



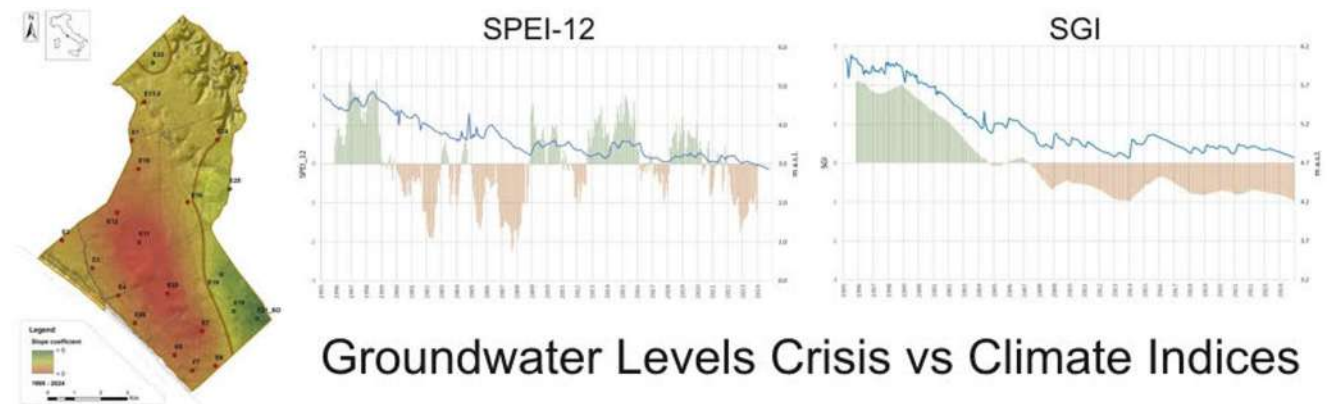
Assessing the effects of climate trends and drought periods on the undeterred aquifer of Castelporziano Nature Reserve (Rome, Italy)

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Abstract Groundwater resource availability is essential for both human needs and ecosystem equilibrium. In the context of ongoing climate change, the water table in the Castelporziano Presidential Estate has shown a significant decline in recent years. To understand this phenomenon, a 30-year analysis of groundwater level trends was conducted. A first comparison of water table fluctuation with rainfall variations does not explain the lowering of the piezometric levels, especially in the central zone of the study area. By comparing the changes in water table levels and soil water content over time with the Standardized Precipitation and Evapotranspiration Index (SPEI at 12 and 3 months temporal scale), a strong correlation among recharge and exhaustion phases and the cycling through wet and dry periods has been inferred, confirming the crucial role of evapotranspiration. Despite the absence of -trend in rainfall, the clear raising trend of temperature triggered higher evapotranspiration values. This process has reduced the water surplus available for aquifer recharge. Nevertheless, the groundwater resilience allows the water table to react to the first multi-year period of drought (1999–2008) in the following years. Unfortunately, since 2016 this fragile equilibrium has been menaced by a new prolonged drought period, having negative consequences on the water table, which is strongly decreasing. The Standardized Groundwater Index SGI values confirm negative conditions since 2008, reaching the most negative values in recent observation years. This crisis, supported by the reduction of the soil moisture during last decade, has likely contributed to the strong problems registered in the Castelporziano forest since 2016.

Graphical abstract



Keywords Groundwater resources · SPEI · SGI · Drought periods · Castelporziano Presidential Estate

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1 Introduction

Drought is a temporary and relative condition characterized by a deficit in available water within a specific period and region (Wilhite 2000). According to Wilhite and Glantz (1985) and American Meteorological Society (2004) drought can be categorized into four main types: meteorological, agricultural, hydrological and socio-economic droughts. All these drought categories are mainly linked to rainfall regime variations, which effects reflected respectively on soil moisture conditions, productive yield of crops, streamflow regime and the failure of water resources to meet water demand. Despite hydrological drought may resulted in a reduction of water resources for both surface and groundwater, Mishra and Singh (2010) introduced for the first time the concept of groundwater drought and how this can be treated as a new type of drought. Specifically, the study assessed that when a groundwater drought occurs primarily groundwater recharge and later groundwater levels as groundwater discharge decrease, considering a time scale of months to years (Van Lanen and Peters 2000). Consequently, the effects of a drought period impact groundwater slower than surface water, exhibiting initially buffer impacts respect to surface processes (Cuthbert et al. 2023; Hellwig et al. 2020).

Although, the negative impacts of storage depletion can be determined, groundwater drought and its intensity has been widely assessed by using water table levels as reliable proxy (Eltahir and Yeh 1999; Chen et al. 2002; Bhuiyan et al. 2006; Bloomfield and Marchant 2013; Cai and Osterdinger 2016; Leelaruban et al. 2017; Lorenzo-Lacruz et al. 2017; Bohn et al. 2020; Secci et al. 2021; Balacco et al. 2022; Dubois and Larocque 2024). These studies are based on the common approach to correlate groundwater levels variations to standardized climate indices, which consider intrinsically the main climatic variables (precipitation and temperature) affecting aquifer recharge.

Specifically, the Standardized Precipitation Index (SPI) (Mckee et al. 1993) was one of the first developed indices and uses monthly rainfall data, at different accumulation time (e.g. 3–6–12-months), to identify alternation of drought and wet periods in a given area. The Standardized Precipitation and Evapotranspiration Index (SPEI), implemented by Vicente-Serrano et al. (2009), considers monthly mean temperature in addition to precipitation data, allowing to delineate wet and dry cycles for defined aggregation time, including also the role of evapotranspiration. Otherwise, the Standardized Groundwater Index (SGI) (Bloomfield and Marchant 2013) analyses groundwater drought with a SPI-like approach going beyond the climatic variables, directly working on water table levels.

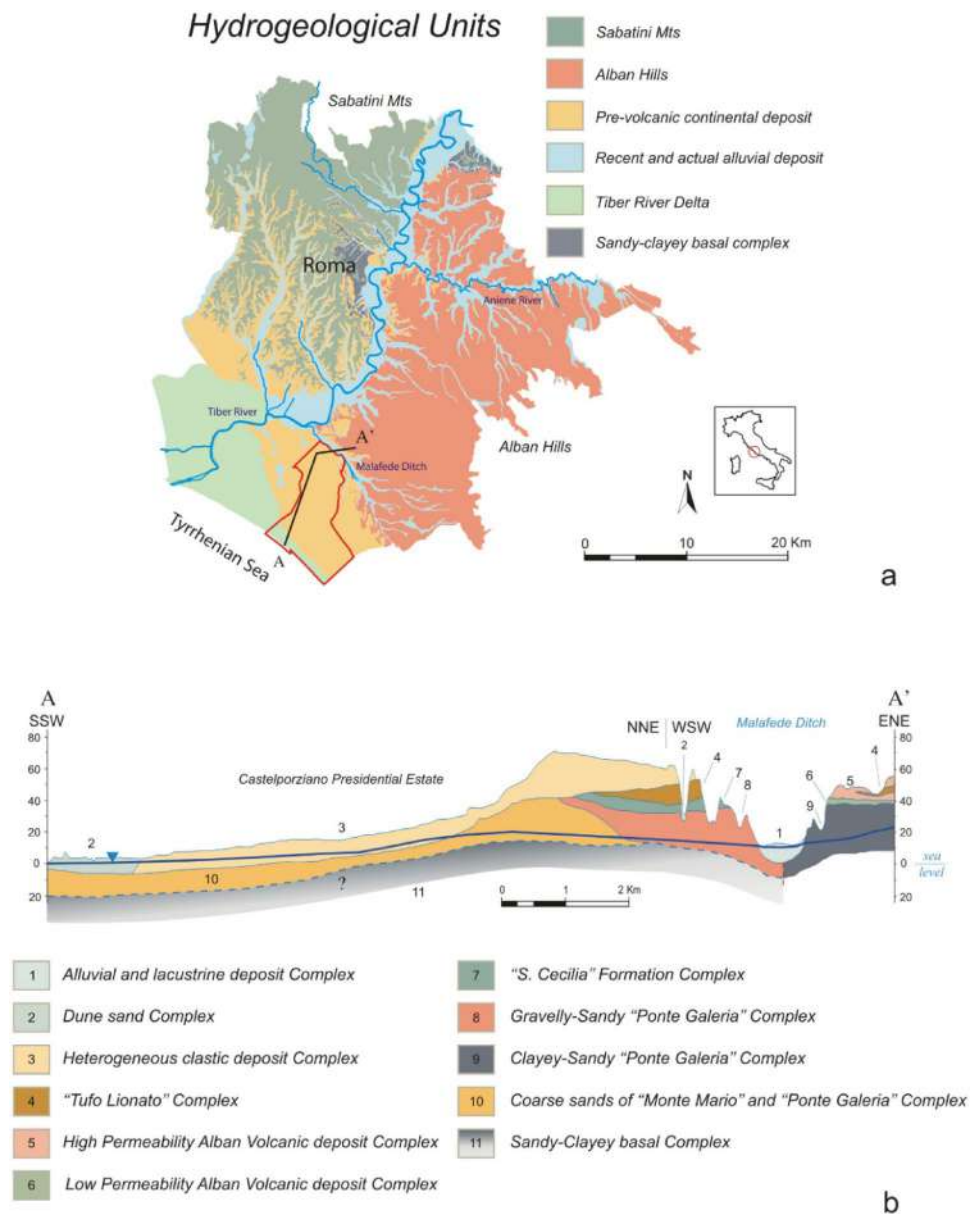
Basing on the consolidated climate indices-groundwater levels correlation approach and considering the ongoing climate stresses involving the Mediterranean area, especially in terms of temperature increase (Toreti et al. 2024), a 30-years analyses (1995–2024) of the drought effects on the Castelporziano Presidential Estate (hereinafter CPE) aquifer has been conducted. This site is located along the Tyrrhenian Sea coast and is classified as “State Natural Reserve” according to the Italian law n. 394/1991 and listed as macro-site in the LTER (Long-Term Ecosystem Research) network due to its unique natural and environmental characteristics (Nardone et al. 2025). CPE experienced during the last years, a crisis both in terms of vegetation (Recanatesi et al. 2018, 2025) and aquifer health (Petitta et al. 2021; Sbarbati et al. 2022). The link between groundwater and ecosystem functions, especially in forests and vegetation, is a widely investigated topic in the scientific literature and particular attention has been given to groundwater dependent ecosystems in the Mediterranean coastal regions which have faced increased anthropogenic activity and changes in climatic conditions in recent decades (e.g. El-Hokayem et al. 2023; Siegel et al. 2023; Erostate et al. 2020; Gomes Marques et al. 2019; Barbeta et al. 2015; Newton et al. 2014). In this view this research offers a comprehensive insight into the effects of drought periods assessed through climatic indices (SPEI-12, SPEI-3) on groundwater resources, focusing on water table levels and soil water content variations. Additionally, the study utilizes the SGI to provide a realistic, 30-year depiction of aquifer conditions, nearly net of anthropogenic pressure, a perspective not commonly explored in the in the existing literature on SGI, as proxy of aquifer drought. Therefore, the outcomes of this research offer a valuable perspective for analyzing groundwater dependent processes, such as forest decline, in natural ecosystems.

