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Operational Assessment of Soil–Atmosphere Interaction Dynamics for Military Terrain Mobility and Decision Support

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Abstract

Understanding how soil systems respond to atmospheric forcing is critical not only for environmental science but also for defence operations requiring accurate terrain assessment. This study quantifies depth-dependent and delayed soil responses to meteorological drivers using lag-correlation analysis across six operational military monitoring stations (2022–2024). The results demonstrate that soil–atmosphere coupling exhibits strong station-specific variability, with response times ranging from hours to several weeks depending on soil type and depth.
The analysis reveals weak instantaneous (lag 0) correlations but significantly delayed relationships, particularly in deeper soil layers, confirming that terrain conditions relevant for military mobility cannot be reliably inferred from current weather alone. Instead, cumulative and lagged atmospheric effects govern soil bearing capacity, trafficability, and subsurface stability.
These findings directly support defence applications, including terrain trafficability forecasting, planning of off-road operations, sensor deployment optimization, and decision-support systems. The proposed lag-correlation framework provides a practical analytical tool to enhance situational awareness and operational readiness under dynamically changing meteorological conditions.

KEY WORDS: ***soil moisture sensors; lag-correlation analysis; terrain trafficability; military mobility; environmental intelligence; decision support***

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1. Introduction

Modern military operations increasingly depend on accurate environmental intelligence, where terrain conditions play a decisive role in mobility, logistics, and deployment effectiveness. Soil moisture, in particular, directly affects vehicle trafficability, load-bearing capacity, and the stability of both temporary and permanent infrastructure. However, soil response to atmospheric forcing is not immediate, which introduces uncertainty into operational planning when relying solely on current meteorological observations.

Since 2022, the network of monitoring stations operated by the Office of Military Geographic and Hydro meteorological (OMGHM) has been systematically measuring soil moisture conditions using automated sensors installed in natural soil profiles beneath short-cut grass vegetation. These measurements represent a significant enhancement of the Army's hydro meteorological observational infrastructure, enabling the continuous monitoring of soil water dynamics in response to changing atmospheric conditions.

Soil moisture is a key environmental variable affecting hydrological processes, evapotranspiration, vegetation health, surface energy balance, and the propagation of surface and subsurface water. Its temporal variability reflects the combined influence of meteorological drivers, soil physical properties, and site-specific land-surface characteristics [2,4].

These atmospheric factors influence soil moisture through several interconnected mechanisms. Solar radiation and sunshine affect the thermal regime of the soil and evaporative demand on the surface. Air temperature and humidity shape the vapour-pressure gradient between soil and atmosphere, controlling the rate of soil water loss. Wind enhances the removal of moist air near the ground and increases evaporation efficiency. Precipitation inputs drive rapid increases in soil moisture in the upper layers, while deeper layers react more gradually depending on soil permeability, structure, and antecedent conditions.

Because these influences occur on different timescales, soil moisture does not respond instantly; rather, it exhibits lagged and depth-dependent behavior that varies across locations and environmental settings.

Against this background, the primary goal of this research is to quantify the temporal relationship between meteorological variables and soil moisture at the stations, and to determine how quickly and strongly the soil system responds to atmospheric changes. By exploiting three years of continuous observations and applying lag-correlation analysis, this study seeks to identify the characteristic response times of different soil layers, classify stations by functional response type (fast, slow, or complex), and provide insights into the dominant environmental drivers shaping soil moisture dynamics across the Czech Republic. These results lay the groundwork for improved hydrological modelling, drought monitoring, and especially for defence-oriented environmental intelligence, including terrain trafficability prediction, deployment planning of military units and sensors and assessment of environmental constraints on operations.

This study contributes beyond standard lag-correlation approaches in several aspects. First, it utilizes a unique dataset obtained from an operational military hydro meteorological network, which is not commonly available in civilian studies. Second, it introduces a station classification based on response dynamics (fast, slow, and complex systems), enabling a structured interpretation of soil–atmosphere coupling. Third, it highlights station-specific anomalies, providing new insights into non-standard soil response regimes [3].

2. The Mathematical Background

2.1 Overview of Observational Network and Meteorological Data

The analysis is based on meteorological and soil-moisture observations collected at six professional monitoring stations operated by the OMGHM in the Czech Republic, in operational use 24/7 in both manual and automatic modes. The stations represent a diverse set of environmental and climatic conditions and are strategically integrated within a uniform technical and operational framework of the Hydrometeorological Service of the Army of the Czech Republic. A description of the properties of the sites is given by Table 1, which provides a detailed description of the monitored sites, including their geographical setting, topographic and environmental characteristics, and the classification of local soil types relevant to the hydrological and meteorological conditions under study.

