

Urban soil moisture dynamics and meteorological controls under changing climatic conditions: a case study of Kraków (Poland)

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Abstract

This study analyzes the relationships between soil moisture and selected climatic variables: air temperature t , relative humidity RH , and the antecedent precipitation index API . The analysis is based on in situ measurements from a research cross-section in the Sudół River catchment in Kraków, Poland, covering the period 2018–2025, supplemented with satellite-derived surface soil moisture data SM_{surf} from the Copernicus program. The study examines the temporal variability, seasonality, and long-term trends of soil moisture, as well as its correlation and regression relationships with climatic factors.

The results reveal a clear seasonal pattern of soil moisture, with maxima in winter and spring and minima in summer. A significant decreasing trend was observed, especially in transitional months (May and September), indicating increasing drought susceptibility. The antecedent precipitation index was the primary control on soil moisture, while air temperature mainly enhanced spring – summer deficits and relative humidity played a secondary role. Moderate but significant agreement between in situ and satellite data supports the value of combining ground-based and remote sensing observations for soil moisture and water resource monitoring under changing climate conditions.

Keywords: soil moisture, climate change, drought, antecedent precipitation index API , urban area

1. Introduction

Soil moisture is controlled by a range of interacting factors such as precipitation, air temperature, soil properties, and vegetation cover (Dincă et al., 2018; Singh et al., 2021) and plays a fundamental role in hydrological processes and land – atmosphere interactions (Sun et al., 2015). In recent years, extreme temperature and precipitation conditions in many European regions, including Poland, have led to exceptionally low soil moisture levels, particularly after 2018 (2018–2019), in spring 2022, and again in 2025, indicating an increasing frequency of soil droughts (Baran Gurgul & Wałęga, 2025; Ghazi et al., 2025; Toreti et al., 2025).

Soil water stored regulates key biophysical and biogeochemical processes (McColl et al., 2017). During multi-year dry periods, the effects of soil moisture deficits accumulate, intensifying ecosystem responses (Rakovec et al., 2022). Soil moisture is also essential for predicting extreme hydrological events such as droughts and floods because it exhibits a much longer “memory” than atmospheric variables (McColl et al., 2017; Orth & Seneviratne, 2012).

The importance of soil moisture research clearly increases in the context of global warming observed in recent decades (Seneviratne et al., 2010). International reports indicate that anthropogenic climate change increases the frequency of heat waves and intensifies soil droughts through enhanced evapotranspiration, particularly during the summer season (Intergovernmental Panel on Climate Change (IPCC), 2023). These effects are especially pronounced in regions with limited water resources, including Central Europe (Hirschi et al., 2014; Orth & Seneviratne, 2012). In Poland, droughts are typically associated with low soil moisture, elevated air temperatures, and prolonged precipitation deficits (IMGW-PIB, 2023).

Soil moisture influences climate primarily through its control on evaporation under water-limited conditions (Seneviratne et al., 2010). Previous studies demonstrated links between soil moisture deficits and extreme heat (Hirschi et al., 2014) as well as precipitation probability (Tuttle & Salvucci, 2016). Reduced latent heat flux during dry conditions leads to higher air temperatures, reinforcing dry regimes (Benson & Dirmeyer, 2021; Seneviratne et al., 2010).

Soil moisture analysis combined with precipitation characteristics enables early drought detection and assessment of soil water replenishment efficiency (Hunt et al., 2009), which is particularly important in Poland, where short precipitation events often fail to restore soil water resources (Rakovec et al., 2022). Although soil moisture represents a small fraction of terrestrial water resources (Gleeson et al., 2016), it is a key variable of ecosystem water balance, shaped by precipitation inputs and evapotranspiration and runoff losses (Pinskwar et al., 2020; Somorowska, 2022).

Increasing urbanization leads to the replacement of natural surfaces reducing the area actively involved in land-atmosphere exchanges and modifying the thermodynamic structure of the urban boundary layer (Husain et al., 2014). Soil moisture is a key variable regulating evapotranspiration, and near-surface air temperature; however, its role in urban environments remains less frequently investigated than the effects of vegetation cover, land use, or urban morphology (Przeździecki et al., 2023). Therefore, understanding soil moisture dynamics in urbanized catchments is increasingly important in the context of climate change and growing drought risk.

