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A statistical approach for describing coastal karst aquifer: the case of the Salento aquifer (southern Italy)

Un approccio statistico per la descrizione degli acquiferi carsici costieri: il caso dell'acquifero del Salento (Italia meridionale)

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Riassunto

Si propone un approccio basato su serie temporali per migliorare la conoscenza di un ampio acquifero carsico costiero. L'approccio combina la decomposizione delle serie temporali, il trend, l'autocorrelazione e le analisi di cross-correlazione utilizzando dati giornalieri e mensili di temperatura, precipitazioni e piezometria con diverse caratteristiche temporali. L'originalità dell'approccio nasce dall'obiettivo di discutere gli unici dati storici disponibili, fondendo la discussione di serie temporali giornaliere più brevi e complete con serie temporali mensili di lunga durata (1965-2011) ma con lacune rilevanti. L'approccio è stato applicato all'acquifero carsico del Salento con lo scopo di migliorare la valutazione delle proprietà idrodinamiche dell'acquifero utilizzando serie temporali sia regolari che lacunose. I risultati sottolineano l'efficacia dell'approccio nel descrivere le proprietà idrodinamiche di un acquifero carsico costiero, svelando la significativa inerzia del sistema carsico studiato per quanto riguarda la trasmissività e la sostanziale capacità di immagazzinamento. Le differenze nell'effetto memoria e nel tempo di risposta tra analisi giornaliere e mensili sottolineano la natura intricata del sistema esaminato e l'influenza della qualità dei dati. È stato osservato una tendenza piezometrica decrescente di lunga durata come effetto del cambiamento climatico globale.

Abstract

A time series approach was proposed to improve the knowledge of a wide coastal karst aquifer. The approach combines time series decomposition, trend, autocorrelation and cross-correlation analyses using both daily and monthly temperature, rainfall and piezometric data with different temporal characteristics. The approach merges shorter and complete daily time series (2007-2011) with long-lasting monthly times series (1965-2011) with relevant gaps. The approach was applied to the Salento aquifer (Southern Italy) to enhance the comprehensive approach of statistical tools and variables in assessing the hydrodynamic properties of karst systems. Results underscore the approach effectiveness in describing the hydrodynamic properties of a coastal karst aquifer, unveiling the significant inertia of the investigated karst system concerning transmissivity and substantial storage capacity. Differences in memory effect and response time between daily and monthly analyses emphasise the intricate nature of the examined system and the influence of dataset quality. A long-lasting declining piezometric trend was observed as an effect of climate change and anthropic pressure.

Introduction

The recent EU Climate Change Adaptation Strategy (EC, 2021) drives EU members to pay great attention by guaranteeing long-lasting drinking water. Climate change will increase the risks of overexploitation, which can often compromise the quality of residual groundwater, e.g. through saltwater intrusion (Polemio and Zuffianò, 2020). To better manage these water resources and mitigate the risks of degradation, it is essential to gain a deeper understanding of how aquifers respond to climatic variables (Green et al., 2011).

Coastal areas, already home to 70 per cent of the world's population, are increasingly populated and attractive to water-demanding activities, many of which are potential pollution sources (Webb et al., 2011). Coastal aquifers are among the most prone to deteriorating groundwater quality due to the overlapping effect of saltwater intrusion and anthropogenic pollution. Therefore, monitoring networks are needed to detect and understand the effect of climate change and human pressures on groundwater. The inferred data from the monitoring will be the reference for defining the more appropriate water management strategies.

Forecasting groundwater response to climate change must start with the knowledge of every natural system; otherwise, the definition of monitoring and sustainable water management strategies remains ineffective. The knowledge of an aquifer's response to climate change starts from understanding the base mechanism of water balance and groundwater recharge (Green et al., 2011).

The issue is particularly complex for karstic aquifers (Goldscheider, 2015). Recharge acts from the surface through the epikarst, passing through the vadose zone to reach the saturated one. Here, the hydraulic phenomenon that permits the infiltration is exceptionally complex and depends on the degree of karstification. Flow depends on an intricate system characterised by conduits, fissures, and fractures of the rock matrix. It is site-specific and highly variable due to its high heterogeneity and anisotropy (Bakalowicz, 2005). The duality of karst aquifers due to conduits vs matrix represents the leading cause of uncertainty. Therefore, every karst system can be a single case with a defined flow velocity and residence time into the matrix (Goldscheider, 2015).

Technical literature reports several methods for characterising and describing a karst aquifer. Goldscheider (2015) gave an insightful classification and description of techniques applied to investigate and describe a karst aquifer. Goldscheider (2015) indicated, as well as numerical models, geological, geophysical, speleological, hydrological, hydraulic, hydrochemical, isotopic, and, finally, artificial tracer methods. Nevertheless, these methods are expensive and time-consuming, especially for vast aquifers. However, the substantial issue is usually not related to the factors mentioned above but, overall, to the difficulty of applying most of them.

For this and other reasons, the most used methods fit into the category of hydrological models. Some of them use a bottom-up approach. Flow recession analysis is one of the more known approaches to describe karst aquifers in this category (Kovács et al., 2005; Birk and Hergarten, 2010; Kovács and Perrochet, 2008). Thanks to spring monitoring, evaluating the time lag between rainfall and the response of groundwater levels and spring discharges is possible. Groundwater can take hours to months to reveal the contribution of a rainfall event, depending on site-specific hydrogeological characteristics (Mojid et al., 2021) and rainfall intensity (Balacco et al., 2022). Knowledge of this lag time is vital because rainfall is the unique source of recharge for numerous groundwater systems.

However, considering their large number, it is challenging to monitor huge aquifers where spring monitoring is unmanageable. A similar approach is not applicable for coastal karst aquifers because most discharge at least a part of their resource directly into the sea. These submarine springs are an unknown part of the groundwater balance (Bakalowicz, 2018) and a solid limit to applying classical models to simulate the hydrodynamic behaviour of a coastal karst aquifer.

Kovacs (2015) suggested a methodology for applying hydrograph data from wells for parameter estimation in karst aquifer systems. This approach can be a valid alternative in case of a lack of data on a spring or difficulties in brackish or numerous springs.

Statistical models, another category of the hydrological model, represent an alternative. Time series are necessary to use these models.

With the help of time series analysis, it is possible to describe a karst system, its internal structure and degree of karstification, and the prevailing karst permeability structure (Balacco et al., 2022). Rainfall is the input, and the spring flow rates, or groundwater levels are the system's output. The karst system (soil, epikarst, and transmission zone) can be described as a filter that can modify the input signal of rainfall in the aquifer's response. Mangin (1984) was the first author to define an effective approach describing a karstic system. This approach had widespread applications worldwide (Padilla et al., 1994; Larocque et al., 1998; Panagopoulos and Lambrakis, 2006; Fiorillo and Doglioni, 2010; Sağir et al., 2020; Balacco et al., 2022).