Table 1. Description of the properties of the given sites

Station	**Index**	**Latitude [DD]**	**Longitude [DD]**	**Elevation [m]**	**Soil type**
Prostějov	B1PROS01	49,4525	17,134722	215	Chernozem
Sedlec	B2SEDC01	49,170833	16,120556	474	Rendzina / Cambisol
Polom	H2POLO01	50,350278	16,322222	747	Podsol
Chotusice	H3CHTU01	49,940833	15,386389	238	Fluvisol
Pardubice	H3PARD01	50,016111	15,740273	224	Fluvizol
Praha Kbely	P1PKBE01	50,123333	14,538056	284	Cambisol

These stations cover diverse environmental and climatic conditions, providing a valuable basis for assessing spatial differences in soil–atmosphere interactions. Soil moisture was measured using TRIFO3G automatic sensors, designed for high-precision field monitoring. Unlike simple consumer-grade devices, TRIFO3G sensors determine soil volumetric water content by measuring the dielectric permittivity of the soil matrix, which strongly depends on its water content, and convert it into percentage values (Fig 1) [1,3].

Measurements are conducted in three (*HPU*1, *HPU*2, *HPU*3) depth layers (0–10 cm, 11–50 cm, 51–100 cm accordingly), capturing both near-surface variability and deeper hydrological processes such as infiltration, percolation, and retention [1,2].

In parallel with soil measurements, each station records a comprehensive suite of meteorological variables capturing the primary atmospheric drivers influencing soil water conditions within the same period. These include wind speed (*F_avg*), which controls near-surface evaporation and turbulent fluxes; sunshine duration (*SSV*), which determine surface heating and energy availability for evaporation; air temperature (*T_avg*) and relative humidity (*H_avg*), which modulate vapour-pressure deficit; and daily sum of precipitation total (*SRA*), which represents the dominant direct input into the soil water balance. For the purposes of this study, atmospheric variables were expressed as daily averages based on Mannheim hours, or as daily totals in the case of precipitation. This harmonized temporal resolution allows for a consistent comparison between meteorological forcing and the soil moisture response.

Each station operates automated instrumentation following standard hydrometeorological practice. Soil moisture is measured inside the natural soil profile beneath short-cut grass vegetation, ensuring minimal vegetation disturbance and stable microclimatic conditions during the observation period.

