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Research Article

Spatiotemporal trends and lagged precipitation–Soil moisture relationships across coastal and inland regions of Türkiye

Ahmet Erdağ [a,*], Pınar Sezin Öztürk Kardoğan [b]

[a] *Department of Civil Engineering, Faculty of Engineering and Architecture, Kafkas University, 36100 Kars, Türkiye*
[b] *Department of Civil Engineering, Faculty of Technology, Gazi University, 06500 Ankara, Türkiye*

ABSTRACT

Soil moisture is a key hydrometeorological variable that links precipitation and temperature to land–atmosphere interactions and strongly influences evapotranspiration, runoff generation, and drought development. This study investigates the long-term variability of surface soil wetness across Türkiye using daily datasets from seven representative cities characterized by contrasting coastal and inland climatic conditions over the period from 1 January 2005 to 1 January 2025. The analysis focuses on (i) trend assessment of precipitation and surface soil wetness, (ii) evaluation of precipitation–surface wetness (P–$GWET_{top}$) and air temperature–surface wetness (T_{2m}–$GWET_{top}$) relationships, (iii) comparison of climatic responses between coastal and inland regions, and (iv) lagged correlation analysis to identify the response time of surface wetness to precipitation within a 0–14 day period. Monthly aggregated data were used to perform descriptive statistical analyses, correlation assessments, and linear trend evaluations. The results show that precipitation–surface wetness relationships vary considerably among the selected cities, reflecting regional differences in climatic regime, precipitation characteristics, and evaporative demand. In several inland cities, the influence of air temperature on surface wetness variability appears more pronounced, indicating the importance of evaporation-driven moisture loss under drier climatic conditions. In contrast, coastal cities generally exhibit weaker and more variable response patterns due to their more humid atmospheric conditions. Overall, the findings provide a comparative framework for understanding climate-related surface soil moisture variability across different climatic regions of Türkiye and offer useful insight for future hydrometeorological and environmental assessments.

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1. Introduction

Soil moisture is a key variable governing land–atmosphere interactions, hydrological processes, and near-surface energy exchange, and it represents the primary control on how precipitation is partitioned into infiltration, runoff, and evapotranspiration. Numerous studies emphasize that soil moisture responds sensitively to climatic variability and precipitation dynamics, making it a critical parameter for understanding environmental processes across different climate zones (Sehler et al. 2019; Asano et al. 2023; Tang and Chen 2017). At longer temporal scales, soil moisture persistence and memory influence drought development, agricultural productivity, groundwater recharge, and ecohydrological feedbacks (Gallagher and McColl 2025; Saadatabati et al. 2021). This sensitivity makes long-term soil moisture datasets essential for national-scale climate assessments, including Türkiye, where hydro-climatic gradients vary sharply across regions.

* *Corresponding author.* E-mail address: ahmet.erdag@kafkas.edu.tr (A. Erdağ)
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Previous global and regional investigations highlight that precipitation anomalies are among the dominant drivers of short-term surface soil moisture fluctuations, while deeper soil layers integrate long-term climatic signals and partially buffer seasonal variability (Li et al. 2024; Chai et al. 2021). Coastal–inland contrasts, vegetation characteristics, and soil texture have also been shown to modulate the magnitude and persistence of soil moisture responses to rainfall events (Reinsch et al. 2024). In particular, surface wetness reacts rapidly to rainfall inputs but decays through drainage and evapotranspiration, whereas profile soil moisture reflects cumulative climatic forcing and is more relevant for drought characterization and long-term hydrological modeling (Afshar et al. 2022).

In Türkiye, pronounced spatial variability in climate from humid Black Sea conditions to continental eastern plateaus and semi-arid southeastern regions leads to distinct soil moisture regimes. Despite this diversity, long-term soil moisture analyses remain limited, and existing studies largely focus on site-specific observations or agricultural applications (Mammadov et al. 2026). However, soil moisture is also a critical parameter in geotechnical engineering, influencing bearing capacity, settlement behavior, slope stability, frost–thaw processes, and unsaturated soil mechanics. Consequently, understanding long-term soil wetness variability provides valuable insight into how climate-driven changes may affect soil performance, infrastructure resilience, and land degradation risk (Schwitalla et al. 2025).

Recent advances in satellite- and model-based soil moisture products, together with reanalysis datasets such as NASA POWER and CHRS PERSIANN, have enabled consistent, multi-decadal assessments of soil moisture dynamics at regional and national scales (NASA Langley Research Center 2025; PERSIANN Data Portal 2024). These datasets facilitate the evaluation of precipitation–soil moisture coupling, temperature-driven drying effects, and long-term trends in near-surface hydrological conditions with high temporal resolution (Vaitkus et al. 2019). Accordingly, comparative analyses across multiple cities representing different climatic regimes offer a robust framework for characterizing soil moisture behavior across Türkiye (Erdağ and Işık 2022).

Against this background, the present study aims to quantify long-term soil moisture variability and its climatic controls across seven representative cities in Türkiye over the 1 January 2005 to 1 January 2025 period. Specifically, the study (i) evaluates city-based trends in daily precipitation and surface soil wetness, (ii) examines long-term linear trends in surface soil wetness using monthly aggregation, (iii) investigates precipitation–surface wetness and temperature–surface wetness relationships with explicit coastal–inland comparisons, and (iv) identifies the characteristic time lag (0–14 days) at which precipitation exerts the strongest influence on surface soil wetness. In addition, statistical summaries and correlation analyses are provided for precipitation, surface soil wetness, and profile soil moisture to distinguish short-term surface responses from longer-term subsurface behavior. By integrating trend, correlation, and lagged-response analyses within a unified framework, this study provides a systematic, multi-city assessment of climate-driven soil moisture dynamics in Türkiye, offering a reference dataset and methodological baseline for future hydrological, agricultural, and geotechnical applications.

2. Materials and Methods

2.1. Study area and selected cities

This study was conducted across seven cities representing different climatic regions of Türkiye: Ankara (Central Anatolia), Kars (Eastern Anatolia), Şanlıurfa (Southeastern Anatolia), Rize (Black Sea), İstanbul (Marmara), İzmir (Aegean), and Antalya (Mediterranean). These locations exhibit substantial differences in precipitation patterns, temperature regimes, evaporation conditions, and overall climatic variability, allowing a comparative evaluation of soil moisture responses under distinct climatic environments.

Such spatial variability provides a suitable framework for assessing the climatic sensitivity of soil moisture, which is an important parameter in geotechnical engineering. In addition, since these cities represent areas with intensive agricultural, urban, and infrastructure activities, variations in both surface and profile soil moisture may have implications for soil behavior, strength, and deformation characteristics.

2.2. Description of datasets

A 20-year daily time series covering the period from 1 January 2005 to 1 January 2025 was used in this study (NASA Langley Research Center 2025; PERSIANN Data Portal 2024). The datasets were obtained from two primary sources. Daily precipitation data (P, mm) were acquired from the PERSIANN system, while two-meter air temperature (T_{2m}), surface soil wetness ($GWET_{top}$), and profile soil moisture ($GWET_{prof}$) were obtained from the NASA POWER portal. The NASA POWER meteorological parameters were retrieved from a global gridded dataset with an approximate spatial resolution of 0.5° × 0.5°. City-level values were extracted using the geographic coordinates of the selected cities, representing point-based grid estimates.

The availability of long-term datasets at daily resolution enabled the evaluation of soil moisture responses to both short-term precipitation events and seasonal to interannual climatic variability. The variables used in the analysis are summarized below.

- Daily precipitation (P, mm): Precipitation represents the primary water input to the soil system and directly influences surface soil moisture conditions. Daily precipitation values were used to evaluate short-term infiltration potential and soil wetting conditions.
- Temperature at 2 m (T_{2m}): Daily air temperature measured at a height of two meters was used to assess evaporation potential, surface drying conditions, and seasonal variability in soil moisture.
- Surface soil wetness ($GWET_{top}$): The $GWET_{top}$ parameter represents surface soil moisture within an ap-

proximate depth range of 0–5 cm. This variable reflects short-term moisture dynamics of the surface layer and responds rapidly to precipitation events. The values are normalized between 0 and 1 (0: completely dry, 1: fully saturated).

- Profile soil moisture ($GWET_{prof}$): The $GWET_{prof}$ parameter represents a profile-averaged soil moisture indicator derived from the NASA POWER dataset, reflecting the integrated moisture condition of the soil profile. Unlike $GWET_{top}$, which describes near-surface moisture dynamics, $GWET_{prof}$ characterizes deeper soil moisture conditions associated with subsurface layers and longer-term moisture storage.

2.3. Data processing and visualization

All climate and soil moisture variables (P, T_{2m}, $GWET_{top}$, and $GWET_{prof}$) were organized as daily time series covering the period from 1 January 2005 to 1 January 2025. During data preprocessing, date formats were standardized and records with missing or physically implausible values were removed. Physically implausible records included negative precipitation values or incomplete entries. After preprocessing, city-specific time series were generated for each variable.

Surface soil moisture ($GWET_{top}$) and profile soil moisture ($GWET_{prof}$) were subsequently visualized over time to examine their temporal variability. In addition, bivariate plots were generated to evaluate the relationships between climatic variables and soil moisture:

- Precipitation (P)–Surface Soil Wetness ($GWET_{top}$)
- Precipitation (P)–Profile Soil Moisture ($GWET_{prof}$)
- Temperature (T_{2m})–Surface Soil Wetness ($GWET_{top}$)

These plots were used to compare soil moisture responses under different climatic conditions across the selected cities.