2 Site description

The CPE, located at short distance south of Rome city centre (Fig. 1a), constitutes a natural reserve. This area remained basically unaffected by urban expansion, preserving a diverse landscape comprising autochthon and allochthonous forest associations, as well as extensive open terrains intended for agriculture and grazing (Nardone et al. 2025).

The geological-stratigraphical, geomorphological and hydrogeological settings of the CPE are determined by its location between the Alban Hills Volcanic System, the Tyrrhenian Sea, and the Tiber River delta (Fig. 1a). These three entities have differently influenced the geological history and lithological composition of the area and its overall morphological features. According to Parotto et al. (2009) and Banzato et al. (2019), progressing inland from the coastline,

Fig. 1 CPE location in the framework of the Hydrogeological Units map of Rome (a); hydrogeological cross-section of CPE area (mod. from La Vigna and Mazza 2015)



the coastal plain is followed by two orders of marine terraces at elevation ranging from 20 to 40 m a.s.l. Beyond these terraces, a plateau extends up to 80 m a.s.l., bounded to the north-east by the Malafede Ditch and the networks of its tributary streams.

The coastal plain is characterized by sandy deposits of littoral or localized deltaic origin. Progressing inland Holocene interdune sediment, followed Upper Pleistocene sandy deposits are found. In the northern sector, beneath the surficial sandy cover, Middle Pleistocene deposits derived from the Alban Hills Volcanic System and heterogeneous sediments indicative of transitional to continental environments are located. Across the entire CPE, underlying the aforementioned formations, there are Lower Pleistocene sands of marine and transitional origin. Clayey, sandy-clayey, and

marly deposits of probable Plio-Pleistocene age constitute the basal stratigraphic unit, which has been identified at varying depths.

From a hydrogeological perspective, the above described lithologies constitute the main extensive aquifer underlying the CPE (Mastorillo and Petitta 2010). The groundwater flow is likely confined at its base by the Plio-Pleistocene sandy-clayey substrate (Fig. 1b). The substrate displays an undulating topography, resulting in significant variations in aquifer thickness (Fig. 1b). Notably, thickness is conditioned by a ridge trending NW-SE direction, representing a groundwater divide, that locally influence groundwater flow directions in the northern area of the CPE (Fig. 2) (Banzato et al. 2019). This ridge leads to localized thinning and near-disappearance of the aquifer in some areas, whereas, near

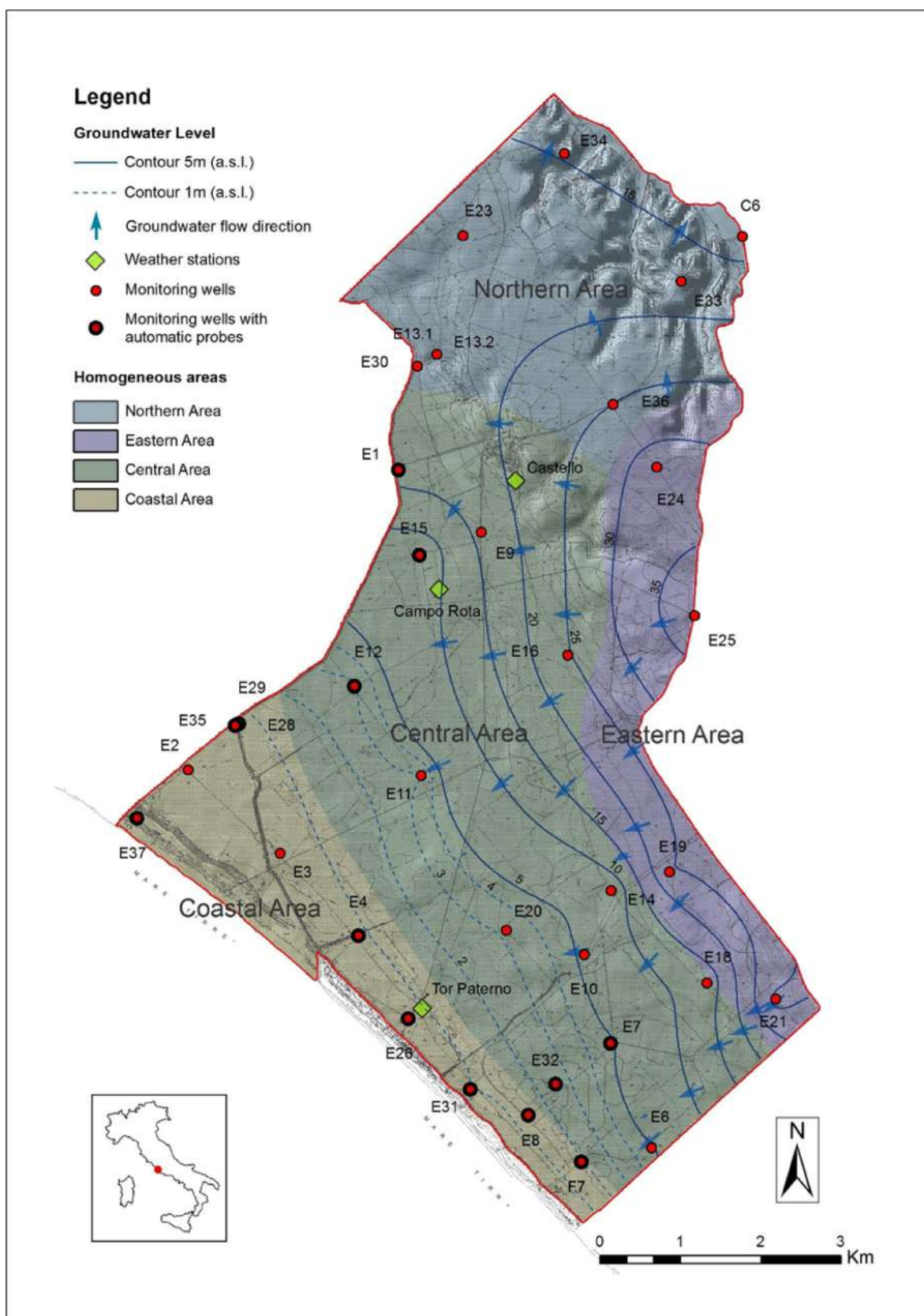


Fig. 2 Map of the CPE showing: homogeneous areas of groundwater recharge; location of the monitoring network points and of the Weather stations; piezometric surface (light blue lines) and main groundwater flow directions (blue arrows). Water table refers to October 2024.

the coastline, it reaches a thickness of 40 m. (Petitta et al. 2021).