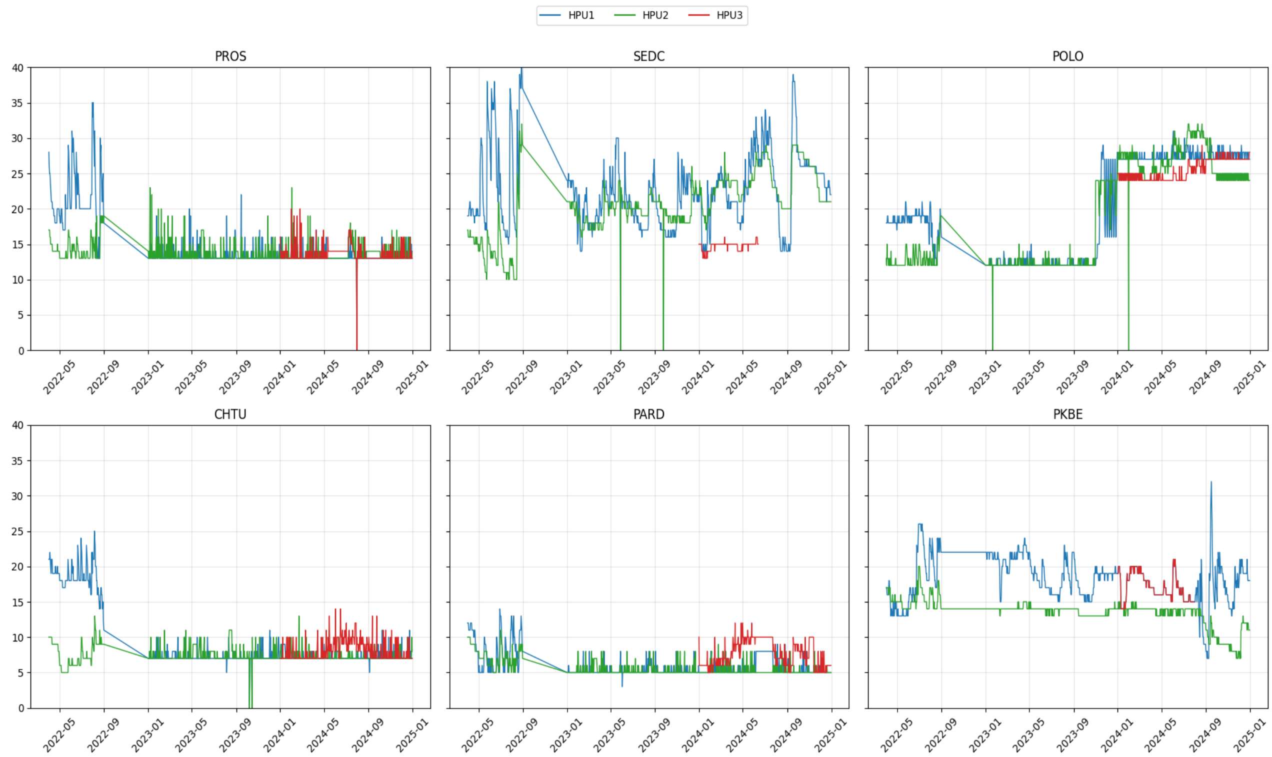

Fig.1. Temporal record of soil-sensor measurements at the respective stations

2.2 Lag-Correlation Framework

Soil moisture does not respond instantaneously to changes in atmospheric conditions. Instead, its response is governed by a combination of physical and biological factors, including infiltration rate, soil texture and structure, evapotranspiration intensity, rooting depth, soil stratification, and hydraulic properties. As a result, the influence of meteorological forcing on soil moisture often manifests with a temporal delay. To account for these delayed responses, lagged correlation analysis was applied between selected meteorological variables and soil-moisture observations [2,4].

For each monitoring station, meteorological variable, soil layer, and time lag, Pearson correlation coefficients were calculated to quantify the strength and direction of the delayed relationship. Specifically, for each station *s*, soil layer soil layer $p \in \{HPU1, HPU2, HPU3\}$, meteorological variable $m \in \{T\_avg, SRA, SSV, H\_avg, F\_avg\}$ and lag $L \in [1, 31]$ days, the Pearson correlation coefficient was computed as follows:

$$r_{s,p,m}(L) = \frac{\sum_{t=1}^{N}\left(HPU_{s,p}(t) - \overline{HPU}_{s,p}\right)\left(M_{s,m}(t-L) - \bar{M}_{s,m}\right)}{\sqrt{\sum_{t=1}^{N}\left(HPU_{s,p}(t) - \overline{HPU}_{s,p}\right)^2 \sum_{t=1}^{N}\left(M_{s,m}\left(t - L - \bar{M}_{s,m}\right)\right)^2}} \qquad (1)$$

where: $r(L)$ is the Pearson product-moment correlation coefficient evaluated at time lag L, quantifying the linear dependence between two time series, $HPU(t)$ denotes soil moisture at time t for a given station and soil layer and average is the temporal mean of the soil-moisture time series over the considered period, $M(t\text{-}L)$ represents the meteorological variable shifted by a lag of L days and average is the temporal mean of the corresponding meteorological variable, t is the discrete time index, L is the time (temporal) lag (in days), N denotes the number of paired, non-missing observations used in the correlation estimate. The lagged correlation analysis was performed under the assumption of weak stationarity of the analyzed time series over the selected period, with missing values excluded pairwise to ensure consistency of the correlation estimates. This yields a dense lag–correlation grid (met × lag) per sensor and station. Fig. 2 illustrates that for station-level visualization, we select the dominant soil sensor (the one achieving the maximum r across all drivers and lags), ensuring that each station's heatmap highlights the strongest functional response. Full matrices are archived in lagcorr_all_6stations.csv; best-lag summaries (L^*, r^*, N – number of valid records) are stored in lagcorr_best_6stations.csv. For each combination (station × *HPU* × meteo variable) has been identified L^* lag with maximum absolute correlation. This assumption is justified by the relatively short and homogeneous observation period and by the absence of structural breaks in the time series.

Pearson correlation coefficient was selected because it provides a robust measure of linear dependence between meteorological forcing and soil response, which is appropriate given the continuous nature of both datasets and the focus on detecting dominant response patterns rather than nonlinear interactions.

