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Climate change, drought and groundwater availability in southern Italy

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Abstract: Data for the period 1821 to 2003 from 126 rain gauges, 41 temperature gauges, eight river discharge gauges and 239 wells, located in southern Italy, have been analysed to characterize the effect of recent climate change on availability of water resources, focusing on groundwater resources. Regular data are available from 1921 to 2001. Many analysis methods are used: principal component analysis, to divide the study area into homogenous portions; trend analysis, considering the Mann–Kendall, Student-*t* and Craddock tests, autocorrelation and cross-correlation analyses, and seasonal, annual and moving-average variables, applying the spatial analysis to each variable with a geographical information system approach.

A widespread decreasing trend of annual rainfall is observed over 97% of the whole area. The decreasing trend of rainfall worsens or decreases as mean annual rainfall increases; the spatial mean of trend ranges from −0.8 mm/a in Apulia to −2.9 mm/a in Calabria. The decrease in rainfall is notable after 1980: the recent droughts of 1988–1992 and 1999–2001 appear to be exceptional. On a seasonal basis, the decreasing trend is concentrated in winter; a slight positive trend is observed in summer, the arid season in which the increase is useless as it is transformed into actual evapotranspiration. The temperature trend is not significant and homogeneous everywhere if the temperature increase seems to prevail, especially from about 1980. Net rainfall, calculated as a function of monthly rainfall and temperature, shows a huge and generalized negative trend.

The trend of groundwater availability is so negative everywhere that the situation can be termed dramatic for water users, due not only to the natural drop in recharge but also to the increase of discharge by wells to compensate the non-availability of surface water tapped by dams, as a direct effect of droughts.

The significant meteorological factors behind droughts include not only rainfall, temperature and evapotranspiration, but also atmospheric circulation patterns (EEA 2001).

Considering Europe and particularly the Mediterranean area, low pressure generally settles over Iceland, and high pressure over the Azores involving the Mediterranean area; this feature occurs quite normally in the summer, very often from March to October. A change in position and/or duration and intensity of anticyclones leads to rainfall/temperature anomalies. A common feature of Mediterranean droughts is the persistence of high-pressure systems. In the Mediterranean area, drought seems to be teleconnected to La Niña, an anomalously high cooling of the equatorial Pacific Ocean; out of 14 La Niña events, occurring between 1865 and 1990, 13 were associated with droughts in the Mediterranean area (Conte & Colacino 1994).

The Mediterranean Oscillation, as is the case for the North Atlantic Oscillation, is defined as the normalized pressure difference between two stations, in the case of the Mediterranean Oscillation Algiers and Cairo; the considered variable is the 500 hPa surface height. Piervitali & Colacino (2002) show the Mediterranean Oscillation is anticorrelated to rainfall in Italy in the period 1951–1995.

The spectral analysis of Italian temperature and rainfall series shows short- (two years), medium- (eight years) and long-term (14–26 years) oscillations caused mainly by solar cycles, according to Nanni & Lo Vecchio (1997), and also by the Atlantic ocean–atmosphere oscillation, according to Brunetti *et al.* (2000).

In the Mediterranean countries, drought is often the result of a sequence of dry years (EEA 2001). Considering the central-western Mediterranean basin, Piervitali & Colacino (2002) detect a trend towards a drop in rainfall equal to −3.2 mm/a from 1951 to 1995 while Piervitali *et al.* (1997) describe an increase in temperature of 1°C during the period from 1860 to 1995, higher than recognized on a global scale.

If Italy is considered, this pattern is confirmed but a distinction can be drawn between northern and central-southern Italy (Brunetti *et al.* 2004). The Italian climate has become warmer and drier, especially in the south, with an increase of both heavy precipitation events and long dry spells, as

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revealed by a study of more than a century of measurements up to 2000. Brunetti *et al.* (2004) show the temperature trend is positive for every season in the south and for autumn and winter in the north; in the former case the annual temperature trend is equal to 0.7°C/100 years and the winter trend is equal to the maximum, as shown also by Nanni & Lo Vecchio (1997) on the basis of a study of data from 1866 to 1975. The southern annual rainfall trend is −1 mm/a, about double that of the northern trend, and these trends, seem more or less null only for the winter season.

Other authors determine the annual rainfall trend equal to −2.2 mm/a in Italy, considering data from 1951 to 1996 (Brunetti *et al.* 2001) and equal to −4 mm/a in the same areas of southern Italy (Brunetti 2002).

Temperature and precipitation trends seem anticorrelated in Italy, as observed by Brunetti *et al.* (2000), using seasonal temperature and rainfall data for 1866 to 1995, and by Cambi *et al.* (2000), using also proxy data of lakes during the last 3000 years; Cambi *et al.* have evaluated the linear gradient ranging from −130 to −40 mm/°C, using regularly monitored data.

Some droughts can be man-made via mismanagement of the resources. Physical and human driving factors include the storage of catchments and aquifers and socio-economic factors controlling water demand. In southern Europe water consumption climbed from 7.1 km^3/year in 1900 to values 15 times higher in 1995, and further increases are expected in the years ahead (16.5 times higher in 2010; Shiklomanov 1999).

With regard to Italy, Brunetti *et al.* (2004) observed the drought worsening from 1980 onwards, studying data from 1950; in the drought period of 1988–1990 a deficit of 43% in Italian total rainfall was recorded (EEA 2001). Cambi *et al.* (2000) observed the effect of droughts on two mountain springs uninfluenced by human activity, evaluating the annual trend of spring discharge equal to 7% (1942–1991) and to 19% of mean discharge (1974–1995).

Future scenarios could be worse: by 2050, annual rainfall is expected to increase in northern Europe and decrease elsewhere in Europe. Temperature and potential evaporation will rise everywhere, with a huge impact on the driest regions of southern and eastern Europe (EEA 2001). Broadly stated, it seems that simultaneous drops in rainfall, increasing evapotranspiration and water demand are occurring in this period in southern Europe, contributing to groundwater resource depletion, decreasing piezometric levels and affecting several related environmental issues, such as seawater intrusion, contamination of land and water, and desertification.

