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Research paper

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Geoinformation analysis of the spatial distribution of soil quality indicators in terms of water erosion

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Summary

Soil organic carbon, clay content and cation exchange capacity play a key role in the productivity of agricultural soils, and are therefore fundamental parameters for environmental monitoring and modelling. However, studying these properties using traditional laboratory methods is labour-intensive and costly. An equally important factor is the steepness of slopes, which affects erosion processes and nutrient distribution in the soil. Geospatial analysis is a powerful tool for examining spatial patterns and the distribution of various indicators. When assessing soil quality indicators, GIS technologies enable the accurate and detailed monitoring of soil conditions in various areas, the assessment of their characteristics, and the identification of potential problem areas. This study presents observation and analysis of the impact of soil quality indicators, including soil organic carbon (SOC), physical clay, and cation exchange capacity (CEC), on the development of soil quality degradation using SoilGrids 250 m 2.0 data. To estimate the level of erosion, a slope steepness map was generated using the SRTM digital elevation model, which was downloaded through Google Earth Engine at a 30-m resolution. The results showed that high organic carbon content and optimal CEC values reduce soil vulnerability to the development of erosion, while steep slopes and low organic carbon content increase the risk of degradation. The vulnerability index developed based on these data allows us to effectively identify areas at high risk of soil degradation and develop protection strategies.

Keywords

geoinformation analysis • soil erosion • erosion vulnerability • organic carbon • global GIS products

1. Introduction

Soil erosion and soil degradation are processes that deteriorate soil natural properties, damaging the most vulnerable components and causing loss of organic matter and nutrients. As a result of erosion processes, the supply of macronutrients, such as phosphorus, calcium, nitrogen, and carbon, changes significantly. Even moderate erosion can harm agricultural productivity, biodiversity, and management conditions [Kanianska 2024]. The primary factor in the intensification of erosion processes is anthropogenic impact, specifically excessive tillage and grazing, inappropriate agricultural practices, deforestation, construction, and urbanisation [Zhang et al. 2023].

Erosion leads to the movement and redistribution of soil organic carbon (SOC) in the soil profile, significantly reducing its content [Yang et al. 2023]. SOC improves the physical properties of the soil, which contributes to more effective moisture retention from precipitation and ensures its availability to crops. As the depletion of organic carbon in agricultural soils increases, soil degradation is exacerbated [Ajai and Bhatnagar 2022].

Soil type is also important: sandy soils, due to their loose structure, are more susceptible to water erosion, while clay soils, although more cohesive, are prone to the formation of surface crusts, reducing water absorption capacity and increasing surface runoff [Firoozi and Firoozi 2024]. Soil structure determines its susceptibility to erosion. Soils with a medium to fine-grained texture, low organic matter content and poor structural development are most vulnerable to erosion. Such soils typically have a low water infiltration rate, which leads to high rates of water erosion, and soil particles are easily displaced by the wind [Bajracharya and Lal 1992].

It is well established that soil texture, including the content of clay and silt, can significantly impact the soil's capacity to store organic carbon [Vaidya et al. 2024]. Clay is responsible for the specific characteristics of soils. Clay particles can either be grouped in small clusters or spread out. They typically possess a high cation exchange capacity and can bind to various chemical elements, such as calcium, sodium, potassium, and magnesium. Thus, nutrients for plants are retained in the soil, and clay-rich soils tend to provide higher levels of nutrients [Samuel and Dines 2023].

Cation exchange capacity (CEC) is the ability of soil and other solid materials to adsorb exchangeable cations. The cation exchange capacity (CEC) of a soil can be influenced by properties such as pH, organic carbon content, and particle size distribution [Mukherjee and Zimmerman 2013, Hazelton et al. 2016, Adam et al. 2021]. Soil CEC is a key indicator that translates to soil quality, which in turn is largely influenced by land use and agricultural practices [Mishra et al. 2022]. This indicator is important for assessing soil fertility, as it facilitates the provision of essential nutrients to plants and mitigates their losses due to leaching [Cocco Lago et al. 2021].