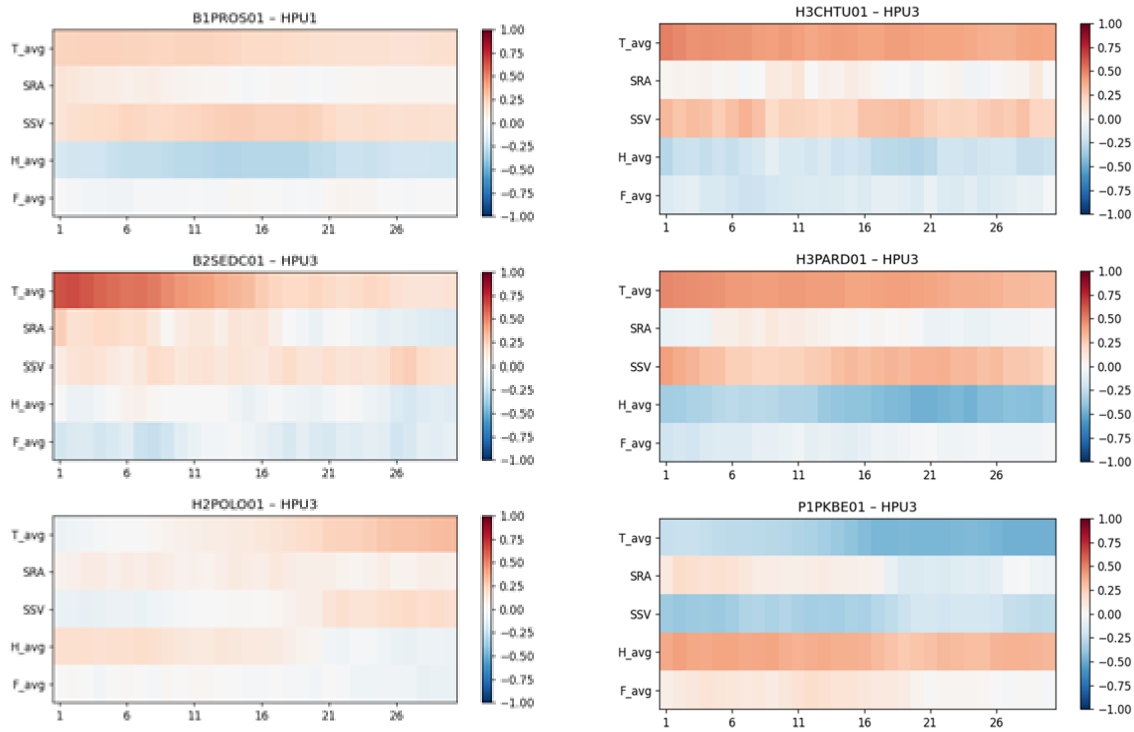

Fig. 2. The Heatmaps showing Pearson lag-correlations between meteorological variables and soil measurements across lags. Positive correlations (red) indicate that increases in a meteorological driver precedes increases in soil sensor values, whereas negative correlations (blue) indicate inverse responses. Rows correspond to meteorological variables and columns to lag days.

3. Results

Across all soil depths, correlations at lag 0 were weak to very weak, consistent with the expectation that soil moisture and related signals respond to atmospheric drivers only gradually. Upper layers show modest instantaneous sensitivity, while deeper layers appear largely decoupled from day-to-day meteorological variability.

The observed patterns align with well-established principles of soil physics:

Surface sensitivity (*HPU*1): The shallow 10 cm horizon reacts directly to atmospheric energy input. Higher temperatures and solar radiation increase evaporative demand and heating of the near-surface layer, resulting in higher *HPU*1 values. Conversely, increased atmospheric humidity reduces evaporative gradients, explaining the negative correlation with *H_avg*.

Decoupling of deeper layers (*HPU*2, *HPU*3): Soil at 50–90 cm depth exhibits minimal same-day response, because thermal waves and water infiltration require days to weeks to propagate downward. These layers integrate longer-term weather patterns rather than instantaneous fluctuations.

Importance of lagged analysis: The weak lag 0 values indicate that the main soil responses will emerge at nonzero lags (e.g., +1 to +31 days) and through cumulative precipitation effects—common in hydrological and ecohydrological studies.

Daily (lag 0) correlations between meteorological drivers and soil variables are weak across all depths, with modest instantaneous effects limited to the shallow 10 cm layer. Mid-soil and deep-soil horizons remain largely unresponsive on the daily scale. These outcomes reinforce the necessity of lagged correlation or causal analyses to capture the true dynamics of soil–atmosphere coupling.

3.1 Selection of Representative Sensor per Station and Heatmap Construction

Because each station has three *HPU* sensors, and because soil response varies with depth, we defined a dominant sensor for each station. The sensor with the highest $|r|$ across all meteorological drivers and all lags. This sensor best describes the strongest atmospheric control on soil behavior and is used for the station's heatmap visualizations (5×30). The heatmap displays pairwise Pearson correlation coefficients (r) among temperature, humidity, soil-sensor, and wind-related variables. Red shades represent positive correlations, blue shades indicate negative correlations, and values close to zero are shown in neutral tones. The matrix provides an overview of linear relationships between individual environmental measurements and soil-sensor outputs.