Soil moisture can be measured directly in situ, estimated using sensors based on soil physical properties, or derived indirectly using empirical and index-based approaches (Seneviratne et al., 2010). A distinction should be made between surface soil moisture, representing the upper few centimetres of the soil profile and responding rapidly to atmospheric forcing, and subsurface (root-zone) soil moisture, which integrates water storage over a deeper layer and exhibits greater temporal persistence (Western et al., 2002; Hirschi et al., 2014; McColl et al., 2017). As these layers are governed by different

hydrological processes and operate on distinct temporal scales, they should be considered complementary rather than interchangeable indicators of soil water status.

Despite extensive research on soil moisture variability in forested, agricultural, and mountain areas (Dincă et al., 2018; Moraes et al., 2024; Singh et al., 2021), urbanized catchments remain underrepresented, even though they exhibit substantially altered hydrological conditions. Due to limited monitoring networks and scale mismatches between remote sensing and ground data (Western et al., 2002), soil moisture indices are widely used in hydrological studies. These indices account for antecedent meteorological conditions, particularly precipitation and atmospheric evaporative demand (Baryła et al., 2017). One of the most commonly used indices is the Antecedent Precipitation Index (API), used, among others, by US hydrological services and in numerous scientific studies (Hunt et al., 2009; Moraes et al., 2024; Niemczyk et al., 2005; Zhao et al., 2019).

The aim of this study was to assess the relationship between soil moisture SM and selected climatic variables: air temperature t , relative humidity RH , and the antecedent precipitation index API based on precipitation P . The analysis was carried out on the basis of daily measurement data series from the research cross-section of the Department of Geoengineering and Water Management of the Cracow University of Technology, located in the Sudół River catchment in Kraków. The study also included an analysis of monthly, seasonal, and half-year variability of the aforementioned climatic variables. In addition, based on monthly time series of soil moisture, the statistical significance of its multi-year trend was examined. This analysis fits into the broader context of intensifying soil droughts in Poland in 2018-2025 and their links with observed climate change.

2. Materials and methods

The study covered the Sudół River catchment in northern Kraków, southern Poland, characterized by a temperate transitional climate (<https://ziw.krakow.pl/klimat-krakowa>) with an average annual temperature of about 9°C and an average annual precipitation total of 700–800 mm. The Sudół River is about 9 km long and with a catchment area of about 18 km² (Godyń et al., 2023). The study used daily data from the period from 4 December 2018 to 14 July 2025, covering the full dataset since the installation of measuring devices in the research cross-section of the Department of Geoengineering and Water Management of the Cracow University of Technology. The selected data for analysis include four climatic variables: soil moisture (SM , %), air temperature (t , °C), relative air humidity (RH , %), and total precipitation (P , mm). Measurements came from the Opolska cross-section located in the Sudół River catchment area (Fig. 1).

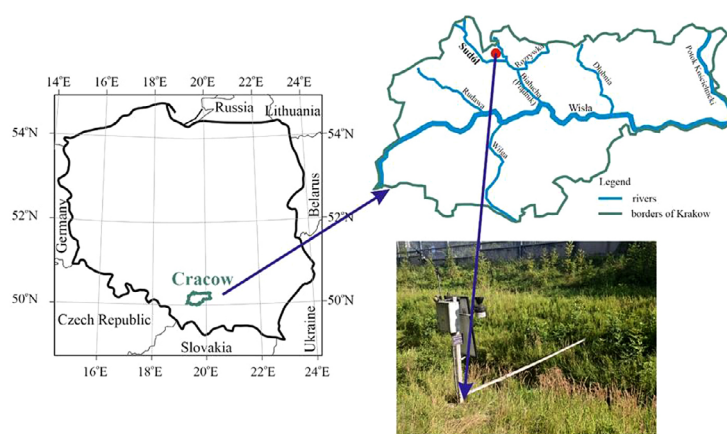


Fig. 1. Location of the measuring station in the Sudół River catchment in Kraków, Poland (own elaboration)