Topographic factors, such as slope steepness and length, determine the rate of runoff and sediment transport capacity, which intensifies erosion processes on steep slopes [Firoozi and Firoozi 2024]. Slopes with steepnesses of 8–15%, 15–25%, and 25–40% are considered vulnerable to erosion, therefore they require special attention and protection measures [Siswanto and Sule 2019]. Natural ecosystems also suffer losses from erosion, especially along the banks of streams. Such erosion occurs naturally due to the force of nearby moving water. Significant soil loss is observed on steep slopes (30% or more), where streams cut through adjacent land. Even on a relatively flat surface with a slope of only 2%, stream banks can be eroded, particularly during heavy rainfall and flooding [Pimentel 2006].

Therefore, the aim of this article is to investigate the spatial distribution of soil quality indicators in the Lokhvytskyi district of the Poltava region, and to assess the soil's vulnerability to water erosion. The results obtained will contribute to the development of an effective plan for preserving and improving soil quality, which is crucial for the sustainable development of agriculture and maintaining ecological balance in the region.

2. Description of the study area

Lokhvytskyi district is located in the central part of Ukraine, within the forest-steppe zone, characterised by a temperate continental climate. The region can be described as warm and lacking humidity. The average annual precipitation amounts to 459–555 mm. At the same time, 68–72% of precipitation falls during the warm period from April to October. In dry years, the amount of precipitation in May is especially low. According to average long-term data, soil freezing typically begins in November, and thawing occurs in March. The depth of soil freezing during the winter period varies within the following limits: average, 61–70 cm; largest, 87–114 cm; smallest, 25–46 cm. The frost-free period lasts from 155 to 175 days.

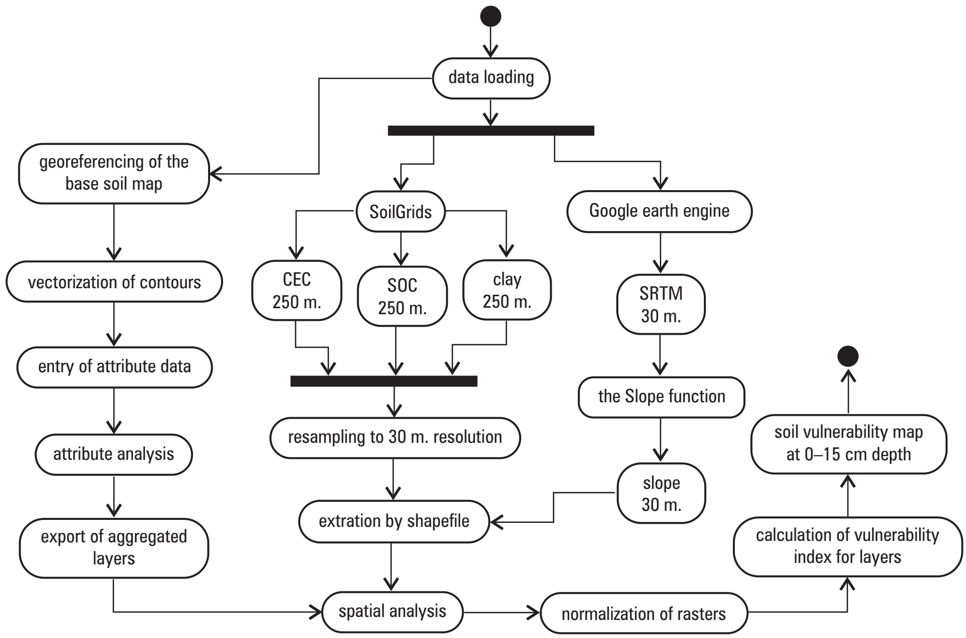
The relief of the district belongs to the Poltava Plain – a low-lying, gently undulating loess plain, dissected by river valleys, gullies and ravines. Majority of the landscapes are forests and steppes. Due to intensive agricultural activity, natural habitats have not been preserved, and anthropogenic, mostly agricultural, landscapes are now predominant.