3.1.1 P1PKBE01 – Praha-Kbely

The Praha-Kbely station (Fig. 3) displays a response pattern that is fundamentally different from all other sites. The deepest probe, *HPU*3, dominates the behavior of the profile and exhibits exceptionally long delays, with peak correlations appearing only after 25–30 days. Unlike the other stations, where soil values typically increase with cumulative warming, the long-lag relationship at Kbely is inverted: air temperature is negatively correlated with *HPU*3, reaching $r \approx -0.48$ at a lag of 27 days. Short-lag patterns follow the same reversed logic, with relative humidity showing a positive influence and sunshine duration a negative one at approximately two days.

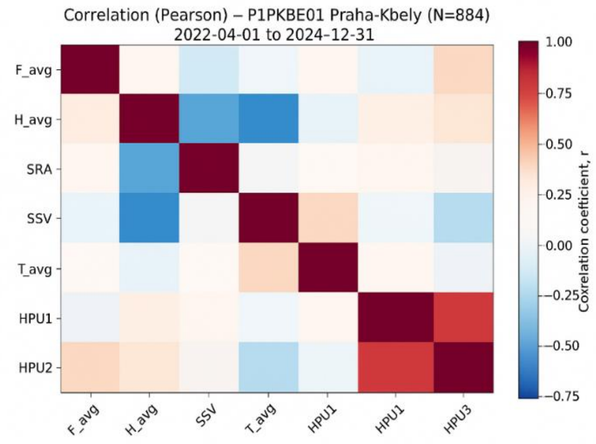

Fig 3. Pearson correlation matrix of all measured variables at the P1PKBE01 Praha-Kbely station (*N* = 884) for the period 1 April 2022–31 December 2024

This combination of negative long-lag temperature effects, opposite radiative responses, and unusually slow propagation suggests that *HPU*3 represents a variable with a reversed or non-standard physical interpretation, or a soil horizon that is considerably deeper or more insulated than expected. The shallower probes (*HPU*1 and *HPU*2) show only mild and conventional relationships, further emphasizing that the atypical behavior is localized to the deepest sensor. Overall, Praha-Kbely is the only station in the dataset where the soil profile reacts through prolonged delays and inverted signatures, indicating a substantially different sensing or environmental regime compared to the other monitored locations.

3.1.2 H3CHTU01 – Chotusice

The correlation structure at the Chotusice station (Fig. 4) shows a clear separation between the behavior of the soil profile and the behavior of atmospheric variables. The soil probes exhibit very strong internal coherence, with correlations between *HPU*1, *HPU*2, and *HPU*3 commonly reaching 0.7–0.9. This indicates a stable and physically consistent vertical response of the soil profile, matching the patterns observed at the other stations.

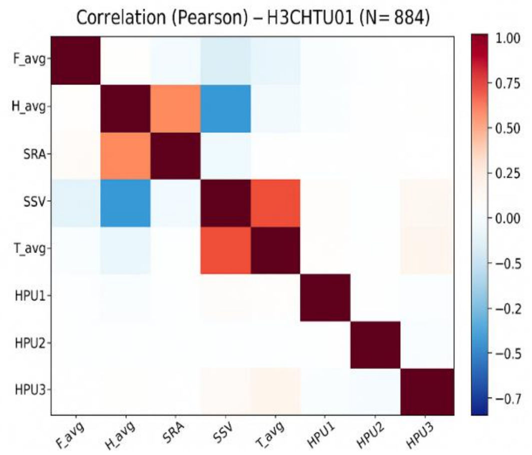

Fig 4. Pearson correlation matrix of all measured variables at the H3CHTU01 Chotusice station (*N* = 884) for the period 1 April 2022–31 December 2024.

In contrast, the instantaneous (lag 0) relationships between meteorological variables and soil measurements are weak. Air temperature shows only a slight positive association with the deepest soil probe, but the magnitude remains small, generally below 0.2. Variables such as solar radiation, sunshine duration, and wind speed do not exhibit a meaningful immediate influence on the soil profile, which is expected given the delayed nature of heat propagation and moisture movement in soils.

The atmospheric variables themselves display strong and physically interpretable relationships, particularly the pronounced negative correlation between relative humidity and sunshine duration, as well as the positive link between temperature and sunshine duration. These internal atmospheric structures confirm that the dataset behaves consistently with known radiative and thermodynamic processes.

Together, the results point to a two-layer soil response: a shallow zone capable of reflecting short-term thermal fluctuations, and deeper layers that react only to slower, cumulative atmospheric forcing. The very weak lag 0 soil–meteorology correlations underscore that meaningful coupling between the atmosphere and deeper soil layers will emerge only at multi-day or multi-week lags, rather than from instantaneous comparisons. Combined very fast thermal response (*T_avg* at ~1–3 d) and slower sunshine/humidity structures (*SSV*/*H_avg* at 7–15+ d).