Figure 2 shows the piezometric map of the CPE aquifer. Groundwater predominantly flows southward towards the sea, westward toward the Tiber River, and minimally northward towards the Malafede Ditch. The isopiezometric lines, on the eastern margin indicate that the water table in that sector is fed by inputs from the Alban Hills volcanic aquifer (Capelli and Mazza 2005; Banzato et al. 2013). In the central and coastal sectors, the isopiezometric lines are parallel to the coastline, showing a gradual decrease in hydraulic gradient towards the sea.

Previous studies (Petitta et al. 2021; Sbarbati et al. 2022) analysing temporal piezometric levels data from monitoring wells within the CPE, identified four sectors showing homogeneous water table level variations (Fig. 2; Table 1). This homogeneity was attributed to different aquifer characteristics and recharge patterns across the CPE.

The Coastal sector, characterized by a shallow water table and poorly consolidated sands, displays a piezometric trend that is directly responsive to local rainfall. Inland, water table shows increased depth (≈ 12 m b.g.s.) and sediments become more cohesive. In this Central sector, piezometric level fluctuations, while less abrupt, appear strictly dependent on local meteoric input. In the Northern and Eastern sectors, where water tables are significantly deeper (≈ 40 and 23 m b.g.s. respectively), seasonal variations, attributable to local meteoric events, occur with a significant time lag and are superimposed upon longer-term oscillations driven by regional aquifer inputs. Furthermore, a trend analysis of

annual mean piezometric levels since 1995, reveals a consistent variation pattern among piezometers within each of the four identified sectors (Sbarbati et al. 2022).

3 Materials and methods

Piezometric monitoring of the CPE aquifer started in 1995 and is still ongoing. The monitoring network has been progressively implemented to its current configuration of 37 monitoring wells, distributed in all the CPE's territory (Fig. 2). Among these 37 monitoring points, 13 are equipped with probes for automated acquisition of groundwater level, temperature and, in selected wells, electrical conductivity. Details about monitoring intervals are widely described in Sbarbati et al. 2022. An additional monitoring well has been recently included in the living laboratory of Grotte di Piastrea (Manes et al. 2025), not considered in Fig. 2 due to the limited available dataset.

Given the availability of a large amount of data covering a significant time frame, for each monitoring well having the most complete dataset, the mean annual piezometric level trend over the last 30 years (1995–2024) has been calculated. The slope coefficients from the trend lines were determined for each of the 22 selected monitoring points, and used as proxy for groundwater level trend. Utilizing a Kriging-based geostatistical interpolation method (ANUDEM, Hutchinson 2011), a spatial distribution map of the slope coefficients, has been carried out. In addition, the long-term water level monitoring data were investigated

Table 1 Monitoring well characteristics.

Area	MW_ID	WT_Depth (m)	MW_Depth (m)	Area	MW_ID	WT_Depth (m)	MW_Depth (m)
Northern	E36	49.94	65	Eastern	E21	8.96	14
	E30	19.70	35		E19	10.59	16
	E13.1*	3.91	6		E25	37.33	54
	E13.2	28.55	32		E24	42.73	57
	E33*	25.60	31	Central	E6	7.84	12
	C6	3.29	17		E32	9.03	25
	E23	47.58	62		E7	12.36	19
Coastal	E34	dry	41		E18	17.38	19
	F7	7.05	10		E10*	11.32	15
	E8	5.80	14		E20	12.93	15
	E31	3.36	23		E14	21.86	25
	E26	3.85	28		E11	11.54	14
	E4	3.70	13		E12	10.17	14
	E3	3.34	17		E16	11.97	28
	E37	4.02	30		E15	15.14	17
	E2	3.80	12		E9*	10.70	15
	E35	5.30	27		E1	6.17	13
	E28	3.26	10				
	E29	3.34	10				

MW_ID: monitoring well name; *WT_Depth*: water table depth referred to October 2024; *MW_Depth*: monitoring well depth; * not used in October 2024 piezometric map (Fig. 2)

Table 2 Statistical parameters of monthly rainfall (mm) and temperature (°C) dataset for Castello and Tor Paterno weather stations

	Castello weather station		Tor Paterno weather station	
	Rainfall	Temperature	Rainfall	Temperature
N° values	348	348	300	300
Min	0	5.3	0	4.6
Max	332.5	26.7	319.8	26.3
Mean	65.3	16.2	65.7	15.2
Median	46.4	15.6	47.8	14.8
Standard deviation	60.9	5.9	59.9	5.7
25th perc.	19.6	10.7	18.7	10.1
75th perc.	96.3	21.6	101.3	20.4

using the non-parametric Mann-Kendall trend test (Mann 1945; Kendall 1948) with a significant level of α equal to 0.05.

To evaluate net infiltration variations and the effects of alternating droughts and wet periods on groundwater levels, monthly rainfall data and mean monthly temperature data from the Castello and Tor Paterno weather stations (Fig. 2; Table 2) have been considered. The time series encompassed two intervals: 1995–2023 for Castello and 1999–2023 for Tor Paterno. The dataset for both rainfall and temperature at these stations results complete since missing data have been imputed by Di Giuseppe et al. (2025), by using FCS multiple imputation approach.

Soil moisture data recorded at the Campo di Rota weather station (Fig. 2) have been also considered to evaluate the effects of drought on the soil matrix. The analysis focused on the 100 cm depth water content, which can be considered representative of potential future aquifer recharge. The Castello, Tor Paterno and Campo di Rota weather stations have been selected among the 12 climate stations present at CPE, since they recorded the longest dataset for rainfall, temperature and soil moisture.

Given the negligible runoff contribution at the CPE site (Petitta et al. 2021), net infiltration has been estimated as equivalent to effective precipitation. Monthly and annual evapotranspiration, derived from data at the Castello and Tor Paterno stations, have been calculated using the Thornthwaite and Mather method (Thornthwaite, and Mather, 1957), with an assumed available water capacity (AWC) of 100 mm (Biondi et al. 2001). Evapotranspiration rate was subtracted to rainfall to estimate effective precipitation at monthly and annual scales. It is essential to note that annual rainfall as well as main temperature and, consequently, net infiltration have been calculated over the hydrologic year (September to August).

To further evaluate the effects of drought periods on the CPE aquifer across different areas over the last 30 years of monitoring, the Standardized Precipitation and

Table 3 Statistical parameters of monthly mean groundwater level data (m a.s.l.) for the selected monitoring wells

	F7	E11	E23	E19
N° values	206	201	180	203
Min	1.92	2.86	17.190	24.19
Max	3.75	4.86	18.75	25.65
Mean	2.54	3.89	17.96	24.72
Median	2.46	3.82	17.96	24.69
Standard deviation	0.38	0.54	0.35	0.32
25th perc.	2.26	3.46	17.67	24.53
75th perc.	2.75	4.38	18.20	24.95

Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2009) has been calculated using dataset from Castello and Tor Paterno weather stations (see Table 2) and compared with water level variations and changes of soil water content. The index is derived from the combination of the Standardized Precipitation Index (SPI) (McKee et al. 1993), which adopts a probabilistic approach to precipitation, and the Palmer Drought Severity Index (PDSI) (Palmer 1965), which is based on a soil water balance equation. The SPEI calculation includes monthly precipitation, monthly mean temperature data and latitude of the weather stations, resulting in a simplified water balance, based on the difference between rainfall and potential evapotranspiration at various time scale. The temporal aggregation scale of SPEI values identifies different types of droughts. In this study, 12- and 3-months scales have been adopted by using monthly rainfall and temperature data (Table 2), describing drought affecting groundwater resources and soil moisture conditions, respectively. Negative SPEI values indicate drier-than-average conditions, the lower the negative value (<-1), the drier the conditions. Conversely, positive SPEI values indicate wetter-than-average conditions. The software and procedure for the SPEI calculation have been downloaded from the Web repository of the Spanish National Research Council (<http://digital.csic.es/handle/10261/10002>).

To compare SPEI and groundwater level variations over time, four representative monitoring wells have been selected from the different homogeneous areas of the Estate (Fig. 2). Table 3 lists the characteristics and statistical parameters of the dataset.

In addition, the Standardized Groundwater Index (SGI) (Bloomfield and Marchant 2013) has been computed for a subset of monitoring wells equipped with automatic probes, located in the Coastal and Central areas of the CPE, having continuous monthly water table time series (1995–2024). Analogous to the SPEI, the SGI is based on a SPI-like normalization methodology, utilizing groundwater levels as a proxy for the quantitative status of groundwater resources during a period of drought. To calculate SGI values the procedure summarized and explained in Guo et al. (2021) has been followed, that consists in four main steps: (i) calculation

of water levels averages over the time scale of interest; (ii) fitting of a probability density function; (iii) determination of the cumulative probability of observed water level values; (iv) conversion of the cumulative probability applying the inverse normal cumulative distribution function to derive SGI. In the present study the SGI has been calculated on a 12-months scale. According with recent literature (Guo et al. 2021; Duboise and Laroque 2024) SGI values below 0 are generally indicative of groundwater drought, whereas values of 0 or greater suggest the absence of groundwater drought.