The largest share of water erosion in the Poltava region is observed in areas with significant elevation differences and increased forest cover, in particular in the Lokhvytsky district. This is explained by the fact that the territory of the Poltava region belongs to the East Ukrainian forest water protection province, which is characterised by the highest share of water protection forest cover among the regions of Ukraine – 69.9% [Lashko et al. 2021].

The total area of the district is 13,057 km². The area of highly eroded soils is 209.8 km², moderately eroded soils are 714.0 km², slightly eroded soils are 1,730.8 km², and eroded soils are 33.8 km². The elevation variation in the study area is from 91 to 199 meters. The average elevation of the region is 132 m above sea level [Temna and Kokhan 2024].

3. Materials and methods

A vector map of the soils of the Lokhvytskyi district on a scale of 1:200,000 was used, digitised on the basis of large-scale soil research data using ArcGIS Desktop 10.8 software. In addition, an attribute database was created that contains the name of the soil, the agro-production group of the soil, and the area of the soil contour. Attribute analysis, which includes sampling by attributes, was used to group a large data set. Plots with the same agro-industrial group were grouped, which were then exported to new layers and a soil map was created. The sequence of the main stages of preliminary and thematic data processing is presented in Figure 1.



Source: Author's own study

Fig. 1. Diagram of pre-processing and thematic data processing activities

The next step was to obtain the SRTM digital elevation model in GeoTIFF format for the Lokhvytsky district of the Poltava region with a 30-metre resolution directly from the Google Earth Engine (GEE) platform. Further processing was carried out in ArcGIS Desktop 10.8. Using the Slope function applied to the SRTM digital terrain model, a slope steepness map in degrees was generated and divided into five classes.

SoilGrids 250 m 2.0 data, namely: clay content in g/kg; soil organic carbon content in g/kg; cation exchange capacity buffered at pH 7 in mmol(c)/kg at 6 standard depths – were loaded with a spatial resolution of 250 m for the period 1950–2020. Separate layers obtained for depths of 0–5 cm and 5–15 cm were transformed in ArcGIS Desktop 10.8. to a spatial resolution of 30 meters and extracted according to the territory's boundary.

The study determined the soil vulnerability index for the 0–15 cm layer by combining a few factors, including clay content, organic carbon, cation exchange capacity, and slope degree. This index is a generalised numerical indicator that reflects the potential for soil degradation or related issues in the research area [Thompson et al. 2020].

In order to calculate this index, it is first necessary to normalise the rasters to values from 0 to 1. Where the indicator 0 is the minimum vulnerability (soil is stable and fertile), while 1 is the maximum vulnerability (soil causes the most issues). Using the raster calculator in the ArcMap software, the indicators were converted and calculated according to the formula:

Negative factors (high values = high vulnerability):

$$\mathbf{Normalized} = \frac{\text{Value} - \text{Min}}{\text{Max} - \text{Min}}$$

Positive factors (high values = low vulnerability, but need to be inverted):

$$\mathbf{Normalized} = 1 - \frac{\text{Value} - \text{Min}}{\text{Max} - \text{Min}}$$

$$\textbf{Soil vulnerability index} = W_1 \times \text{Clay\_Normalized} + W_2 \times \text{SOC\_Normalized\_Inverted} + W_3 \times \text{CEC\_Normalized\_Inverted} + W_4 \times \text{Slope\_Normalized}$$

where:

Clay_Normalized – normalized clay layer,
SOC_Normalized_Inverted – normalized and inverted SOC layer,
CEC_Normalized_Inverted – normalized and inverted CEC layer,
Slope_Normalized – normalized slope layer,
W_1, W_2, W_3, W_4 – weight coefficients for each factor (sum = 1).

