jan–96	–0.011
51	Jul–75	Apr–08	56	1.52	2.85	3.56	0.45	2.04	Sep–03	Nov–96	–0.028
52	Sep–73	Sep–03	53	7.87	15.24	16.03	1.12	8.16	Sep–03	Sep–73	–0.222
54	Mar–73	Apr–08	57	3.17	4.80	5.62	0.68	2.45	Aug–07	Apr–73	–0.049
55	Sep–73	Sep–03	62	1.19	2.34	2.68	0.20	1.49	Sep–03	Dec–76	–0.020
56	Sep–73	Sep–03	65	2.90	7.33	8.70	1.10	5.80	Jan–96	Mar–77	–0.149
119	May–75	Oct–03	157	17.94	23.33	38.31	3.61	20.37	May–77	Apr–84	–0.160
125	Jan–65	Sep–03	311	1.00	2.01	2.29	0.13	1.29	Sep–03	Jan–85	–0.064

temperature, which was recorded throughout the area as having peaks in July or August and lows between November and February.

The piezometric regime of the Murgia groundwater is the same throughout the area; it shows only one peak, typically in February or March, and only one minimum, observed between July and September, the range of each well being extremely inhomogeneous. The piezometric regime in the Salento area is more homogeneous; the peaks are observed between November and March and the lows in July or August. In the Tavoliere area, the piezometric regime varies according to the locations of the stations, depending on whether they are located in urban areas or in farmlands. The measurements taken in urban areas show relatively low variability in each well and irregular piezometric regimes between wells, with extreme values generally unexplainable if water aqueduct and sewage system leaks are not considered. Conversely, the stations in farmlands show piezometric regimes that are similar and regular, with only one peak, between February and March, and one low during September (Polemio *et al*., 1999). Little can be said with regard to the Gargano due to the very low number and the short duration of available time series.

The piezometric trend of each piezometric time series is determined as the Angular Coefficient (AC) of the straight line regression. The piezometric trend, generally speaking, is generally downward (AC negative), since there is a widespread tendency, albeit in some cases a very slow one, towards a piezometric drop (Table 1).

AC approaches zero as we approach the coastal areas, as would be expected. The minimum of AC values or the maximum trend to the piezometric decrement was observed in the Murgia (Table 1) and Tavoliere (Polemio *et al*., 2005) areas, with the lowest values equal to –1.88 and –0.36 m/year, respectively. The only positive AC values were observed in Salento (two time series). The mean AC values of Murgia and Salento HSs are –0.26 and –0.02 m/year, respectively. The lower value of Salento is paradoxically worse than the higher one of Murgia due to the lower piezometric head observed in Salento and the higher risk of quality degradation by seawater intrusion (Polemio *et al*., 2009a).

An anomalous succession of low rainfall years was recorded starting about 1980 in all of southern Italy: there was a significant drought in 1989–1991, and then in 1996–1997 a rainy period preceded the worst known Apulian drought which began in 2000 and ended in the second half of 2002 (Polemio & Casarano, 2008). Using the latest data of Murgia and Salento, a piezometric trend has been calculated until 2003–2008 and compared with the trend up to 1997.

The 2003 situation is everywhere worse than in 1996–1997, except for two wells (7% of the total available time series). The latest drought has worsened the quantity degradation of the groundwater, even though the drought ended one year before the 2003 measurements. The trend is still negative in both wells for which data are available until April 2008.

On the basis of the results, the more probable spatial piezometric trend of each HS ranges from low, as is likely for Gargano (well 32), to average, as in the case of Salento, and to a high decrease rate, as in the case of Murgia and Tavoliere. The widespread trend to piezometric lowering increases the risk of salt pollution by seawater intrusion, the effects of which were already dramatic by the year 2000 (Polemio *et al*., 2009a).

The regional trend of actual and net rainfall is also decreasing. The mean actual and net rainfall in the region have dropped by about 10% and 30%, respectively, in the last 80 years (Polemio & Casarano, 2008). The comparison of the results of trend analysis with those of autocorrelation and cross-correlation shows that the steady and generalised piezometric drop is not entirely due to a drop in rainfall, but also to the over-exploitation of resources, which plays a very clear role in this process.

ANALYSIS OF A COASTAL SPRING TIME SERIES

The groundwater of Apulian karstic aquifers flows from inland recharge areas to spring coastal areas where all of the groundwater yield naturally outflowed before intensive increasing well discharge started in the 1950s. Hundreds of subaerial and submarine springs exist along the Apulian coast, creating large or diffuse spring areas or concentrated outflows.