3.1.3 H3PARD01 – Pardubice

The Pardubice station (Fig. 5) exhibits one of the clearest and physically most coherent response patterns in the entire dataset. The deepest probe, *HPU*3, dominates the soil profile and exhibits the strongest correlations across all sites. This probe responds rapidly to atmospheric heating: both air temperature and sunshine duration peak at a lag of approximately one day, with correlation coefficients around +0.48 and +0.41, respectively. Such short-lag positive responses reflect fast near-surface warming and drying that propagate downwards into the deeper soil layer.

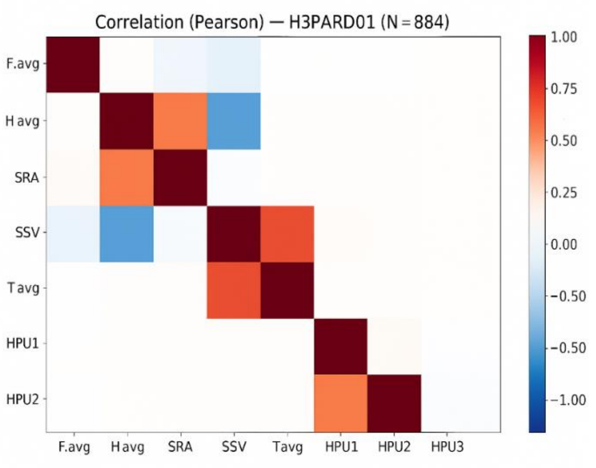

Fig 5. Pearson correlation matrix of all measured variables at the station H3PARD01 Pardubice (N = 884) for the period 1 April 2022–31 December 2024.

In addition to these rapid reactions, *HPU*3 also displays a pronounced delayed sensitivity to atmospheric humidity. Relative humidity is negatively correlated with the *HPU*3 signal at long lags of about 20–22 days, reaching magnitudes comparable to the temperature response. This pattern indicates that extended periods of higher humidity, which suppress evaporative drying, eventually translate into deeper moisture retention, while prolonged dry-air episodes lead to gradual desiccation detectable at depth weeks later.

The shallower probe *HPU*1 follows the same general structure but with weaker amplitudes and intermediate lag times, confirming a consistent vertical gradient of soil response. Together, these results reveal a dual dynamic regime: a fast component driven by temperature and radiation that affects the upper profile almost immediately, and a slow component governed by atmospheric humidity whose effects accumulate and propagate downward over several weeks.

Overall, Pardubice stands out as a highly interpretable and physically consistent site, where both rapid surface processes and slow subsurface adjustments are clearly expressed. This makes the station an excellent reference point for model calibration and for studying coupled thermal-hydrological responses in soils.

3.1.4 B2SEDC01 – Sedlec

The Sedlec station (Fig. 6) displays a fast-responding soil profile dominated by the shallow probe *HPU*1, which shows the clearest atmospheric relationships. The soil reacts within only a few days to changes in radiative and humidity conditions, with global radiation exerting the strongest influence. *SRA* peaks at a lag of three days with a correlation of approximately +0.28. Atmospheric humidity follows a similarly rapid but positive pattern, reaching about +0.23 at a lag of two days. This contrasts with several other sites where humidity typically suppresses near-surface soil signals, indicating that the Sedlec soil environment responds differently—most likely due to lighter, more permeable textures that promote quick moisture redistribution and short-term thermal changes. Air temperature shows only a weak delayed effect, with correlations remaining modest even at longer lags.

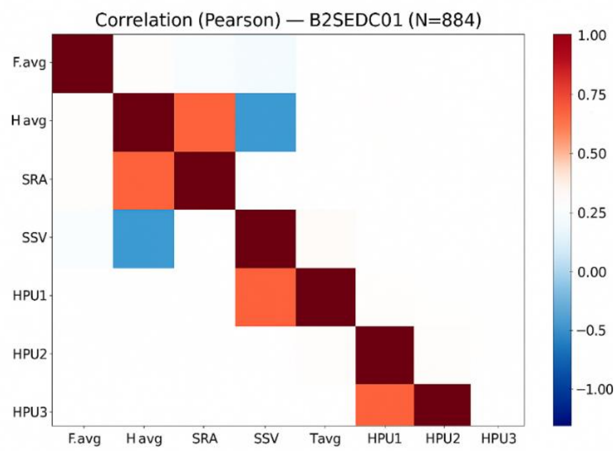

Fig 6. Pearson correlation matrix of all measured variables at station B2SEDC01 Sedlec station (*N* = 884) for the period 1 April 2022–31 December 2024.