2.4. Classification of cities: Coastal and inland regions

To distinguish climatic influences on soil moisture, the selected cities were classified into two groups: coastal and inland regions. İstanbul, İzmir, Antalya, and Rize were categorized as coastal cities, while Ankara, Kars, and Şanlıurfa were classified as inland cities.

Coastal cities generally experience higher humidity and more frequent precipitation events, whereas inland cities are characterized by greater temperature variability and more pronounced dry periods.

This classification was used as a comparative framework for evaluating soil moisture variability across different climatic settings

2.5. Statistical analyses and trend assessment

To quantitatively evaluate the relationships between climatic variables and soil moisture, descriptive statistics, correlation analyses, linear trend estimations, and lagged correlation methods were employed in combination. All analyses were conducted on a city-specific basis, followed by comparative evaluations between the coastal and inland regional groups.

For each city, the mean, standard deviation, minimum, and maximum values of daily precipitation (P, mm), surface soil moisture ($GWET_{top}$), profile soil moisture ($GWET_{prof}$), and two-meter air temperature (T_{2m}) were calculated. To identify the linear relationships between climatic variables and soil moisture, the Pearson correlation coefficient (r) was employed. The Pearson correlation coefficient is defined as follows (Castaldi et al. 2015);

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (1)$$

where x_i and y_i represent the paired observations of the two variables, $\bar{x}$ and $\bar{y}$ denote their respective mean values, and n is the number of observations.

Long-Term Trend Analysis to assess long-term variations in surface soil moisture, daily $GWET_{top}$ data were aggregated into monthly mean values. Linear trends were estimated using the ordinary least squares (OLS) method based on the following linear model (Kumar et al. 2024), and the statistical significance of the trends was evaluated using p-values derived from the OLS regression, while potential seasonality and autocorrelation in the time series are acknowledged as possible limitations.

$$\mathrm{GWET_{top}}(t) = a + bt \quad (2)$$

Here, $GWET_{top}(t)$ represents the surface soil moisture at a given time step (monthly), a denotes the intercept, and b is the slope coefficient. The trend coefficients are expressed in terms of change per decade and are summarized in Table 2.

Lagged Correlation Analysis to determine the lagged effect of precipitation on surface soil moisture, the daily precipitation time series $P(t)$ was correlated with the surface soil moisture series $GWET_{top}(t)$ using time lags (τ) ranging from 0 to 14 days. Within this framework, the lagged correlation was defined as follows (Na et al. 2021);

$$r(\tau) = \mathrm{corr}\left[P(t-\tau), \mathrm{GWET_{top}}(t)\right] \quad (3)$$

For each lag step, the Pearson correlation coefficient was calculated, and the lag duration corresponding to the maximum correlation value was defined as the effective lag for the respective city. These results are presented on a city-by-city basis in Table 3. In addition, mean lagged correlation coefficients were computed for the coastal and inland groups, and precipitation $GWET_{top}$ lag–response curves were constructed.

3. Results

Fig. 1 illustrates that daily precipitation in Ankara during the 1 January 2005 to 1 January 2025 period exhibits high temporal variability. Precipitation generally occurs as short-duration and irregular peaks, with prolonged low-precipitation or dry periods coexisting with abrupt rainfall events. This behavior indicates that, consistent with Ankara's continental climate characteristics, precipitation is predominantly event-based rather than continuous. Although no visually dominant increasing or decreasing trend is apparent in the daily precipitation series, the periodic recurrence of high-intensity isolated rainfall events is noteworthy.

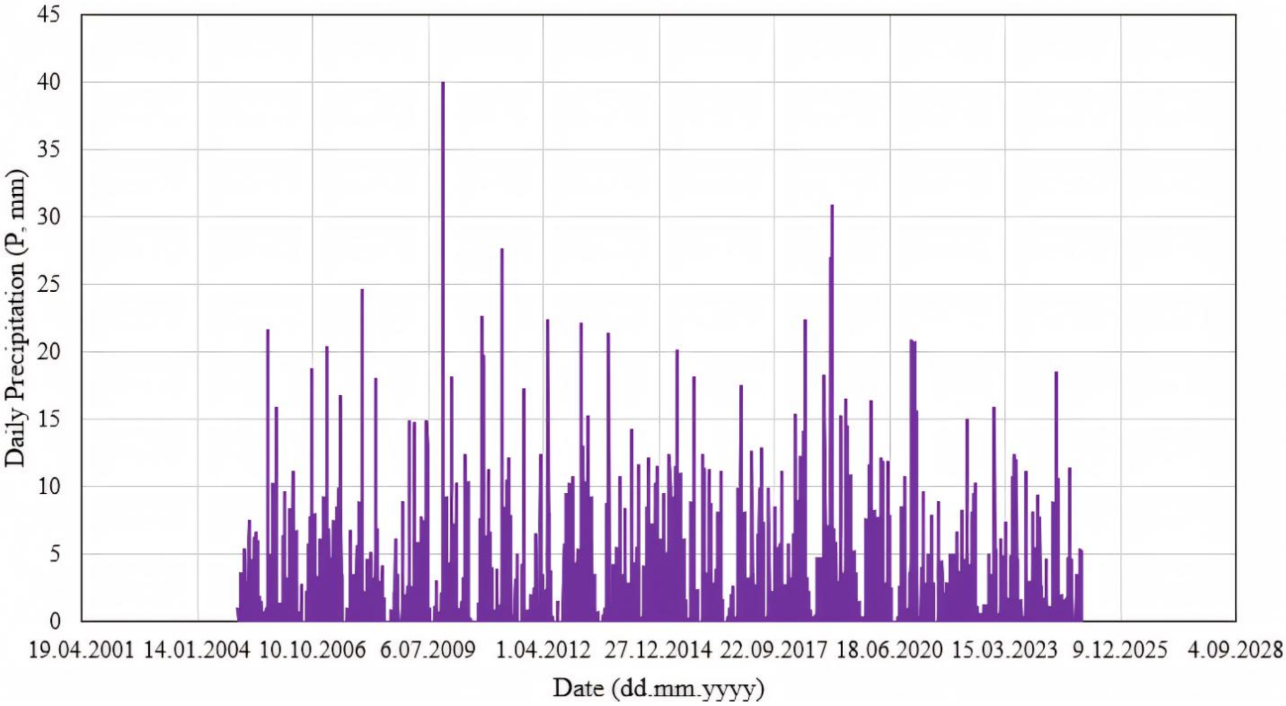

Fig. 1. Daily precipitation trend for Ankara.

Fig. 2 shows that daily precipitation in Antalya is distinctly episodic and dominated by high-intensity events. In particular, the occurrence of very high precipitation peaks on individual days reflects the short-duration but intense rainfall characteristics typical of the Mediterranean climate. Over the long term, days with low precipitation are predominant, whereas infrequent but high-impact rainfall events exert a primary control on the overall precipitation regime. This pattern suggests a hydrometeorological setting in which surface soil moisture may exhibit abrupt increases followed by rapid declines.

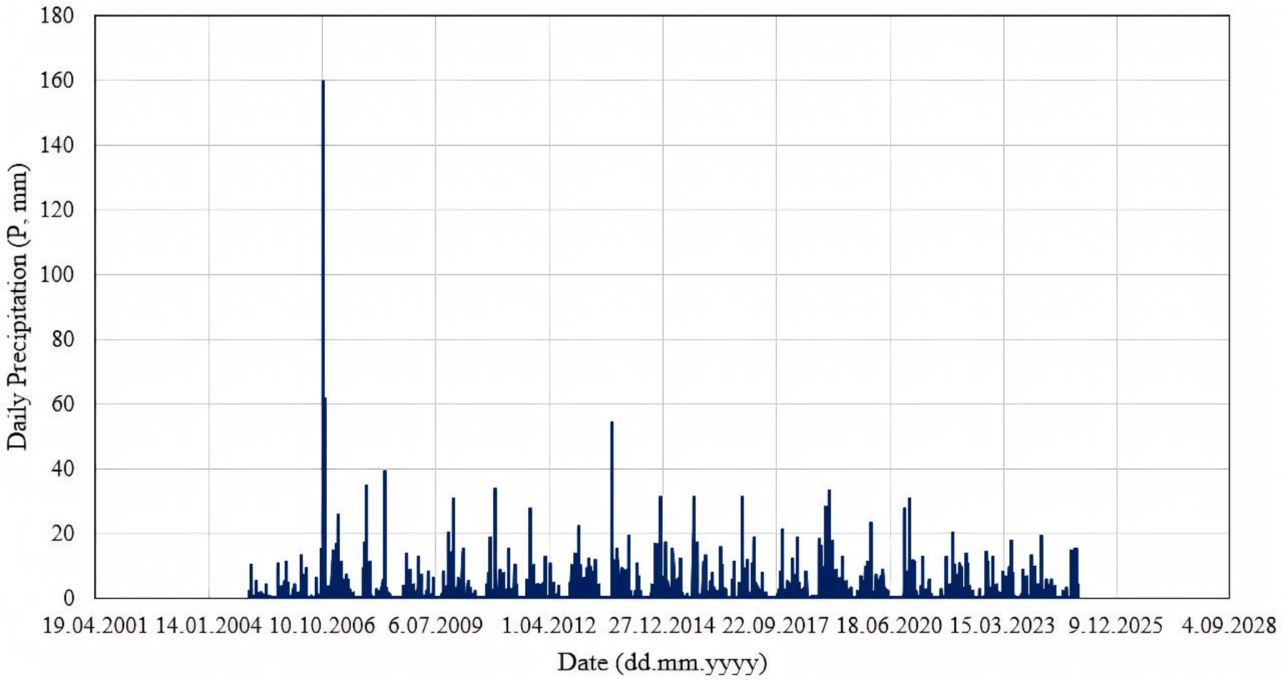

Fig. 2. Daily precipitation trend for Antalya.