Considering mainly the availability of historical measurements, we selected a spring to assess the whole effect of well discharge and of a decrease in natural recharge. The outflow yield of Fiume Grande Spring (Figs 2 and 3) was measured from 1926 to 1951 by the National Hydrographic Service (LL.PP., 1953).

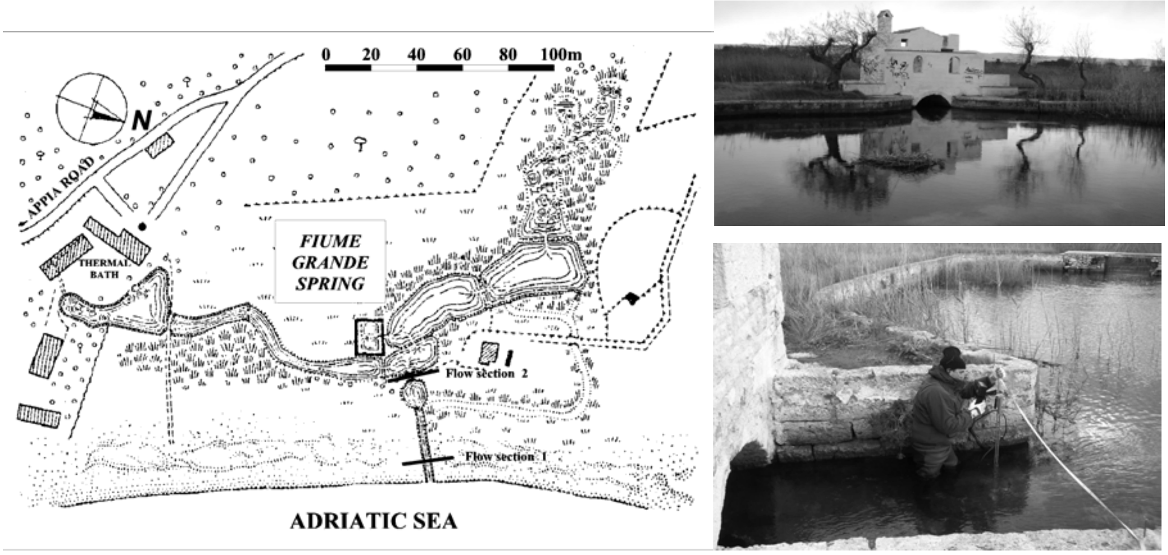

Fig. 3 Fiume Grande Spring map (LL.PP. 1953, modified) and view of discharge area and flow section 2.

The spring area is located in the Murgia, which is made up of a thick basement of carbonatic rocks of the Apulian foreland. The Murgia (maximum height 680 m asl) is a large asymmetric horst affected by two neotectonic fault systems (NW–SE and NE–SW). Because of these faults, the morphological structure slopes down towards the Adriatic Sea and towards the adjoining regions, by means of a succession of stepping ledges bounded by small fault throws. The karst environment consists of platform Cretaceous limestone and dolostone covered by thin layers of Pliocene-Quaternary rocks and soils, especially in the coastal areas (Figs 2 and 3). The carbonate rock is bedded, jointed, and subject to karst phenomena (Polemio, 2005).

The authors restarted the monthly spring outflow measurement in September 2008, adding water sampling and a chemical and bacteriological characterisation (Fig. 3 and Table 2). The high concentration of nitrate, the presence of bacteriological activity and the TOC value suggest that the pollution is due to urban and agricultural activities. The quality degradation of this groundwater, which is of drinking quality some tens of kilometres upstream, is due to both high aquifer vulnerability (Polemio *et al.*, 2009b) and the cumulative effect of different sources of contamination, as highlighted at the regional scale (Polemio *et al.*, 2006). The high salinity is due to the seawater intrusion.

Table 2 Chemical and bacteriological characteristics of Fiume Grange Spring water.

T (°C)	Sp. Electrical conductivity (mS/cm at 20°C)	pH	Dissolved Oxigen (%)	Total Hardness (°F)	TDS (g/L)	Cl (mg/L)
18.6	16.8	7.9	76	126	10.70	5429

NH_4 (mg/L)	NO_2 (mg/L)	NO_3 (mg/L)	TOC (mg/L)	Total coliforms (MPN/100 mL)	Faecal coliforms (MPN/100 mL)	Faecal streptococcus (MPN/100 mL)
<0.1	0.01	102	4.60	>16	>16	0