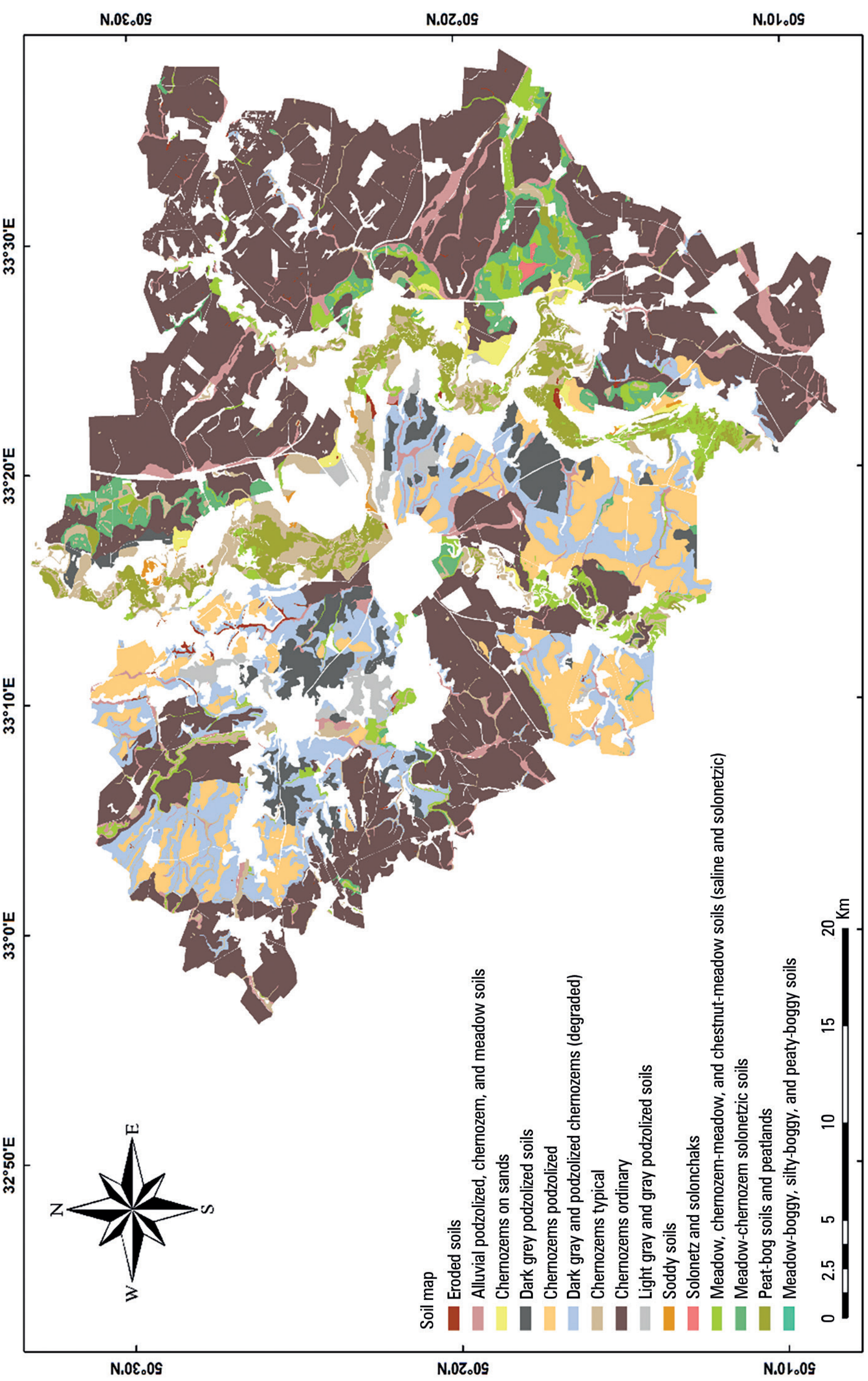
4. Results and discussion

In the created soil map of the Lokhvytsia district, the number of vectorised soil contours is 73950. There are also 14 soil classification units (Fig. 2).