All studies previously cited are characterized by low gauge density or by considering relatively small areas. This study focuses on the whole of southern Italy, involving the Apulia, Basilicata, Calabria and Campania regions (Fig. 1), where the mean annual precipitation (MAP) is equal to 901 mm.

This study is based on rainfall and air temperature (hereafter referred to as simply ‘temperature’) monthly data from 126 gauges, river discharge data from 8 gauges, and piezometric data of 239 wells. The main purposes are to determine the existence of a trend of these variables, to determine the role of drought periods, and to describe the contribution of variation of the water cycle on the availability of groundwater.

Climatic data and spatial approach

Rainfall and temperature monthly time series of the Italian hydrological service (Servizio Idrografico e Mareografico Nazionale, SIMN), have been considered (SIMN 1916–2000). A total of 126 rainfall gauges were finally selected from among 817 gauges (SIMN 1976) (Fig. 1). The gauges were selected to obtain a sufficient gauge density and spatial continuity mainly of rainfall and secondly of temperature, covering the maximum monitoring period with the minimum of data gaps; 41 of the selected gauges were also temperature gauges. The unpublished data are available courtesy of the Naples, Bari and Catanzaro SIMN departments. Data before 1915 were collected by Eredia (1918). The time series can be considered almost complete only from 1921 to 2001, the so- called main study period (MSP). Climatic time series utilized by previous authors (Polemio & Casarano 2004; Polemio *et al.* 2004*a*) have been enlarged, reducing gap percentages, and have been improved afterwards by homogeneity evaluation.

Residual gaps of time series are filled using multiple regressions based on a selection of the best correlated data series of the nearest gauges. The multiple regressions were performed on the normalized deviation of the considered value from the annual mean of the same time series, considering the best-correlated time series ($r > 0.7$) of the nearest gauges (up to six).

The spatial analysis of each variable is carried out by interpolation of point values (gauges) in a Geographical Information System (GIS) environment, operating with a 1-km spaced grid. The mean annual precipitation (MAP) plot, as in any case of variables related to rainfall, has been calculated in the MSP for each cell by weighting data from the 12 nearest gauges, with weights proportional to the inverse square of the distances (Fig. 1).

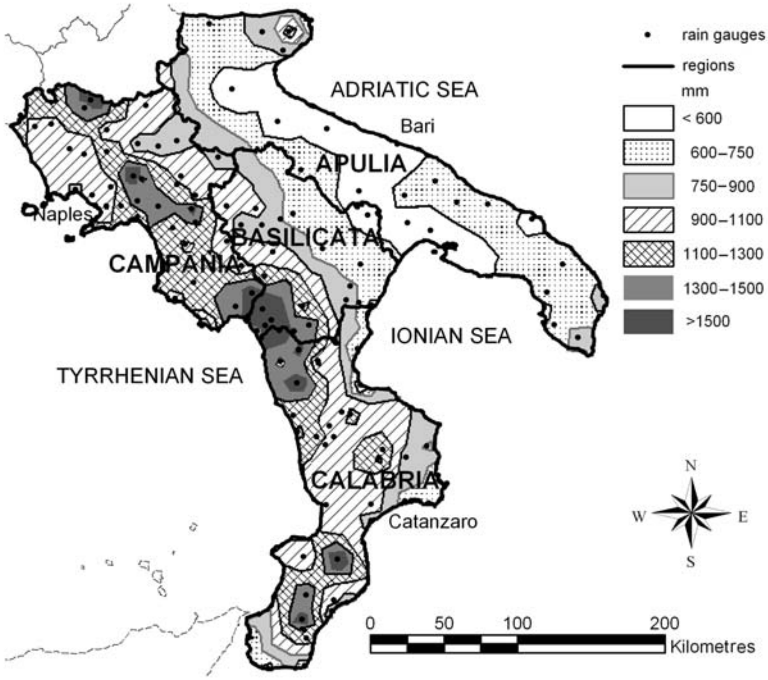

Fig. 1. Studied area, selected rain gauges and mean annual precipitation of main study period.

The climatic homogeneity of the study area has been evaluated on the basis of principal component analysis applied to the deviation of annual rainfall from the average normalized by the respective standard deviation; each time series or gauge is considered an individual while each year is a character or component.

Two main homogeneous climatic areas (HCAs) can be recognized, located along the Tyrrhenian and the Ionian–Adriatic coasts respectively (Fig. 2). The former can be divided into two sub-areas, Campania and the Tyrrhenian Basilicata–Calabria. The latter includes the Ionian Basilicata–Calabria and all of Apulia. Transitional sub-areas between the Tyrrhenian and Ionian–Adriatic influenced areas can be considered sub-areas of the SW portion of Calabria and Inner Basilicata.

The principal component analysis result is coherent with the spatial rainfall distribution in southern Italy (Fig. 1), mainly influenced by humid air circulation and by its arrival along the Italian coasts across the Mediterranean sea, moved by winds of the third and fourth quadrants and secondly by altitude and by the Apennine range which is located along the Tyrrhenian coast in Calabria and Basilicata and inland in Campania.

The statistical and spatial calculations (Table 1) have been performed considering both administrative regions (Fig. 1), where local governments are entirely in charge of water cycle management, and homogeneous climatic areas (Fig. 2). The results are quite similar; they are described here preferring the administrative zonation in order to enhance the message to water cycle managers.

Changes of climate, droughts and net rainfall

Time and spatial variability of annual rainfall

The annual rainfall trend is determined as the Angular Coefficient (AC) of the least-square line for each rainfall time series in the MSP. The increasing trends or positive values of AC are typical only of 12 of the whole 126 series; the maximum observed slope is about 2.5 mm/a. Decreasing trends are observed for 114 series (90%); the minimum is about −9 mm/a. If a 5% significance level is considered for correlation coefficients, 60 negative trends are found versus only two positive trends.

