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LONG-TERM SOIL MOISTURE DYNAMICS IN A MINING REGION: TEMPORAL TRENDS AND SPATIAL PATTERNS FROM GLDAS NOAH DATA

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EXTENDED ABSTRACT

Questo studio analizza la dinamica spaziotemporale a lungo termine dell'umidità del suolo superficiale in una regione interessata da attività estrattive, con particolare enfasi sull'identificazione dei pattern di disseccamento persistenti e delle loro caratteristiche stagionali su un arco temporale di 25 anni. I dati mensili di umidità del suolo superficiale (profondità 0-10 cm) sono stati estratti dal modello numerico di superficie GLDAS Noah Land Surface Model per il periodo 2000-2024, fornendo un dataset coerente e spazialmente continuo, idoneo per analisi a scala climatica e di superficie. Lo strato di profondità selezionato risulta particolarmente rilevante per valutare le variazioni ambientali nei paesaggi minerari, poiché riflette direttamente le interazioni tra precipitazioni, evapotraspirazione, disturbi della copertura del suolo e alterazioni della struttura edafica. Integrando metodi statistici di identificazione dei trend con analisi spaziali e di persistenza, lo studio mira a fornire una comprensione esauriente dell'evoluzione dei regimi di umidità del suolo sotto l'influenza a lungo termine delle attività estrattive e del mutamento delle condizioni ambientali.Per quantificare i trend temporali, è stato applicato il test non parametrico di Mann-Kendall al fine di rilevare variazioni monotone statisticamente significative nelle serie temporali mensili di umidità del suolo, mentre lo stimatore della pendenza di Sen (Sen's slope estimator) è stato impiegato per misurare l'entità e la direzione di tali trend. Questi metodi robusti sono particolarmente indicati per dataset idroclimatici che possono presentare distribuzioni non normali e correlazione seriale. Le distribuzioni spaziali stagionali sono state esaminate per identificare la variabilità intra-annuale e per confrontare i pattern tra inverno, primavera, estate e autunno. Le anomalie di umidità del suolo sono state calcolate rispetto alla media a lungo termine, allo scopo di evidenziare gli scostamenti dalle condizioni basali (baseline) e di valutare l'intensità e la frequenza dei periodi siccitosi. Inoltre, sono stati condotti confronti spaziali tra l'anno iniziale (2000) e l'anno più recente (2024) per valutare le variazioni cumulative e visualizzare l'estensione del deficit idrico nella regione.I risultati rivelano un trend decrescente coerente e diffuso dell'umidità del suolo nella quasi totalità dei mesi durante il periodo di studio, indicando un progressivo disseccamento dello strato edafico superiore. Le diminuzioni più marcate e statisticamente significative si verificano nel tardo autunno e all'inizio dell'inverno, in particolare nei mesi di novembre e dicembre, in cui i trend negativi risultano pronunciati in ampie porzioni dell'area di studio. Tali evidenze suggeriscono che i processi di ricarica stagionale si stiano indebolendo, potenzialmente a causa di variazioni nei regimi precipitativi, dell'aumento dell'evaporazione, del disturbo della superficie del suolo o di alterazioni delle proprietà idrauliche del terreno associate alle attività estrattive. L'analisi spaziale stagionale conferma ulteriormente che le riduzioni dell'umidità del suolo non sono localizzate ma spazialmente estese, interessando la maggior parte della regione in tutte le stagioni. Il confronto tra il 2000 e il 2024 dimostra una netta transizione verso condizioni più asciutte, con anomalie negative che divengono più frequenti e spazialmente dominanti nel tempo.L'indice di Hurst è stato impiegato per valutare la memoria a lungo termine e le caratteristiche di persistenza della variabilità dell'umidità del suolo. I risultati indicano un comportamento persistente ($H>0,5$) prevalentemente durante i mesi autunnali e all'inizio dell'inverno; ciò implica che i deficit di umidità del suolo verificatisi in questi periodi tenderanno verosimilmente a continuare o a intensificarsi in futuro. Tale persistenza riflette una forte dipendenza temporale e suggerisce che i trend di disseccamento in queste stagioni siano strutturalmente intrinseci al sistema. Al contrario, i mesi primaverili ed estivi sono caratterizzati da un comportamento anti-persistente ($H<0,5$) o quasi casuale ($H\approx 0,5$), indicando una maggiore variabilità a breve termine e una più elevata sensibilità alle condizioni meteorologiche immediate. Tali differenze stagionali evidenziano la complessa interazione tra forzanti climatiche e processi di superficie in ambienti perturbati dalle attività estrattive.Nel complesso, i risultati dimostrano che il disseccamento del suolo nell'area di studio è cumulativo, spazialmente esteso e differenziato stagionalmente, con una persistenza a lungo termine particolarmente marcata nel tardo autunno e all'inizio dell'inverno. L'integrazione degli output dei modelli di superficie con l'analisi dei trend non parametrici, la valutazione delle anomalie, il confronto spaziale e la stima della persistenza fornisce un quadro metodologico completo per il monitoraggio del cambiamento ambientale nelle regioni minerarie.

Lo studio sottolinea l'importanza di una valutazione continua dell'umidità del suolo per la gestione ambientale, la pianificazione del ripristino topografico e ambientale (land reclamation) e le pratiche minerarie sostenibili, specialmente in condizioni di persistente disturbo del territorio e variabilità climatica. Identificando sia l'entità sia la persistenza del declino dell'umidità del suolo, la ricerca offre preziosi elementi di valutazione per i decisori politici e i tecnici orientati a mitigare la degradazione del suolo e a incrementare la resilienza degli ecosistemi nei paesaggi antropizzati dalle attività estrattive.

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ABSTRACT

This study examines long-term spatiotemporal trends of soil moisture in a mining region using monthly surface soil moisture (0-10 cm) data from the GLDAS Noah Land Surface Model for the period 2000-2024. Temporal trends were analyzed using the non-parametric Mann-Kendall test and Sen's slope estimator, while seasonal spatial patterns and soil moisture anomalies were used to assess long-term changes. In addition, the Hurst index was applied to evaluate the long-term memory of soil moisture variability. The results indicate a consistent declining trend in soil moisture across all months during the study period. The strongest decreases occur in late autumn and early winter, with November and December showing statistically significant downward trends. Spatial analysis reveals widespread soil moisture reductions across all seasons when comparing conditions in 2000 and 2024. Hurst index results show persistent behavior mainly in autumn and early winter months, indicating strong long-term memory and a tendency for soil moisture deficits during these periods to persist over time. In contrast, spring and summer months exhibit mainly anti-persistent or near-random behavior, reflecting greater short-term variability. Overall, the findings suggest that soil moisture drying in the study area is cumulative and long-lasting. This study demonstrates the usefulness of integrating land surface model data with trend and persistence analyses to better understand soil moisture dynamics in mining-affected regions and to support environmental management and land rehabilitation under changing mining conditions.