Time series analysis represents one of the main ways to characterise whole or vast portions of peculiar karst aquifers, as in the case of the Salento aquifer (Southern Italy). It is approximately 2760 km^2 wide and is bounded by the Adriatic and the Ionian coastlines, along which more than two hundred submarine and coastal springs can be distinguished (Cotecchia and Tulipano, 1989).

Time series analyses were applied to this coastal karst aquifer to improve the integrated use of statistical tools and variables and to evaluate the hydrodynamic properties of the karst systems, considering complete daily time series and discontinuous monthly time series of longer duration.

This assessment contributes to a better understanding of the Salento aquifer, improving previous research results. The attention is focused on the effect of karstic features on the piezometric response to climate variability and the indirect anthropogenic actions (mainly in terms of withdrawal).

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The autocorrelation and cross-correlation functions in the time domain were performed using the noise component of the hydrological and hydrogeological data. Therefore, time series were pre-processed by decomposing them through a moving average of six months technique. The approach considers daily and monthly rainfall, temperature, and groundwater level data. The methodology compares results with different temporal resolutions, considering gaps and different availability of monitoring wells in 47 years (1965-2011). This research improves previous experiences with different datasets regarding selected variables, duration and number of gauges/ wells (Polemio and Dragone, 1999; Balacco et al., 2022).

Material and methods

Study areas

The Salento Peninsula is a nearly flat area (peak altitude 150-180 m above mean sea level - AMSL). The deepest and oldest outcropping formation in the peninsula is the Altamura Limestone Formation (Cretaceous), which comprises layers of limestone, dolomitic limestone, and dolostone with a thickness of hundreds of meters (Fig. 1a). This formation is partially covered by different post-Cretaceous, calcarenite, coralgal limestones, micrites and biocalcarenites, calcilutites, and coastal and alluvial deposits, with a global thickness which generally varies from a few meters to some tens of meters. The deep pre-neogenic carbonate formations are commonly affected by fissuring and karst processes and forms, which gave rise to red clays as continental residual deposits and exhibit several variously karstified and fissured horizons, interbedded with more compact limestone strata located at different depths from the ground surface (Santaloia et al., 2016). A combination of E-W dextral and sinistral strike-slip faults and NW-SE sub-vertical normal faults dislocated these rocks, creating horst and graben structures.

These rocks constitute the so-called limestone aquifer. Due to the absence of superficial water courses, as typical for karstic areas, the limestone aquifer is the unique local water source. The limestone aquifer bottom is undefined at several thousands of meters below the ground level. Where the limestone aquifer does not outcrop, it is covered by pervious formations, permitting the recharge of the deep limestone aquifer, except for some narrow areas where clay strata define the existence of shallow and secondary aquifers (Romanazzi and Polemio, 2013). The highest hydraulic heads occupy the central part of the aquifer, exceeding 3 m AMSL in narrow areas (Figure 1b, Regione Puglia, 2015).

The Salento area presents a Mediterranean climate with mild, wet winters and hot, dry summers. The mean annual precipitation is about 700 mm, with wet periods concentrated during the autumn-winter season.

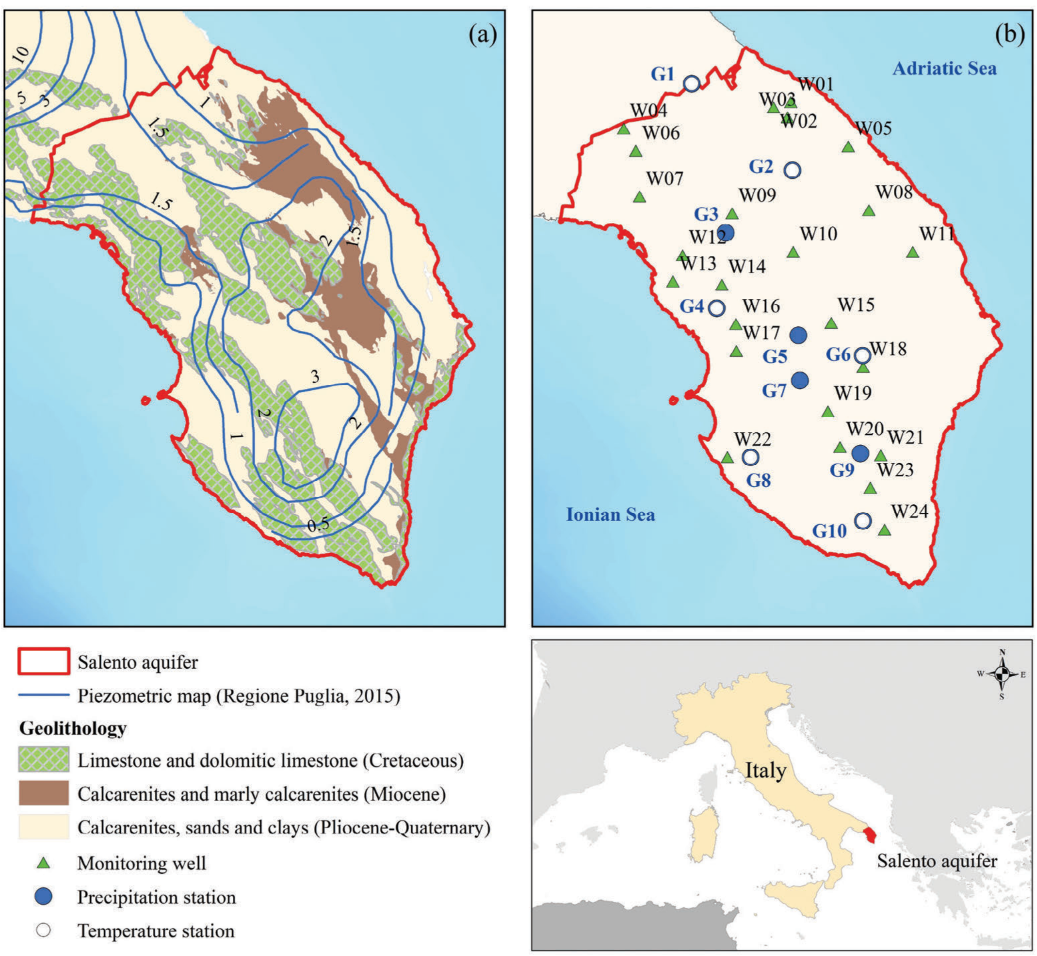

Fig. 1 - Study area map and location of temperature and rain gauges and monitoring wells.

Fig. 1 - Carta dell'area di studio e ubicazione delle stazioni di misura di precipitazione e temperatura e pozzi di monitoraggio.