Fig. 3 indicates that daily precipitation in İstanbul exhibits a more evenly distributed pattern throughout the year, with moderate-intensity rainfall events being dominant. Although precipitation generally occurs as short-duration peaks, the rainfall regime is noticeably more regular and continuous compared to Ankara and Antalya. This behavior reflects the transitional climatic characteristics of the Marmara Region and provides a basis for a more balanced temporal variation in surface soil moisture. Over the long term, the limited occurrence of extreme isolated rainfall events contributes to a hydroclimatic setting in which surface soil moisture is more likely to exhibit gradual changes rather than abrupt and sharp fluctuations.

Fig. 4 shows that daily precipitation in İzmir exhibits a distinctly seasonal and event-driven distribution. While precipitation generally occurs within the low-to-moderate intensity range, the presence of high-intensity isolated rainfall events during specific periods reflects the Mediterranean-influenced climatic characteristics of the Aegean Region. Over the long term, the predominance of short-duration precipitation peaks rather than sustained rainfall suggests a hydroclimatic setting in which surface soil moisture is characterized by rapid post-rainfall increases followed by subsequent drying phases. This behavior indicates that, in İzmir, surface soil moisture may be highly sensitive to precipitation yet limited in its persistence over time.

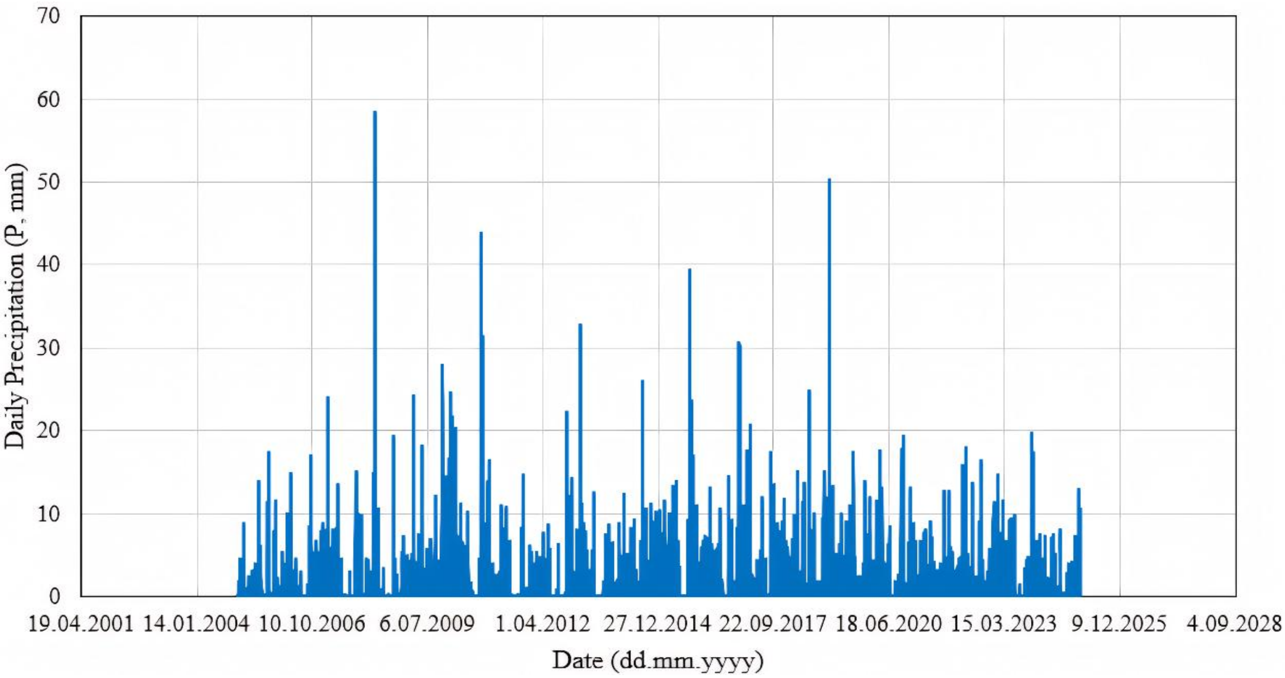

Fig. 3. Daily precipitation trend for İstanbul.

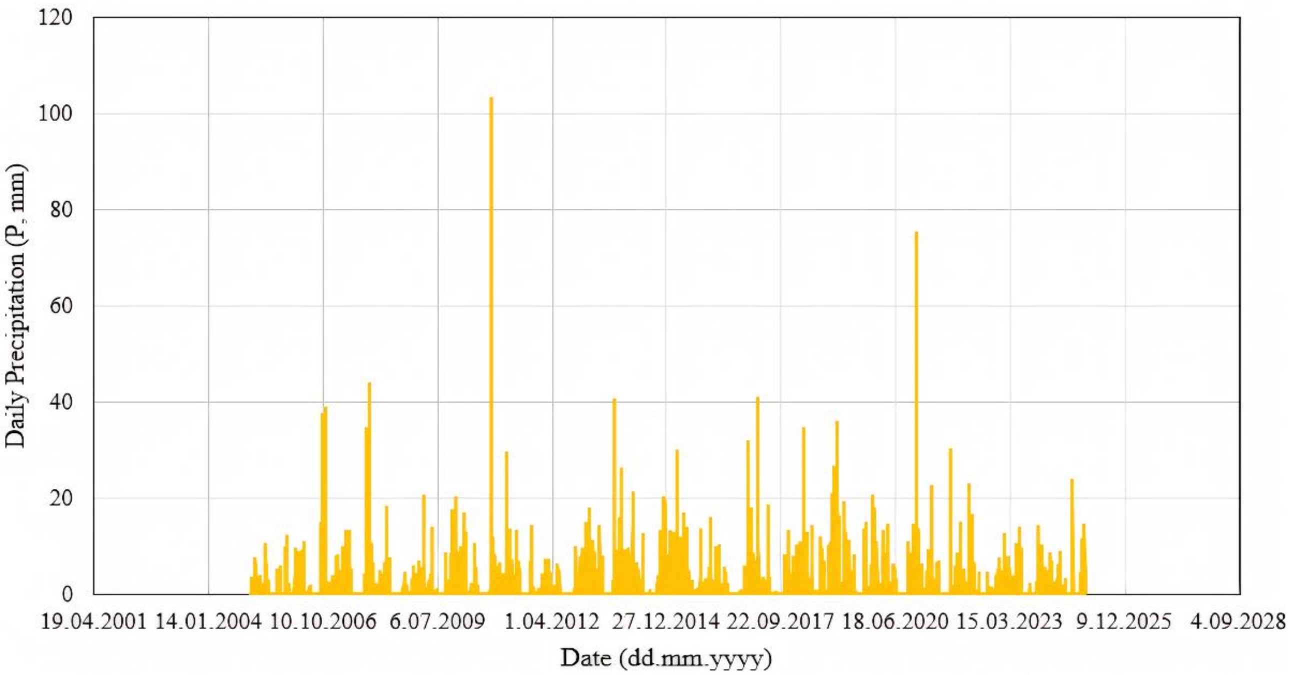

Fig. 4. Daily precipitation trend for İzmir.

Fig. 5 reveals that daily precipitation in Kars exhibits pronounced seasonality, with low-precipitation days dominating much of the year. Precipitation generally occurs as short-duration and moderate-intensity events, while isolated high-intensity rainfall peaks, particularly during the summer months, are also evident. Consistent with the continental climatic conditions of Eastern Anatolia, extended dry periods between precipitation events create a hydroclimatic setting in which surface soil moisture is likely to increase only for limited durations and remain at low levels for most of the year. This pattern suggests that the surface soil moisture response to precipitation is rapid but characterized by limited persistence.

Fig. 6 demonstrates that daily precipitation in Rize exhibits a high-frequency and persistent distribution throughout the year. Under the influence of the Black Sea climate, precipitation is predominantly of low to moderate intensity, although episodic high-intensity peaks are also observed. Compared to the other cities, the limited number of dry days indicates a hydroclimatic setting that allows surface soil moisture to be maintained at relatively stable and elevated levels. This pattern suggests that, in Rize, surface soil moisture responds rapidly to precipitation, while drying phases tend to be shorter in duration.