Keywords: *soil moisture, Mann-Kendall test, GLDAS, mining, spatiotemporal trends*

INTRODUCTION

The mining industry has always been one of the key sectors of Ukraine's economy (Bazaluk *et alii*, 2021). However, its activities create significant human impact on the environment. One of the most serious problems is the degradation of land resources (Zhang, 2023). Land loses its productivity and ecological stability because of mining operations. The development of open pits and underground mines destroys the natural landscape, creates waste rock dumps, and removes the fertile top layer of soil (Feng *et alii*, 2019). The extraction of minerals and surrounding rock further increases the size of the empty underground space. This leads to the expansion of the so-called depression cone (Bubnova, 2019), meaning that the direction and pressure of groundwater change. As a result, the natural water balance is disturbed. This can cause flooding in some areas or, on the contrary, drying of nearby territories. These changes in the water regime have a complex effect on the geomechanical conditions of technogenic objects and the quality of land plots. When groundwater levels rise, the land can become waterlogged and lose its fertility. When groundwater levels drop, there may be a lack of moisture, soil degradation, and reduced biological productivity. As a result, an unstable ecosystem is formed, which requires constant monitoring and land reclamation measures to restore the natural balance (Lapshyn & Shevchenko, 2025).

One of the main environmental measures for regional recovery is mandatory land reclamation. To determine the best methods for biological reclamation, it is necessary to analyze climatic conditions, soil moisture, groundwater depth, and the level of soil disturbance (Cooke & Johnson, 2002). These factors are important for choosing plant species that can adapt to specific conditions and for predicting how quickly the soil cover can recover. Climate determines temperature and rainfall, which affect plant growth. Soil moisture and groundwater levels form the water balance of the area, which is critical for biomass production. The degree of land disturbance helps to decide whether additional measures are needed, such as adding organic fertilizers, planting protective vegetation, or using biotechnologies to restore soil microbial activity.

Soil moisture is a key part of the land water cycle and is important for how ecosystems function. It controls how much water is available to plants, how much water evaporates from the land surface, and how groundwater is replenished (Wankmuller et al., 2024). Changes in soil moisture can affect crop production, the development of droughts, and the ability of natural and managed environments to cope with climate change (Liu *et alii*, 2020).

Mining is one of the most intensive forms of land disturbance. It strongly alters land cover by removing vegetation and soil, exposing rock surfaces, and changing the shape of the land (Xu *et alii*, 2023). These changes affect soil properties and water movement, leading to altered soil moisture conditions in and around mining areas (Lian *et alii*, 2021). When combined with ongoing climate changes, these impacts highlight the importance of carefully studying soil moisture variability in mining regions to support environmental management and land rehabilitation efforts (Blanche *et alii*, 2024). Recent contributions in engineering geology also highlight the critical role of analyzing interactions between geological processes and human activities for predicting environmental changes and supporting risk mitigation (George *et alii*, 2025). Such an approach is particularly relevant for mining-affected regions, where soil moisture dynamics reflect the combined influence of natural processes and anthropogenic disturbance, making them essential for environmental management and land reclamation planning. Despite its importance, long-term monitoring of soil moisture in mining areas is challenging due to sparse in situ observations, heterogeneous surface conditions, and the complex interplay of climatic and land surface processes (Ortenzi *et alii*, 2024). Remote sensing and land surface models have emerged as valuable tools for overcoming these limitations. In particular, the Global Land Data Assimilation System (GLDAS) provides physically-based estimates of soil moisture and related hydrological variables by integrating satellite observations with land surface modeling frameworks (Xiao *et alii*, 2016). Among the GLDAS model options, the Noah Land Surface Model has been widely used for hydrological and climatological studies owing to its capability to simulate soil water content across multiple layers and its robust parameterization of evapotranspiration and energy fluxes (Liang *et alii*, 2019). Numerous studies have utilized GLDAS and other large-scale datasets to examine soil moisture trends at regional to global scales. For example, Zhang *et alii* (2025) and Peng *et alii* (2023) documented widespread declines in soil moisture across several mid-latitude regions, attributing these trends to rising temperatures and increased atmospheric evaporative demand under a warming climate. Similarly, Sun *et alii* (2024) identified significant soil moisture reductions, linking these changes primarily to precipitation deficits and enhanced evapotranspiration. In mining-affected landscapes, existing studies have documented important changes in soil moisture related to land surface disturbance, subsidence, and altered hydrological pathways resulting from mining activities (Li *et alii*, 2924; Jing *et alii*, 2025). However, comprehensive analyses that integrate long-term temporal variability with spatial patterns of soil moisture across mining regions are still relatively scarce, highlighting the need for studies that assess cumulative and evolving hydrological impacts over extended periods. Trend detection methods such as the Mann-Kendall test and Sen's slope estimator have become standard approaches for identifying monotonic changes in hydrometeorological time series (Arra *et alii*, 2025). These non-parametric techniques are widely applied in drought and climate trend analyses because they are robust to non-normal distributions and missing data (Ozocak *et alii*, 2024). Recent applications to soil moisture time series have revealed significant temporal trends in both seasonal and monthly scales (Qiu *et alii*, 2026), highlighting the utility of these methods for detecting gradual hydrological shifts. Despite advances in remote sensing and statistical trend analysis, there remains a research gap in integrating high-resolution land surface model data with long-term trend detection specifically within regions affected by mining activities. Understanding both seasonal and monthly soil moisture trends is critical because soil water dynamics are strongly modulated by seasonal cycles of precipitation, temperature, and evapotranspiration (Liu *et alii*, 2024). Moreover, mining-induced disturbances may alter these cycles in ways not captured by broad-scale climate assessments (Babaremu *et alii*, 2024). Recent studies have further demonstrated the applicability of non-parametric trend detection methods, such as the Mann-Kendall test and Sen's slope estimator, in analyzing environmental changes across different land systems. For example, Ghaderpour *et alii* (2025) applied these methods to MODIS land cover/use time series across Italian administrative regions, revealing statistically significant transitions between major land cover types, such as a decline in grasslands and an increase in woodlands in several regions. Their findings highlight the effectiveness of Mann-Kendall-based approaches for detecting gradual environmental changes and supporting land management decisions. Similarly, Buczyńska *et alii* (2025) investigated surface water dynamics in a post-mining area in Poland using multi-source remote sensing and spatial statistical methods. Their results demonstrated significant spatiotemporal variations in surface water and vegetation water content, emphasizing the importance of integrating remote sensing data with statistical analysis to understand hydrological changes in mining-affected environments. These recent contributions confirm that combining remote sensing datasets with statistical trend analysis provides a powerful framework for monitoring environmental dynamics. However, most existing studies focus either on land cover change or surface water dynamics, while fewer studies specifically address long-term soil moisture variability with its persistence characteristics in mining regions.