Hydro-meteorological data

The dataset comprises the selected daily and monthly time series of rainfall (10 gauges) and air temperature (6 gauges) (Fig. 1b). Moreover, it includes the analysis of the monthly groundwater time series of 24 wells of the Apulian groundwater monitoring network, for 11 of which daily measurements are also available from July 2007 to December 2011. Different public institutions or project initiatives have managed the network by sixty of the last century (previously Ente Irrigazione e la Trasformazione Fondiaria di Puglia, Lucania e Irpinia and later Apulia Region, in the framework of the regional Water Reclamation Plan, Maggiore Project, and Tiziano Project). The available measurements, including sporadic surveys realised by some authors (CNR-IRPI), span from 1965 to 2011 but include many gaps. The selected groundwater measurements refer to daily or to average monthly head values (m AMSL).

Figure 1b shows the location of selected monitoring wells and rainfall and temperature gauge stations, to which a simplified code was associated.

Table 1 summarises the main features of selected monitoring wells and their descriptive statistics. The monthly piezometric series have quite a different duration and numerosity, referring up to 47 calendar years and ranging from 34 to 377 monthly observations (85 as the mean value). This difference also lies in the fact that many wells were always included in monitoring periods and each survey, while the remaining were recently activated, some for sporadic measurements.

The maximum measured head is 5.17 m AMSL (W11). Some negative minima were observed (W13, W14, W22, W24), highlighting the high withdrawal rate in some areas. The range is not correlated to the number of observations. The variability of ranges is relatively low, from 0.92 to 4.07; it seems realistic that the piezometric effect of the relevant withdrawal is limited both by excellent hydrogeological characteristics and by the boundary conditions, dominated by the effect of the sea.

Each monthly rainfall and temperature time series associated with each piezometric series covers the entire duration (1965-2011) without gaps. Daily time series exhibit a low missing

Tab. 1 - Monitoring well characteristics and descriptive statistics of monthly piezometric data.

Tab. 1 - Caratteristiche dei pozzi di monitoraggio e statistiche descrittive dei dati piezometrici mensili.

Code	X	Y	Elevation	N. Obs	Period (year)		Piezometric head (m AMSL)			Std. Dev	Range
	WGS84-UTM33N	WGS84-UTM33N	[m AMSL]		From	To	Min	Max	Mean	[m]	[m]
W01	768990	4481549	13	34	1995	2011	0.37	1.4	0.73	0.286	1.09
W02	766422	4480779	29	52	1978	2011	0.18	1.99	0.95	0.448	1.81
W03*	768481	4479309	23	111	1973	2011	0.61	1.85	1.26	0.428	1.24
W04	744279	4477616	55	105	1973	2011	1.32	2.94	2.19	0.448	1.62
W05	777490	4475005	19	93	1973	2011	1.01	2.41	2.05	0.295	1.4
W06	746085	4474341	53	149	1968	2011	1.17	2.61	2.11	0.307	1.44
W07	746638	4467567	43	50	1995	2011	0.91	2.02	1.54	0.287	1.11
W08*	780535	4465574	35	88	1973	2011	1.82	3.62	3.14	0.31	1.8
W09*	760312	4465095	42	377	1965	2011	1	3.24	1.97	0.188	2.24
W10*	769335	4459391	22	97	1975	2011	1.52	3.56	2.51	0.551	2.04
W11	787015	4459364	13	108	1973	2011	3.38	5.17	4.36	0.498	1.78
W12*	752992	4458874	49	61	1995	2011	0.05	3.88	0.61	0.64	3.83
W13	751547	4455009	26	114	1973	2011	-1.39	0.92	-0.19	0.454	2.31
W14	758784	4454513	33	58	1995	2011	-0.31	1.58	0.69	0.319	1.89
W15*	774948	4448877	77	59	2007	2011	1.48	2.87	1.91	0.324	1.39
W16	760869	4448709	55	35	1995	2010	0.77	3.46	1.86	0.616	2.7
W17*	760919	4444734	91	42	2007	2011	1.41	2.33	1.78	0.268	0.92
W18*	779667	4442350	87	71	1973	2011	1.44	3.73	3.18	0.552	2.29
W19*	774450	4435798	155	58	1995	2011	2.23	4.64	3.69	0.484	2.41
W20*	776237	4430534	143	44	1995	2011	1.53	2.53	1,85	0.21	1
W21*	782287	4429291	106	59	1995	2011	1.13	3.17	1.82	0.628	2.04
W22	759607	4429039	47	113	1973	2011	-2.22	1.85	0.39	1.463	4.07
W23	780736	4424491	170	45	1995	2011	1.14	4.13	3.19	0.561	2.99
W24	782843	4418290	167	56	1995	2011	-2.84	0.61	-1.02	0.776	3.45
* Wells used for the daily analysis.											

data percentage (on average, 0.8 % for precipitation and 3 % for temperature data).

Table 2 summarises descriptive statistics of monthly rainfall and temperature time series (1965-2011). The maximum rainfall ranges from 275 to 536 mm. The average monthly rainfall is between 50 and 65 mm, while the standard deviation ranges from 48 and 65 mm.

Temperature values show lows between 5 and 7 C°, generally between December and February, and highs in the summer months, July or August, with temperatures between 28 and 32 C°.

Methods

The Thiessen polygon method was used to associate each well with the most significant rainfall and temperature gauge. They were generated by partitioning the study area into polygons based on the locations of meteorological station points. Each polygon encompasses the region closest to a specific station relative to any other point. Consequently, each well was paired with the meteorological station corresponding to the Thiessen polygon in which it was located.

The approach to the piezometric data discussion proposes to combine short but complete daily time series, from 2007 to 2011, with long discontinuous monthly time series, the only data available for the selected aquifer, to overcome the inherent weaknesses of the data set. Time series analyses were applied to this coastal karst aquifer to improve the integrated use of statistical tools and variables and to evaluate the hydrodynamic properties of the karst systems, considering

There are parametric and non-parametric approaches for detecting significant climatic and groundwater time series trends. Non-parametric methods request that the data be independent, whereas parametric methods demand that the data be independent and normally distributed. The analyses of potential trends in precipitation, air temperature and groundwater time series were calculated following a practice widely diffused in the scientific literature, i.e., the non-parametric Mann-Kendall (Mann, 1945; Kendall, 1975) and Sen's slope (Sen, 1968) tests. The piezometric trend analysis was realised both for annual time series, calculated by long-lasting monthly data with gaps (1965-2011), and daily piezometric residuals (2007-2011).