There are 17 time series available before 1921 (three before 1829) and they are located in Campania and Apulia (Polemio & Casarano 2004). If the start of the study period is moved back with respect to the MSP, in Campania a downward trend in rainfall

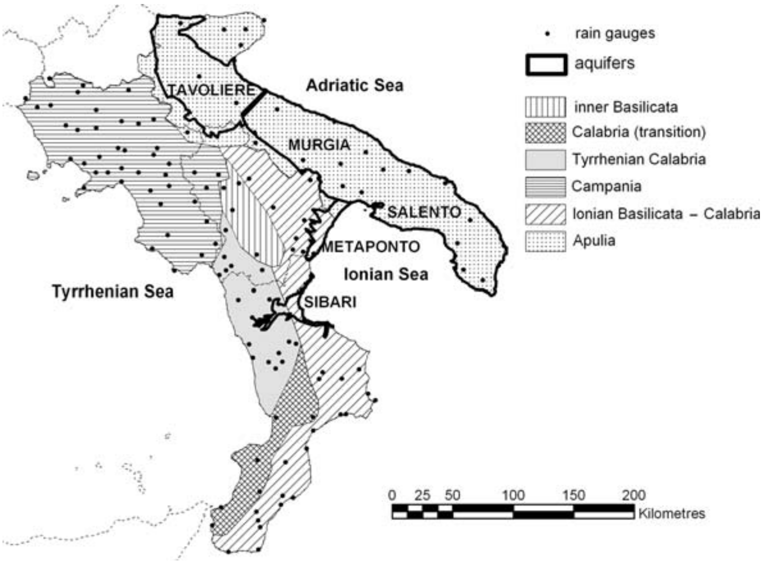

Fig. 2. Homogeneous climatic areas as classified by principal component analysis, rain gauges and aquifers.

is not evident while in Apulia a slight but almost continuous downward trend in rainfall is quite evident, even in the nineteenth century.

The results of the MSP are consistent with previous studies if average spatial values are considered (Brunetti 2002; Cambi *et al.* 2000; Piervitali & Colacino 2002). The higher density of gauges used in this study implies that the trend range is wider and the determination of extreme values is more accurate.

The spatial analysis of AC shows that 96.8% of the study area is affected by a negative trend (Fig. 3). Considering MAP and AC values as cell attributes, the spatial average of AC or the trend values for MAP class highlight the fact that the rainfall trend worsens or decreases as the MAP increases (Table 2). This figure is extremely worrying in the context of water management because high MAP areas are wide Apennine portions of the drainage basins of the artificial lakes which guarantee a relevant percentage of water supplies.

The reliability of detected rainfall trends has been evaluated by the Mann–Kendall test (Mann 1945; Kendall 1975). The Mann–Kendall variable S is:

$$S = \sum_{i=2}^{k} \sum_{j=1}^{i-1} \operatorname{sgn}(z_i - z_j)$$

where z_i is the rainfall of the i-th year of the considered gauge z, and k is the number of data or dur-

Table 1. *Regions or HCA and rainfall*

	MAPR (mm)	TR (mm/a)	PVR (mm)	PVR/MAPR (%)
Region				
Apulia	644	−0.80	−65	−10.1
Basilicata	893	−1.81	−145	−15.9
Calabria	1043	−2.87	−230	−22.0
Campania	1118	−2.44	−196	−17.5
HCA				
Apulia	650	−0.82	−66	−10.2
Inner Basilicata	986	−1.66	−133	−13.5
Tyrrhrnian Calabria	1262	−2.90	−232	−18.4
Calabria (transition)	1054	−3.12	−250	−23.7
Ionian B.-C.	865	−2.33	−186	−21.5
Campania	1118	−2.39	−191	−17.1

For each row the mean is determined considering the MSP: MAPR, MAP of a region; TR, precipitation trend; PVR, precipitation variation due to the trend and to the duration of MSP.

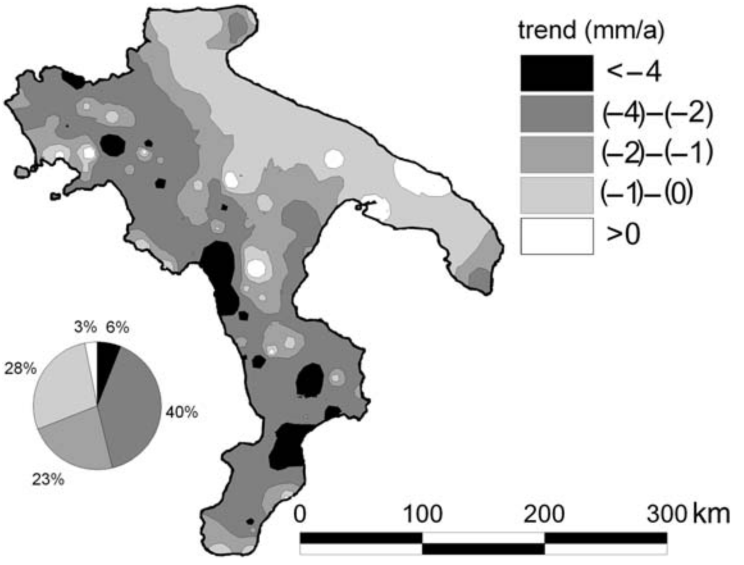

Fig. 3. Trend of annual rainfall as angular coefficient of regression line and pie chart of rainfall trend classes and area of interest in the main study period.

ation of the time series. S is distributed with null mean and variance σ^2 function only of k. This statistic, normalized to the respective standard deviation, highlights a negative trend with regard to 98% of the area, with the Mann–Kendall variable lower than average for more than one standard deviation over 75% of the area, and more than two standard deviations over 39%. It is clear that there is a relevant and generalized downward rainfall trend in the MSP.