Understanding long-term soil moisture dynamics in mining-affected regions is essential for effective environmental management and land reclamation planning. Soil moisture directly controls vegetation establishment, plant survival, and ecosystem recovery. In particular, knowledge of seasonal and long-term moisture availability is crucial for understanding hydrological conditions in disturbed environments and supporting environmental management strategies. Such information is also essential for selecting plant species adapted to site-specific conditions and improving biological reclamation success (Muzzillo *et alii*, 2024). Furthermore, identifying persistent drying trends allows for early anticipation of soil water deficits, which may constrain reclamation efforts and require adaptive management approaches. Despite the growing availability of remote sensing products and land surface models, several research gaps remain. First, most existing studies focus either on temporal trends or spatial patterns of soil moisture, while integrated analyses combining both aspects over long time periods in mining regions are still limited. Second, the persistence characteristics of soil moisture variability, which are important for understanding long-term system behavior, are rarely investigated in disturbed environments. Third, the practical implications of soil moisture changes for land reclamation and environmental management are often not explicitly addressed. To address these gaps, this study aims to investigate long-term soil moisture dynamics in a mining region using GLDAS Noah Land Surface Model data from 2000 to 2024. Specifically, the main contributions of this research are:

- quantification of long-term temporal trends in soil moisture using the Mann-Kendall test and Sen's slope estimator;

- analysis of monthly spatial patterns and their changes over time to identify areas and periods of significant moisture decline;
- evaluation of persistence and long-term memory of soil moisture variability using the Hurst index;
- interpretation of soil moisture dynamics in the context of environmental management and biological land reclamation in mining-affected regions.

The remainder of this paper is organized as follows. Section 2 describes the study area, data sources, and methodology. Section 3 presents the results of temporal trend analysis, spatial distribution, and persistence assessment. Section 4 discusses the implications of the findings in relation to mining impacts and environmental management. Finally, Section 5 summarizes the main conclusions and outlines directions for future research.

MATERIALS AND METHODS

Study area

The study area is located in the Kryvyi Rih Iron Ore Basin, situated in south-central Ukraine. Fig. 1 represents the geographical location of Kryvyi Rih Iron Ore Basin on the map of Ukraine. Kryvyi Rih represents one of the largest and oldest mining and metallurgical regions in Eastern Europe and is a nationally significant center of iron ore extraction and processing (Bazaluk *et alii*, 2024). The study area exhibits relatively gentle regional topography, however significant local topographic variability is observed within the mining zone. Elevation minimum of around -300 m corresponds to open-pit mining areas.

Mining in Kryvyi Rih is carried out using both open-pit and underground methods, making it one of the most intensively exploited mining landscapes in Europe. The mining corridor enclosed by the red rectangle in Fig.1 includes both surface and underground extraction systems. Among them, there 9 active open-pit mines and 8 active underground iron ore mines. This area also contains more than 35 closed mines and at least 10 large closed open-pit quarries. According to statistical data from the official reports (Bazaluk *et alii*, 2021; Mykhailov, 2024), mining enterprises of the Kryvbas region extract more than 150 million tons of iron ore every year (Fig. 2). In addition, about three times more waste rock is removed from the surrounding rock mass to provide access to the productive ore layer.

Large mines represent the most visible land disturbance features and include pits exceeding several kilometers in length and hundreds of meters in depth (Fig. 1). These open pits are accompanied by extensive waste rock dumps and tailings storage facilities. Underground mining is also widespread, particularly in deeper ore bodies, and contributes to surface subsidence zones that further modify land surface morphology and hydrological pathways. The long history of mining activity has resulted in profound transformation of the natural landscape. Large areas have experienced complete removal of soil and vegetation cover, exposure of bedrock, and the creation of technogenic landforms such as spoil heaps and reclaimed dumps (Bazaluk *et alii*, 2024; Bubnova *et alii*, 2025). These disturbances significantly

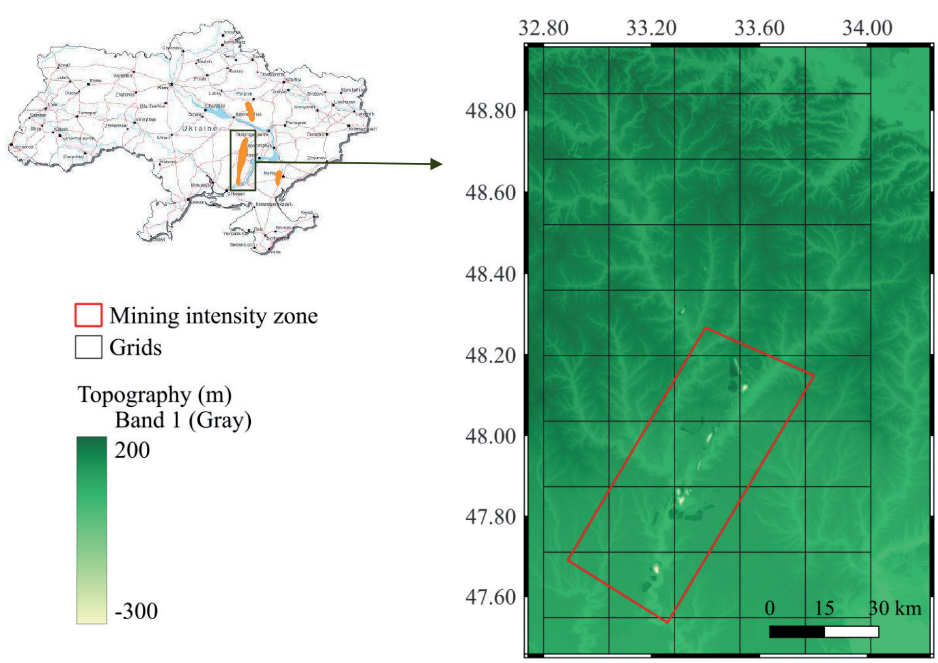

Fig. 1 - Kryvyi Rih iron ore basin: study area, including topography, analysis grid, and major mining area shown in red rectangle

alter soil structure, porosity, and hydraulic properties, affecting infiltration, runoff generation, and soil moisture retention. As a result, the Kryvyi Rih region exhibits highly heterogeneous surface conditions, with strong contrasts between undisturbed areas, reclaimed lands, and actively mined zones.