The additive decomposition processing, based on moving average of six months, was performed on each daily time series. It consists of separating a time series into (i) trend, (ii) seasonality, and (iii) noise components. Figure 2 shows the decomposition results of some wells. After detrending time series from long-term movement in the data, and removing the seasonal component, i.e., the cyclic fluctuations, the non-parametric tests were applied to the residual component, which represents the random variability of the signal. Because of the presence of missing data within monthly time series, we extrapolated the seasonal components of groundwater level from the daily time series using them for the decomposition of the monthly ones. Therefore, the monthly-scale ACF and CCF were only calculated for the wells with daily time series, namely W03, W08, W09, W10, W12, W15, W17, W18, W19, W20, and W21.

Time series analyses were applied in the time domain with univariate and bivariate approaches. Mangin (1984) and Box et al. (2013) were pioneer researchers who applied these methods to karst studies to interpret the internal structure of such systems and their response to meteorological variability. The autocorrelation (ACF) and the cross-correlation (CCF)

Tab. 2 - Rain gauge station characteristics and descriptive rainfall and temperature statistics of monthly values (1965-2011); P (mm) indicates precipitation and T temperature (°C).

Tab. 2 - Caratteristiche delle stazioni pluviometriche e statistiche descrittive delle precipitazioni e delle temperature mensili (1965-2011); P (mm) indica la precipitazione e T la temperatura (°C).

Code	Station Name	Variable	Lat	Long	Elevation [m AMSL]	Min	Max	Mean	Std. Dev.
G1	S. Pietro Vernotico	P	40.47	18.00	49	0	299	52.6	48.823
		T				6.5	28.08	16.81	5.815
G2	Lecce	P	40.35	18.17	51	0	326	55.2	51.867
		T				5.2	32.19	17	5.987
G3	Copertino	P	40.27	18.05	34	0	275.2	50.9	48.603
G4	Nardò	P	40.17	18.03	54	0	286.2	51.3	48.805
		T				6.5	31.1	17.28	6.376
G5	Galatina	P	40.13	18.17	73	0	303.6	59.8	55.322
G6	Maglie	P	40.10	18.28	102	0	315	59	52.135
		T				5.6	28.66	16.54	6.072
G7	Collepasso	P	40.07	18.17	120	0	536	60.6	64.625
G8	Taviano	P	39.97	18.08	65	0	452	50.5	53.765
		T				7.4	30.8	17.85	6.134
G9	Ruffano	P	39.97	18.27	134	0	291.6	64.6	59.295
G10	Presicce	P	39.88	18.27	105	0	305	64.7	61.88
		T				6.1	28.6	17.25	6.441

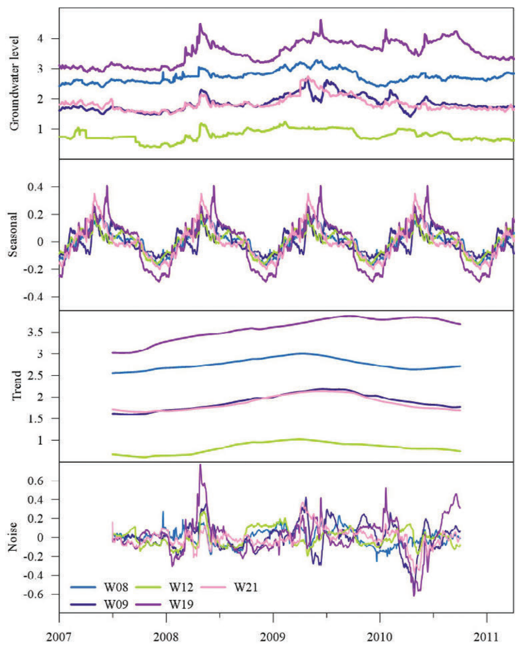

Fig. 2 - Moving average decomposition results of five out of eleven daily time series. From up to the bottom, each panel of the decomposition reports the original time series, the seasonal, trend, and noise components. Thicks are centred on the first October of each year.

Fig. 2 - Risultati della decomposizione con media mobile di cinque delle undici serie temporali giornaliere. Dall'alto verso il basso, ciascun pannello della decomposizione riporta la serie temporale originale, le componenti stagionali, di tendenza e di rumore. Le tacche sono centrate sul primo ottobre di ogni anno.

functions were applied to the time series of precipitation, temperature and piezometric residual on a daily and monthly scale to evaluate the hydrogeological behaviour of the Salento aquifer.

Kendall's tau and Sen's slope tests

We used the non-parametric Mann–Kendall method to assess the statistical significance of piezometric, rainfall and air temperature trends (Mann, 1945; Kendall, 1975). The test considers the τ statistical test and the p value. The τ statistic ranges from −1 to 1, with positive or negative values indicating increasing or decreasing trend, respectively. The p value determines the trend significance or the rejection of the null hypothesis, according to the selected significance level, α. The null hypothesis is rejected se τ is different from zero and p value $\leq \alpha$ (Meals et al., 2011). The trend magnitude was estimated with the non-parametric method Sen's slope.

The Mann–Kendall test with the Sen's slope estimator is widely used to detect monotonic trend in temporal series of hydrological data (Xu et al., 2003; Partal and Kahya, 2006; Gocic and Trajkovic, 2013; Sharma and Babel, 2014; Wu et al., 2014). This method does not assume a specific statistical distribution for data and is less sensitive to outliers and data skews than parametric statistics (Sen, 1968).

Autocorrelation function

Defining a discretised chronological series of length N, the ACF measures the degree of similarity between a time series at a given time and its past values over successive time intervals. It is calculated as the ratio between the covariance at lag *k, C(k)* and the covariance at value 0, *C*(0), where *k* is the lag (*k = 0, 1,2, …, m*) and m the cutting point.

$$ACF = \frac{C(k)}{C(0)} \quad (1)$$

Based on his empirical research, Mangin (1984) indicated an m value less than N/3, verifying that correlograms were skewed for a truncation point between N/3 and N/2. The ACF provides information on the analysed system's memory effect, i.e., the time to forget the initial conditions (Larocque et al., 1998; Box et al., 2013; Chiaudani et al., 2017). Mangin (1984) recommended that the memory effect is the lag time to reach an ACF value of 0.2. For a random variable, the ACF decreases quickly and reaches zero for very short time lags (Delbart et al., 2016). A more reliable statistical approach considers the confidence interval calculation (Box-Steffensmeier et al., 2014), usually fixed at 95%, outside of which the correlation significance can be considered significant.

This approach relies on the hypothesis that the karst aquifer acts as a filter that modifies, retains, or attenuates the input signal, represented by the precipitation, into an output signal as the spring discharge (Larocque et al., 1998; Fiorillo & Doglioni, 2010), the groundwater level (Delbart et al., 2014; Cai and Ofterdinger, 2016, Chiaudani et al., 2017), the river flow rate (Bailly-Comte et al., 2008, Chiaudani et al., 2017) The extent to which the input signal is transformed provides valuable information about the flow dynamics within the system. Specifically, a gentle slope of the ACF indicates a karst aquifer with high or relevant groundwater storage that could show great inertia in terms of lag between infiltration and outflow. In contrast, a steep slope implies a poor storage capacity due to a rapid flow (Padilla and Pulido-Bosch, 1995; Panagopoulos and Lambrakis, 2006; Duvert et al., 2015; Chiaudani et al., 2017).