The Mann–Kendall test has been improved taking into consideration three more detailed approaches (Douglas *et al.* 2000; Hirsch *et al.* 1982; Polemio *et al.* 2004*a*): pre-whitened series, trend estimator and spatial correlation calculation.

Pre-whitened series may be necessary since the Mann–Kendall test formulates the hypothesis that the data of a time series are independent and not autocorrelated. If the time series is autocorrelated a false trend could be detected. Each time series was then pre-whitened, obtaining a new series with null autocorrelation typical of a white process, and subjected to the Mann–Kendall test again. Widespread negative values of the Mann–Kendall variable and downward rainfall trends were substantially confirmed.

An extension of the Mann–Kendall test also allows an alternative and independent estimate of the trend. It is defined, for each rainfall time series, as the median of the slopes $d_{ij} = (z_i - z_j)/(i - j)$ of any combination with i and j equal to 1, 2, … , k and $i \neq j$. This estimator, being based on a median, is more 'robust' with respect to extreme or anomalous values in the time series. The results are substantially similar to these obtained with the standard approach. The spatial correlation of the m rainfall time series allows the number of 'equivalent' independent rain time series to be estimated. It is useful to estimate the expected variance of a regional average for the Mann–Kendall variable, and then the significance of the trend over a wide area.

If S_i is the Mann–Kendall variable value for the ith rain gauge and all the time series have the same length, then the variance is equal for all the S_i, and a regional average $\bar{S}$ for the Mann–Kendall variable can be calculated. If the m time series are not correlated with each other, then the variance of $\bar{S}$ would

Table 2. *Spatial average of angular coefficient (SAAC) of rainfall straight line trend for MAP class areas*

	MAP class (mm)						
	<600	600–750	750–900	900–1100	1100–1300	1300–1500	>1500
SAAC (mm/a)	−0.64	−1.00	−1.89	−2.38	−2.64	−3.01	−4.74

Table 3. *Distribution of the Mann–Kendall variable for the 41 temperature time series*

	>0	$>\sigma$	$>2\sigma$	<0	$<-\sigma$	$<-2\sigma$
Original series	21 (51.2%)	16 (39.0%)	11 (26.8%)	20 (48.8%)	9 (21.9%)	7 (17.1%)
Pre-whitened series	24 (58.5%)	11 (26.8%)	2 (4.9%)	17 (41.5%)	8 (19.5%)	3 (7.3%)

simply be σ^2/m. Since time series are actually correlated, with ρ_{ij} correlation coefficient between the rain gauges i and j, it is possible to define an 'equivalent' gauge number m_{eq}:

$$m_{eq} = \frac{m^2}{m + 2\sum_{k=1}^{m-1}\sum_{l=1}^{m-k}\rho_{k,k+l}}$$

The variance of the regional average $\bar{S}$ will then be $\sigma_s^2 = \sigma^2 m_{eq}$.

The selected rain gauges have been divided into three groups on the basis of HCAs and administrative boundaries: Campania (41 gauges), Apulia (28 gauges) and Calabria–Basilicata areas (56 gauges). If the original (not pre-whitened) series are considered, m_{eq} is 1.95 for the Campania group, 1.85 for the Apulian group and 2.54 for the Calabria–Basilicata group. The regional average $\bar{S}$ is, respectively, $-2.81\ \sigma_s$, $-1.17\ \sigma_s$ and $-3.59\ \sigma_s$. For the pre-whitened series, m_{eq} is 1.84 for Campania, 1.85 for Apulia and 2.47 for Calabria–Basilicata, and $\bar{S}$ is, respectively, $-2.26\ \sigma_s$, $-1.18\ \sigma_s$ and $-3.21\ \sigma_s$. It can be assessed that the negative trend is only slightly attenuated if the autocorrelation is considered, and thus the substantial statistical relevance of trend results is confirmed.

The existence of relevant rainfall variations in periods shorter than MSP can be better highlighted with the moving average analysis: the deviation from MSP average of moving averages of decreasing duration (5, 3 and 2 years) is considered (Fig. 4).

The 5-year duration allowed the evaluation of significant deviations from the average over long periods. Dry periods were recorded in Apulia for 1942–1950, 1988–1992 and 1997–2001; the last two periods were almost the driest periods in Basilicata, Calabria and Campania.

The 5-year average deviation has been continuously negative since 1978 in Basilicata and Calabria and since 1983 in Campania, whereas the negative deviation in Apulia was observed from 1980 to 1995. The analysis of 3-year and 2-year moving averages shows the drought duration of 2 or 3 years is longest from 1980 as from this year the minimum rainfall has been reached and has been exceeded one or more times in each considered region, particularly with the latest drought of 1999–2001. In Apulia and Campania, some dry periods of the late 1920s and 1940s were as dry as the latest droughts.

The decade's average analysis also highlights a persistent succession of low-rainfall years and drought periods from about 1980; the results are consistent with those of other authors, obtained using different time series and lower data density (Brunetti *et al.* 2004). It can be hypothesized that the observed downward trend in rainfall is strongly influenced by low rainfall observed after 1980. On a

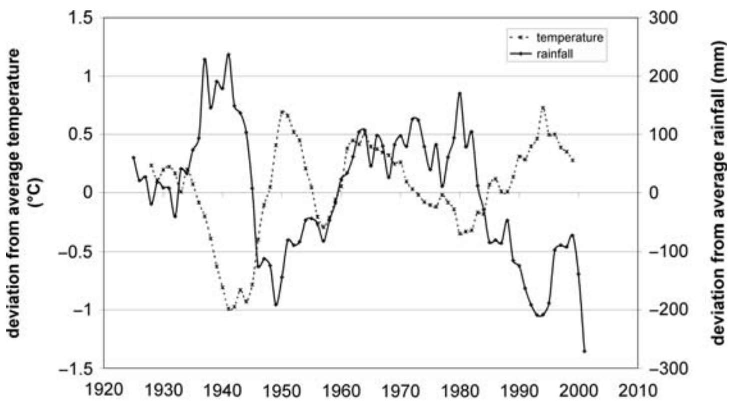

Fig. 4. Regional moving average of 5-year annual temperature and rainfall, expressed as deviations from mean values.