4 Results

Temporal analysis of piezometric level variations allowed the determination of trend lines and corresponding slope coefficients, for each of the 22 selected points of the monitoring network. Table 4 shows the slope coefficients calculated for the mean annual piezometric level in the four representative piezometers compared with Mann-Kendall trend test results in terms of Z and p-value. This comparison corroborates the validity of the slope coefficient as representative index of groundwater level trends.

Figure 3 shows the spatial distribution map of the slope coefficient values, computed at individual points and the annual mean piezometric level variations over time in the four representative monitoring well. This map serves as an interpretation of piezometric levels trend over the preceding 30 years, with green hues indicating a positive trend and red hues representing a negative trend. In detail, the colour distribution on the map closely aligns with the homogeneous areas of groundwater recharge delineation shown in Fig. 2. The Eastern area shows a distinct positive trend as represented by monitoring well E19. Following minimum levels recorded in 2004 and 2005, a gradual increase in the piezometric levels occurred until 2016. While a decline has occurred since 2017, current levels remain significantly above the historical 30-year minimum. The Northern area, indicated by yellow tones and represented by E23 monitoring well, is characterized by substantial stability in groundwater levels. Both a slope coefficient near zero and the Mann-Kendall test confirm a stable trend, despite some fluctuations with maximum in 1998 and minima in 2004–2005 and 2008.

Table 4 Slope coefficient and Mann-Kendall trend test results for mean annual groundwater level

	F7	E11	E23	E19
Slope coefficient	−0.017	−0.056	0.001	0.023
Z	−2.818	−6.529	0.652	3.301
p-value	0.005	6.59×10^{-11}	0.514	0.001
Nature of trend	Decreasing	Decreasing	No trend	Increasing

In contrast, the Coastal and Central sectors show critical negative trends. The Coastal sector, represented by F7 monitoring well, has experienced a negative trend since 2016, with mean annual levels consistently below the 30-year average (2.46 m a.s.l.) and a record low of 2.0 m a.s.l. in 2024. The Central sector, marked by red tones and well E11, shows an even more pronounced and continuous decline, reaching its lowest value of 2.91 m a.s.l. in 2024.

This map provides an updated representation of CPE aquifer trends across the area, extending the record up to 2024, respect to Sbarbati et al. (2022). It reveals a slight increase in water table levels only in a limited portion of the Northern area, while confirms the sustained and sharp decline of groundwater levels in Coastal and Central areas.

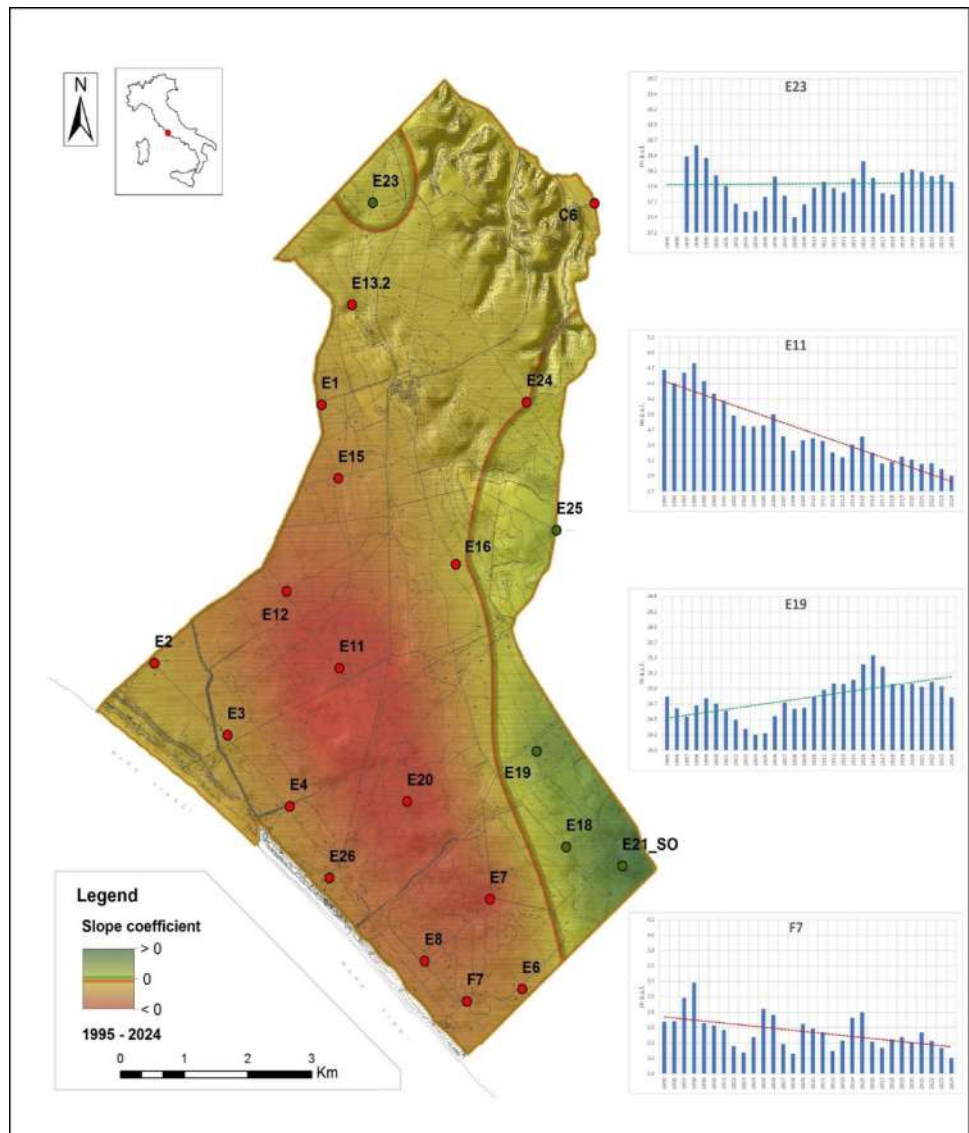
Given that the CPE aquifer is primarily recharged by local meteoric inputs (Mastrorillo and Petitta 2010; Banzato et al. 2013; Petitta et al. 2021), evaluating the magnitude of precipitation-related recharge was deemed crucial. Figure 4a and b show the annual precipitation, annual effective infiltration, and annual mean temperature data over the last 30 years. These data were recorded at the Castello weather station, located at the boundary between the Central and Northern sectors, and the Tor Paterno weather station situated in the Coastal sector (Fig. 2; Table 2).

A comparative analysis of the two graphs shows discrepancies in the recorded and calculated parameters between the two stations, despite their proximity of approximately six kilometres. Table 5 lists minimum, maximum and mean annual values for rainfall, temperature and net infiltration computed for the 1999–2023 period common to both stations. The precipitation patterns exhibit comparability in the alternation of rainy and non-rainy phases, with the notable exception of the 2004–2006 period, during which Tor Paterno recorded significantly higher precipitation. Temperature was the most significant divergence between the two weather stations with one degree divergence.

The mean annual net infiltration is greater at Tor Paterno than at Castello. For the Castello station (Fig. 4a), a prolonged period from 1999 to 2008 exhibited significantly lower net infiltration values, averaging 158 mm/y compared to the overall period mean of 289 mm/y. Specifically, values for 2002 were null, while 2005 and 2007 were near-zero. Conversely, the Tor Paterno data (Fig. 4b) did not show a similar continuous low-infiltration period; only the years 2002, 2007, and 2016 had significantly below-average values. No clear temporal trends in rainfall or net infiltration were inferred from the data.