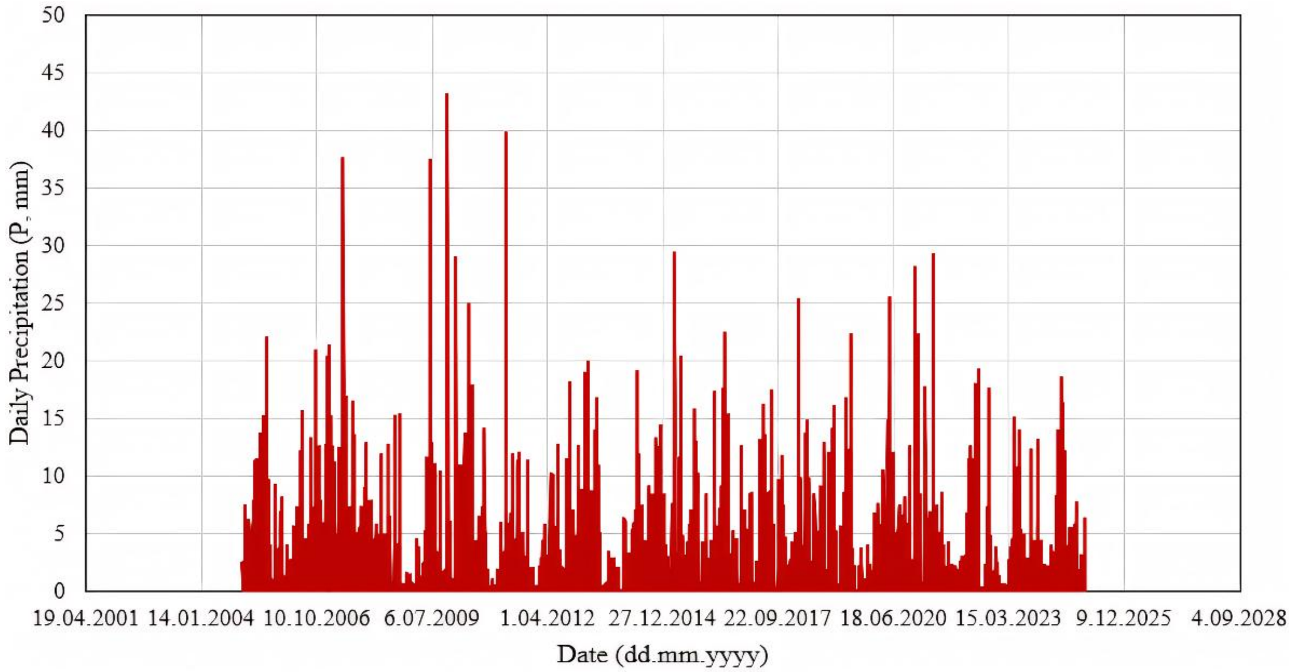

Fig. 5. Daily precipitation trend for Kars.

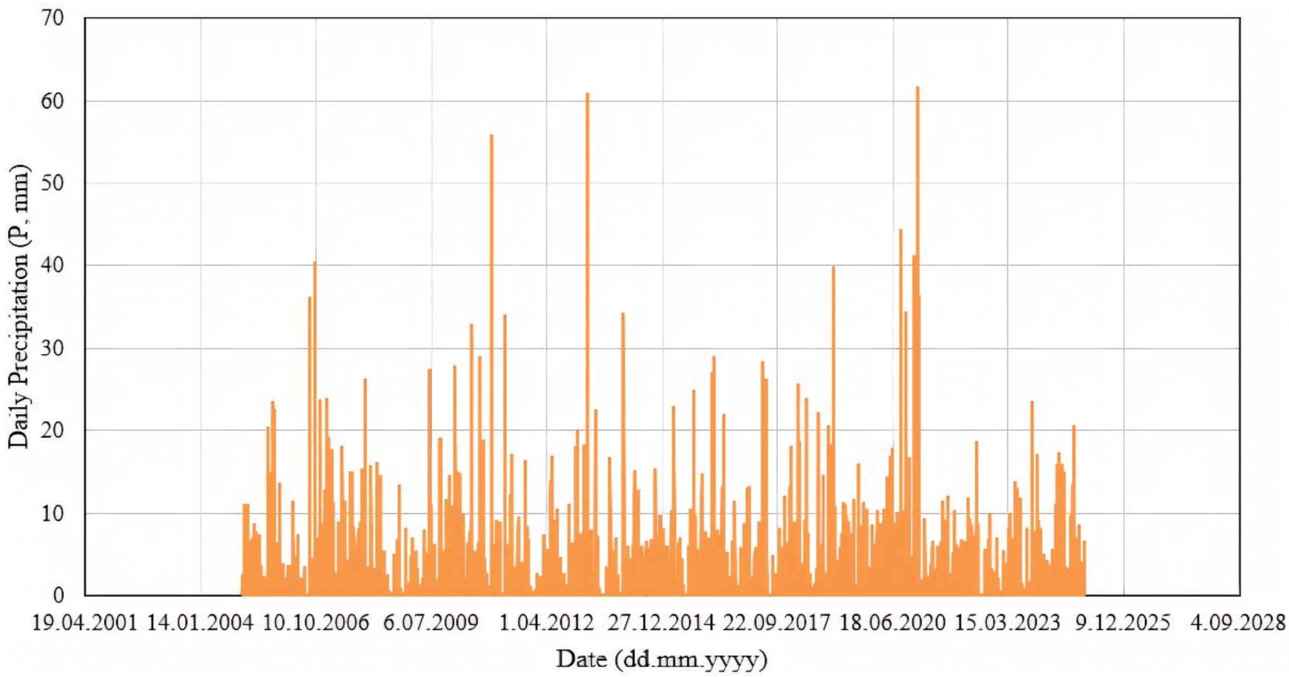

Fig. 6. Daily precipitation trend for Rize.

Fig. 7 indicates that daily precipitation in Şanlıurfa exhibits a distinctly low-frequency and highly variable character. Precipitation generally occurs in very small amounts; however, rare periods of high-intensity isolated rainfall events are also evident. Consistent with the semi-arid climatic conditions of Southeastern Anatolia, prolonged dry periods cause surface soil moisture to remain at low levels for much of the time. This precipitation regime reflects a hydroclimatic setting in which the surface soil moisture response to rainfall is short-lived and limited, while drying processes are dominant.

Fig. 8 shows that surface soil moisture in the coastal cities (Antalya, İstanbul, İzmir, and Rize) exhibits a pronounced seasonal cycle and remains at relatively high mean levels throughout the year. While Rize is distinguished from the other coastal cities by persistently high and stable moisture values, İzmir and Antalya display noticeable drying periods during the summer months. Nevertheless, within the coastal group, intra-annual fluctuations in surface soil moisture are limited, and a generally stable moisture regime is maintained over the long term. This pattern highlights the moderating role of precipitation continuity and maritime climatic influence in regulating surface soil moisture in coastal regions.

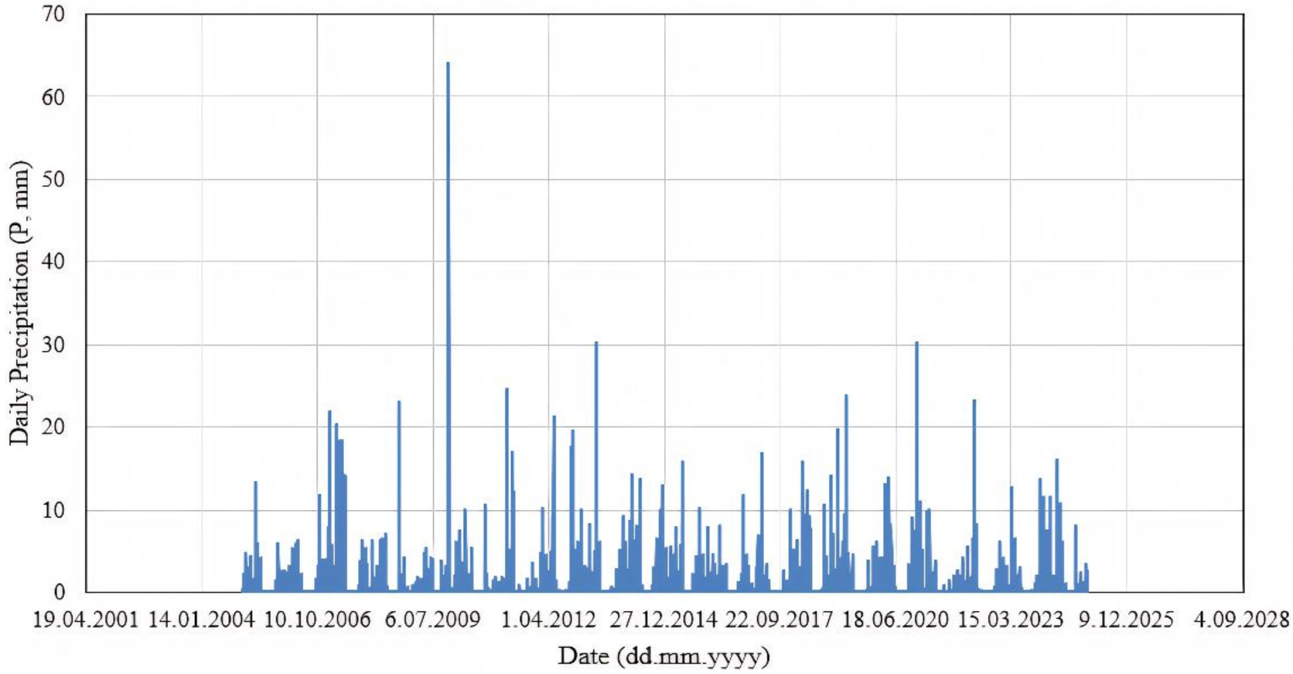

Fig. 7. Daily precipitation trend for Şanlıurfa.