Measurements were taken at the Opolska cross-section, with a soil moisture sensor installed at 15 cm depth in grass-covered silty alluvial (fluvisol) soil (Skiba et al., 2023). The dataset was complemented with daily satellite-derived surface soil moisture (SM_{surf} , 0–5 cm) from the Copernicus Climate Data Store (C3S, ASCAT, 0.25° resolution) (Dorigo et al., 2017), used only for general trend comparison due to differences in depth and scale. In this study, soil moisture measured *in situ* at a depth of 15 cm was treated as subsurface soil moisture SM , whereas the Copernicus product represents surface soil moisture SM_{surf} corresponding approximately to the upper 0–5 cm soil layer.

The Antecedent Precipitation Index API was calculated from daily precipitation totals P as the sum of antecedent precipitation amounts weighted by an exponential decay factor, where precipitation on each preceding day P_{i-1} was multiplied by the moisture decay coefficient k raised to the power of $i-1$, and the summation was performed over n antecedent days. In this study, a decay coefficient of $k = 0.84$ and an antecedent period of $n = 5$ days were adopted, consistent with catchment-scale applications and suitable for capturing short-term soil moisture dynamics (Hunt et al., 2009; Zhao et al., 2019).

Temporal variability of soil moisture SM , surface soil moisture SM_{surf} and climatic variables (t , RH , API , P), was analyzed using daily multi-year time series, including monthly and seasonal aggregation. Due to the seasonal character of soil moisture, long-term trends were assessed using the nonparametric Seasonal Kendall test and Sen's slope estimator, which enable robust trend detection in data with cyclic seasonal structure (Helsel et al., 2020). Relationships between soil moisture SM and air temperature, relative humidity, and API were evaluated using Spearman rank correlation and multiple regression analyses, performed for the entire study period as well as on a monthly basis to account for seasonal differences. All statistical analyses were performed in the R environment (R Core Team, 2024). Statistical tests were performed at the assumed significance level $\alpha = 0.05$.

3. Results

3.1. Monthly, seasonal, and half-year variability of the analyzed variables

Figure 2 illustrates the monthly, seasonal, and half-year variability of daily soil moisture measured by the probe at a depth of 15 cm (SM), daily surface soil moisture from satellite data (SM_{surf}), and: t , RH , API , P_m . The analysis was performed based on the meteorological division of seasons and half-years, i.e., spring lasts from 1 March to 31 May, summer – from 1 June to 31 August, autumn – from 1 September to 30 November, winter – from 1 December to 28 February, summer half-year (from V to X), winter half-year (from XI to IV).

Soil moisture SM shows clear seasonality, with highest values in winter – early spring and lowest in summer (June–July), when variability is greatest due to episodic rainfall and strong evapotranspiration. **Surface soil moisture SM_{surf}** follows a similar pattern but with larger amplitude and faster responses to wetting and drying. SM and SM_{surf} are moderately and significantly correlated (Spearman's $\rho = 0.429$); differences result from measurement depth, spatial scale, and the rapid reaction of the surface layer to atmospheric conditions.

Air temperature t displays a strong annual cycle. **Relative air humidity RH** shows an opposite seasonal pattern, reflecting the temperature-dependent capacity of air to retain water vapor. **Monthly precipitation totals P_m** are highly variable and strongly right-skewed, with the highest and most diverse values in summer and the lowest in winter. In contrast, the **antecedent precipitation index API** shows a smoother temporal pattern, reflecting the cumulative

effect of earlier rainfall. Higher *API* values occur during periods of frequent precipitation and reduced evaporation, while lower values are typical of summer months.

