Introduction

The sloping uplands of western Ukraine, such as the Rivne Plateau, are actively used in agricultural business. However, the main problem of these lands is the spread of soil erosion on slopes of even a small steepness. The main factors of erosion are long-term use of soils without proper restoration of their fertility; plowing along the slope; overdrying of the land during frosty snowless periods and hot summers; heavy rains, etc. Over the last quarter of the last century, the area of eroded arable land in Ukraine increased by 26%, and the average annual soil washout exceeded the permissible limits by 2-3 times. The study area of the Rivne plateau is no exception, with soil erosion reaching 51-60% (*Erodibility map..., 2024*). Monitoring and controlling soil erosion are key aspects of preserving fertile land in Ukraine and ensuring sustainable agriculture. Satellite data is one of the ways to monitor soil erosion. They allow for rapid and accurate monitoring and assessment of erosion over large areas, which is important for detecting and preventing land degradation.

Theory

Geographic information systems (GIS) and remote sensing (RS) techniques allow for the creation of highly accurate digital elevation models (DEMs) to identify the location of washouts on specific terrain elements. Based on detailed DEMs, it is possible to determine the density and distribution of microdepressions, which are the paths of water flows during storms. The use of multispectral imagery allows us to analyse the state of vegetation: vegetation is sparse or absent in areas of washouts. By analysing the spectral characteristics of soils from satellite images for organic matter content, we identify areas potentially prone to erosion where the amount of organic matter is reduced. Soil erosion is visible on high-resolution satellite imagery and appears as whitish amorphous spots on fields. The brightness of the spots increases from the periphery to the center and they are more visible on plowed fields than on fields with vegetation in the early spring and late autumn seasons.

Method

Satellite data with a resolution of 1 m/pixel from Google Earth Pro were used to identify modern processes of soil erosion. Key areas on the Rivne Plateau were selected that have different forms of process manifestation. Digital elevation models were used to detail the distribution of processes within different relief elements of the key areas. In the QGIS software environment, we installed the Open Topography DEM Downloader module and downloaded the Copernicus Global DSM 30 m DEM. Next, we used the SAGA software product. Its tools were used to perform hydrological modeling using DEMs via the QGIS interface. The idea behind the simulation is that virtual water flows from a cell with a higher elevation to an adjacent cell with a lower elevation. A series of consecutive cells form drainage networks, which reflect the direction of water flow from the slopes. Small water streams flowing intensively and densely down slopes cause planar washouts. To analyse the forms of the processes, QGIS combined DEM, satellite images and a vector layer of water streams (flow direction).

Using multi-temporal satellite data, we analysed the dynamics of soil erosion processes. For one of the key sites, the eroded areas were calculated as of 2002 and 2018. It was important to analyse satellite images of one season – early spring, when there is no cultivated vegetation in the fields and the boundaries of the washouts are visible. For comparison with the current state (March 2024), satellite data from the EO Browser resource were used. They have a resolution of 10 m/pixel and reflect the occurrence of processes poorly, but provide information on changes in land cover or field establishment.

To confirm the manifestations of soil erosion processes, field and laboratory soil studies were carried out. During the field research, four soil samples were collected: the first sample was taken from the top of the micro-watershed, the second from the sub-watershed, the third from the valley side of the slope, which have different degrees of soil erosion, and the fourth from the bottom of the micro-depression, where the material is accumulating. After that, laboratory methods were used to determine the content of humus and carbon dioxide, as well as the granulometric analysis of the collected soil samples. The low humus content and small amount of CO_2 emitted by the soil as a result of microbiological processes indicates that the soil has been subjected to significant erosion. Changes in soil granulometric analysis are also an important indicator of erosion, as eroded soils have fewer fine particles and a higher sand content.

Region

The Rivne Plateau is an elevated part of the undulating Volyn Upland with prevailing absolute heights of 230-250 m. The Rivne Plateau is based on the washed-out surface of Upper Cretaceous sediments, which in some places is overlain by Neogene (Lower Sarmatian) sandstones and limestones. The plateau is covered by thick Quaternary sediments, dominated by loess up to 25 m thick and more (*Bogucki et al., 2007*). The loess cover is one of the determining factors in the formation of the modern microrelief of the territory. The loess-soil stratum of the Volyn Upland was formed as a result of alternating warm and cold periods of the Pleistocene. Researchers have identified several palaeocryogenic stages that are recorded in the loess-soil stratum of the upland. The most extreme of them was the Krasyliv Paleocryogenic stage, which is associated with the origin of the polygonal microrelief of the upland (*Novak & Fedorovych, 2015*). The study area of the Rivne Plateau is characterised by podzolised soils on loess rocks, soddy carbonate soils mainly on the eluvium of dense carbonate rocks, and shallow, slightly humic and low-humic chernozems, etc. (*Erodibility map..., 2024*).