Given the substantial weather-climate datasets, the SPEI-12 climate index was computed for both Castello and Tor Paterno stations. This index is reliable indicator for assessing the impact of drought conditions on groundwater recharge availability, consequently SPEI-12 trends have

Fig. 3 Distribution map of slope coefficients of water level trends (1995–2024) in 22 monitoring wells. Temporal trends of average annual water levels in four representative monitoring wells, each corresponding to a homogeneous area of the CPE



been compared with piezometric levels variations focusing on the Central and Coastal areas, most affected by groundwater level decline. In these areas, local meteorological input plays a pivotal role in aquifer recharge, which is reflected in water table variations (Petitta et al. 2021; Sbarbati et al. 2022). Figure 5a and b illustrate the relationship between monthly SPEI-12 values at the Castello and Tor Paterno stations and groundwater levels in the F7 monitoring well, located in the Coastal area. Due to data availability, the index calculation begins in 1996 for Castello and 1999 for Tor Paterno. Both stations show similarities and differences in their SPEI trends. The Castello's SPEI-12 (Fig. 5a) negative values (173) slightly outnumbered positive ones (164). Drought conditions (SPEI-12 < -1) have been observed for 56 months, about 17% of the monitored period. At Tor Paterno (Fig. 5b) positive (145) and negative (143) values were nearly balanced, with 64 months

classified as drought period (about 22% of the total). Consistent with net infiltration data, the Castello station showed a prolonged dry period from 1999 to 2008, with 100 out of 120 months having negative SPEI-12 values, and 43 of these months showing drought conditions (< -1). A second critical period occurred from 2020 to the end of 2023, where 35 of 48 months had negative values, with 12 months < -1 (Fig. 5a). In contrast, Tor Paterno SPEI-12 did not show an equivalent prolonged crisis period. Instead, a critical period is observed from 2016 to 2023, where 69 of 96 months shown index below zero, with 33 months with SPEI < -1 (Fig. 5b).

Groundwater levels in the F7 monitoring well show a clear correlation with SPEI-12 trends from both stations (Fig. 5a-b). The correlation is stronger with the Tor Paterno SPEI-12 (Fig. 5b) than with the Castello SPEI-12 (Fig. 5a) which is expected since the Tor Paterno weather station is located in the same Coastal sector as the F7 piezometer. For

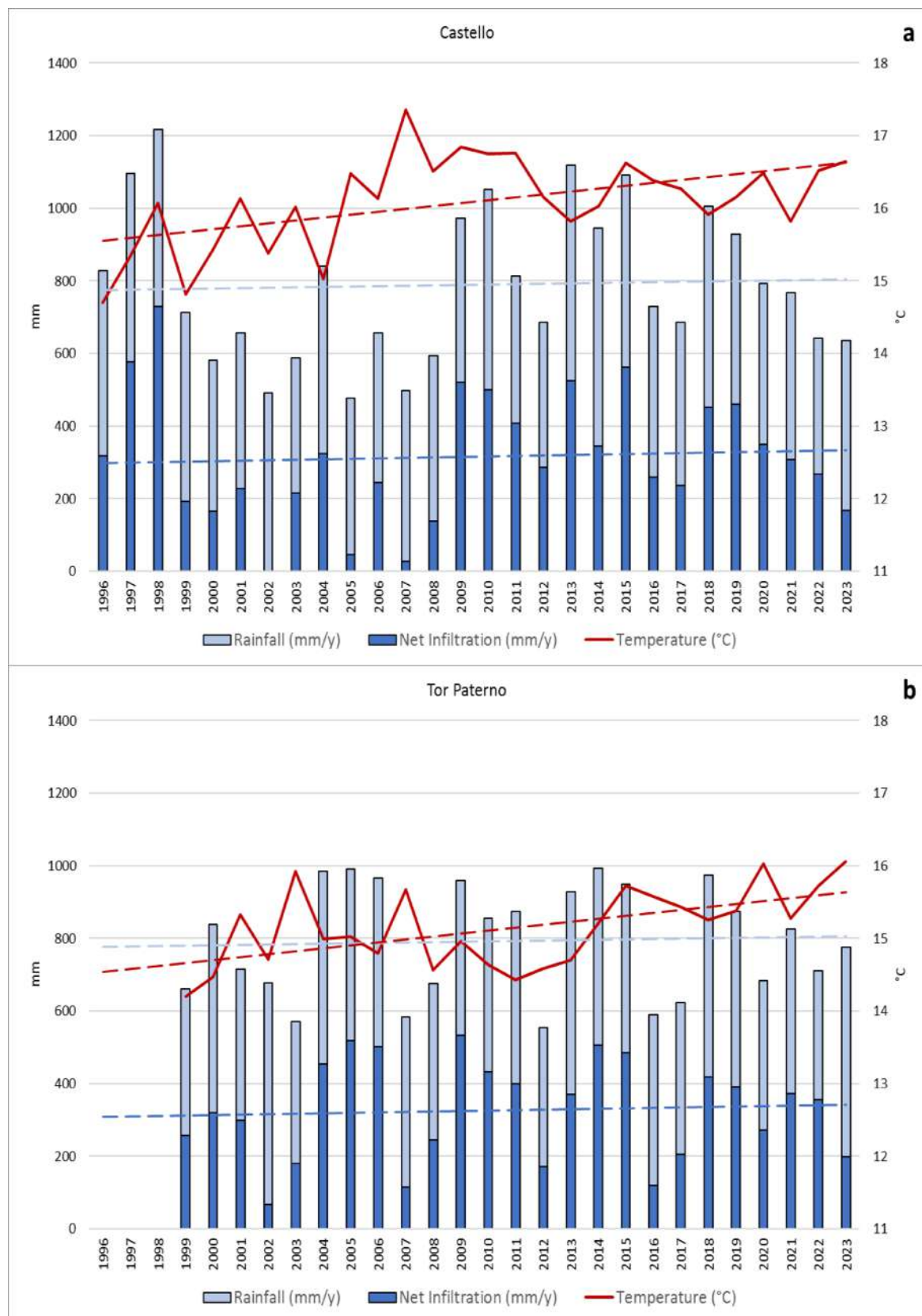
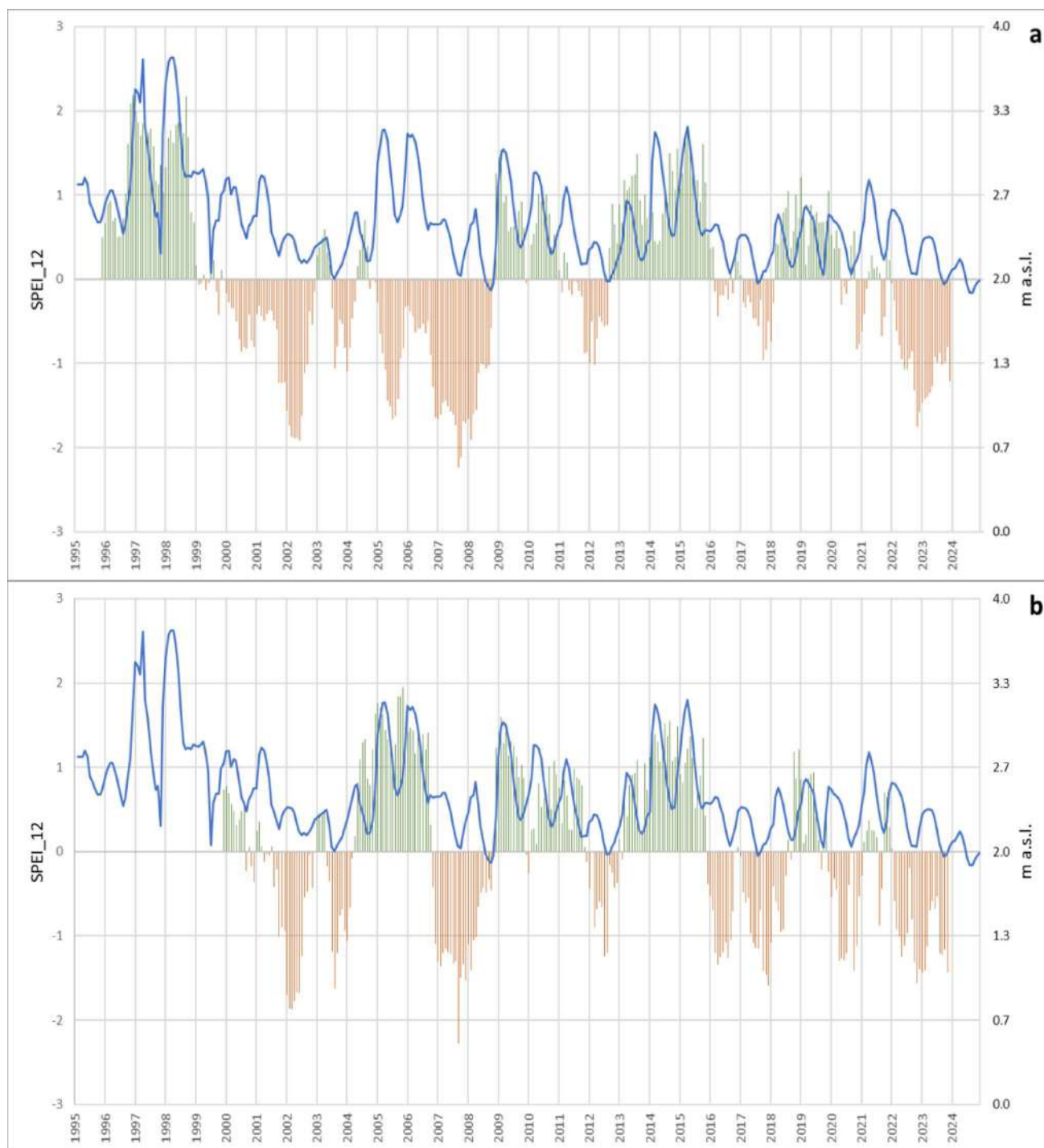


Fig. 4 Cumulated annual rainfall (mm/y), net infiltration (mm/y) and average annual temperature (°C) calculated for the Castello weather station (a) and Tor Paterno weather station (b) in the 1995–2023 monitoring period

Table 5 Minimum, maximum and mean rainfall (mm), temperature (°C) and net infiltration (mm) annual value computed for Castello and Tor Paterno weather stations (1999–2023).