Cross-Correlation function

Defining the two discretised chronological series of length N so that the first causes the second, the CCF measures the degree of similarity between the former at a given time and the latter late by *k* (*k = 0, 1,2, …, m*). The mathematical structure is the same as the ACF, but the covariance is calculated between the two-time series.

$$CCF = \frac{C_{xy}(k)}{C_{xy}(0)} \quad (2)$$

The CCF function provides two types of information: (i) the degree of relationship, i.e., the correlation coefficient, and (ii) the lag, i.e., response time, between the two series. The response time is the delay calculated from a time lag equal to 0 to a time lag corresponding to the maximum value of CCF (Cai and Ofterdinger, 2016). It represents the transfer velocity of the aquifer.

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The shape of the cross-correlogram provides qualitative information about the karst system: (i) short lag and an abrupt peak indicate high permeability due to karstification and/or fracturing and low storage capacity (Short Response). In contrast, high delay and late or low peak indicate low permeability and/or almost intact limestone (Long Response Time). The confidence interval calculation can be again used to bound significant results (Box-Steffensmeier et al., 2014).

Results

The non-parametric Kendall's tau and Sen's slope tests were applied to assess the trend's statistical significance (95% significance level) and quantify it for groundwater level, precipitation, and temperature data.

Groundwater level annual trend was significant for 7 out of 24 wells (Table 3). All significant piezometric trends are negative with Sen's slope estimator varying from -0.016 to -0.074.

Note that the piezometric time series end all in 2011 (except W16, which ends in 2010) but have different beginnings. The non-significant trends relate to the shorter and more recent time series, generally starting in 1995 (W07, W12, W14, W16, W20, W21 and W23) or, in the case of W15 only, in 2007. As noted by previous studies (Polemio and Casarano, 2004; Casarano et al., 2019) and confirmed by this broader study, 1995 as well as 2007 are years that lie in periods following severe droughts and, therefore after piezometric minima. Similarly, the negative trends, in the range from -0.016 to -0.074 m/year (Sen's Slope), are associated with time series in which the most recent years have in any case recorded a piezometric recovery, but not such as to cancel out the negative significance or invert the sign.

The rainfall and temperature trends were assessed for 16 time series (10 rainfall and 6 temperature series) from 1965 to 2016 (Table 4) yearly (very similar results were obtained from 1965 to 2011).

The rainfall trends are not statistically significant, while the temperature trends were significant and positive (increasing trend). Regarding the precipitation, this finding agrees with the results found by D'Oria et al. (2018) and Alfio et al. (2020).

Casarano et al. (2019) found a downward trend in rainfall over the entire 1924-2016 period, even though it is significantly lower (as absolute value) than the trend for the 1924-2001 period, confirming the presence of a significant recovery of rainfall after 2001. In contrast, the thermometric trend was significant and positive everywhere, with values between 0.011 and 0.068 C°/month (Sen's Slope). These trends are worsening, i.e., increasing compared to assessments up to 2001 (Polemio and Casarano, 2004), a circumstance that further reduces recharge and increases irrigation water demand and thus irrigation outflows.

Tab. 3 - Kendall's tau test and Sen's slope estimator (m/year) for piezometric time series (n.s.t. = not significant trend).

Tab. 3 - Test di Kendall's tau e stima della pendenza di Sen (m/anno) per le serie temporali piezometriche (n.s.t. = tendenza non significativa).

Code	Mean m	Kendall's tau	Sen's slope m/year
W01	0.962	-	n.s.
W02	0.822	-	n.s.
W03	1.263	-0.67	-0.023
W04	1.966	-0.647	-0.028
W05	1.832	-0.604	-0.016
W06	2.019	-	n.s.
W07	1.434	-	n.s.
W08	2.979	-0.397	-0.026
W09	1.939	-	n.s.
W10	2.629	-	n.s.
W11	4.398	-0.56	-0.022
W12	0.997	-	n.s.
W13	-0.093	-	n.s.
W14	0.682	-	n.s.
W15	2.059	-	n.s.
W16	2.078	-	n.s.
W17	1.820	-	n.s.
W18	2.636	-0.692	-0.044
W19	3.465	-	n.s.
W20	6.794	-	n.s.
W21	1.740	-	n.s.
W22	0.474	-0.676	-0.074
W23	3.267	-	n.s.
W24	-0.741	-	n.s.

Tab. 4 - Sen's slope estimator using monthly rainfall (mm) and temperature (°C) time series (n.s.t. = not significant trend).

Tab. 4 - Stima della pendenza di Sen utilizzando le serie temporali mensili di precipitazione (mm) e temperatura (°C) (n.s.t. = tendenza non significativa).

Code	Variable	Sen's slope
G1	P	n.s.t.
	T	0.011
G2	P	n.s.t.
	T	0.048
G3	P	n.s.t.
G4	P	n.s.t.
	T	0.048
G5	P	n.s.t.
G6	P	n.s.t.
	T	0.068
G7	P	n.s.t.
G8	P	n.s.t.
	T	0.027
G9	P	n.s.t.
G10	P	n.s.t.
	T	0.018

Before applying ACF and CCF methodologies, the decomposition of each time series was performed. The seasonal, the trend and the noise components were determined, and the above methods applied to the residual signals. As shown in Figure 2, the three components are comparable between all wells. The seasonal components show a cyclic semi-annual fluctuation between around -0.4 to 0.4 m, with peaks corresponding to the end of the wet periods and minima after the summer. The trend signals are increasing until the end of 2010, after which a decreasing pattern was observed. The seasonal component derived from the daily time series was applied to decompose the monthly data. Therefore, ACF and CCF for monthly time series were calculated only for those wells having daily data (W03, W08, W09, W10, W12, W15, W17, W18, W19, W20, and W21).

The ACF and CCF were implemented in the time domain to derive qualitative information on the hydrogeological behaviour of the Salento aquifer. Specifically, they were evaluated by using the monthly noise time series. Figure 3 shows graphical results in the case of five out of eleven wells.

To compare the results obtained with the monthly rainfall and temperature approach, CCF between daily temperature and GWLs for these eleven wells were also performed. The duration and magnitude of the statistically significant autocorrelation coefficients give a measure of the memory effect of the aquifer, as it makes explicit the ‘memory’ of past groundwater levels. These parameters depend on the storage capacity, the type of flow (confined or phreatic) and the hydraulic conductivity of the aquifer.