Black soils typical for forests and steppes dominate in the eastern part of the region, while the western part of the district features areas with podzolic chernozems and dark grey soils. In the central part of the study area, various soil types are present, including meadow-chernozem, meadow, meadow-bog, marsh, and peat-bog soils. Their presence is caused by a regional hydrological network.

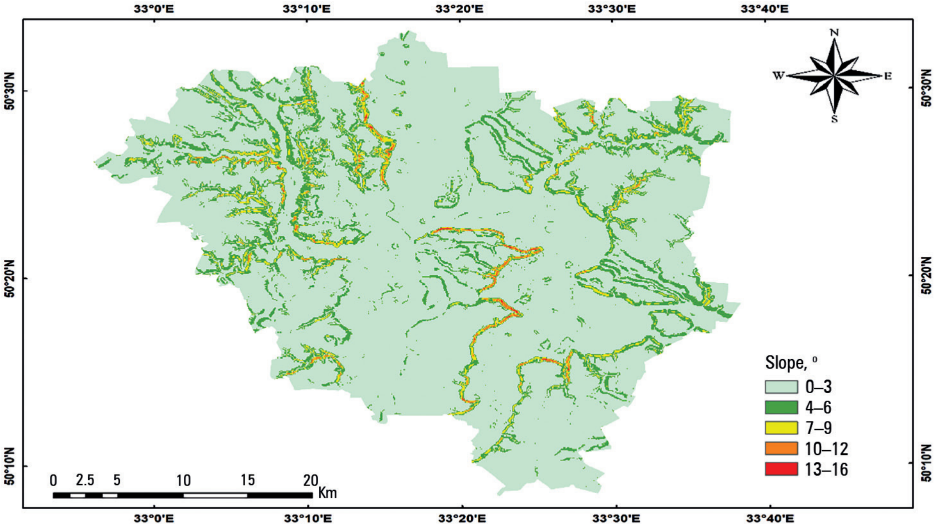
The resulting slope steepness map indicates that the greater part of the region is flat (slopes are from 0 to 3 degrees), with some very gentle (4–6 degrees), gentle (7–9 degrees), and medium steepness slopes (10–16 degrees) (Fig. 3).

As a result of spatial analysis of SoilGrids data, it was determined that the clay content in Lokhvytsky district ranges 0–350 g/kg (recalculated to 35%). On average, the regional indicator at a depth of 0–5 cm is 24%, at a depth of 5–15 cm – 25%. The minimum content of clay in the soil is confined to the location of settlements, and the maximum content is noted under perennial plantations.



Source: Author's own study

Fig. 2. Soil map of Lokhvytsia district



Source: Author's own study

Fig. 3. Slope steepness map

The content of organic carbon in soil in the Lokhvytsky district varies from 0 to 118 g/kg. On average, the regional indicator at a depth of 0–5 cm is 7.6%, and at a depth of – 15 cm, it is 2.7%. High organic carbon content is characteristic of areas with dense and developed vegetation.

The cation exchange capacity, buffered at pH 7 in mmol(c)/kg, varies from 0 to 469 mmol(c)/kg (converted to 46.9 mg-eq/100 g of soil). On average, the indicator for the region at a depth of 0–5 cm is 33.1 mg-eq/100 g, and at a depth of 5–15 cm, it is 26.6 mg-eq/100 g. The cation exchange capacity in soils depends on the granulometric composition, chemical composition, content, and quality of humus, as well as acid-base conditions. The maximum value of the indicator is in areas with fertile soil that retains cations well and has a high potential for supporting plant growth.

The study determined the soil vulnerability index for two distinct layers, 0–5 cm (Fig. 4A) and 5–15 cm (Fig. 4B). This approach was necessary because the SoilGrids dataset provides soil property data for specific standard depth intervals.

Three vulnerability zones within the territory were identified. The areas with the highest SOC content pose the minimal risk. High risk is observed in areas with steeper slopes. The more substantial impact of slopes causes increased erosion processes. As a result, by combining the two layers and calculating the average vulnerability index, we obtained a soil vulnerability map at a depth of 0–15 cm is presented in Figure 5.