	Castello weather station			Tor Paterno weather station		
	Rainfall	Temperature	Net infiltration	Rainfall	Temperature	Net infiltration
Min	477	14.8	0	555	14.2	67
Max	1120	17.4	561	993	16.1	533
Mean	758	16.2	289	327	15.2	327

**Fig. 5** Trend of the SPEI-12 index computed for the Castello Weather Station (**a**) and for the Tor Paterno Weather Station (**b**) compared with groundwater levels measured in F7 monitoring well located in the Coastal area

instance, during 2004–2006, when water table levels were relatively high, the Tor Paterno SPEI-12 was positive, while the Castello SPEI-12 was negative. Anyway, the Castello SPEI-12 also correlates with water levels showing a perfect relationship from 1996 to 1998, a period for which Tor Paterno data are unavailable.

The groundwater level in the E11 monitoring well, which represents the Central area, was compared with the SPEI-12

values from the Castello and Tor Paterno stations (Fig. 6a, b).

The trend line of piezometric levels shows three distinct and consecutive phases. From 1999 to 2008, a marked decline in the water table level from approximately 6 m a.s.l. to below 5 m a.s.l. occurred. From 2009 to the end of 2021, minimum water table levels were relatively stable, with oscillations of less than 50 cm. In 2022, a new phase

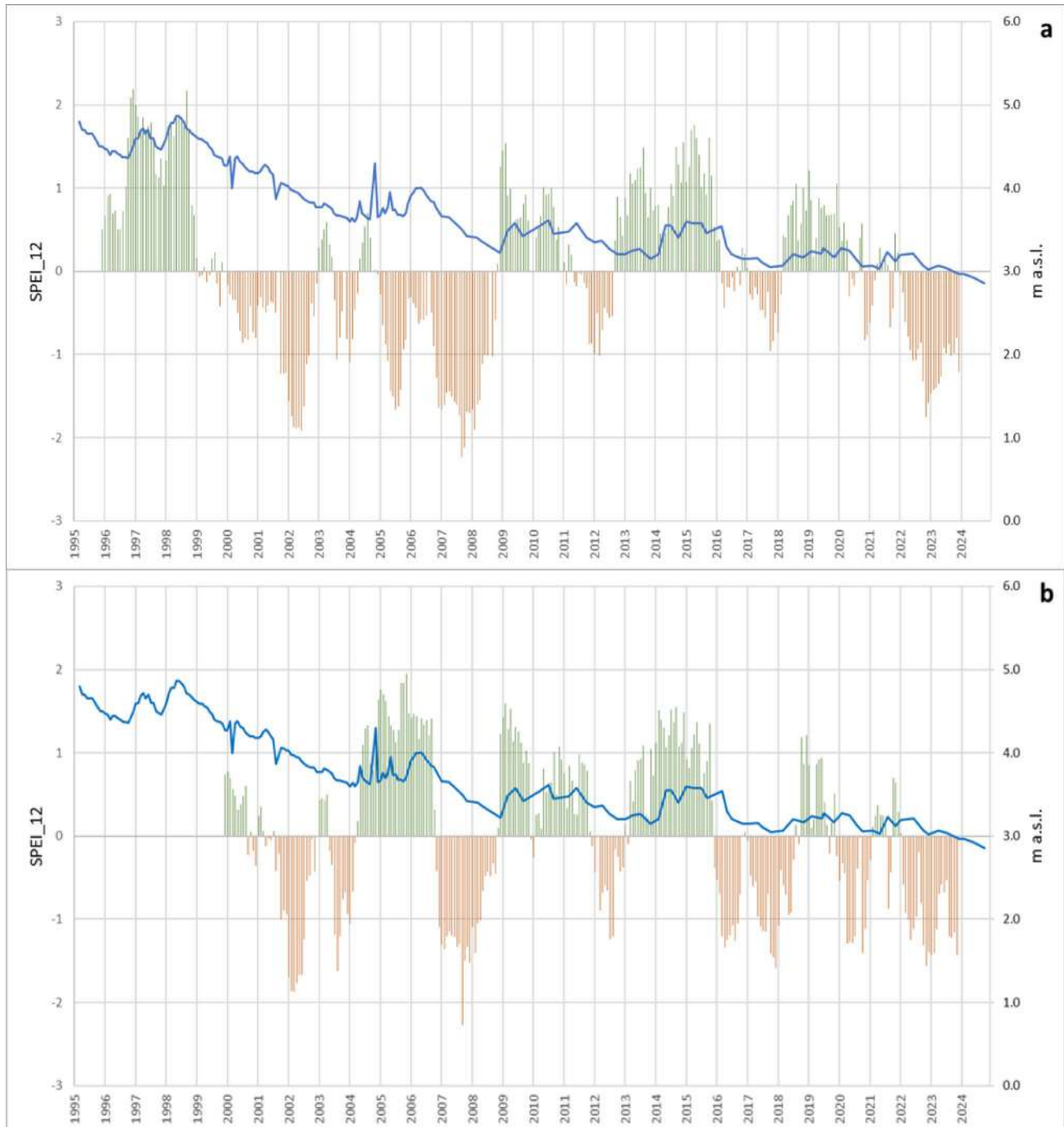


Fig. 6 Trend of the SPEI-12 index computed for the Castello Weather Station (a) and for the Tor Paterno Weather Station (b) compared with the groundwater levels measured in the monitoring well E11 located in the Central area.

of water table decline began, and persisted until the end of 2024, reaching the lowest recorded values.

The correlation between groundwater levels and the Castello SPEI-12 is evident, confirming that the water table decline observed from 1999 to 2008 was caused by a prolonged dry period. During this time, the SPEI-12 index predominantly showed negative values, including values below -1 in 2007 and 2008, indicating a period of severe drought.

A comparison of the graphs in Fig. 6a, b also highlights a key aspect of groundwater recharge mechanisms. During the extended depletion phase of 1999–2008, a slight rise in piezometric levels during 2004 and a more significant one in 2006 perfectly coincide with a wet period shown on the Tor Paterno graph. Likewise, a sustained decline of the water table level from 2016 to the present is mirrored by a clear dominance of dry periods at Tor Paterno. The already impaired water level conditions recorded since 2021 were further worsened by the 2022–2023 drought phase, clearly highlighted by SPEI-12 data for both weather stations. These observations suggest that aquifer recharge in this sector relies almost solely on local meteorological inputs and consequently its oscillations therefore derive from the combined influence of the weather and climate conditions recorded across the different sectors of the CPE.

Analyses of the Northern and the Eastern areas of the CPE reveals no critical conditions in terms of aquifer depletion. These sectors are influenced by external regional aquifer inputs (Banzato et al. 2019). In the Northern sector, groundwater levels have progressively increased since 2008, despite the 1999–2008 drought period. This is followed by alternating high and low levels, corresponding to

SPEI-12 wet and dry periods. Overall, the average groundwater table level trend in this area remains largely steady. The piezometric level trend in Eastern sector is generally characterized by a positive trend over the 30-years monitoring period. The only exception is a decreasing phase from 2016 to 2024, which correspond to the drought phase particularly evident at Tor Paterno. This has resulted in current levels comparable to the thirty-year average value (24.7 m a.s.l.). Even in this case, correlation between positive and negative piezometric level peaks and the wet and dry periods is good. Nevertheless, in the Eastern sector local meteoric and climate variations have a partial impact on groundwater level, which appears to be regulated at its minimum level by inputs from the Alban Hills aquifer. Consequently, external contributions buffer the detrimental effects of drought periods observed at the CPE's weather stations within the Northern and the Eastern areas.

According to Sbarbati et al. (2022), the soil plays a pivotal role in the recharge of the CPE aquifer. For this reason, this study used the SPEI-3 index to evaluate the impact of drought on soil water content. As shown in Fig. 7, the comparison of the SPEI-3 (from Castello data) with soil water content at 100 cm b.g.s. (from the Campo di Rota station) shows a direct correspondence: positive and negative SPEI-3 peaks align with rising and falling soil moisture, respectively. Since soil water content at this depth is largely unaffected by evaporation processes, it can be inferred that aquifer recharge occurs when infiltration from rainfall increases the soil water content at a depth greater than the root zone.