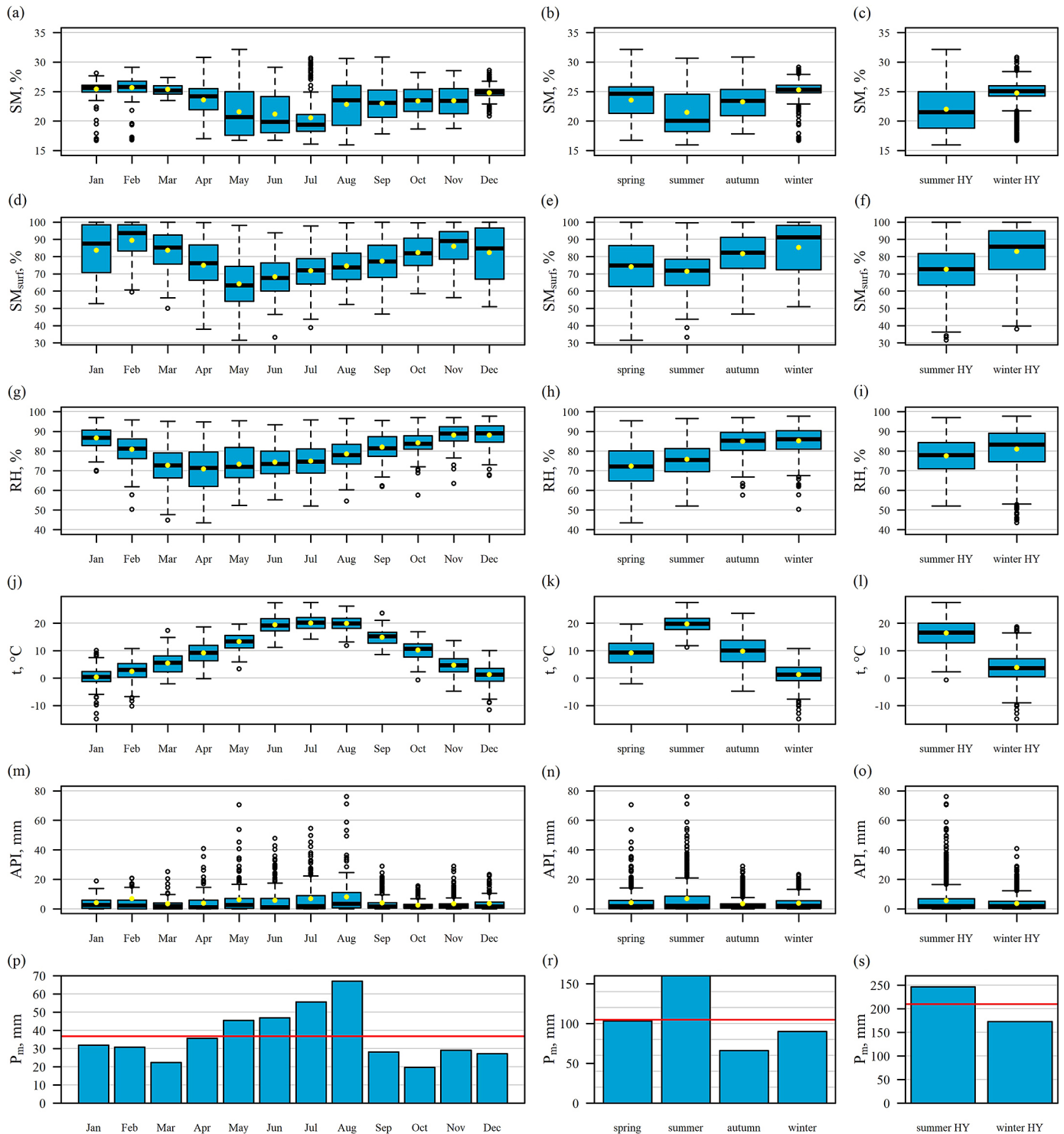


Fig. 2. Monthly, seasonal, and half-year variability of: daily soil moisture *SM* and *SM_{surf}*, daily climatic variables (*API*, *t*, and *RH*), and monthly precipitation totals *P_m*. The black horizontal line on the boxplot charts (a–o) indicates the median, yellow dots – the mean, and black circles – outliers. Red lines on the lower charts (p–s) indicate the mean precipitation total over the multi-year period (own elaboration)

3.2. Multi-year variability of soil moisture

Figure 3 presents the multi-year variability of daily *SM* in the analyzed period, with red lines indicating average soil moisture values in individual years. The *SM* time series reveals a clear seasonal pattern. At the same time, a gradual decline in average annual soil moisture is evident over the study period, particularly after 2019 and during the dry years 2022 and 2025.