At greater depths (*HPU*2 and *HPU*3), correlations remain very small, confirming that only the uppermost layer responds directly and rapidly to atmospheric inputs. The overall behavior points to a soil profile with low water–holding capacity and high responsiveness, where radiative forcing and short-term variations in air humidity translate quickly into measurable changes in the near-surface soil signal.

3.1.5 H2POLO01 – Polom

The Polom station (Fig. 7) exhibits a response pattern closely resembling that of Sedlec, with the shallow probe *HPU*1 acting as the dominant and most sensitive component of the soil profile. The strongest and most coherent relationships arise from radiative forcing: global radiation (*SRA*) shows the clearest positive influence on *HPU*1, typically peaking at lags of 3–7 days. This reflects a rapid drying response of the near-surface soil following several days of increased solar energy input, a pattern characteristic of soils with low water-retention capacity and efficient surface exchange.

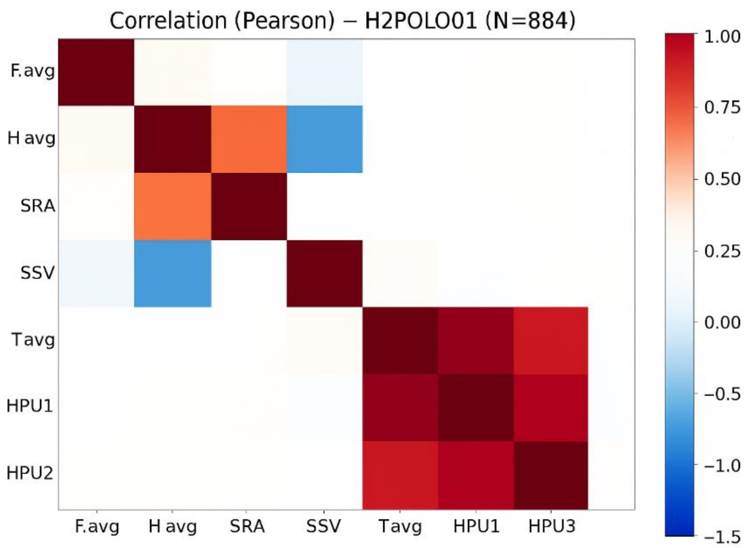

Fig 7. Pearson correlation matrix of all measured variables at station H2POLO01 Polom station (*N* = 884) for the period 1 April 2022–31 December 2024.

Deeper probes (*HPU*2 and *HPU*3) show only weak correlations, generally in the range of $|r| \approx 0.05–0.12$, indicating that atmospheric signals attenuate quickly with depth at this site. The soil system, therefore, behaves as a fast-responding upper layer superimposed on a largely insensitive deeper zone. This structure is consistent with light or mixed-texture soils, where moisture and thermal changes propagate quickly near the surface but dissipate rapidly in deeper layers.

Overall, Polom represents a rapidly reacting soil environment dominated by short-lag energy-driven processes, with a modest mid-term drying response and minimal deeper-layer coupling. Its dynamics align closely with the behavior observed at Sedlec, reinforcing the interpretation of a low-retention soil profile with strong surface control.

3.1.6 B1PROS01 – Prostějov

The Prostějov station exhibits a moderately responsive soil profile dominated by the shallow probe *HPU*1, which shows the clearest and most stable atmospheric relationships. Correlations are modest but consistent, typically ranging between 0.20 and 0.29, with soil responses occurring over intermediate lag times of roughly 5–15 days. The strongest effect is the delayed negative influence of atmospheric humidity, with *H_avg* reaching about -0.29 at a lag of fourteen days, suggesting that prolonged humid periods eventually lead to cooling or moistening of the near-surface soil. Sunshine duration shows an opposite delayed pattern, with positive correlations around +0.25 at lags of approximately fifteen days, reflecting gradual drying and warming following extended sunny conditions. Temperature exerts a weaker but still positive influence at shorter lags of about five days. Deeper probes show distinctly reduced sensitivity. *HPU*2 responds only minimally to atmospheric drivers, while *HPU*3 exhibits weak and mixed associations, including a slight positive short-lag humidity effect and a weak long-lag negative temperature response. These patterns indicate that deeper layers in Prostějov are buffered and slow to adjust, consistent with a soil environment characterized by higher water retention and slower thermal propagation.

Overall, Prostějov represents a heavier or more moisture-retentive soil type, where atmospheric signals penetrate gradually and produce delayed but stable responses. The dominance of *HPU*1 and the multi-day lags in temperature, humidity, and sunshine suggest a soil system with stronger buffering and slower drying than at the more rapidly responding stations such as Sedlec or Polom.