For nine out of eleven wells, the maximum autocorrelation coefficient occurs at the lag of one month (Table 5). For these 9 wells, the coefficient is very high, varying from 0.26 to 0.78, with an average value of 0.44, attesting to an enormous influence of the memory effect. The remaining two wells (W12 and W15) show higher lags, 2 and 6 months, respectively.

The ACF remains statistically significant (Figure 3a), although decreasing with delay, for several months, averaging up to 6, with the maximum being 15 months (W03). It should be noted that the minimum statistically significant autocorrelation coefficient of each well is always greater than 0.2, which can be considered an empirical decorrelation threshold (Mangin, 1984; Chiaudani et al., 2017).

Tab. 5 - Summary of autocorrelation coefficient values and lag of monthly piezometric time series. n.s. means not significant.

Tab. 5 - Riepilogo dei valori dei coefficienti di autocorrelazione e dei ritardi delle serie temporali piezometriche mensili. (n.s. indica non significativo).

Well code	Maximum coefficent		Maximum statistically
	Value	Lag	significant lag
W03	0.34	1	15
W08	0.263	1	1
W09	0.64	1	5
W10	0.421	1	4
W12	0.453	6	6
W15	0.287	2	2
W17	0.781	1	3
W18	0.266	1	1
W19	0.468	1	2
W20	0.432	1	1
W21	0.537	1	3

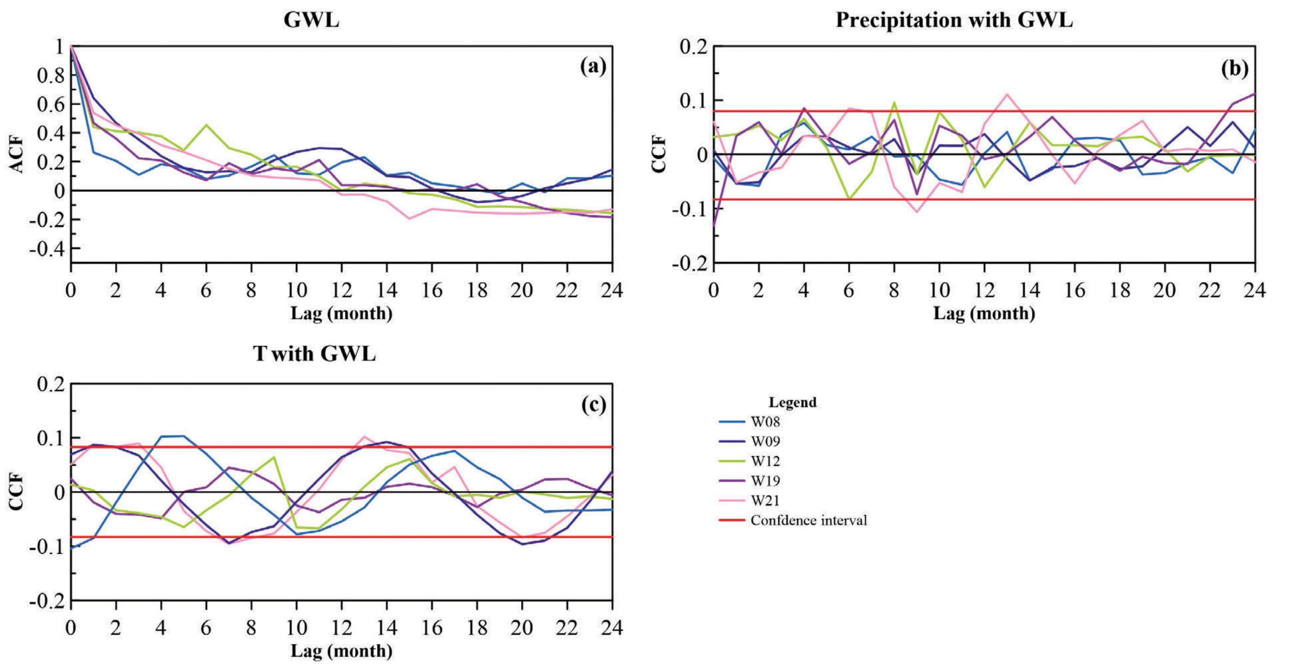

Fig. 3 - (a) Autocorrelation of GWLs and Cross-correlation functions between monthly (b) precipitation, (c) mean air temperature and GWLs for five out twenty-four wells.

Fig. 3 - (a) Autocorrelazione dei livelli piezometrici (GWLs) e funzioni di correlazione incrociata tra (b) precipitazione mensile, (c) temperatura media dell’aria e livelli piezometrici (GWLs) per cinque dei ventiquattro pozzi.

Table 6 summarises the results of CCF calculated for each well with the selected rainfall and temperature gauges by using the noise signal. The maximum values of the CCF with monthly rainfall define the range from 0.08 to 0.18. The absolute maxima of the cross-correlation coefficient with temperature are negative, i.e. they indicate an inverse correlation. It ranges from -0.08 to -0.26.

The maximum cross-correlation occurs predominantly up to one month for both rainfall and temperature, but cases are not rare where the maximum occurs for delays of 3 months, with a maximum of 8-10 months.

The cross-correlation between rainfall and groundwater level and between temperature and groundwater level residual components are statistically non-significant for two and five wells out of eleven, respectively. The lack of GWL autocorrelation and GWL and precipitation/temperature cross-correlation could be due to the prevalent anthropogenic factors (withdrawal, leakage and/or artificial recharge) in the well surrounding area.

Finally, it should be noted that for those wells where maximum autocorrelation was recorded with high lag, maximum cross-correlation was also recorded for lag generally greater than one month.

These results are coherent with previous research which investigated precipitation and GWL relationships only through raw or unmodified time series of daily data wells (Table 1) (Balacco et al. 2022).

Balacco et al. (2022) suggested that the gradual reduction of ACF in daily groundwater levels differs for certain wells depending on whether it was a less rainy or significantly wetter hydrological year. With the long-term analyses, the correlograms generally exhibited a gentle slope, with varying time lags (ranging between 40 to up 200 days) observed among the wells. Additionally, an annual cycle ranging from 30 to 125 days was identified for the Salento aquifer, indicating a significant seasonal pattern. These results were also confirmed by applying ACF to the noise component of daily groundwater levels (Fig. 4a). This finding could imply a shorter-term seasonal effect in addition to an annual pattern, probably due to the variability of precipitation during the hydrological year and the consequent anthropic pressure for agricultural purposes.

The daily-scale CCF analysis between precipitation and groundwater levels reveals that the shape of the correlograms varies from case to case, with variable order (Fig. 4b). The CCF values with precipitation remain small in all cross-correlograms, ranging between 0.05 to 0.16 (Table 7). W08, W15, W17, and W18 shows no cross-correlation with precipitation. The response time varies between 16 and 280 days, except for W19 (3 days) and W20 (1 day).