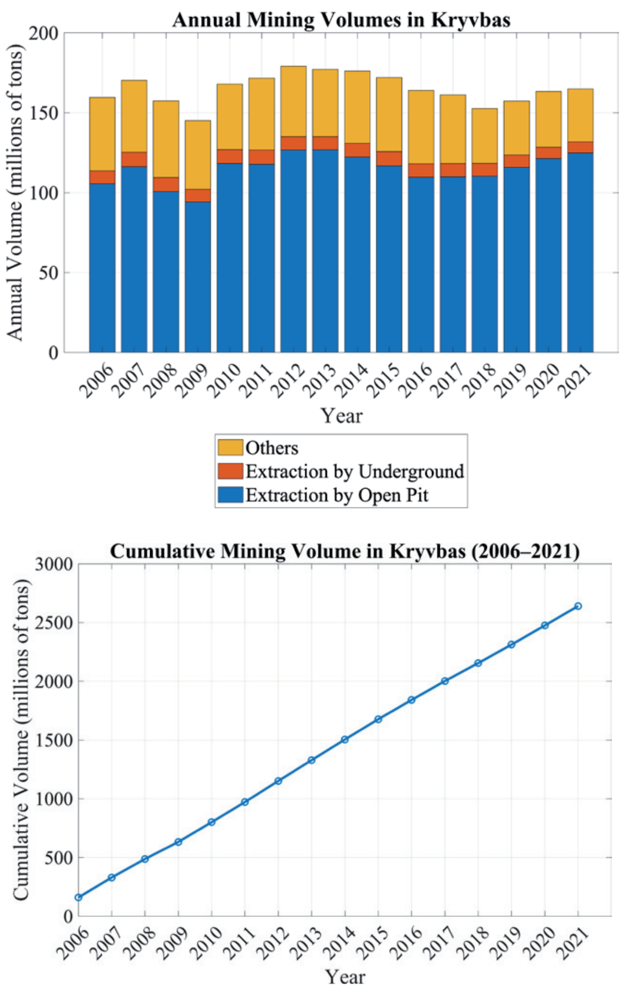

Fig. 2 - Iron ore volumes in Kryvyi Rih: (top) annual iron ore production by mining enterprises; (bottom) total volume of extracted material including waste rock (data for 2022 - 2025 are not available due to the military actions in Ukraine)

Data sources

Soil moisture data were taken from the NASA Giovanni Earth Data open-source platform, which provides access to various environmental satellite-based and model-based datasets, including both short- and long-term temporal resolutions. In this research, we used a soil moisture dataset obtained from the GLDAS Noah Land Surface Model version 2.1. This dataset includes in situ meteorological measurements such as precipitation, wind speed and direction, humidity, and air temperature, as well as combined data from various satellite observations and atmospheric reanalysis products that incorporate historical data with models. Variables represent 10 cm of depth thickness from the surface and are measured in kg per m². Surface soil moisture of 10 cm was selected due to its highest sensitivity to various surface processes, including those of mining, therefore making it suitable for assessing the impact of mining activities on it (Dorigo *et alii*, 2017). The spatial resolution was 0.25 degrees, which means that the Earth's surface is divided into equal rectangular cells, each measuring 0.25 degrees of latitude and longitude. The study area was divided into 0.25° × 0.25° grids to match the spatial resolution of the satellite-derived soil moisture product used in this study (approximately 27-28 km at the study latitude). The mining complexes in the Kryvyi Rih iron-ore basin are spatially elongated and occur as a north-south corridor consisting of active open-pit mines, underground operations, waste dumps, and abandoned or reclaimed mining areas. Since individual mining sites are substantially smaller than a single satellite pixel and their influence on land-surface conditions extends beyond the excavation boundaries, restricting the analysis only to the active mining footprint would not adequately represent the soil moisture signal observed by the satellite sensor. Therefore, the selected grid extent was intentionally designed to include both the active mining zone in the southern section of the study area (red rectangle in Fig. 1) and the broader northern section containing abandoned mines, historical open pits, and associated disturbed land surfaces. The temporal resolution was selected to be a monthly interval covering the period from 2000 to 2024. To analyze long-term spatiotemporal trends of soil moisture, a time series of area-averaged variables was derived by averaging each grid within the study region. The resulting time series were then used as input in the Mann-Kendall test for spatiotemporal trend analysis. Fig. 3 illustrates monthly distributions using box plots,

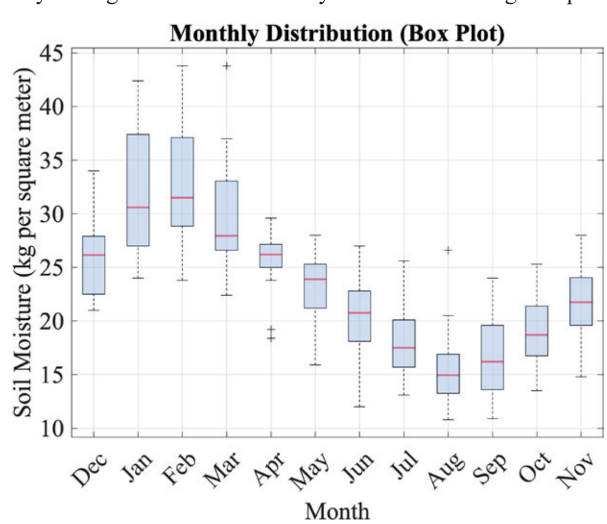

Fig. 3 - Box plots of monthly distribution of soil moisture data for 2000-2024-time window