HCA basis, the 1981–2001 average is lower than the 1921–1980 average of 10% in Apulia, 14% in Basilicata–Calabria and 16% in Campania.

The Student *t*-test is used to assess whether each time series of 1921–1980 and 1981–2001 can be considered part of the same population. The 1981–2001 average is lower than the 1921–1980 average for 98% of the time series. The 5% and 1% significance level is, respectively, found for 75% and for 53% of the time series: the rainfall of the latest 20 years can be considered anomalously low.

Monthly data have been utilized to characterize the rainfall seasonal trend. The most important contribution to the annual negative trend is due to the winter (the months from December to February, which is the rainiest season) rainfall trend (Fig. 5). The precipitation deficit of the last 20 years is mostly due to a reduced contribution of winter rainfall. Spring (March–May) and autumn (September–November) also show negative trends, although much less evident. A positive trend appears for summer, the arid season: the effect is null in terms of water resources availability.

Temperature and net rainfall trend

Monthly temperature series are available from 1924 onwards. To fill the residual monthly gaps the time series were grouped into HCA. A different approach, based on gap filling and homogenization, was necessary for 15 time series of gauges located in Campania due to the abundance of very anomalous values, in particular for the last 20 years (the homogeneity evaluation is based on the Craddock (1979) test).

The linear trend analysis shows the temperature trend is not as homogeneous as the rainfall trend both in the whole study area and in each HCA (Tables 3 and 4). A prevailing increasing trend is observed in Campania but is weak in Apulia and is substantially absent in the remaining area.

To apply the Mann–Kendall test, pre-whitening of the temperature series is necessary due to their significant autocorrelation. The Mann–Kendall *S* distribution is close to Gaussian; there is a slight prevalence of increasing trends in the Campania region where an increase of temperature starting from about 1980 is observed, as shown in Figure 4. However, this is not enough to assess a significant and generalized temperature trend over the whole area in MSP, since this behaviour is not so evident elsewhere. These results are thus quite different from those by other authors (Brunetti *et al.* 2004; Cambi *et al.* 2000), probably due to the strong difference of data set length and spatial density of examined gauges.

The real or actual evapotranspiration E_r was calculated using Turc's formula (Turc 1954) with the correction suggested by Castany (1968), using temperature and rainfall monthly data. In this way an approximate but simple evaluation of the annual variation of actual evapotranspiration can be obtained.

The average annual net rainfall (ANR) of a time series ranges from 52 to 1565 mm for the whole group of 41 available time series in the period 1924–2001. The AC of net rainfall (ACNR) is strongly negative everywhere. The absolute value of ACNR is directly correlated to MAP: it increases or gets worse as MAP increases. ACNR ranges from −0.4 to −4.3 mm/a, grouping the time series by

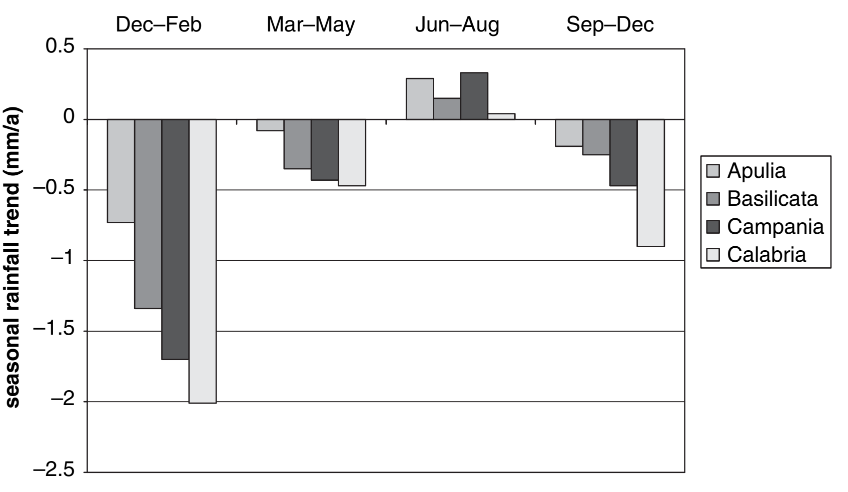

Fig. 5. Spatial average of seasonal rainfall trends of the main study period.

Table 4. *Number of time series as percentage of the total for each HCA and classes of angular coefficient of temperature trend (ACT, °C/100 years)*

HCA	ACT < −1	−1 < ACT < −0.5	+0.5 < ACT < +1	ACT > +1
Apulia	7	7	20	7
Calabria–Basilicata (all)	17	25	8	8
Campania	7	0	13	27

MAP (Table 5). In the whole period, the reduction of net rainfall can be roughly assessed as from 27% to 33% of ANR: this percentage is everywhere higher than that calculated for actual rainfall.

This dramatic situation is due to different phenomena. First of all, the downward rainfall trend is more relevant during winter, when generally net rainfall reaches maximum levels and actual evapotranspiration minimum levels. The entire winter decrease in actual rainfall becomes a decrease in net rainfall. The summer is arid everywhere and the actual evapotranspiration is less than the potential one due to low rainfall. The increase in summer rainfall is completely ‘burned’ by actual evapotranspiration. The recent trend towards a rise of annual temperature and the regime variation amplify the effect of rainfall variations.

Groundwater availability and role of climate change

Main characteristics of selected aquifers

The effects of recent climate variations on groundwater availability are evaluated considering five wide hydrogeological structures (HSs). In each HS the shallow or outcropping aquifer is considered; three are porous, two are constituted by carbonate rocks, all are coastal aquifers.