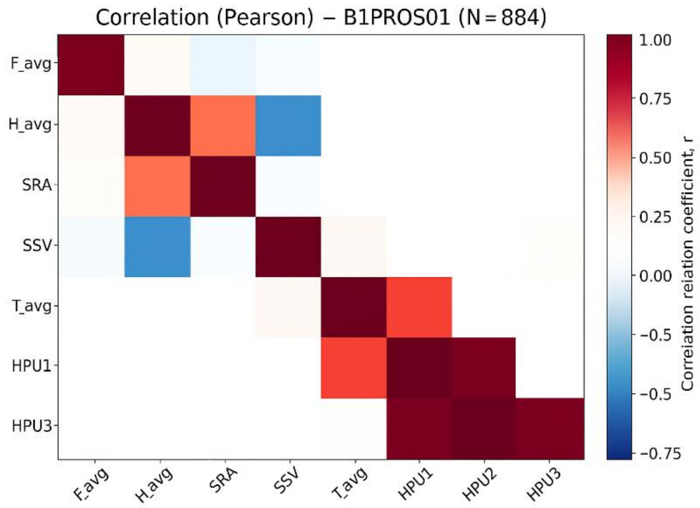

Fig 8 Pearson correlation matrix of all measured variables at station B1PROS01 Prostějov station ($N = 884$) for the period 1 April 2022–31 December 2024.

Across all stations, three primary response types can be identified: (i) fast-response systems (Sedlec, Polom), characterized by rapid shallow-layer reactions; (ii) buffered systems (Prostějov), showing delayed but stable responses; and (iii) complex or anomalous systems (Praha–Kbely), exhibiting long-lag and inverted behavior. This classification highlights that soil–atmosphere coupling is not uniform but strongly site-dependent, which is critical for any operational application.

4. Discussion

The observed lag dynamics confirm that soil–atmosphere interactions must be interpreted as time-dependent processes, particularly in operational environments. The variability between stations demonstrates that no universal terrain model is sufficient; instead, site-specific calibration is required for accurate predictions.

From a military perspective, this variability represents both a challenge and an opportunity. While it complicates generalized assessments, it also enables the development of tailored terrain intelligence models based on local conditions and historical response patterns.

The anomalous behaviour observed at Praha-Kbely highlights the operational risk of misinterpreting sensor data or neglecting subsurface processes. In real deployments, such misinterpretations could lead to incorrect route selection, equipment damage, or mission delays.

By incorporating lag-based analysis, commanders and planners can transition from reactive to predictive environmental assessment, significantly improving operational effectiveness.

5. Conclusions

Across all monitored stations, the soil–atmosphere relationships demonstrate a clear and physically coherent structure shaped by local soil properties, sensor characteristics, and the depth-dependent propagation of thermal and hydrological signals. While each site exhibits its own distinct response regime, several robust patterns emerge. Shallow sensors (*HPU*1) dominate the short-term variability at most stations, showing rapid adjustments to radiative forcing and atmospheric temperature, with characteristic lag times ranging from a few days in Sedlec and Polom to more than a week in Prostějov. These responses reflect differences in soil texture and water-holding capacity, with lighter soils reacting faster and heavier soils adjusting more slowly.

Deeper probes generally show weaker immediate correlations, but at some sites, particularly Pardubice and Praha-Kbely, *HPU*3 becomes the key indicator of integrated subsurface dynamics. Pardubice exhibits the clearest and most physically interpretable signal, combining rapid responses to temperature and sunshine with a strong, delayed sensitivity to atmospheric humidity, forming a dual short-lag and long-lag signature that makes the site an excellent reference for model calibration. Chotusice, in contrast, shows only weak instantaneous links to meteorological variables but maintains a highly coherent soil profile. The most exceptional case is Praha-Kbely, where the deepest sensor displays inverted and unusually long-lag relationships, suggesting either a distinct sensor interpretation or a unique environmental regime.

Together, these findings highlight the need to account for both rapid surface-driven processes and slower subsurface adjustments when analyzing or modelling soil–atmosphere interactions. The diversity of response types across stations confirms that no single scaling or parameterization can capture the full soil profile dynamics; instead, the behavior is inherently site-specific. Nevertheless, the consistent detection of radiative and humidity-driven signals, albeit with different magnitudes and lag structures, shows that meaningful coupling exists across the network and can be robustly quantified. The results provide a solid empirical basis for further mechanistic modelling, lag-based causal analysis, and site-specific calibration of soil process models. These findings have direct implications for defence applications. The ability to predict soil response to atmospheric forcing enables improved terrain analysis, supports operational planning, and enhances environmental intelligence capabilities within military frameworks.

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