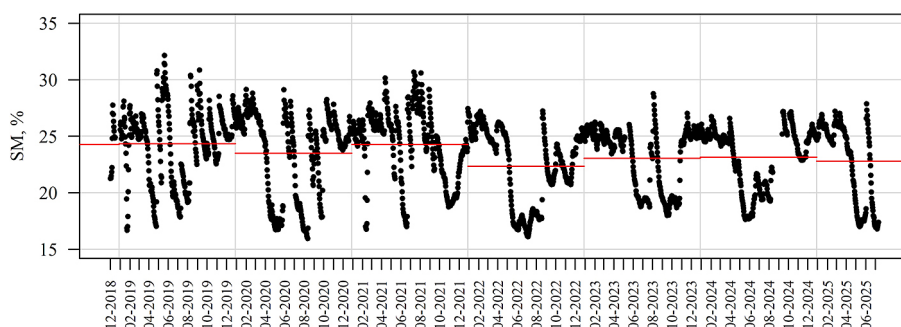


Fig. 3. Multi-year variability of daily soil moisture values (*SM*) in the analyzed period. Red lines indicate the average soil moisture values in individual years (own elaboration)

The significance of long-term changes in soil moisture was assessed using the Seasonal Kendall test with a monthly seasonal structure (Table 1), allowing the natural seasonality of *SM* to be accounted for in trend detection. The results indicate a statistically significant decreasing trend in soil moisture over the entire analyzed period (Kendall's Tau = -0.129^*). The Sen slope estimator shows an average decline of $-0.1875\% \cdot \text{yr}^{-1}$, confirming a persistent long-term drying tendency.

Table 1. Results of the Seasonal Kendall's Test for individual months (own elaboration)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kendall Tau	-0.027	-0.319	-0.143	0.048	-0.296	-0.163	-0.082	-0.082	-0.255	-0.196	-0.126	0.064
Sen slope, [$\% \cdot \text{yr}^{-1}$]	-0.019	-0.305	-0.104	0.138	-1.163	-0.454	-0.182	-0.413	-1.099	-0.61	-0.346	0.04
Trend	–	↓	↓	–	↓	↓	–	–	↓	↓	↓	–

In addition, the performed seasonal heterogeneity test confirmed significant differentiation of trends between individual months (Chi-Square = 74.43; $p < 0.0001$). The strongest, statistically significant decreases in soil moisture were recorded in May, which means a decrease in soil moisture by about 1.2 percentage points per year, and in September. These periods fall in late spring and the end of summer, when evaporation intensity is high and precipitation frequency and effectiveness can be limited, which favors the deepening of moisture deficit in the soil. In turn, a slight increasing tendency was noted only in April and December, but these values were not statistically significant.

3.3. Correlation analysis between *SM* and meteorological factors in monthly terms

Spearman's rank correlation was used to assess relationships between meteorological variables and soil moisture *SM* using daily data for the entire study period and for individual months to identify seasonal differences (Table 2, Fig. 4).

Table 2. Spearman correlations between daily soil moisture *SM* and daily climatic variables (*API*, *t*, *RH*), in the multi-year period and in individual months (only statistically significant at $\alpha = 0.05$)

	entire study period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
corr (<i>SM</i> , <i>API</i>)			0.282	0.301	0.206	0.190		0.292	0.412				0.403
corr (<i>SM</i> , <i>t</i>)	−0.374	0.390	0.401		−0.258			0.256	−0.243				0.280
corr (<i>SM</i> , <i>RH</i>)	0.203				0.332			0.204	0.255	−0.218			