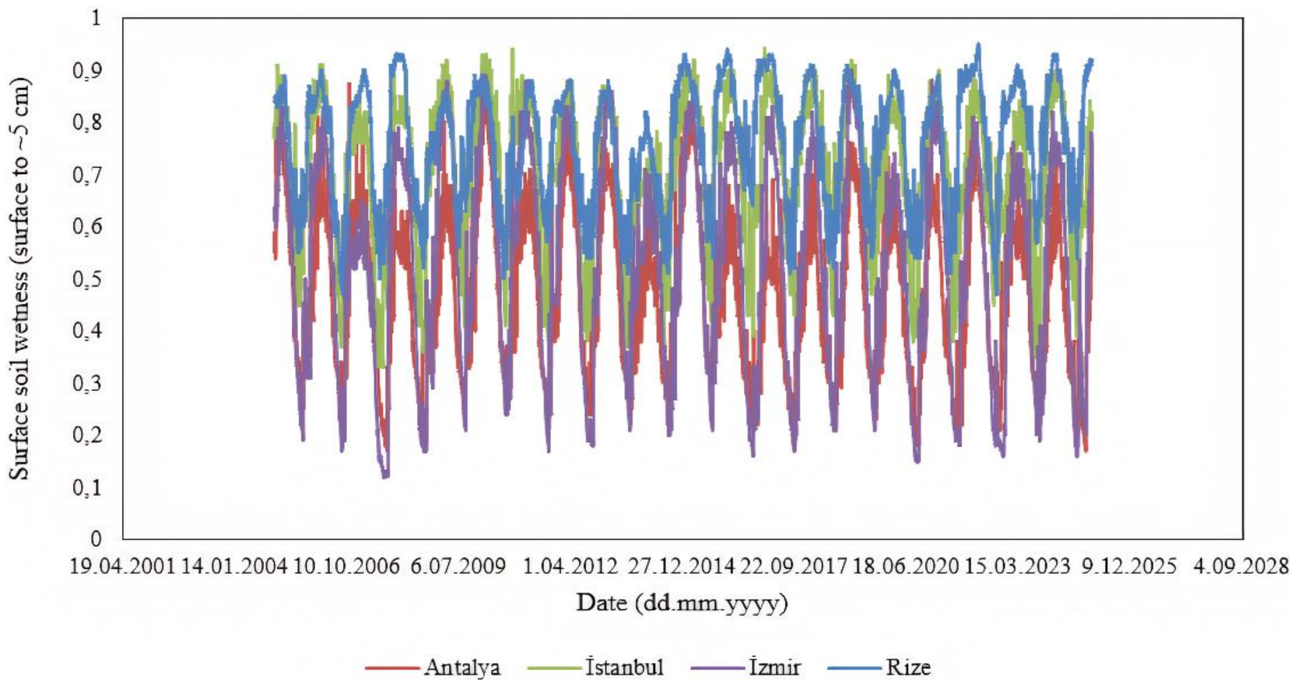

Fig. 8. Long-term variation of surface soil wetness ($GWET_{top}$, 0–5 cm) for coastal cities (Antalya, İstanbul, İzmir, and Rize) over the 1 January 2005 to 1 January 2025 period.

Fig. 9 shows that surface soil moisture in the inland cities (Ankara, Kars, and Şanlıurfa) exhibits lower mean values and higher temporal variability compared to the coastal cities. In particular, prolonged low-moisture conditions and pronounced seasonal minima are evident in Şanlıurfa, while moisture levels in Ankara and Kars fluctuate over a wide range throughout the year. This pattern indicates that continental and semi-arid climatic conditions exert a dominant control on surface soil moisture, with drying processes being more pronounced in inland regions.

Fig. 10 indicates a pronounced yet saturating relationship between daily precipitation and surface soil moisture in the coastal cities. At low precipitation values, $GWET_{top}$ exhibits a rapid increase, whereas with increasing precipitation, surface soil moisture approaches an upper limit and displays a diminishing rate of increase. In Rize and İstanbul, relatively high $GWET_{top}$ values are maintained even under low precipitation conditions due to elevated initial moisture levels, while precipitation sensitivity is more pronounced in İzmir and Antalya. This behavior suggests that, in coastal regions, surface soil moisture is sustained not only by precipitation but also by precipitation continuity and persistently humid atmospheric conditions.

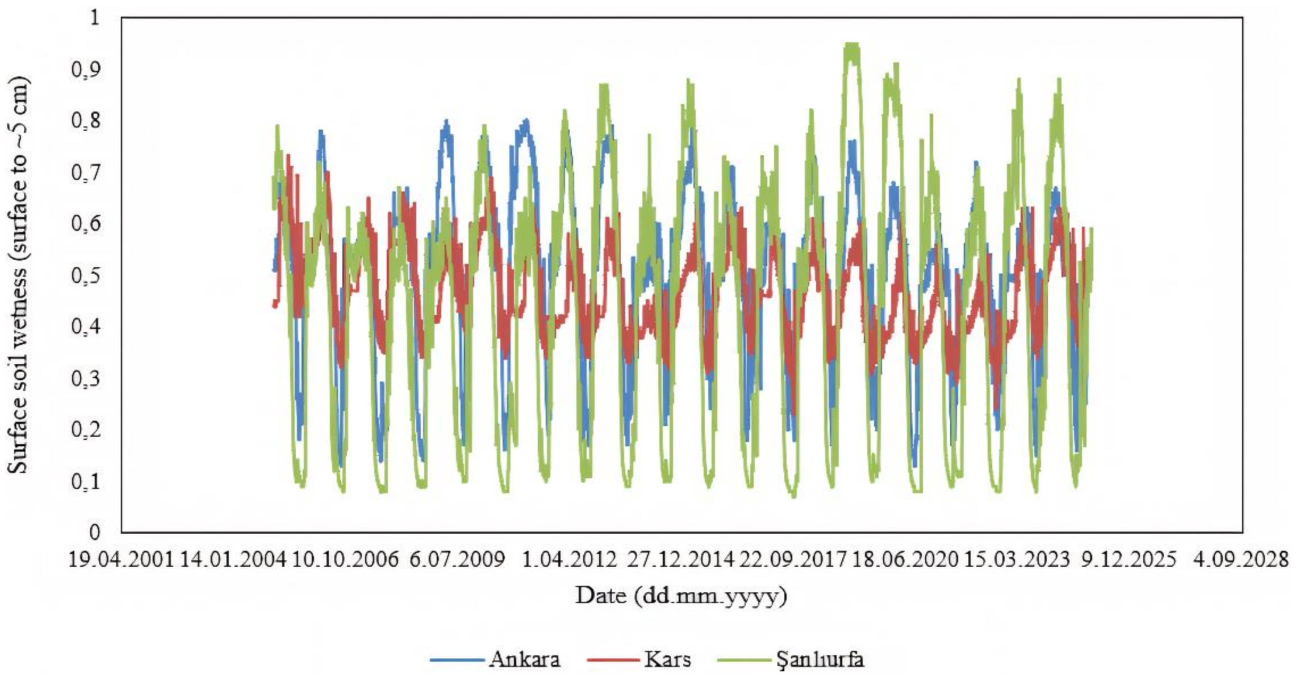

Fig. 9. Long-term variation of surface soil wetness ($GWET_{top}$, 0–5 cm) for inland cities (Ankara, Kars, and Şanlıurfa) over the 1 January 2005 to 1 January 2025 period.

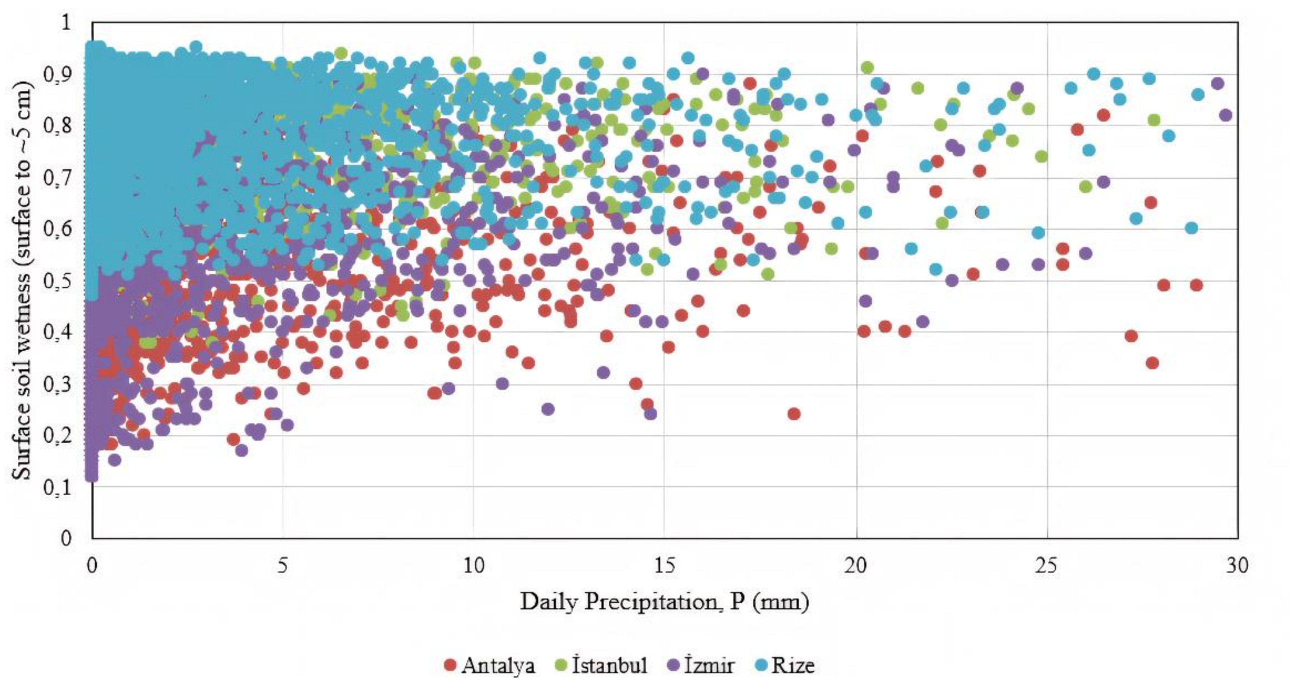

Fig. 10. Scatter relationship between daily precipitation (P, mm) and surface soil wetness ($GWET_{top}$, 0–5 cm) for coastal cities (Antalya, İstanbul, İzmir, and Rize) over the 1 January 2005 to 1 January 2025 period.