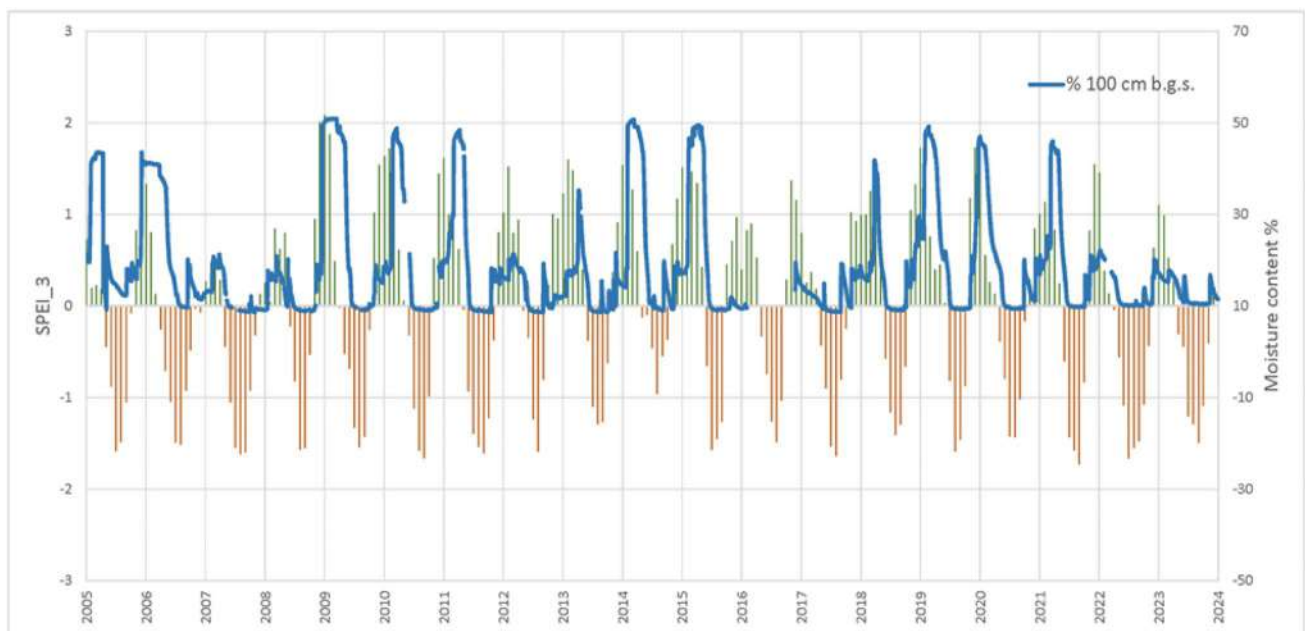


Fig. 7 Trend of the SPEI-3 computed for the Castello Weather compared with soil water content measured at 100 cm b.g.s

The temporal analysis of moisture variations at 100 cm b.g.s. shows a general decline in soil water content since 2016–2017, coinciding with a previously identified drought period. Specifically, the number of months with water content exceeding 30% decreased by half, from 1.9 months/year in the 2005–2015 period to 1 month/year from 2016 to 2023. In addition, the comparison of piezometric levels in F7 and E11 monitoring wells with soil moisture at 100 cm (Fig. 8), suggests that aquifer recharge is not primarily correlated with the maximum moisture percentage achieved, but rather with the duration of the period during which the soil remains moist, due to the persistence of water surplus corresponding with positive SPEI-3 values.

5 Discussions

The climate conditions in the study area reveal significant variability in space and time, with direct effects on the water availability both in soils and groundwater. Time-trends clearly emerged for temperature (with an increase >1 °C during last 28 years) and for groundwater table (up to >1.5 m of depletion in the same period in selected zones). Conversely, precipitations do not show a significant temporal trend in both the main stations of Castello and Tor Paterno (Di Giuseppe et al. 2025).

The assessment of the relationship between temperature and water availability has been analysed by the SPEI index, taking into account that the rise in evapotranspiration is driven by temperature increases. The decade 1999–2008

shows negative persistent values of SPEI-12 at Castello, less pronounced for Tor Paterno. It is followed by a period (until 2016) with general positive values, while in the last years new negative values are predominant. For the last decade, the negative values are more consistent for Tor Paterno respect with Castello station (see Fig. 5a, b). Even soil water content, recorded at Campo di Rota station (see Fig. 7), confirmed a lowering since 2016 to date mainly in terms of duration of the peaks of soil moisture higher than 30%, fundamental to allow aquifer recharge.

Assuming the water surplus (effective precipitation after subtracting the effective evapotranspiration) as totally available for infiltration, both water content in soil and groundwater recharge are expected to follow the SPEI variability with time. Nevertheless, the results for the water table are geographically different, for hydrological and hydrogeological reasons such as the influence of external hydrogeological basins in the Northern and Eastern areas.

With the aim to overcome the initial assumption of the transfer of water surplus into the ground, the use of a different index (SGI, Standardized Groundwater Index) was useful and able to assess the real groundwater availability, with particular focus on the Central and Coastal areas characterized by groundwater level depletion.

SGI for the Coastal area has been calculated with the continuous monitoring water table data in F7 (see Fig. 2). The alternance of positive and negative values of SGI (Fig. 9a) is characterizing the first two decades of observation (1995–2016), but since 2016 the SGI remains negative, despite some oscillations, and the absolute minimum

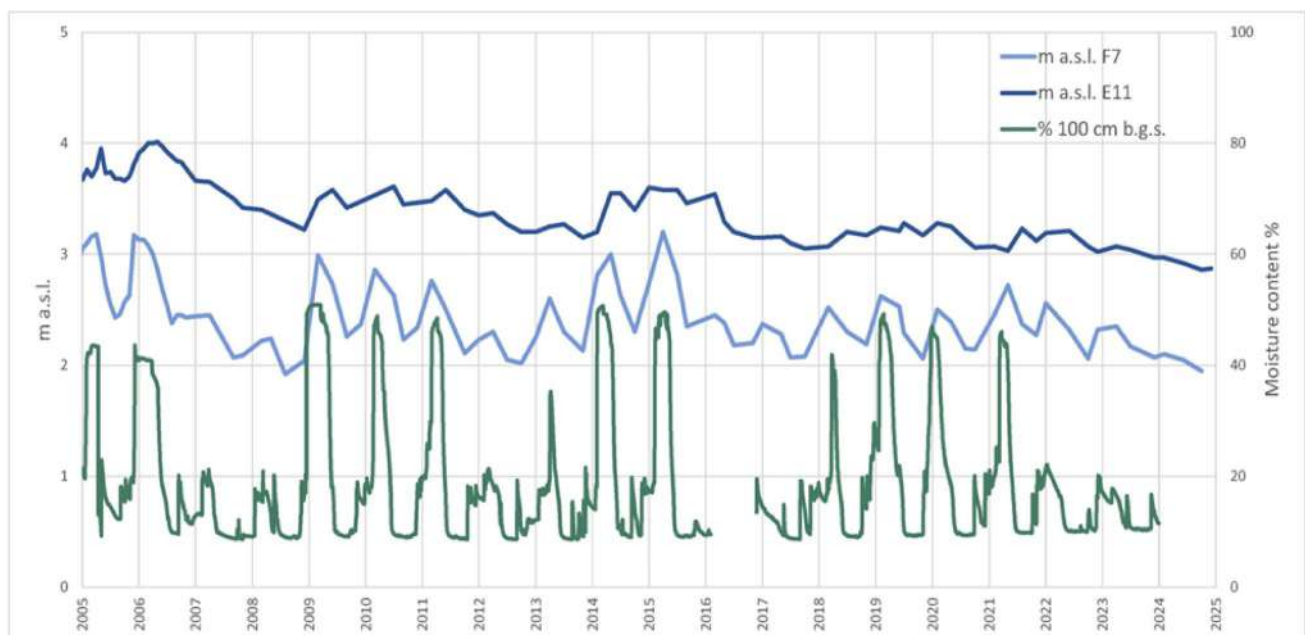
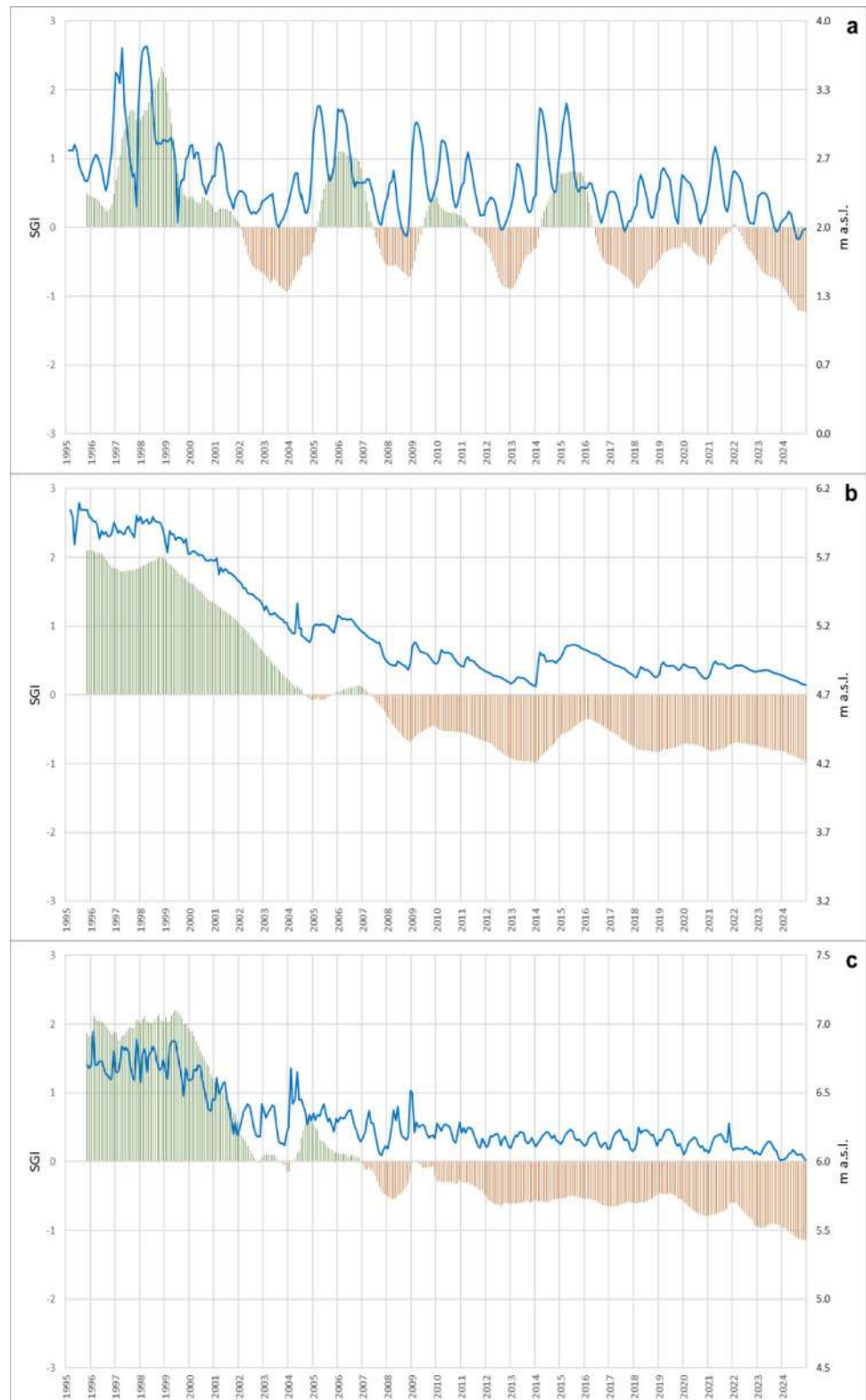