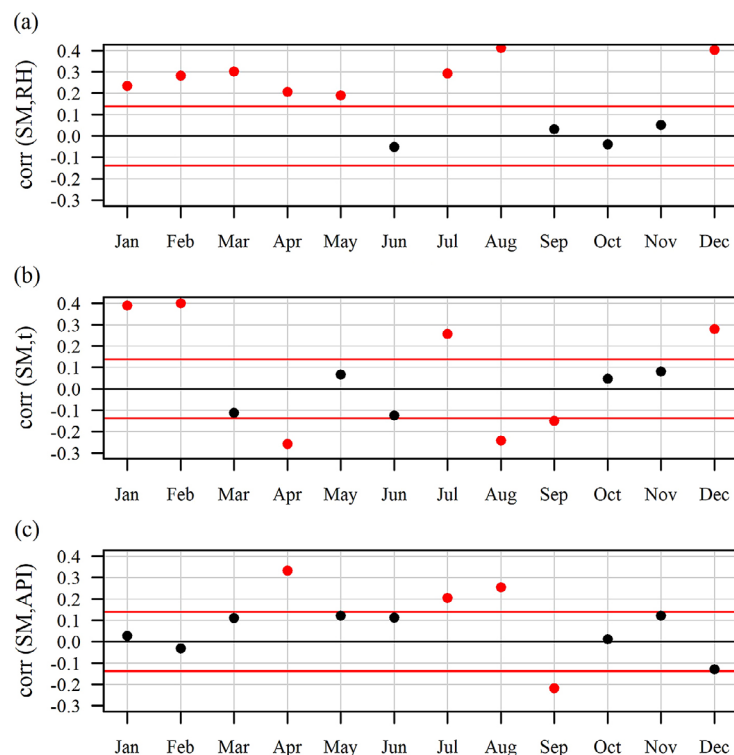


Fig. 4. Annual course of Spearman's correlation coefficient. Black points represent nonsignificant correlations, and red points – statistically significant at $\alpha = 0.05$. Red lines mark the area the nonsignificant range (own elaboration)

Correlations over the entire study period. In the multi-year perspective, statistically significant correlations were observed between soil moisture and all analyzed meteorological variables. Soil moisture showed a positive correlation with *API*, indicating the influence of antecedent precipitation on soil wetness. A stronger negative correlation was found between *SM* and air temperature, highlighting the role of evapotranspiration in reducing soil moisture. The correlation between *SM* and relative humidity was positive but weaker.

Seasonal variability of correlations. Monthly correlations show strong seasonal variation (Fig. 4). The most consistent positive relationships occurred between soil moisture and *API*, especially in winter, early spring, August, and December. The *SM* – temperature relationship is characterized by clear seasonal differentiation; was positive in winter (linked to snowmelt and low evaporation) and negative in spring – summer due to intensified evapotranspiration. Relative humidity showed the weakest and most irregular correlations, indicating a secondary and seasonally variable influence.

3.4. Regression analysis

Multiple regression was used to assess the effects of *API*, air temperature *t* and relative humidity *RH* on soil moisture *SM*. Models were developed for the multi-year period and for individual months to capture seasonal variability (Table 3).

Table 3. Result of multiple regression analysis (own elaboration)

Period / Month	Model $SM = \alpha_0 + \alpha_{API} \cdot API - \alpha_t \cdot t + \alpha_{RH} \cdot RH$	Adjusted R^2	F-statistic:	p-value
the multi-year period	$SM = 23.376 + 0.082 \cdot API - 0.173 \cdot t + 0.017 \cdot RH$	0.205	201.6	< 2.2e-16
January	$SM = 25.188 + 0.047 \cdot API + 0.120 \cdot t$	0.108	13.83	2.266e-06
February	$SM = 27.569 + 0.083 \cdot API + 0.202 \cdot t - 0.034 \cdot RH$	0.245	22.29	1.907e-12
March	$SM = 25.182 + 0.069 \cdot API$	0.065	16.00	8.7e-05
April	$SM = 19.678 + 0.079 \cdot API - 0.120 \cdot t + 0.066 \cdot RH$	0.192	17.62	3.206e-10
May	$SM = 20.343 + 0.202 \cdot API$	0.201	51.95	1.11e-11
June	$SM = 15.349 - 0.066 \cdot API + 0.084 \cdot RH$	0.044	4.842	0.00881
July	$SM = 14.879 + 0.148 \cdot API + 0.227 \cdot t$	0.257	35.17	8.882e-14
August	$SM = 21.751 + 0.130 \cdot API$	0.161	33.61	3.228e-08
September	$SM = 37.183 - 0.217 \cdot t - 0.135 \cdot RH$	0.076	7.833	0.000565
October	–	0.015	3.791	0.0631
November	–	0.0071	2.29	0.1318
December	$SM = 26.762 + 0.113 \cdot API - 0.026 \cdot RH$	0.211	26.62	6.428e-11