Results

Based on the analysis of remote sensing data, we have identified different forms of soil erosion on the Rivne Plateau. They are related to the specifics of the development of a microdepression erosion network in the loess cover, in the micro-watersheds of which washouts develop, and to local denudation surfaces. The development of a specific erosion network is based on relict cryogenic genesis (*Bayrak, 2006; Dabski et al., 2007*). It was found that during the Pleistocene glaciations, ice wedges were formed and filled with material that differed in characteristics from the adjacent surfaces (*French, 2011; Meerschman et al., 2011*). In modern times, these wedges have been inherited by the erosion network. It is a zone of accumulation of material that is worn away from adjacent surfaces. Soil erosion develops on these inter-erosion surfaces, which is consistent with their morphology.

As a result of the research, we distinguish the following planned forms of soil erosion: 1) rounded-spotted, developed on the sub-watershed surfaces; 2) branched, widespread on the valley floor surfaces (sheet erosion); 3) massive, widespread in areas where the bedrock of the Neogene is close to the surface.

The first type of soil erosion forms develops on rounded microhighs, around which short micro-depressions wind (***Figure 1. a***). They form a ring-shaped system. The depressions are up to 1 m deep and 30-40 m long before they merge with another similar shape. They are poorly visible even during field observations, but their network is best seen on large-scale satellite images. The slope of the sub-watershed surfaces is low, and the streams flow concentrically into the depressions formed. Their waterlogging, as well as the predominance of soil with a higher humus content, causes a dark image on the images. In contrast, humus-poor soils on microhighs show a lighter image. The area of the microhighs is 0.2-0.3 ha. Erosion is widespread in the area of microhighs, which are the highest from the valleys and amount to 0.05-0.15 ha.

The second type of soil erosion forms is common where the dendritic erosion network is developed (***Figure 1. b***). In the micro-watersheds between the depressions, the forms of outwash are elongated. The dendritic network includes short (70-90 m in length) and long (up to 500 m) depression forms that are connected at sharp angles. It is common near river valleys, on slopes with a steepness of 2-3°. Steeper slopes are characteristic of valley floor surfaces, with a higher concentration of water streams and higher velocity. Consequently, the removal of loose material from slopes is more active.

Therefore, the degree of washout and the area of washed away soils are greater than in the previous case. The area of eroded soils within one micro-watershed of the dendritic network is 0.3-1.1 ha.

Denudation surfaces are characterised by large areas of eroded soils, but they can be divided into zones of weak, medium and strong erosion (***Figure 1. c***). Denudation surfaces are locally found on the Rivne Plateau. They are characterised by the absence or low thickness of loess cover, and Neogene limestone is exposed at the tops of watersheds. Soils are of low capacity. The most famous denudation surfaces are located in the west of the Goshcha Plateau and near the village of Mohyliany.