The Apulian Tableland HS, 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 *et al.* 1999). It is deep enough to allow seawater intrusion only in the vicinity of 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 a.s.l.

Except for the Tavoliere, the Apulian region is characterized by the absence of rivers and the non-availability of surface water resources due to its karstic nature. Considerable groundwater resources are located in large and deep carbonate coastal aquifers, as in the case of the Gargano (not considered in this study due to the low data availability), the Murgia and the Salentine Peninsula (Salento) HSs. The Murgia and Salento areas show some common features (Cotecchia *et al.* 2005). They consist of large and deep carbonate aquifers, constituted mainly of limestone and dolomite rocks. Carbonate rocks are affected by karstic and fracturing phenomena, which occur 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 coastline strip. The maximum piezometric head is about 200 m a.s.l in the Murgia area and 5 m a.s.l in the Salento area (Spizzico & Tadolini 1997).

Five rivers cross the Metaponto plain, located along 40 km of Ionian coast. Marine terraced deposits, mainly sands, conglomerates and silts, crop out in the upland sectors of the Metaponto plain, while alluvial, transitional, marine and coastal deposits crop out in the coastal plain and along the rivers (Polemio *et al.* 2003). Two main types of porous aquifers can be distinguished in the Metaponto plain. The first one encloses the aquifers of the marine terraces and the alluvial river valley deposits. The marine terrace aquifers display medium to high hydraulic conductivity; the river valleys regularly break their spatial extent. The aquifers of the river valleys display low to medium hydraulic conductivity and they do not generally permit an accumulation of significant groundwater resources. The second type of aquifer includes one of the coastal plain deposits and has a medium hydraulic conductivity. This aquifer is the most exploited one for practical purposes due to its extension (about 40 km wide), thickness, continuity across

Table 5. *Net rainfall trend and MAP classes considering data from 1924 to 2001*

MAP Class	ANR (mm)	NRT (mm/a)	NRV/ANR (%)
<600 mm	85.5	−0.39	−33.1
600–900 mm	227.9	−0.89	−27.1
900–1300 mm	464.8	−1.99	−32.2
>1300 mm	967.9	−4.30	−32.3

ANR, average net rainfall; NRT, net rainfall trend; NRV, net rainfall variation from 1924 to 2001 and ANR ratio.

the plain and also because its outcropping surface is more affected by economic growth and increasing water demand.

The groundwater of the coastal plain aquifer flows in a multilayered aquifer; it is mainly phreatic, otherwise it is confined due to an upper, almost impervious and outcropping stratum.

The Sibari plain is located in NE Calabria and covers the final sector of the Crati river. The Sibari plain is bordered by the carbonate relief of the Pollino Massif to the north and by the intrusive and metamorphic rocks of the Sila Massif to the south; it is composed of sedimentary lithotypes, varying from sand to marl and clay and including gravel locally.

The Sibari plain houses multilayered aquifers, the recharge of which is partially ensured by groundwater flowing from massifs and by leakage of rivers. For this study the shallow sandy aquifer alone has been considered (Polemio & Petrucci 2003).

Hydrological data

Piezometric data (Table 6) and river discharge measurements (five time series ranging from 1930 to 1992 for the Tavoliere and three series ranging from 1929 to 1971 for the Metaponto plain; SIMN 1916–2000) are considered together with already analysed rainfall and temperature data. The continuous or regular monthly piezometric data are derived from gauges managed by SIMN (1916–2000) or by the Irrigation Development Agency (Regione Puglia 1983). Occasional and recent data were collected on-site by the IRPI hydrogeological staff (Polemio & Dragone 2003, 2004; Polemio *et al.* 2003, 2004*b*, 2004*c*; Polemio & Petrucci 2003) and by other sources (Regione Puglia 2002) for the Tavoliere aquifer; Lopez *et al.* (2003) and CASMEZ (1987) for the Sibari aquifer.

Data from 58 wells or piezometric gauges are available for the three Apulian HSs – the Tavoliere, the Murgia and the Salento (Polemio & Dragone 2004). The piezometric data sets regarding the Tavoliere are available for a minimum of 17 years and for a maximum of 55 years, covering a continuous period between 1929 and 1994 (Polemio *et al.* 1999). Continuous data are available from 1973 to 1978 for the Murgia and the Salento. Furthermore, sporadic recent data were collected in Apulia for the periods 1995–1997 and 2001–2003.

Piezometric time series of monthly data are available in the Metaponto plain for 60 wells in two periods, 1927–1940 and 1951–1984 (Polemio & Dragone 2003). Occasional but high density data are available in the whole plain for 1953 and 1990 and in a selected study area for each season of 2002 (Polemio *et al.* 2004*a*).

Data from 121 wells in the Sibari plain were considered, for which discontinuous piezometric data are available from 1932 to 2002. Data are concentrated in the 1930s, the 1950s and the 1970s. The surveying was managed by different institutions in these different periods: the location and the identification of wells are not detailed enough to permit linking of the series. The oldest data were regularly collected from 1932 to 1940 in 27 wells; this data set has been used as a reference for spatial analyses. In June 2002 a high density piezometric survey was carried out. Due to the shortness of regular piezometric time series, the analysis for the Sibari plain is limited to the spatial analysis of piezometric surface modifications.

Data analysis

Piezometric data are explored by typical approaches of time series analysis such as autocorrelation, cross-correlation and trend analysis tools, and of spatial analysis, using kriging to obtain grid data of piezometric surfaces to compare using simple arithmetic operations and volume determinations.