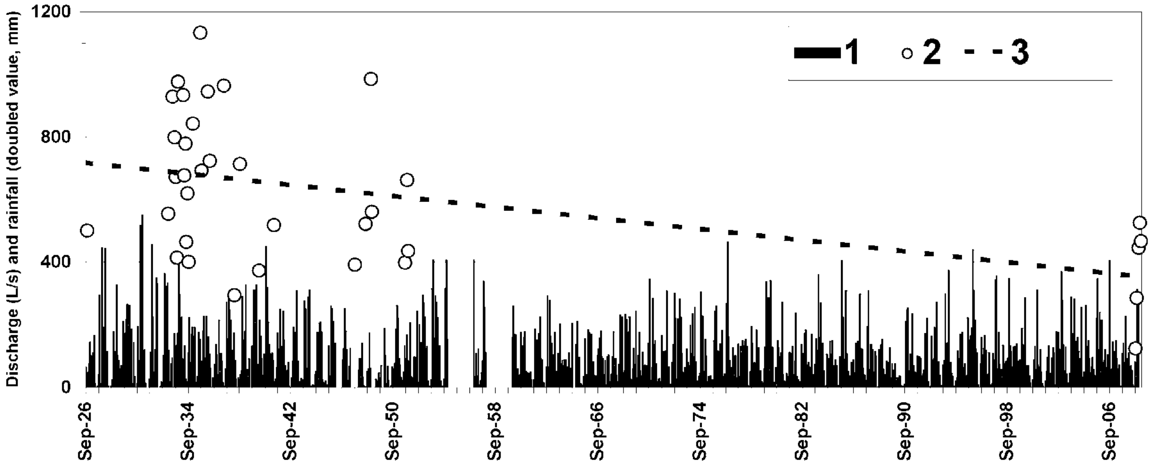

Fig. 4 Fiume Grande Spring discharge and rainfall. (1) Monthly rainfall (doubled value, gauge location in Fig. 2), (2) spring discharge (L/s); (3) straight line trend of spring discharge.

The spring outflow was measured with a single-point Doppler current meter designed for field velocity measurements (Fig. 3). The method provides accurate 2-D or 3-D velocity measurements (accuracy of 1% of measured velocity from 1×10^{-4} to 4.5 m/s). The measurement method considers water temperature and salinity with a built-in temperature sensor and with an external probe, respectively.

The measurement is realised about 10 cm upstream from the acoustic transmitter-receiver system, and for this reason is free of any disturbance caused by the instrument or the operator, which works downstream. The equipment does not use moving parts.

Measuring discharge involves wading across the stream while taking measurements of water depth and velocity at different locations. Standard and affordable procedures are used to compute the discharge on the basis of water depth and velocity.

Thirty-seven measurements of spring discharge are available from 1926 to 2009 (April). The discharge ranges from 124 (September 2008) to 1132 L/s (August 1935), with a mean of 620 L/s (Fig. 4). The discharge measurements were almost bi-monthly from 1933 to 1936. The mean discharge of this period was 757 L/s, considering complete hydrological years (September to August). These discharge values were due to rainfall about 30% greater than the mean of the period 1923–2008, equal to 636 mm at the nearest gauge (Fig. 2).

The mean of monthly discharge was 378 L/s from September 2008 (beginning of the hydrological year) to April 2009; this mean value is equal to 62% of the mean of the whole data set (if we consider only values measured from September to April before 2008–2009, the mean value is 635 L/s of which the 2008–2009 mean of monthly discharge is equal to 60%). The straight line trend of discharge highlights a decreasing trend equal to –4.4 L/s year^{-1} in the whole period. In the same period, the rainfall trend of the nearest gauge is slightly negative (–0.13 mm year^{-1}). We have not completed the hydrological monitoring year 2008–2009, nevertheless it is sure the decrease of discharge cannot be justified only as the effect of the rainfall or of the recharge decrease, if the trend of the net rainfall at the regional scale is considered (Polemio & Casarano, 2008). To this phenomenon, observed from about 1980, must be added over-exploitation due to well discharge, which has increased since the 1950s.

CONCLUSIONS

The trend characterisation of the piezometric head and spring discharge highlights a remarkable lowering and a widespread quantity degradation of groundwater resources in each considered aquifer. These effects are more relevant in some inner portions of Tavoliere and Murgia. The piezometric lowering in Salento is slower but extremely risky due to the naturally low piezometric level above sea level, which is characteristic of this hydrogeological structure. In this case, a piezometric lowering can increase the salt pollution risk due to seawater intrusion. The results together indicate a progressive impoverishment of high quality Apulian groundwater due to the decreasing recharge because of climate modification and increasing over-exploitation.

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