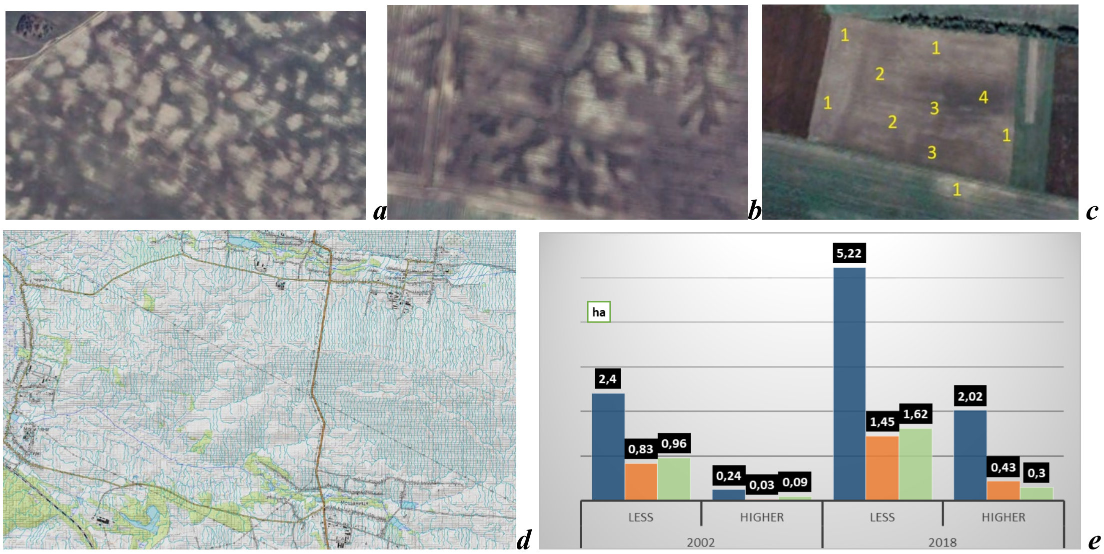

Figure 1. *Research of soil erosion on the Rivne plateau using GIS and remote sensing methods:* ***a*** *- rounded-spotted forms of erosion;* ***b*** *- branched forms of erosion within the dendritic network;* ***c*** *- degrees of erosion in the key area near the village of Mohyliany (1 - strong, 2 - medium, 3 - weak erosion, 4 - accumulation);* ***d*** *- hydrological modeling map in QGIS with display of water flows on the denudation surface; a,b,c - Google Earth space images with 1 m/pix resolution;* ***e*** *- growth of different degrees of soil erosion on the denudation surface in the vicinity of Mohyliany village*

We performed hydrological modeling in QGIS, where we showed the nature of the stream network on the inter-watershed surfaces of the key area (***Figure 1. d***). We observe its almost parallel, dense extension along the slopes, just where the washouts are the largest. In other areas, the microdepression network is chaotic and drainless. At this site, we took soil samples and performed laboratory analyses for humus and carbon dioxide content, as well as determined its granulometric analysis.

The primary task was to determine the humus content, which is one of the indicators of soil erosion. Heavily eroded soils lose part of the humus horizon as a result of washout, and low-fertile layers are exposed on the surface. The humus content of the first sample, which was taken from the highest point, is 0.74%, the second sample, which was lower on the slope, has 1.53%, the third sample has 1.95%, and the last sample, which was taken in the depression, has a humus content of 2.21%. Thus, we observe a pattern of soil erosion in the spatial plan, when the highest point of the denudation surface has the highest erosion, and at the bottom of the slope it is the lowest. Accordingly, the accumulation of washed-out material occurs in the microdepression. The same pattern is observed after determining the carbon dioxide content of the collected soil samples. In the first sample, the CO_2 content was 9.36%, in the second – 6.66%, in the third – 6.12%, and in the last – 4.14%. The granulometric analysis of the collected soil samples showed a pattern of leaching of particles smaller than 0.01 mm from the top of the slope to the bottom. Near the top, the soil is sandy loam with a total of 14% of particles smaller than 0.01 mm, in the middle part of the slope it is sandy-light loamy with 20.4% of particles smaller than 0.01 mm, and at the bottom of the slope it is loamy sand with 27.7-

29.5% of these particles. This indicates that dust and silt are actively washed out of the soil when erosion processes occur.

Using multi-temporal satellite data, we investigated the development of erosion processes on denudation surfaces. We calculated the areas of spatial distribution of moderately and severely eroded soils as of 2002 and 2018 based on high-resolution satellite images (***Figure 1. e***). The analysis showed that the area of eroded soils in all three study sites is increasing from year to year. Moreover, areas with medium soil erosion have expanded and covered a larger slope area than areas with highly eroded soils. As of 2024, as shown by Sentinel-2 satellite images from the EO Browser resource, one large field was divided into several smaller ones to reduce the degree of washout. In one of the fields, the direction of plowing was changed, which somewhat localised one of the washes. However, in other areas, erosion is stable, as in 2018.

Conclusion

The GIS and remote sensing methods made it possible to perform detailed mapping of the distribution and intensity of eroded land. Using DEMs and hydrological modeling in QGIS, the landforms and associated stream network elements were reconstructed, showing the direction of water flows during rains. Different time studies have shown that washouts are developing, and field and laboratory studies have confirmed that the soils are depleted in humus and carbon dioxide, are compacted and dominated by large particles. All of this gives grounds to recommend that landowners and farmers whose fields are subject to erosion change their plowing style and crops to reduce soil degradation.

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