	Max	Min	Range	Mean	Median	Mode	St. Dev.	Kurtosis	Skewness
Jan	42.40	24.00	18.40	31.49	30.30	37.90	5.66	-1.03	0.46
Feb	43.80	23.80	20.00	32.92	31.20	43.80	6.34	-0.87	0.50
Mar	43.80	22.40	21.40	29.61	27.90	37.00	5.19	0.75	0.99
Apr	29.60	18.40	11.20	25.89	26.40	27.00	2.59	3.19	-1.58
May	28.00	15.90	12.10	23.26	23.90	23.90	2.82	0.50	-0.68
June	27.00	12.00	15.00	20.48	20.80	22.80	3.49	0.29	-0.23
July	25.60	13.10	12.50	17.96	17.60	15.40	2.99	0.22	0.58
Aug	26.60	10.80	15.80	15.31	14.90	14.70	3.33	4.54	1.64
Sep	24.00	10.90	13.10	16.46	16.00	12.50	3.77	-0.75	0.33
Oct	25.30	13.50	11.80	19.08	18.60	18.60	3.15	-0.71	0.26
Nov	28.00	14.80	13.20	21.93	21.80	23.00	3.17	-0.32	-0.10
Dec	34.00	21.00	13.00	25.88	26.30	26.70	3.46	-0.43	0.37

Tab. 1 - Descriptive statistical summary of soil moisture monthly values

where each box summarizes the spread of yearly observations, and Table 1 provides the corresponding descriptive statistics.

The descriptive statistics in Table 1 describe how the values change from month to month over the 25-year period and represent averages calculated over the entire study area (i.e., all grid cells). The mean values clearly show a seasonal pattern: the highest values occur in winter (January and February), while the lowest values are observed in summer (July and August). The median values are close to the means in most months, which means the data are not strongly affected by extreme values. Larger standard deviations (St. Dev.) in winter and early spring (especially January-March) indicate that the values vary more during these months than in others. Skewness shows that some months have more occasional high values (for example March and August), while other months have more low values (such as April and May). Most months have kurtosis values close to zero, suggesting the data follow a roughly normal distribution, although April and August show more concentrated values with a few stronger extremes.

Mann-Kendall trend test

Long-term trends in soil moisture were analyzed using the Mann-Kendall trend test, which is widely used in various environmental studies. This test is particularly suitable for soil moisture time series because it does not assume a normal data distribution which makes it thus statistically robust. In particular, the Mann-Kendall test examines whether a time series exhibits a monotonic trend over time. For the time series [x_1, x_2, …, x_n], the statistics *S* is calculated by comparing each data point with all subsequent data points as shown in equations (1-2) (Geng *et alii*, 2021).

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \quad (1)$$

$$sgn(x_j - x_i) = \begin{cases} +1, & if\ x_j - x_i > 0 \\ 0 & if\ x_j - x_i = 0 \\ -1, & if\ x_j - x_i < 0 \end{cases} \quad (2)$$

where *n* is total number of observations in the time series; *i* and *j* are indexes of the earlier and later observations, respectively; $sgn(x_j - x_i)$ is sign function that compares two observations; x_i and x_j are soil moisture value at time *i* and *j*, respectively.

A positive value of *S* indicates an increasing trend in soil moisture, while a negative value indicates a decreasing trend. For large sample sizes (*n*>10), the statistic *S* is defined using equation (3).

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k(t_k-1)(2t_k+5)}{18} \quad (3)$$

where *Var(S)* is variance of the Mann-Kendall statistic; *n* represents the total number of observations; t_k is the number of tied values in the *k-th* group of ties; and *m* is the number of tied groups.

The standardized test statistic *z* is defined as shown in equations (4).

$$z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if\ S > 0 \\ 0, & if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if\ S < 0 \end{cases} \quad (4)$$

where *z* is defined as standardized Mann-Kendall test statistic; S is the Mann-Kendall statistic; *Var(S)* is variance of *S*.

The significance of trend is evaluated using the p-value associated with the standard normal distribution. A trend is considered statistically significant if the p-value is less than the selected significance level (in this study, α=0.05).

To estimate the magnitude of the trend, Sen's slope estimator is used. It is calculated as the median of all pairwise slopes as it is shown in equation (5). A positive Sen's slope indicates increasing trend, while a negative one indicates a decreasing trend.

$$\beta = median\left(\frac{x_j - x_i}{j-i}\right), \quad \forall\ j > i \quad (5)$$

where *β* represents the Sen's slope estimator or magnitude of trend; x_i and x_j are soil moisture values at time *i* and *j*, respectively.

Hurst index analysis

The Hurst index is a statistical method originally proposed by the British hydrologist Hurst and later improved by Mandelbrot and Wallis (Geng *et alii*, 2021). It is based on rescaled range *R/S* analysis and is widely used to analyze the long-term behavior of time series. In this study, the soil moisture time series is analyzed using the Hurst index to assess whether future changes are likely to follow past trends. The analysis compares the cumulative variability of the given time series with its standard deviation over different time scales. The Hurst index *H* is calculated using the rescaled range relationship as shown in (6).

$$\frac{R}{S} \propto \tau^H \quad (6)$$

where *R* is the range of cumulative deviations from the mean, *S* represents the standard deviation of the time series, and τ is the length of the time window.

The Hurst index ranges from 0 to 1 and is interpreted as follows (Geng *et alii*, 2021):

- $0<H<0.5$: the time series shows anti-persistence, meaning future variations tend to reverse past trends;
- $H=0.5$: the time series behaves like a random process with no dependence on past behavior;
- $0.5<H<1.0$: the time series shows persistence, meaning future changes tend to continue past trends.

RESULTS

Temporal trends of soil moisture

The temporal analysis of soil moisture shows clear variations over time, with an overall tendency toward decreasing soil moisture across most months during the study period. The Mann-Kendall trend analysis indicates that all months have negative statistics (S) and negative Sen's slope values, suggesting a general decline in soil moisture over time. Monthly time series plots (Fig. 4) reveal strong