The correlograms of daily minimum and maximum air temperature in 2007-2011 and GWLs for 5 out of 11 wells are illustrated in Figure 4c-d. Results agree with the implemented monthly analyses in determining an inverse and statistically significant relationship between groundwater level and air temperature. The maximum correlation with minimum air temperature ranges between -0.04 (W08) and -0.16 (W09), and the response time varies between 0 (W03) and 312 (W15) days (Table 7). With maximum air temperature, the maximum correlation ranges between -0.05 (W18) and -0.16 (W09), and the response time varies between 1 (W03) and 308 (W20) days.

Discussion

This study assesses the hydrogeological behaviour of the coastal karst aquifer of Salento through trend analysis and autocorrelation and cross-correlation analyses applied in the time domain to the residual signals. The selected dataset comprises monthly rainfall, temperature data, and monthly groundwater levels of 24 monitoring wells from approximately 1965 to 2011. The analysis was extended to a daily data, using 11 out of 24 wells, for which daily time series were available from 2007 to 2011.

Tab. 6 - Summary of cross-correlation coefficient values and lag on a monthly scale (n.s. = not significant).

Tab. 6 - Riepilogo dei valori dei coefficienti di correlazione incrociata e dei ritardi su scala mensile (n.s. = non significativo).

Well code	Gauges code	Cross correlation with rainfall		Cross correlation with temperature	
		Value	Month	Value	Month
W03	G2	0.097	2	-0.083	1
W08	G2	n.c.		n.c.	
W09	G3	n.c.		-0.094	7
W10	G3	0.083	3	n.c.	
W12	G3	0.096	8	n.c.	
W15	G5	0.122	7	n.c.	
W17	G4	0.177	10	-0.258	23
W18	G6	n.c.		n.c.	
W19	G7	0.085	4	n.c.	
W20	G9	0.104	1	-0.084	6
W21	G9	0.111	13	-0.096	7

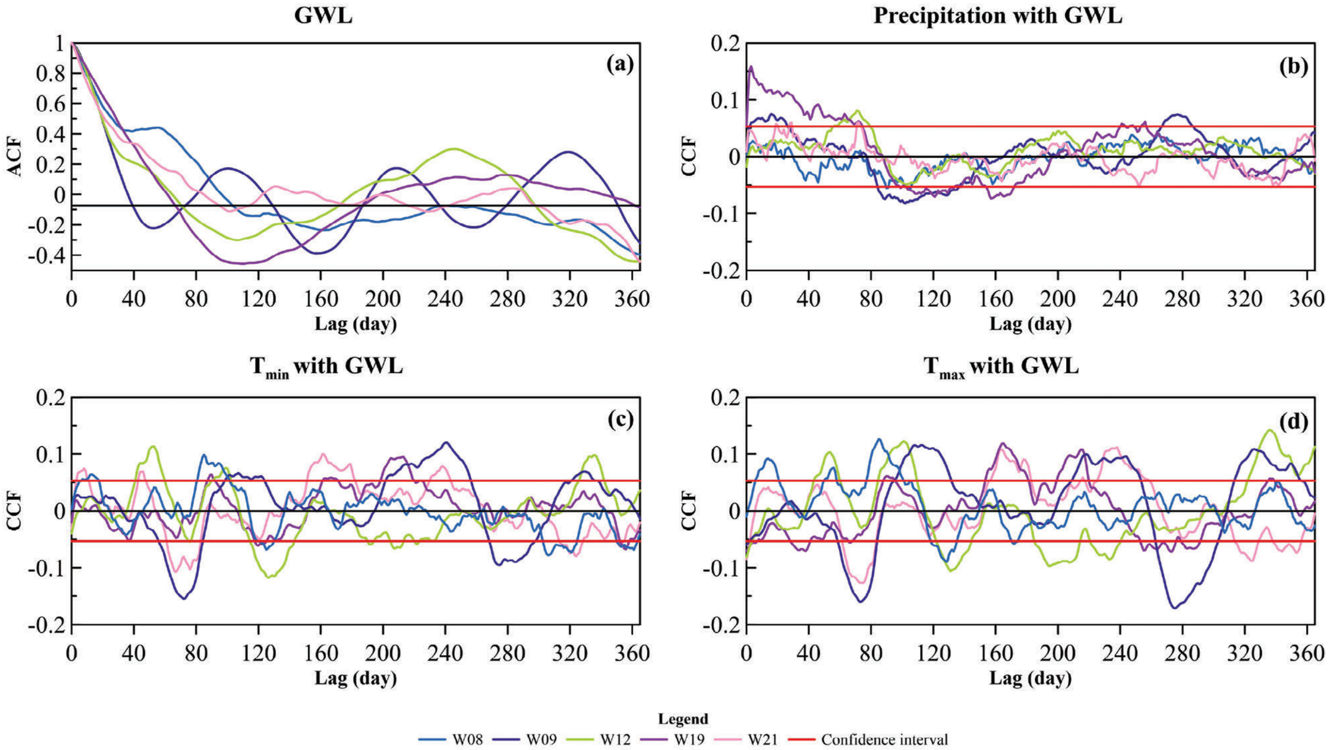

Fig. 4 - (a) Autocorrelation of GWLs and Cross-correlation functions between daily (b) precipitation, (c) minimum and (d) maximum air temperature and GWLs for five out of eleven wells.

Fig. 4 - (a) Autocorrelazione dei livelli piezometrici (GWLs) e funzioni di correlazione incrociata tra (b) precipitazione giornaliera, (c) temperatura minima e (d) temperatura massima dell'aria e livelli piezometrici (GWLs) per cinque degli undici pozzi.

*Tab. 7 - Summary of cross-correlation coefficient values and lag on a daily scale. *Maximum defined considering the absolute value; n.s. = not significant.*

Tab. 7 - Riepilogo dei valori dei coefficienti di correlazione incrociata e dei ritardi su scala giornaliera. *Massimo definito considerando il valore assoluto. (n.s. = non significativo).

Well code	Gauges code	Cross correlation with rainfall		Cross correlation with min temperature		Cross correlation with max temperature	
		Value	Day	Value	Day	Value	Day
W03	G2	0.050	70	-0.063	0	-0.118	1
W08	G2	n.s.		-0.042	35	-0.089	128
W09	G3	0.074	16	-0.155	72	-0.160	73
W10	G3	0.062	280	-0.102	152	-0.068	81
W12	G3	0.081	71	-0.117	127	-0.106	131
W15	G5	n.s.		-0.095	312	-0.063	41
W17	G4	n.s.		-0.094	185	-0.101	186
W18	G6	n.s.		-0.062	191	-0.054	204
W19	G7	0.158	3	-0.061	120	-0.071	38
W20	G9	0.056	1	-0.096	307	-0.075	308
W21	G9	0.061	72	-0.107	67	-0.127	75

The analyses for evaluating the potential presence of a trend in each selected time series were applied using standard statistic tests. Groundwater levels indicate a statistically significant negative trend for 7 out of 24 wells. The negative trend could be justified considering that the Salento aquifer has experienced numerous periods of drought since the 1980s, for the increasing effect of climate change, especially in terms of temperature increase, and overexploitation (Polemio and Casarano, 2004; Casarano et al., 2019; Alfio et al., 2020). However, the decreasing magnitude of the trend is very low, maybe due both to a partial rainy recovery and mainly to the recent regional measures addressed to the reduction of the groundwater withdrawal for the qualitative and qualitative protection of the aquifer.