The piezometric value recorded in any month is strongly dependent upon the values of the previous months, the link being significant, diminishing as the time lag increases. The duration and the

Table 6. *Piezometric data availability for each hydrogeological structure (HS) and straight line trend (AC)*

HS	Well number	Data range	Minimum AC (m/a)	Trend more probable at 2002 or 2003
Tavoliere	11	1929–2002	−0.408	High decrease
Murgia	30	1965–2003	−0.240	High decrease
Salento	17	1965–2003	−0.060	Decrease
Metaponto	60*	1927–2002	−0.236†	Decrease
Sibari	121	1932–2002	‡	Decrease

*The number of wells available for occasional years is higher and variable.
†In the periods 1927–1940 and 1951–1984.
‡Determination not available due the characteristics of data set.

intensity of this dependence, called the memory effect, is a function of specific yield, saturated thickness, hydraulic conductivity and extent of the aquifer. High values of these parameters are typical of aquifers of high quality to tap groundwater; in these cases the autocorrelation decreases slowly as the lag increases.

The cross-correlation for each piezometric series is determined by comparing it pairwise with data from a hydrogeologically significant series of rainfall, temperature and, where available, river discharge, the data of which are utilized step by step with increasing lag from 1 to 12 months. The cross-correlation coefficient expresses a measure of effect of the latter variable, rainfall, temperature or river discharge, on the variability of the former variable, the piezometric height or level.

The spatial analysis is utilized to complete the trend analysis of piezometric data when sporadic but high density data are available.

The three considered porous aquifers are subject to similar hydrological conditions: the range of mean annual rainfall and temperature is, respectively, 440–600 mm and 15.9–16.9°C. The Tavoliere area is a little cooler and drier than the other two areas. With regard to the monitored river discharges, the whole range of mean annual values is 1.0–20.0 m^3/s.

In the Tavoliere aquifer the autocorrelation coefficient always decreases slightly and quite linearly. There is a very high autocorrelation in 56% and 22% of wells, decreasing the coefficient respectively from 1 to about 0.8 and to 0.5, increasing the lag up to 12 months. The autocorrelation of remaining wells is insignificant after six lags.

The piezometric height is cross-correlated with river discharge, temperature (in this case this is an anticorrelation) and rainfall in decreasing order of maximum absolute value of coefficient. The river bottom is generally higher than the piezometric height in the monitored locations.

The maximum of the cross-correlation coefficient (MCC, as absolute value if the coefficient is negative, as in the case of temperature) and of maximum significant lag (MSL, the maximum lag for which there is statistical significance of cross-correlation) are, respectively, 0.5 and 2 months for discharge, 0.4 and 3 months for temperature, and 0.3 and 5 months for rainfall. MSL seems well correlated to depth to water, and thus appears to be a useful parameter to evaluate the time necessary to transfer a surface water impulse to groundwater.

The fact that even temperature variations are significant, more widespread than rainfall, has already been observed in similar hydrogeological conditions (Polemio *et al.* 1999). This can be explained by considering the nature of the climate, which is semi-arid everywhere for the selected aquifers. In this type of climate, the temperature is significant because of two separate and cyclic phenomena. The first is a natural phenomenon, real evapotranspiration, which 'regulates' the availability of net rainfall for infiltration from autumn to spring. The second is anthropogenic and is mainly linked to groundwater discharge from spring to autumn, due to high temperatures and potential evapotranspiration: the farms use more groundwater to offset the water deficit. In this way, temperature variation more than rainfall explains piezometric variations over the whole hydrologic year.

The trend of river discharge has been characterized by five gauges: the trend is clearly decreasing, especially since 1980, as in the case of rainfall in the whole Apulian region. It should be recognized that this variable is also influenced by human activity due to depletion by dams or by diffuse withdrawals from rivers for farm use, which strongly increased by 1980.

The piezometric trend everywhere is decreasing (Table 6). The continuous piezometric lowering has transformed many confined wells into phreatic wells; after that, the shallow groundwater of the Tavoliere is completely depleted in places. In terms of straight line trend, the trend everywhere is strongly negative, constituting a severe problem for groundwater discharge by wells (Table 6). The trend is confirmed by the spatial analysis of sporadic 2002 data: the spatial mean of piezometric decrease is 7.93 m over about 15 years.

In the Metaponto plain, the autocorrelation coefficient is quite linear from the maximum, a bit lower than 1, to the minimum, equal to not less than 0.3, increasing the lag up to MSL, equal to 6 months (after that the piezometric values are independent). The memory effect is high everywhere, but generally higher where groundwater is confined.

The MCC is generally less than 0.5 while MSL is 3 months, with some exceptions up to 4 months in the case of rainfall. As in the case of the Tavoliere, the MCC is low and lower than the absolute value of temperature MCC which is, in this case, also greater than the river discharge MCC. The temperature MCC is generally less than 0.7 while MSL is 2 months, with some exceptions of up to 4 months; everywhere, the coefficient is negative. The river impulse in terms of piezometric variations is extremely quick and important: MSL is generally 1 month and MCC less than about 0.6.

The trend of the piezometric series has been defined both on a synoptic scale, for the whole plain, and on a detailed scale, in the selected study area. With regard to the synoptic scale, the trend is described by AC while for the detailed scale it is the result of a comparison of the piezometric surfaces of different years.

The piezometric minimum occurred generally between 1952 and 1954 (up to 1984), when the exploitation of the aquifers was very high, after the end of land reclamation works (Polemio & Dragone 2003).

The time series analysis shows a widespread negative trend for the period 1927–1940 with a piezometric drop, on average, equal to 0.05 m/a. In the same period of time, the rainfall trend is slightly positive locally. This figure can be explained, as the groundwater represented the only irrigation resource during these years. Conversely, a positive trend is observed from 1951 to 1984 (75% of the total available time series), even if rainfall and river discharge trends are not positive. This figure can be explained considering the fact that many dams were built in this period; the dams started to supply more irrigation water than ever before. This allowed a reduction of groundwater tapping and also created a sort of artificial recharge, due to over-irrigation.