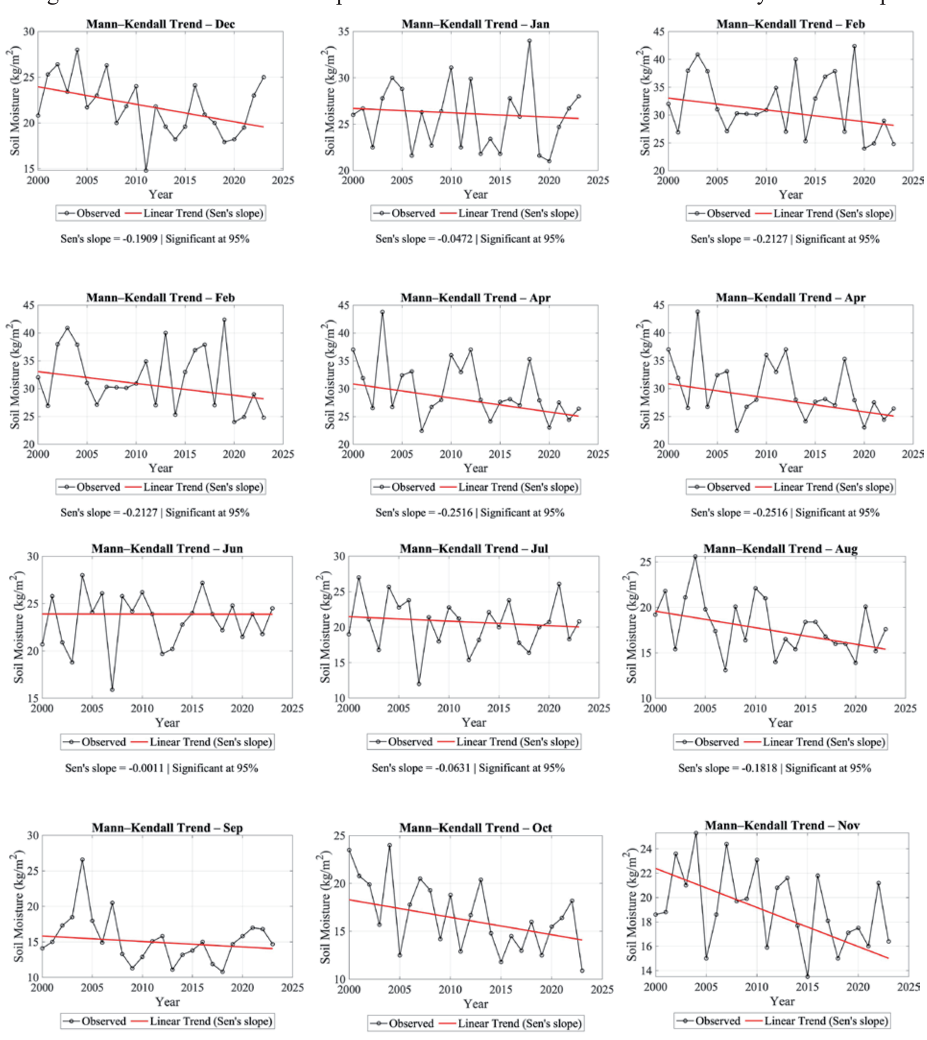

Fig. 4 - Monthly soil moisture time series and Mann-Kendall trend analysis for the period 2000-2024. Linear trend is estimated using Sen's slope

interannual variability, with frequent fluctuations between wetter and drier years. However, despite these short-term variations, the fitted trend lines show a downward tendency across all months.

The anomaly heatmap shown in Fig. 5 further supports this pattern. Earlier years are characterized by more positive anomalies, especially during winter and spring months, indicating above-average soil moisture conditions. In contrast, more recent years show a dominance of negative anomalies across most months, particularly after the mid-2000s. This shift toward negative anomalies reflects an increasing frequency of drier-than-average conditions over time.

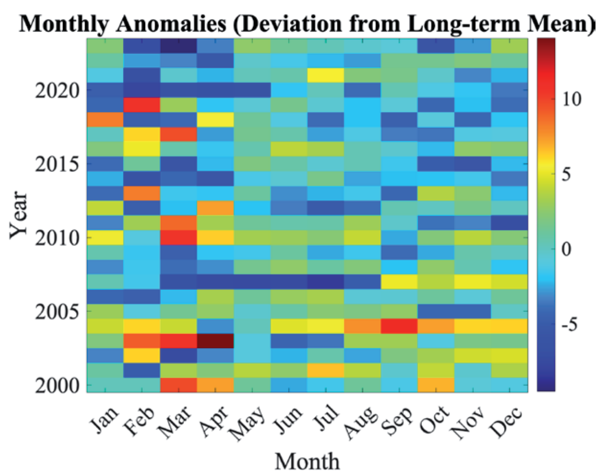

Fig. 5 - Heatmap of monthly soil moisture anomalies relative to the long-term mean (2000-2024)

Based on the Mann-Kendall test results in Table 2, all months show a statistically significant decrease in soil moisture. This is confirmed by the negative z-values (from -2.0000 to -2.6293) and p-values below 0.05. The Sen's slope values are also negative in every month, which means soil moisture is consistently decreasing over time throughout the year. The strongest decrease is in November (z=-2.6293, Sen's slope=-0.3211), followed by March (-0.3238), April (-0.2516), and December (-0.1909). These months are important for soil water recharge, but the results show that this recharge is getting weaker, especially in late autumn, winter, and early spring. In summer months like June and July, the decrease is smaller, but still present. Overall, the results clearly show a steady and significant decline in soil moisture in all months, with stronger drying during the main recharge seasons.

Spatial distribution of soil moisture time series

The spatial distribution of soil moisture shows clear seasonal differences across the study area in both 2000 and 2024. In general, soil moisture is highest during winter, decreases in spring, reaches its lowest levels in summer, and begins to recover in autumn. However, when comparing the two years, a clear reduction in soil moisture is observed in all seasons. Figure 6 illustrates the soil moisture spatial distribution across all seasons.

In winter 2000 (Fig. 6a), most of the study area shows relatively high soil moisture values, indicating strong soil water storage during this season. In winter 2024, soil moisture remains higher than in other seasons, but overall values are lower than in winter 2000. The difference map confirms a widespread decrease in winter soil moisture, suggesting that winter water availability has declined over time. Spring soil moisture (Fig. 6b) also shows a noticeable decrease between 2000 and 2024. In 2000, moderate to high soil moisture is observed across most of the area, reflecting the influence of winter precipitation. In contrast, spring 2024 displays lower values over large regions. The difference map highlights strong negative changes, indicating that spring soil moisture has experienced one of the largest declines among all seasons. Summer (Fig. 6c) is characterized by the lowest soil moisture levels likely due to high temperatures and increased evapotranspiration. Both years show generally dry conditions; however, summer 2024 is consistently drier than summer 2000. The negative differences across most of the area indicate intensified summer drying over the study period. In autumn (Fig. 6d), soil moisture begins to increase after the dry summer period, but values remain lower than in winter and spring. Compared to 2000, autumn 2024 shows reduced soil moisture across much of the region. The difference map indicates that soils enter the wet season in a drier state than in the past, suggesting delayed or weakened soil moisture recovery.