Regression for the multi-year period. All three predictors were statistically significant ($p < 0.001$). The model explained 40% of SM variability (adjusted $R^2 = 0.405$). API and RH were positively related to SM , whereas temperature had a negative coefficient, indicating that higher temperatures reduce soil moisture. Temperature showed the strongest overall effect.

Regression in monthly terms. Monthly models demonstrated clear seasonal variability. Adjusted R^2 ranged from 0.027 (November; non-significant) to 0.457 (July). In most months, API was a significant positive predictor of SM . Temperature was positively related to SM in winter (January–February), but negative or insignificant in other months. RH was significant only in selected months. Overall, the results indicate seasonal changes in the climatic controls of soil moisture.

4. Discussion

The obtained results confirm that soil moisture variability in the Sudół River catchment is a resultant of seasonal meteorological conditions and long-term climatic changes, which in recent decades have led to intensification of soil and hydrological droughts in Poland. The distinct seasonality of soil moisture, with maximum values in the winter-spring period and minima in summer, is consistent with observations conducted both at local and regional scales for Central Europe (Baran Gurgul & Wałęga, 2025; Orth & Seneviratne, 2012; Somorowska, 2022). These results indicate that even in small, partially urbanized catchments, the basic mechanisms controlling seasonal soil wetness are preserved. Similar downward trends in soil moisture and increasing evapotranspiration stress have been reported in other studies and climate projections for Poland, which indicate a growing frequency and intensity of drought episodes in the 21st century (Ghazi et al., 2025; Somorowska, 2022).

The observed decline in soil moisture may have implications extending beyond hydrological processes. Previous studies conducted in urban environments have shown that soil moisture contributes to moderating land surface temperatures through enhanced evaporation and evapotranspiration (Przeździecki et al., 2023; Gobatti et al., 2025). Consequently, the progressive drying tendency observed in the Sudół catchment may not only increase drought susceptibility but may also reduce the climate regulating functions of urban green areas under future warming conditions. Although the analysed

catchment is only partially urbanized, the observed long-term drying trend indicates that urban areas may be particularly vulnerable to the combined effects of climate warming and reduced soil water availability.

Both correlation and regression analyses confirm the dominant role of atmospheric precipitation in shaping soil moisture, consistent with previous hydrological and agroclimatic research (Hunt et al., 2009; Moraes et al., 2024; Niemczyk et al., 2005; Zhao et al., 2019). In particular, the antecedent precipitation index *API* proved to be a stable and significant predictor in most months, supporting its usefulness in representing soil water availability. Reported delays between precipitation and soil wetting (Dincă et al., 2018) further justify the use of *API*-based approaches, as also observed in Polish studies on green roofs and agricultural soils (Baryła et al., 2017).

The seasonal influence of air temperature's influence on soil moisture, positive in winter and negative in the warm period, reflects well-known land-atmosphere feedback mechanisms. Increased temperatures intensify evapotranspiration and accelerate soil moisture depletion under limited precipitation supply (Benson & Dirmeyer, 2021; Seneviratne et al., 2010). In contrast, relative air humidity showed weak and inconsistent relationships with soil moisture, confirming its secondary and indirect role compared to precipitation and temperature (Benson & Dirmeyer, 2021; Pinskiwar et al., 2020).