A new trend variation, a widespread downward trend, started during the 1980s; this trend remains unchanged. During 1988–1991 a heavy drought hit the area. The effect was the depletion of artificial lakes and the massive re-utilization of groundwater. The piezometric effects of drought in 1990 were relevant, particularly as compared to the situation in 1953, defined almost as a minimum until 1984. Negative piezometric variations are generally also prevalent in the case of the selected study area, where a more detailed analysis was carried out during 2002 (Polemio *et al.* 2003). For this area, the 2002 spatial mean of piezometric height is 1.12 m less than that of 1953, while that of 1990 is 0.34 m higher.

The maps of the piezometric variations in the Sibari plain highlight a decreasing trend which started around the 1950s, assuming as reference piezometric surface that of the 1930s. The plain as a whole is characterized by piezometric heights in the 1950s which were higher than in the 1930s (positive piezometric variation). Major decreases of piezometric height (negative variations) appear inland during the 1970s while two separate positive variation areas remain, involving main rivers and portions of the coast. Both a lowering of the piezometric negative variations, in term of absolute values, and a narrowing of the positive variation area are observed in 2002, the positive variation area becoming quite similar to a strip along the coast. The spatial mean of piezometric variation of 2002 is the lowest or the worst observed; it is equal to a lowering of 4.42 m with respect to the 1930s.

In the case of the considered Apulian carbonate hydrogeological structures, the autocorrelation piezometric coefficients consistently show a progressively declining trend, starting from one to the statistically significant minimum, everywhere not less than 0.5, increasing the lag to 4 months for the Murgia and 5–6 months for the Salento area. The consistent memory effect of Apulian groundwater is a characteristic feature which is of great importance during droughts or dry spells. The Salento has shown very strong and long-lasting memory effects, which is only further proof of the good hydrogeological characteristics of these aquifers.

There is a cross-correlation between the piezometric and climatic variables of an acceptable significance level for a time lag up to 4 months. The effects of rainfall are perceptible up to a maximum period of 2–3 months, whereas the best correlation with temperature is felt with a time lag of 4 months. The temperature variations are more significant than rainfall in some portions of the Murgia and the Salento.

The calculated piezometric trend, generally speaking, is downward, since there is a widespread tendency, albeit in some cases a very slow one, towards a piezometric drop. The lowest piezometric decrements have been observed in the Salento area, which has an AC in the range of −0.060 to −0.012 m/a; worse AC values are typical of the Murgia HS (Table 6). In the Murgia, as in each HS, the AC approaches zero the closer one gets to the coastal areas, as would be expected.

During 2002, a widespread and dramatic drought period ended. On the basis of the available data set, the most likely piezometric trend, ending in the second half of 2002, was very negative and serious in terms of the sustainability of the groundwater demand, over the entire area covered by porous aquifers, as in the case of the Tavoliere, the Metaponto plain and the Sibari plain (Table 6). This situation is confirmed by sporadic data of 2003 in the case of the Murgia and the Salento, notwithstanding the effect of more than a year of abundant rainfall.

Conclusions

A widespread decreasing trend of annual rainfall is observed over 97% of the whole area from 1921 to 2001. The spatial average of trend value and MAP highlight the fact that the rainfall trend worsens or decreases as the MAP increases. This phenomenon is extremely worrying because high MAP areas are wide Apennine portions of the widest drainage basins of the artificial lakes which guarantee a relevant percentage of water supplies. The spatial mean of trend ranges from −0.8 mm/a in Apulia to −2.91 mm/a in Calabria.

The downward trend is mainly the effect of a succession of low-rain years; this succession is anomalous from about 1980, in terms of frequency and intensity of annual rainfall less than MAP; in this context, the droughts of 1988–1992 and 2000–2001, the worst since 1921, appear to be more important.

On a seasonal basis, the downward trend is concentrated in winter: the precipitation deficit of the last 20 years is mostly due to a reduced contribution of winter rainfall.

A Mann–Kendall test does not show a significant prevalence of negative or positive temperature trends. Although in some stations the highest temperatures have been recorded in the last ten years and a slight increase seems to prevail, especially from about 1980 onwards, this is not enough to determine a significant and generalized increasing temperature trend for the whole area.

The annual mean of net rainfall ranges from 52 to 1565 mm. The trend of net rainfall is everywhere strongly negative; in the whole study period the reduction of net rainfall can be roughly assessed from 27 to 33% of the annual mean.

The selected aquifers show high hydrogeological characteristics as confirmed by the consistent memory effect, which is not shorter than 4 months. This characteristic is of great importance during droughts or dry spells.

The cross-correlation with piezometric level shows that the variability of groundwater availability can be explained in terms of rainfall, temperature and, where it exists, river discharge variability. The significant lag or duration of this influence generally decreases from the first variable, rainfall, to the last, river discharge, and respectively from 3–5 to 1–2 months. The intensity of this influence, in terms of maximum cross-correlation coefficient, is generally due to temperature, river discharge and rainfall in decreasing order.

The piezometric trend is on the decline everywhere, so widespread as to determine serious effects in terms of groundwater discharge sustainability. The worst trend in each aquifer or structure ranges from 0.06 to 0.41 m/a notwithstanding the limiting effect of sea level boundary condition. Detailed spatial studies show an average decrease of 7.93 m over the last 15 years in the Tavoliere, 1.1 m over 50 years in the Metaponto plain and 4.4 m over 70 years in the Sibari plain.

During 2002 the latest widespread and dramatic drought ended. On the basis of the data set available, the most likely piezometric trend, ending in the second half of 2002, was a very serious one over the entire area covered by porous aquifers, as in the case of the Tavoliere, the Metaponto plain and the Sibari plain. This situation is confirmed by sporadic data of 2003 in the case of the Murgia and the Salento, notwithstanding the effect of more than a year of abundant rainfall.

The whole piezometric downward trend appears to be due to the overlapping effects of natural recharge and of increasing well discharge. The effects of the latter phenomenon appear to be influenced by the progressive availability of surface water resources tapped by dams. The increasing role of these water resources to cover the water demand does not prevent a return to pumping water from aquifers during the recent and unusual droughts.

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