Month	Mann-Kendall statistics (S)	z-value	p-value	Sen's slope	Trend
January	-17	-2.0039	0.0450	-0.0472	Downward
February	-62	-2.0500	0.0130	-0.2127	Downward
March	-63	-2.0800	0.0124	-0.3238	Downward
April	-71	-2.1073	0.0282	-0.2516	Downward
May	-10	-2.0000	0.0450	-0.0100	Downward
June	-12	-2.0248	0.0098	-0.0011	Downward
July	-25	-2.0353	0.0451	-0.0631	Downward
August	-74	-2.1218	0.0401	-0.1818	Downward
September	-41	-2.0121	0.0321	-0.0769	Downward
October	-70	-2.1015	0.0469	-0.1825	Downward
November	-107	-2.6293	0.0085	-0.3211	Downward
December	-81	-2.0094	0.0472	-0.1909	Downward

Tab. 2 - Monthly Mann-Kendall trend test results for soil moisture

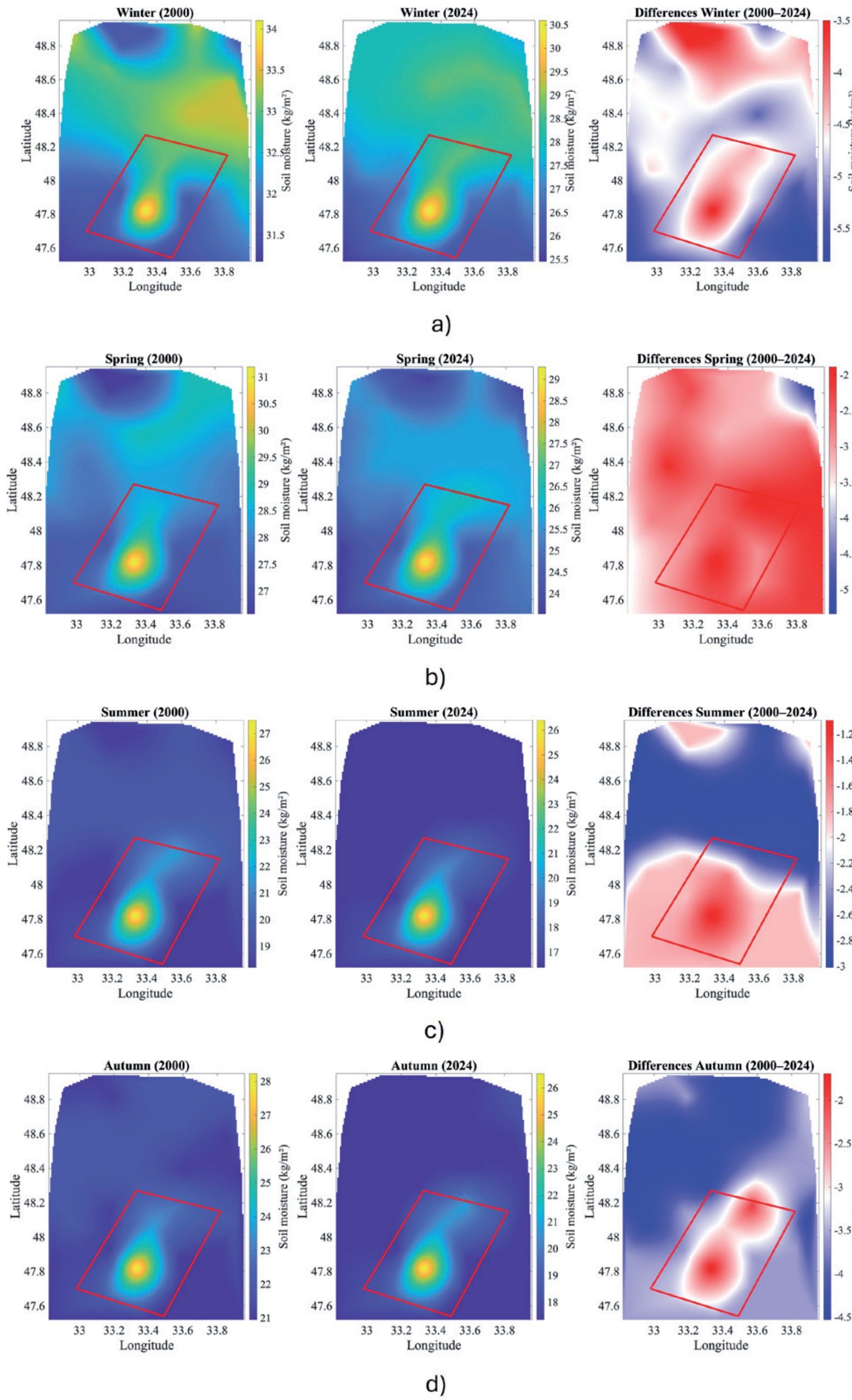

Fig. 6 - Seasonal spatial distribution of soil moisture in 2000 and 2024 and their differences across the study area. Red rectangle indicates area of intensive mining operations

Soil moisture persistence based on the Hurst Index

The Hurst index analysis reveals clear differences in the long-term memory characteristics of soil moisture across months. Fig. 7 shown the monthly Hurst Index results. Anti-persistent behavior (H<0.5) is observed in January, March, May, June, and July, indicating that soil moisture variations during these months tend to reverse over time, and future changes are less likely to follow past fluctuations. February, April, and August show Hurst values close to 0.5, suggesting a largely random behavior with weak dependence on previous conditions. In contrast, September, October, November, and December exhibit persistent behavior (H >0.5), implying that soil moisture changes during these months are more likely to continue in the same direction as past trends. Notably, the strongest persistence is detected in December and September, indicating a pronounced long-term memory in late-year soil moisture dynamics. Overall, the Hurst index results suggest that soil moisture persistence is more prominent in autumn and early winter months, while spring and summer months tend to exhibit more reversible or random variability.