Fig. 11 shows that the relationship between daily precipitation and surface soil moisture in the inland cities exhibits greater scatter and higher variability. Under low precipitation conditions, $GWET_{top}$ values are distributed over a wide range, and even with increasing precipitation, surface soil moisture does not consistently reach high levels. In Şanlıurfa, the precipitation–moisture relationship is weaker due to low initial moisture and high drying potential, whereas in Ankara and Kars, precipitation-driven increases are more evident but discontinuous. This pattern indicates that, under continental and semi-arid climatic conditions, surface soil moisture increases rapidly following rainfall but declines shortly thereafter.

Fig. 12 indicates a pronounced inverse relationship between surface soil moisture and air temperature in the inland cities (Ankara, Kars, and Şanlıurfa). As temperature increases, $GWET_{top}$ generally exhibits a decreasing trend, with surface soil moisture dropping to very low levels at high temperatures, particularly in Şanlıurfa. In Ankara and Kars, although the temperature–moisture relationship displays greater scatter, drying tendencies remain dominant at elevated temperatures. This pattern highlights the controlling role of evaporative processes on surface soil moisture under continental and semi-arid climatic conditions.

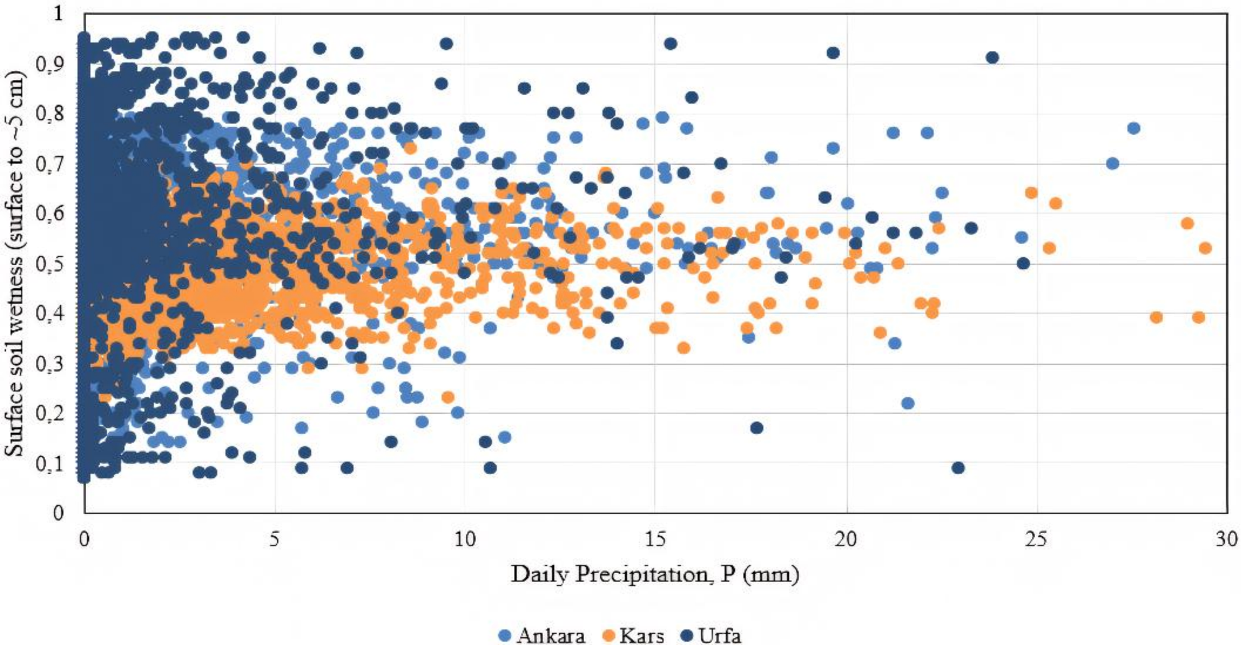

Fig. 11. Scatter relationship between daily precipitation (P, mm) and surface soil wetness ($GWET_{top}$, 0–5 cm) for inland cities (Ankara, Kars, and Şanlıurfa) over the 1 January 2005 to 1 January 2025 period.

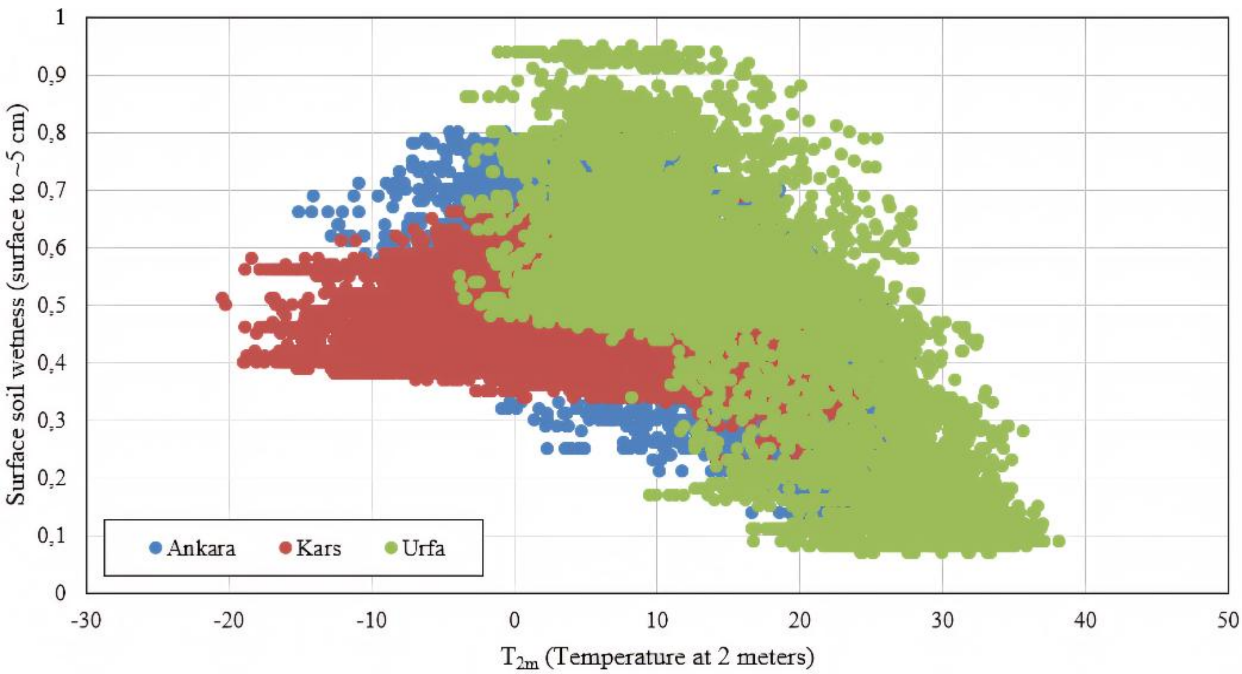

Fig. 12. Scatter relationship between air temperature at 2 m (T_{2m}) and surface soil wetness ($GWET_{top}$, 0–5 cm) for inland cities (Ankara, Kars, and Şanlıurfa) over the 1 January 2005 to 1 January 2025 period.

Fig. 13 shows that, despite increasing air temperature, surface soil moisture in the coastal cities (Antalya, İstanbul, İzmir, and Rize) remains at higher and more stable levels compared to the inland regions. In Rize and İstanbul, $GWET_{top}$ values are maintained at relatively high levels across a wide temperature range, reflecting the moisture-buffering effect of the maritime climate. In contrast, İzmir and Antalya exhibit a more pronounced decrease in surface soil moisture with increasing temperature; however, this decline remains more limited than that observed in inland cities. This pattern indicates that, in coastal regions, the influence of temperature on surface soil moisture is partially offset by precipitation continuity and elevated atmospheric humidity.