The rainfall trends are not statistically significant, as an effect of recent rainy years, while the temperature time series highlights a statistically significant increasing trend. This achievement agrees with the results of D'Oria et al. (2018) and Casarano et al. (2019).

The monthly ACF analysis results show that wells present a high time lag value, confirming the aquifer's overall storage capacity. It is plausible to consider that there are other factors, typically anthropogenic, that alter or depower the 'memory', as evidenced by wells that are in the vicinity of heavily anthropized areas (Polemio et al., 1999), and a peculiar memory feature, that reduces the relevance of short-term 'memory', as could be justified by lower hydrogeological parameters. The results of the cross-correlation reinforce this second hypothesis.

The daily ACF analyses of groundwater levels over 2007-2011 confirm the high storage capacity of the investigated aquifer since the memory effect is often longer than 100 days. This achievement highlights the predominant role of the rock matrix in slowly releasing the infiltration water preserving the aquifer system reserves.

The monthly cross-correlation analyses between rainfall and groundwater level and between temperature and groundwater level were statistically significant for two and five out of eleven wells, respectively. As expected, there is a direct correlation between rainfall and groundwater levels and an inverse one with temperature. However, the correlation degree between hydrological and hydrogeological variables is low. The maxima for temperature are all greater than or equal to those for rain. In other words, the temperature variability generally explains the variability of groundwater level better than rain. This behaviour was described by Polemio et al. (1999) for the Tavoliere aquifer, also in the Apulia region, under similar climatic conditions. They explained that in these semi-arid areas, temperature has a significant effect on evapotranspiration throughout the year. The higher evapotranspiration reduces recharge during the dry season, from late spring to late autumn, a period when precipitation is very often zero or negligible. During the summer period, when temperature rises and water demand for tourism and agricultural sectors increases, the decrease in water level is evident. A recent study by D'Oria et al. (2024) showed that the reduction in water level at the end of this century in response to rising temperatures is more pronounced than in response to reduced precipitation.

Chen et al. (2004) found that the relationship between temperature and GWL strengthens during higher average annual temperatures, particularly in regions where the aquifer is closer to the surface, for the Upper Carbonate Aquifer of southern Manitoba (Canada).

Basically, given that rainfall and temperature are characterised by a very high inverse correlation and that temperature contributes to determining the actual evapotranspiration and the recharge but also the water deficit, as irrigation withdrawals from wells increase, the temperature ends up better describing the monthly piezometric variability.

Higher correlation coefficients are also achieved when analysing the daily temperature dataset. In contrast to monthly analyses, low-correlated relationship between daily precipitation and groundwater levels was obtained in most cases. It is probably due to the limited extension of the available time series, which prevents capturing the long-term climatic variability.

From 2007 to 2011, the period was moderately rainy but preceded by a fairly severe drought. Therefore, given the inertia of the investigated aquifer, the inverse correlation may be obtained because the groundwater levels are still responding to the previous drought events rather than the more recent precipitation. The cross-correlation results provided important information on the temporal response of the aquifer to impulses due to climate variables, rainfall, and temperature. The relevant hydrogeological characteristics of the aquifer are capable of greatly modulating the response to climatic variability, thus deferring an effect in piezometric terms over time. The results demonstrated that daily analysis provides a more precise understanding of the effects of climatic variability compared to monthly-scale data. Therefore, in complex contexts, like the one analysed, where regional dimensions, geomorphological-structural complexity, coastal conditions, and overexploitation of water resources are just some of the factors influencing the aquifer response, it is essential to have daily time series that cover a broad temporal range to intercept the transition from drought to wetter periods.

Conclusion

Autocorrelation and cross-correlation functions help identify the internal dynamics of the aquifer system and its interactions and dependencies with external factors. Findings demonstrate that these methods effectively describe the hydrodynamic properties of a coastal karst aquifer, distinct from the typical karst aquifers examined in previous studies.

The overall analysis revealed the high inertia of the Salento karst system in terms of transmissivity and significant storage capacity.

The differences in the results regarding memory effect and response time between the daily and the monthly analyses in this paper confirm the complexity of the system examined and the influence of the dataset quality. Indeed, having data sampled at a higher frequency makes it possible to identify peculiarities otherwise hidden on a monthly scale. Furthermore, the numerous gaps in the analysed period do not allow the different responses of the system to varying climatic conditions to be captured effectively. The relatively low correlations obtained between precipitation and groundwater levels may be due, in addition to the high anisotropy and heterogeneity of the system, to the anthropic role, to be quantitatively characterised in the future, with further research and data. In contrast, the stronger correlations observed between temperature and groundwater levels indicate the significant influence of temperature on the mechanisms governing groundwater flow. Temperature is crucial in triggering groundwater droughts directly through evapotranspiration and indirectly through increased water withdrawals. Therefore, it is vital to thoroughly investigate the relationship between temperature and groundwater dynamics, particularly in regions where future rising temperatures may lead to reduced net recharge and subsequently impact groundwater levels.

Paying attention to the "evolution" of the coastal aquifer system is challenging but, at the same time, essential for water resources planning and management. It requires analysing time series data from carefully selected monitoring points, which should capture the aquifer's responses at appropriate frequencies. While precipitation and air temperature are usually available for long periods, continuous monitoring of groundwater levels is frequently fragmented or missing.

Although there are limitations, we can rely on the results that demonstrate the Salento aquifer has a high storage capacity, ensuring that, despite ongoing climate change, there will be sufficient water reserves on the peninsula for drinking and irrigation purposes. However, it is essential to conduct further analyses and monitor its qualitative status due to the high vulnerability of the groundwater to seawater intrusion.

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All authors, the corresponding author states that there is no conflict of interest.

Author contributions
Maria Rosaria Alfio: Methodology, Formal analysis, Data curation, Visualization, Writing-original draft preparation. Gabriella Balacco: Conceptualization Methodology, Supervision, writing-review and editing. Vittoria Dragone: Methodology, Formal analysis, Data curation, Visualization, Writing-original draft preparation. Maurizio Polemio: Conceptualization Methodology, Supervision, Writing-review and editing. The authors read and agreed to the final version of the manuscript.

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