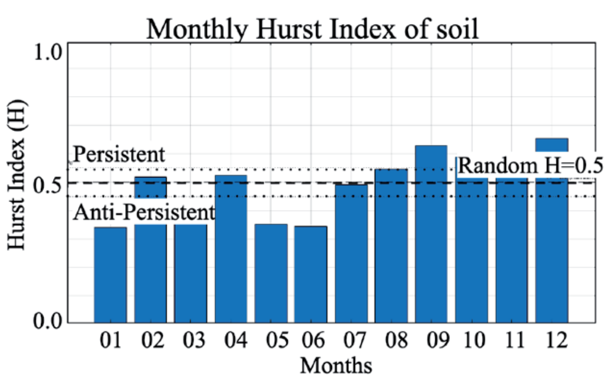

Fig. 7 - Monthly Hurst Index and persistence behavior of soil moisture time series

DISCUSSIONS

The analysis of soil moisture in the Kryvyi Rih Iron Ore Basin reveals a widespread and progressive decline across all months over the study period (2000-2024), with the most pronounced and statistically significant reductions observed in late autumn and early winter, particularly November and December. These months are critical for soil water recharge, and declines during this period may have cascading effects on both natural ecosystems and surrounding agricultural lands. Such patterns are consistent with findings from other mining-affected regions, where extensive soil disturbance, vegetation removal, and altered hydrological regimes intensify drying trends (Zhao *et alii*, 2025). Spatial trends further indicate that soil moisture reductions are not confined to a single season but occur throughout the year. Spring and summer exhibit substantial declines, suggesting that mining operations significantly impact seasonal hydrology. The highest soil moisture values observed near 33.4°E-47.8°N across all seasons in both 2000 and 2024 correspond to the core active mining sector of the study area. Although mining activities are commonly associated with land degradation and reduced water retention capacity, active mining areas may locally exhibit higher soil moisture than surrounding non-mining regions due to altered topography and hydrological redistribution processes. Large open-pit excavations create low-elevation depressions that promote the accumulation of precipitation, surface runoff, and groundwater inflow from adjacent areas. In addition, exposed fine-grained materials, waste deposits, and modified surface conditions can temporarily retain moisture and contribute to localized increases in soil water storage. Consequently, these mining zones may act as moisture accumulation areas and therefore exhibit higher absolute soil moisture values than nearby undisturbed landscapes. However, despite the relatively elevated values within the mining sector, the difference maps (Fig. 6) reveal a persistent long-term decline in soil moisture between 2000 and 2024, with reductions of approximately 2 kg/m² across most seasons and reaching approximately 4 kg/m² in winter. This indicates that while active mining zones retain comparatively higher moisture levels than surrounding areas, they are still undergoing progressive moisture depletion over time. Excavation of large open pits alters local topography, reduces vegetation cover, and exposes soil surfaces to increased evaporation and surface runoff, which decreases infiltration efficiency and enhances drainage losses. Therefore, results reflect two concurrent processes: localized moisture accumulation within topographic depressions associated with mining activity and a broader long-term decline in soil moisture caused by continued landscape disturbance and mining expansion. The presence of persistent moisture deficits in autumn and early winter, as evidenced by the Hurst index, indicates that these drying trends are not merely transient but may reflect long-term memory effects in the soil water system (Mao *et alii*, 2024).

Summer drying appears to be influenced by a combination of climatic and anthropogenic factors. In addition to rising regional temperatures and variable precipitation, large exposed pit surfaces increase solar radiation exposure, enhancing evapotranspiration and further reducing soil moisture availability (Berg & Sheffield, 2018). The cumulative effects of these processes may exacerbate soil water scarcity during critical growing periods, potentially impacting both crop productivity and the resilience of local vegetation. The identified patterns of gradual soil moisture reduction have a negative impact on land reclamation and the productivity of agricultural lands. At the same time, from another research perspective, this dynamic has a positive effect on the geomechanical condition of technogenic and natural objects within the studied region. A decrease in soil moisture improves the stability of tailings dam structures, waste dump slopes, and open-pit quarry walls, which will be investigated in the next stage of the research.

While this study provides important insights into long-term soil moisture dynamics, several limitations must be considered. The reliance on satellite-based GLDAS Noah model data introduces inherent uncertainties associated with input data sources (e.g., satellite retrieval errors, in situ measurement sparsity, and reanalysis assimilation biases) as well as model structural assumptions and parameterizations governing land surface processes. These uncertainties may influence the accuracy of simulated soil moisture, particularly in heterogeneous environments such as mining landscapes where local conditions can deviate from generalized model representations. In addition, the GLDAS framework may not fully capture fine-scale heterogeneity within the mining landscape, particularly in areas with complex terrain or small-scale reclamation efforts. Moreover, specific mining practices, such as water management in tailings ponds, groundwater extraction, or soil rehabilitation techniques, were not explicitly incorporated into the model structure, which may further contribute to representational uncertainty. Future studies should combine higher-resolution remote sensing with in-situ soil measurements and hydrological modeling to better constrain these uncertainties and disentangle the relative contributions of mining activities and climatic variability. Such integrated analyses would provide a more robust basis for sustainable land and water management in Kryvyi Rih and other intensive mining regions. Finally, the observed persistence of soil moisture deficits in autumn and early winter highlights the potential for cumulative effects of mining disturbance on soil hydrology. These persistent deficits suggest that once soils enter the colder months in a drier state, recovery is limited, potentially affecting soil fertility, erosion susceptibility, and water availability in subsequent seasons. Environmental management strategies should therefore prioritize mitigation measures that enhance water retention, restore vegetation cover, and minimize further disruption to natural hydrological processes.

The identified relationships indicate climate change in the region, particularly a decrease in annual precipitation. These changes are intensified by mining activities. The increase in the volume of mined-out space leads to the expansion of depression cones. As a result, the natural hydrological balance worsens, groundwater and underground water pressure decreases, and soil moisture is reduced (Kopach *et ali*, 2022). The land reclamation process is long-term. The restoration of soil fertility and stabilization of the ecosystem can take decades and requires continuous investment in maintenance and monitoring. Biological reclamation involves significant financial costs because it includes soil preparation, application of organic and mineral fertilizers, planting vegetation communities, and long-term monitoring to support their development. To avoid wasting time and money, it is proposed to optimize costs by creating stable and self-sustaining ecosystems. In future research, the obtained results will be used to justify the selection of plant species that can adapt to specific environmental conditions and to predict the rate of soil cover restoration.

CONCLUSIONS

This study demonstrates a long-term decline in soil moisture across the Kryvyi Rih mining region, with the most pronounced and persistent reductions occurring across all months and especially in late autumn and early winter. Spatial analysis confirms that these declines are widespread across seasons, reflecting the combined influence of intensive mining disturbance and regional climatic variability. Hurst index analysis indicates that soil moisture deficits during autumn and early winter exhibit strong persistence, suggesting that these drying trends are likely to continue over time. Overall, the findings underscore the need for long-term monitoring and integrated water and land management strategies in mining-affected regions. Addressing persistent soil moisture deficits through targeted reclamation, vegetation restoration, and hydrological interventions can help mitigate environmental impacts and enhance ecosystem resilience.

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