The soil vulnerability index map for the 0–15 cm depth is an important tool for assessing the spatial heterogeneity of soil conditions and predicting the risks associated with degradation processes. It can be used to identify areas with increased sensitivity to erosion, loss of organic matter, compaction, or depletion, as well as to plan meas-

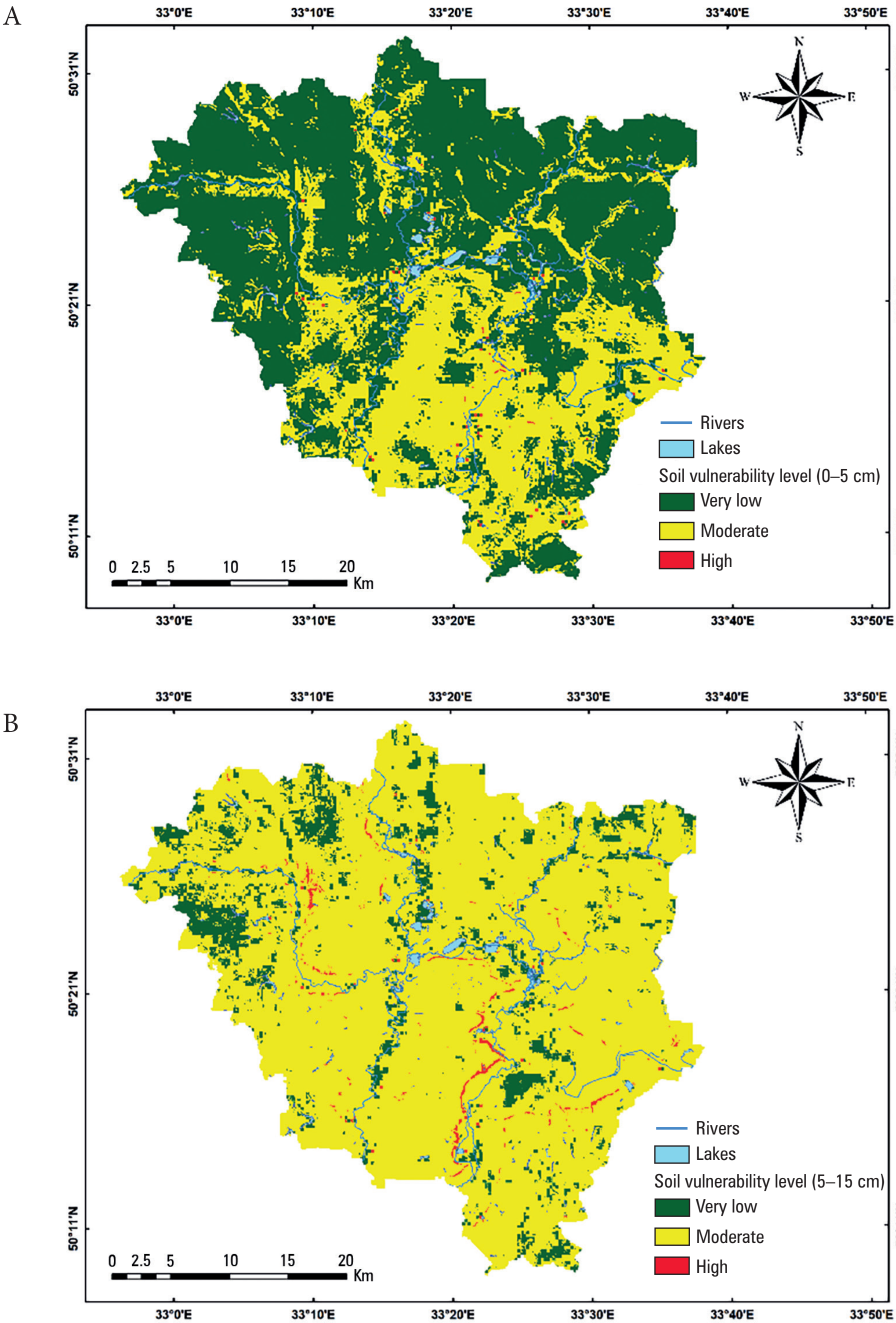


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Fig. 4. Soil vulnerability index maps: A. for the 0–5 cm layer; B. for the 5–15 cm layer