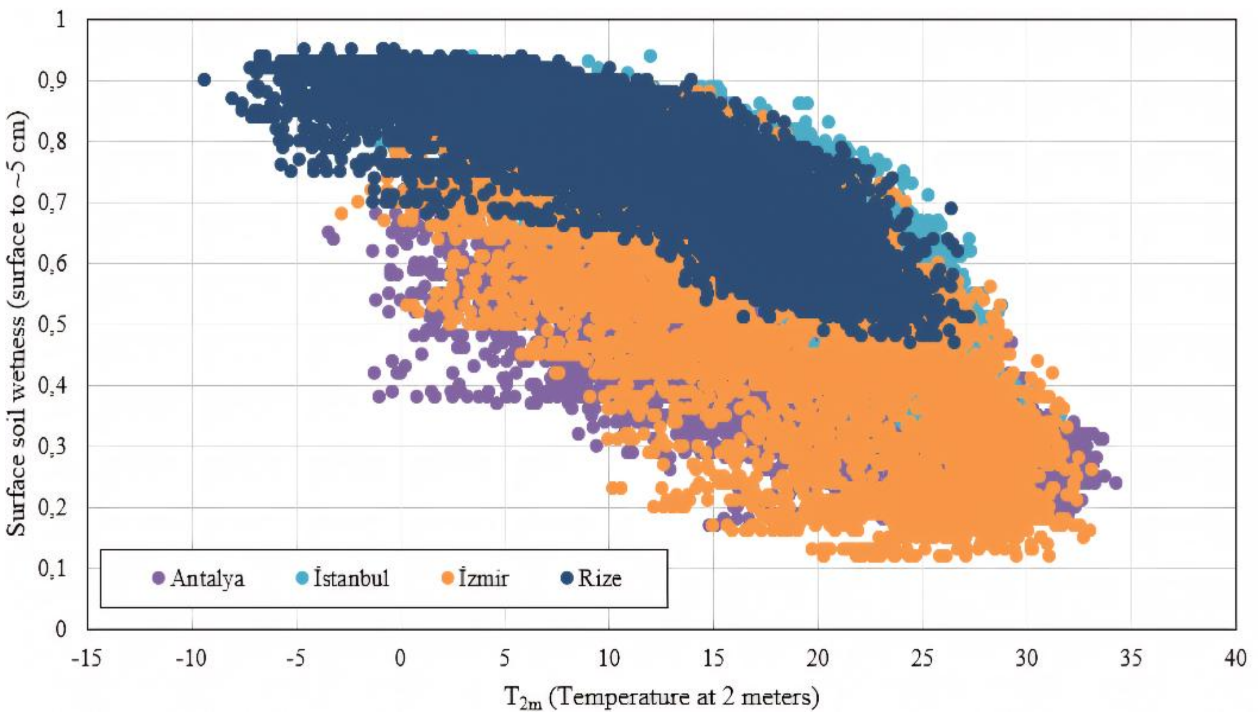

Fig. 13. Scatter relationship between air temperature at 2 m (T_{2m}) and surface soil wetness ($GWET_{top}$, 0–5 cm) for coastal cities (Antalya, İstanbul, İzmir, and Rize) over the 1 January 2005 to 1 January 2025 period.

Table 1 summarizes the basic statistics and correlation results of precipitation, temperature, and soil moisture parameters on a city-by-city basis. Total precipitation amounts and the frequency of rainy days are higher in the coastal cities, particularly Rize and İstanbul, which is associated with higher mean values of both surface and profile soil moisture. In contrast, in warmer and relatively drier regions such as Şanlıurfa and Antalya, the mean values of $GWET_{top}$ and $GWET_{prof}$ remain at lower levels.

The correlations between precipitation and surface soil moisture exhibit weak positive values across all cities (corr(P, $GWET_{top}$) ≈ 0.04–0.12), indicating that surface soil moisture is not solely controlled by daily precipitation amounts but is also strongly influenced by evaporative processes and antecedent moisture conditions. In contrast, the relationship between air temperature and surface soil moisture shows a pronounced negative correlation in all cities (corr(T_{2m}, $GWET_{top}$) = −0.35 to −0.84). The strongest negative relationships are observed in Rize, İstanbul, and Şanlıurfa, highlighting that temperature-driven evaporation acts as a dominant control mechanism on surface soil moisture.

Table 1. Basic statistics and correlation results of precipitation, temperature, and soil moisture for the selected cities.

City	P_{total}(mm)	Wet-day frequency (P>0.1 mm)	T_{2m} (°C)	$GWET_{top}$	$GWET_{prof}$	corr(P, $GWET_{top}$)	corr(T_{2m}, $GWET_{top}$)
Ankara	4139.98	0.251	10.607	0.5	0.545	0.068	-0.634
Antalya	4031.25	0.189	17.779	0.46	0.485	0.119	-0.739
İstanbul	4736.07	0.249	15.123	0.697	0.816	0.107	-0.815
İzmir	4286.2	0.208	17.507	0.521	0.565	0.106	-0.719
Kars	6581.8	0.341	5.828	0.459	0.453	0.106	-0.346
Rize	7000.24	0.313	10.937	0.756	0.741	0.04	-0.835
Şanlıurfa	2029.22	0.167	18.041	0.426	0.548	0.078	-0.806

Overall, Table 1 indicates that temperature exerts a stronger control on surface soil wetness than daily precipitation across both coastal and inland regions. Table 2 summarizes the linear trends calculated based on monthly aggregated data, expressed as rates of change per decade. Positive trends were obtained for air temperature (T_{2m}) in all cities, with increase rates ranging from approximately 0.63 to 0.94 °C per decade. However, the associated p-values indicate that the statistical significance of these temperature trends is limited and varies among cities.

Precipitation trends exhibit pronounced spatial variability. Positive precipitation trends are observed in the coastal cities (İstanbul, İzmir, and Rize), whereas a decreasing trend is evident in Kars. Nevertheless, precipitation trends are not statistically significant in most cities.

Trends in surface soil moisture ($GWET_{top}$) are generally negative, with more pronounced decreases calculated for Ankara, Antalya, and Kars. In contrast, positive surface soil moisture trends are observed in Rize and Şanlıurfa. Profile soil moisture ($GWET_{prof}$) trends display a similar pattern, showing significant decreases in Ankara, Antalya, and Kars, while increasing trends are estimated for Rize and Şanlıurfa. These results suggest that long-term temperature increases impose increasing stress on soil moisture in many regions; however, region-specific climatic conditions lead to differentiated responses in coastal and semi-arid areas.

Table 2. Linear trends (per decade) derived from monthly aggregated data.

City	Trend(T_{2m}) (°C decade-1)	PT_{2m}	Trend(P) (mm decade^{-1})	pp	Trend($GWET_{top}$) (decade^{-1})	$PGWET_{top}$	Trend($GWET_{prof}$) (decade^{-1})	$PGWET_{prof}$
Ankara	0.8357	0.3851	13.206	0.7503	-0.0319	0.0569	-0.0246	0.0026
Antalya	0.8238	0.3421	12.537	0.7962	-0.0329	0.0468	-0.0317	0.0209
İstanbul	0.7417	0.327	2.749	0.5171	-0.0062	0.6695	-0.0066	0.3311
İzmir	0.709	0.361	28.737	0.5273	-0.0261	0.2269	-0.0204	0.1713
Kars	0.9437	0.3715	-50.872	0.2957	-0.0402	0.0	-0.0326	0.0
Rize	0.6726	0.4017	32.301	0.4909	0.0212	0.0942	0.021	0.094
Şanlıurfa	0.6334	0.5715	13.657	0.7268	0.032	0.2281	0.0283	0.0177

The trend analysis indicates that long-term warming represents a consistent signal across all cities, whereas precipitation and soil moisture trends exhibit strong regional variability. Table 3 summarizes, on a city-by-city basis, the time lag at which the effect of daily precipitation on surface soil moisture is maximized. The results show that, in all cities, the precipitation–surface soil moisture relationship reaches its maximum strength at very short lag times (0–1 day). In Antalya, the highest correlation is observed on the day of precipitation occurrence (lag = 0), whereas in all other cities, surface soil moisture exhibits its strongest response one day after precipitation (lag = 1).

The fact that the maximum correlation coefficients remain low but positive across all cities ($r \approx 0.05$–0.12) indicates that surface soil moisture responds rapidly to precipitation, yet this effect is short-lived and limited in magnitude. This finding further suggests that surface soil moisture is not governed solely by precipitation amounts but is also strongly influenced by antecedent moisture conditions and evaporative processes.

Overall, the lag analysis confirms that surface soil wetness responds rapidly to precipitation inputs, with limited persistence beyond one day across both coastal and inland regions. Fig. 14 shows that the lagged correlation between precipitation and surface soil moisture reaches its maximum at very short lag times for both regional groups. For both coastal and inland cities, the highest correlation values are observed within the first 1–2 days following precipitation, after which the correlation gradually decreases with increasing lag time. At short lags, correlation values are slightly higher in the coastal regions than in the inland regions, indicating that wetter antecedent conditions enhance the rapid surface moisture response to precipitation. As lag time increases, the difference between the two groups diminishes, further demonstrating that the surface soil moisture response is short-lived in both climatic settings.

Table 3. City-specific lag (0–14 days) at which precipitation exerts the strongest influence on surface soil moisture.

City	Lag_{days}	corr(P_{lag}, $GWET_{top}$)
Ankara	1	0.077
Antalya	0	0.119
Kars	1	0.117
Rize	1	0.053
Şanlıurfa	1	0.082
İstanbul	1	0.117
İzmir	1	0.11

Fig. 15 shows that, in the coastal cities, the relationship between precipitation and surface soil moisture exhibits a saturating behavior with a limited rate of increase. At low precipitation amounts, $GWET_{top}$ values are distributed over a wide range, whereas with increasing precipitation, surface soil moisture approaches an upper bound and the rate of increase diminishes. This scatter pattern indicates that, in coastal regions, surface soil moisture is controlled not only by precipitation amounts but also by high antecedent moisture levels and persistently humid atmospheric conditions. The clustering of surface soil moisture values around an upper limit even on rainy days further suggests that the persistence of surface moisture is limited.