Comparison of *in situ* soil moisture measurements with satellite SM_{surf} data showed moderate but statistically significant agreement, confirming the usefulness of remote sensing for analysing soil moisture variability and trends. The differences are related to the fact that SM_{surf} represents near-surface soil moisture, which reacts almost immediately to precipitation and evaporation events, whereas the *in situ* measurements characterize subsurface soil moisture at 15 cm depth, where moisture dynamics are more buffered and reflect longer-term water storage conditions (Hirschi et al., 2014; McColl et al., 2017). The literature indicates that the variability of surface soil moisture decreases substantially during drought periods, leading to a progressive decoupling from the trends observed in subsurface (root-zone) soil moisture, which tends to retain its temporal variability for a longer period (Hirschi et al., 2014). Such a phenomenon may have occurred in the Sudół catchment during the dry years of 2022 and 2025, potentially explaining the differences in the response amplitude observed between these two soil moisture indicators.

The results show that statistical models based on precipitation and air temperature can effectively support agriculture, irrigation planning, and drought monitoring, even in urbanized catchments (Baran Gurgul & Wałęga, 2025; IMGW-PIB, 2023). The observed decline in soil moisture also highlights the need for adaptation measures to enhance water retention and reduce losses, especially given projected temperature increases and more frequent extreme events (IPCC 2023).

5. Conclusions

Based on the analyses conducted concerning soil moisture variability and its links with selected meteorological factors, the following conclusions were formulated.

- ▶ Soil moisture in the Sudół River catchment exhibits pronounced seasonality, with maximum values occurring during the winter – spring period and minimum values in summer. This pattern confirms the dominant influence of the annual climatic cycle on soil moisture conditions, even in a small, partially urbanized catchment. The low summer values indicate increased susceptibility of the area to water deficits during the warm season.
- ▶ Multi-year trend analysis revealed a statistically significant decrease in soil moisture over the period 2018–2025, with particularly strong

downward tendencies observed in May and September. These months are crucial for vegetation development and soil water balance, suggesting an increasing risk of soil and agricultural drought. The results highlight the need to implement measures aimed at enhancing water retention, especially in the agricultural part of the catchment.

- ▶ The antecedent precipitation index *API* proved to be the dominant factor controlling soil moisture variability at both multi-year and monthly scales. The positive and statistically significant relationship between soil moisture and *API* confirms the key role of precipitation in replenishing soil water resources and indicates the usefulness of this index as a simple and effective tool for modeling and forecasting soil water availability.
- ▶ Air temperature influences soil moisture in a distinctly seasonal manner: positively in winter and negatively in the spring – summer period. The negative summer correlation reflects intensified evaporation and evapotranspiration processes, leading to the deepening of soil moisture deficits. These findings underline the importance of including air temperature in soil and agricultural drought monitoring and forecasting systems.
- ▶ Relative air humidity showed a weaker, indirect, and seasonally variable influence compared to precipitation and temperature, indicating its limited usefulness as an independent predictor in soil moisture analyses.
- ▶ Comparison of in situ soil moisture *SM* measurements with satellite-derived surface soil moisture SM_{surf} data demonstrated moderate but statistically significant agreement. This confirms the value of remote sensing in analyzing soil moisture variability and long-term trends. However, differences related to measurement depth and spatial scale require cautious interpretation, and satellite data should be treated as complementary to ground-based observations. The results confirm that surface soil moisture SM_{surf} and subsurface soil moisture (*SM* measured at a depth of 15 cm) represent two distinct, although interconnected, components of the soil water balance. Their relationship is modified by the intensity of evaporation and the degree of saturation within the soil profile.
- ▶ Overall, the results indicate increasing susceptibility of soils in the study area to drought episodes under progressing climate change. Statistical models based on meteorological variables, particularly precipitation and air temperature, can provide effective decision-support tools for water resource management, agriculture, irrigation planning, drought monitoring, and climate change adaptation.
- ▶ In partially urbanized catchments such as the Sudół River basin, maintaining soil moisture through retention-oriented management and protection of permeable surfaces may become increasingly important for climate change adaptation and mitigation of drought impacts.

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