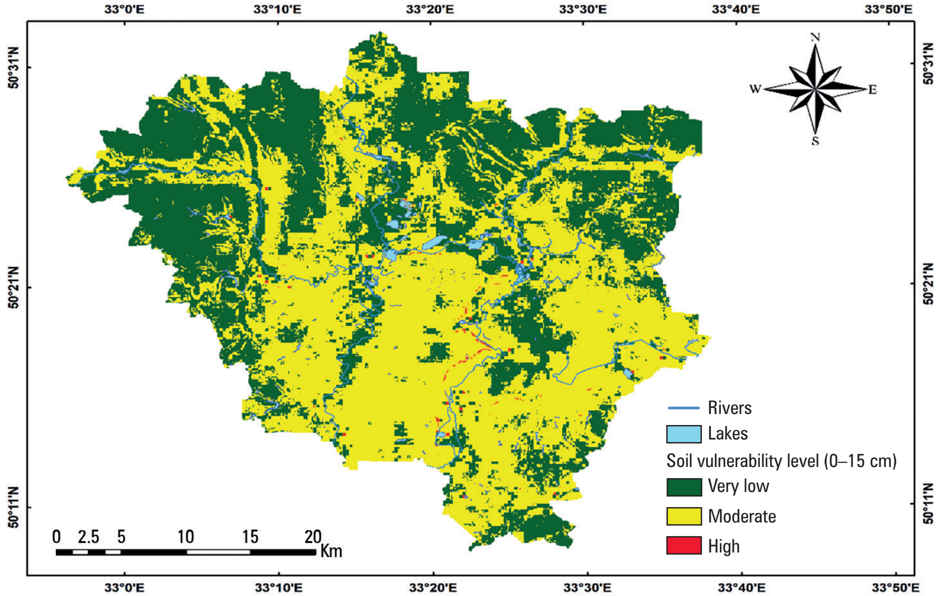

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Fig. 5. Soil vulnerability index for depth 0–15 cm

ures for preserving and restoring soil fertility. The adoption of this map will facilitate informed management decisions in land use and the implementation of soil protection technologies at both local and regional levels.

In the context of the development of digital farming technologies [Kokhan et al. 2024], combining the soil vulnerability index with other sources of spatial data – specifically, sensor monitoring systems and satellite images – will enable accurate and timely monitoring of changes in soil conditions.

5. Conclusions

Data analysis revealed that SOC levels are a key factor in ensuring soil erosion resistance, as they impact fertility, soil structure, and nutrient retention capacity. High SOC is observed in areas with dense vegetation cover and forests, reducing the risk of water erosion. Meanwhile, low organic carbon content on steep slopes and within settlements increases the risk of degradation.

Clay content and cation exchange capacity are key factors influencing the retention of soil organic carbon. High CEC, characteristic of clay soils, promotes the binding of nutrients and organic compounds, which maintains the fertility and stability of organic matter. In addition, clay particles provide physico-chemical stabilisation of organic matter, protecting it from microbial decomposition. At the same time, excessive clay can reduce soil aeration, which limits microbial activity and slows down mineralisation processes. Under such conditions, the decomposition of organic carbon slows down. It contributes to its accumulation, but also reduces its bioavailability.

Global GIS datasets allowed us to spatially assess the distribution of these characteristics, highlighting areas at risk of degradation. Soil is more stable and fertile in 43% of the territory of the Lokhvytskyi district, 56% requires control and additional measures, and only 1% of the territory is at high risk of vulnerability. Preservation of SOC, in combination with control of other indicators, is the key to rational land use and the prevention of degradation processes.

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