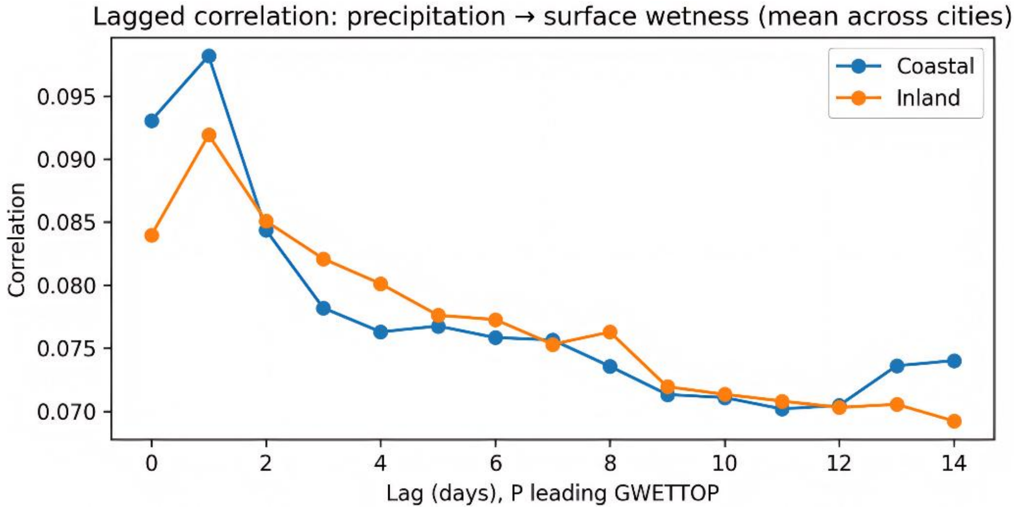

Fig. 14. Lagged correlation between daily precipitation and surface soil wetness ($GWET_{top}$, 0–5 cm), averaged across coastal and inland city groups, for lag times ranging from 0 to 14 days.

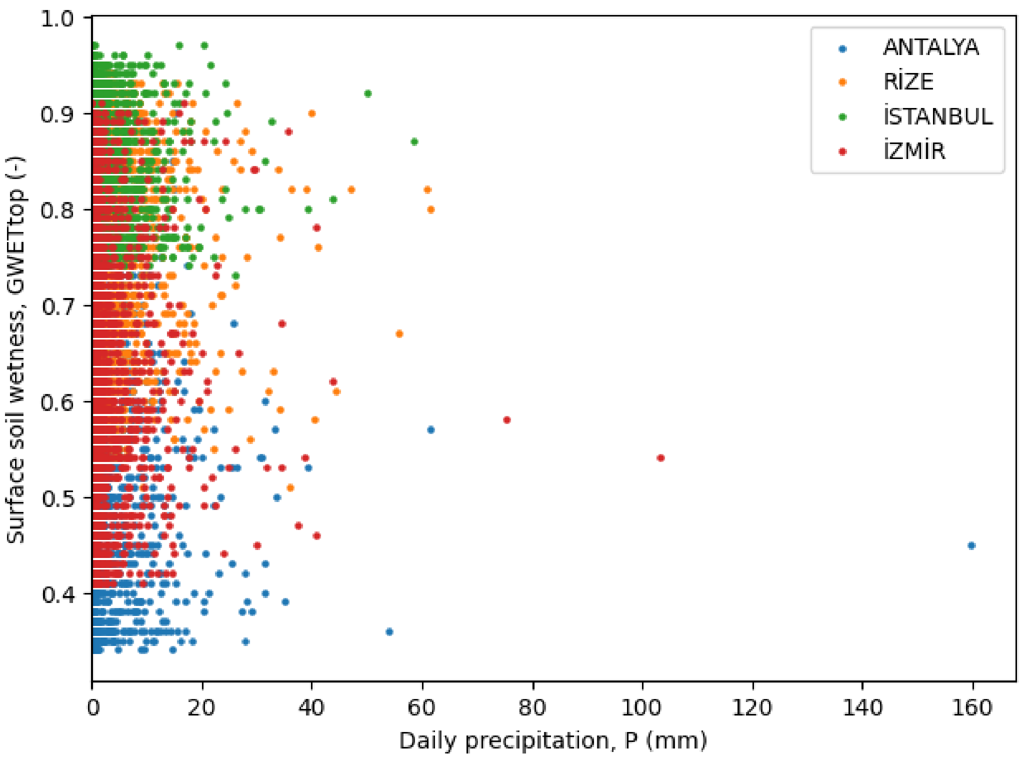

Fig. 15. Relationship between daily precipitation (P, mm) and surface soil wetness ($GWET_{top}$) for coastal cities.

4. Discussion

This study provides a comparative assessment of long-term surface soil moisture dynamics across coastal and inland climatic regions of Türkiye by jointly evaluating precipitation, temperature, surface soil wetness, and profile soil moisture over a 20-year period. The results highlight that soil moisture behavior is governed by a combination of short-term precipitation inputs and persistent climatic controls, with clear contrasts between coastal and inland settings.

Daily precipitation analyses demonstrate pronounced regional variability, with coastal cities exhibiting more frequent rainfall events and inland cities characterized by episodic and highly variable precipitation regimes. Despite these differences, the correlation analyses reveal that daily precipitation alone explains only a limited fraction of surface soil moisture variability. The consistently weak positive correlations between precipitation and $GWET_{top}$ across all cities indicate that surface soil wetness responds rapidly to rainfall but lacks persistence, particularly under conditions of high evaporative demand. This finding is consistent with previous studies reporting that surface soil moisture is strongly influenced by antecedent conditions and atmospheric controls rather than by rainfall magnitude alone. Although precipitation shows a positive association with surface soil wetness, the relatively low correlation magnitudes indicate that precipitation alone explains only a small fraction of the observed variability in $GWET_{top}$.

In contrast, air temperature emerges as a dominant control on surface soil moisture across both climatic groups. The strong and consistent negative correlations between T_{2m} and $GWET_{top}$, particularly in inland and semi-arid regions, emphasize the role of temperature-driven evapotranspiration in regulating near-surface soil moisture. Inland cities such as Şanlıurfa and Ankara exhibit pronounced drying under elevated temperatures, reflecting limited moisture retention and rapid post-rainfall depletion. Coastal cities, while also showing temperature-related drying trends, maintain comparatively higher and more stable surface moisture levels, likely due to maritime humidity and more frequent precipitation.

Long-term trend analysis further supports these interpretations. While a warming signal is observed consistently across all cities, trends in precipitation and soil moisture display substantial regional variability. Negative trends in surface and profile soil moisture in several inland and Mediterranean-influenced cities suggest increasing susceptibility to drying under ongoing climatic warming. Conversely, positive or near-neutral soil moisture trends in regions such as Rize highlight the moderating influence of persistent rainfall and humid atmospheric conditions. These contrasting responses underline the importance of regional climate context when interpreting soil moisture trends and their implications.

The lagged correlation analysis indicates that surface soil moisture responds to precipitation with minimal delay, typically within zero to one day, across all cities. This rapid response confirms that $GWET_{top}$ primarily captures short-lived wetting events rather than longer-term storage effects. The limited persistence beyond one day reinforces the interpretation that surface soil moisture is highly sensitive to evaporative losses, particularly in inland regions. Coastal cities exhibit slightly higher early-lag correlations, reflecting more favorable antecedent moisture conditions, yet the overall transient nature of the response remains evident.

From a broader perspective, these findings also have implications for geotechnical and infrastructure-related processes. Variations in near-surface soil moisture influence infiltration behavior, pore-water pressure development, and soil shear strength, which are key factors controlling slope stability and soil–structure interaction. In regions where precipitation events rapidly affect surface wetness, short-term wetting followed by rapid drying may modify soil stiffness, bearing capacity, and settlement behavior, particularly in fine-grained soils. The observed coastal–inland contrasts therefore suggest that climate-driven changes in soil moisture may differentially influence soil performance and geotechnical stability across Türkiye. Incorporating long-term soil moisture variability into regional assessments may therefore support improved evaluations of climate resilience in both natural slopes and engineered infrastructures.

5. Conclusions

This study investigated long-term soil moisture variability and its climatic controls across seven representative cities in Türkiye using daily precipitation, air temperature, surface soil wetness, and profile soil moisture data for the 1 January 2005 to 1 January 2025 period. Based on the analyses conducted, the following conclusions can be drawn:

- Pronounced coastal–inland contrasts were identified in precipitation regimes and surface soil moisture behavior, with coastal regions exhibiting more frequent rainfall and more stable moisture conditions, while inland regions showed higher variability and extended dry periods.
- Daily precipitation exhibited only weak positive correlations with surface soil wetness, indicating that rainfall alone is insufficient to explain surface moisture variability and that antecedent moisture and atmospheric conditions play a significant role.
- Air temperature was found to exert a stronger and more consistent control on surface soil wetness than precipitation, as evidenced by robust negative correlations across all cities, particularly in inland and semi-arid regions.
- Long-term warming trends were observed across all cities, whereas trends in precipitation and soil moisture varied regionally, highlighting differential climatic sensitivity among coastal and inland environments.
- Lagged correlation analysis showed that surface soil wetness responds rapidly to precipitation, with maximum influence occurring within zero to one day, confirming the transient nature of near-surface moisture dynamics.

The relatively low precipitation–surface wetness correlations and short lag times may partly reflect the normalized nature of the $GWET_{top}$ parameter and the combined influence of antecedent soil moisture conditions, evapotranspiration processes, soil properties, and rainfall intensity on near-surface moisture dynamics.

Overall, the results demonstrate that surface soil moisture across Türkiye is primarily governed by short-term wetting events combined with temperature-driven drying processes, with regional climate conditions modulating the magnitude and persistence of these responses. The integrated framework presented in this study provides a robust basis for future investigations into climate–soil interactions and offers valuable insights for hydrological, agricultural, and geotechnical applications under changing climatic conditions.

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Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

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