Fig. 8 Comparison between soil water content measured at 100 cm at Campo di Rota Weather Station and groundwater levels measured in F7 and E11 monitoring wells

Fig. 9 Trend of the SGI index computed the monitoring well F7 (a), located in the Coastal area, and the monitoring wells E7 (b) and E15 (c), located in the Central area



values < -1 appear for the first time in 2024. To sum up, the first recorded crisis of SPEI-12 (1999–2008) induced a limited shortening in groundwater availability in this area, as testified by the SGI oscillation. Due to the resilience of

groundwater resources, the aquifer menaced by the climate conditions remained in a steady condition. But this initial sufferance moves to a persistent crisis since 2016, where the

negative trend of water table become irreversible, at least until the current situation (end of 2024).

A similar behaviour has been recorded in the Central area, where the SGI has been calculated respect with water table recording in E7 (Fig. 9b) and in E15 (Fig. 9c). This zone has been considered as affected only by the processes occurring in the study area, without external factors which influenced the other zones (as the proximity of the sea for the Coastal area, groundwater flow from eastern hydrogeological basins, and also human withdrawals, concentrated mainly at the border of the Northern area).

In both locations, SGI was very high at the beginning of the time series (until 1999–2000), followed by a decrease, but remaining in the positive domain until 2006–07. Since this date, the SGI becomes negative and worse until the more recent data (end of 2024), when also in this case the lowest values of SGI (<-1) have been recorded in both observation wells.

Consequently, it can be inferred that the occurrence of pronounced drought periods (observed in the 1999–2008 decade and in 2016–2024) triggered a clear water crisis in the subsoil of the CPE.

During the first drought phase (1999–2008), the conditions of the water table and of the unsaturated zone were able to tackle this negative period with some sufferance. The “memory effect” of groundwater resources (e.g. their resilience to scattered climate changes), the persistence of annual precipitation values in line with past observation, the limited increase of temperature, allowed the system to withstand stress up to 2008–2009. The onset of a following drought period started in 2016, produced more negative effect on water availability, translating on a real crisis scenario happened with the increase of evapotranspiration due to temperature rise, on an underground system posed on edge conditions from the previous drought period.

As a result, the new negative climate period definitely breaks this fragile equilibrium, at least in the area where the sole groundwater input is from the precipitation recharge. At the moment, the decrease in water availability both in soils and groundwater does not show trend inversion. We argue that the underground water conditions have some effect on the forest health, contributing to the stress that clearly started in the same period (2016), possibly facilitating the *Tomicus* attack on the pines, as the fast decay of the oak forest (Recanatesi et al. 2025), which shows a positive spatial correlation with the hydrogeological defined Central area.

After the clear trigger of this water crisis since 2016, the very alarming news is the continuous decrease of the water table and of the water content in soils, which seems until now unstoppable. A persistent positive trend of temperature will surely enhance the water crisis, and only higher rate of

precipitations in the future years can smooth this negative trend.

6 Conclusions

This study investigates the response of the Castelporziano Presidential Estate aquifer to the meteorological and climatic variations recorded over the past thirty years, with a particular focus on the drought periods. Analysis of piezometric level variations from 1995 to 2024 shows a progressive decline, especially in the Coastal and Central sectors.

Meteorological and climatic data from the CPE's stations (Castello and Tor Paterno) reveal significant differences in rainfall and temperatures, even over short distances which result in different aquifer recharge patterns. While net infiltration calculations identified years with limited recharge, they only partially explained the prolonged aquifer crisis in the Central area.

A comparison of the 12-month Standardized Precipitation Evapotranspiration Index (SPEI-12) between Castello and Tor Paterno stations highlights both similarities and discrepancies. Castello showed major drought periods from 1999 to 2008 and in 2022–2023, while Tor Paterno data did not show the early 2000s drought but a continuous one from 2016 to 2024.

Correlation of piezometric data with SPEI-12 revealed distinct drought impacts across the CPE's four sectors. The Western and Northern sectors are influenced by external inputs, which mitigate the effects of drought. Conversely, the Coastal and Central sectors are strongly influenced by local meteorological and climatic conditions. In the Coastal sector, piezometric level variations closely align with the Tor Paterno SPEI-12. Since 1995, a gradual decline in the water table has been observed. The impacts of the 1999–2008 drought were partially offset by coastal rainfall events. However, from 2016 onwards, recharge and exhaustion cycles exhibited progressively reduced amplitudes, reaching minimum values in 2024. The Standardized Groundwater Index (SGI) for Coastal piezometer confirms this with consistently negative values since 2016.

The Central sector experienced the most severe water table decline (up to 2 m), which strongly correlates with the prolonged 1999–2008 drought shown in the Castello SPEI-12 data. Although some recharge occurred from 2009 to 2015, levels never fully recovered, and further depletion from 2016 to 2024 was confirmed by negative SGI values. The negative impact of drought on the unsaturated zone was also revealed by comparisons of soil moisture and the SPEI-3 index, which showed a significant decrease in soil water content since 2016.

The integrated analysis of hydrogeological parameters with SPEI-12 and SPEI-3 climatic indices provides a clearer understanding of aquifer recharge mechanisms and the processes leading to aquifer crises in the Coastal and Central sectors of the CPE. Despite the relatively limited extension of CPE, the study revealed significant variability in both climatic parameters and the aquifer's response to drought events, indicating that the crises are primarily driven by prolonged drought periods, increasing temperatures, and the rising frequency of extreme weather events. These findings are crucial for understanding groundwater-dependent processes, such as forest decline, and for the future safeguarding and proper management of natural ecosystems like the CPE, especially given ongoing climate trends.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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