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**GEOMORPHOMETRIC ASSESSMENT OF SOIL EROSION
AND GULLY DEVELOPMENT IN FOOTHILL AGRICULTURAL
LANDS USING REMOTE SENSING AND GIS**

ABSTRACT

This article explores the application of remote sensing (RS) and geographic information systems (GIS) to assess soil erosion and land degradation in the foothill agricultural areas of the East Kazakhstan Region. The study focuses on the vicinity of Beryozovka village, where erosion processes are particularly evident. High-resolution satellite imagery and SRTM-based Digital Elevation Model (DEM) were used to extract morphometric parameters such as slope, aspect, and valley depth. Spatial indicators including the LS-factor, Topographic Wetness Index (TWI), and surface runoff accumulation were applied to determine zones of erosion susceptibility and quantify soil degradation intensity. As a result, the total volume of gully erosion in the study area was estimated at 864,467.4 m³, and the annual soil loss based on LS-factor modeling was calculated to be 46,154 m³. These figures highlight the scale of degradation in foothill croplands and the need for targeted mitigation. Based on the findings, a set of erosion control measures was proposed, including contour plowing, terracing, maintaining vegetation cover, and installing hydraulic structures. The outcomes of this research provide critical spatial data and actionable recommendations for sustainable land management and agricultural planning in erosion-prone environments.

KEYWORDS: soil erosion, remote sensing, gully formation, GIS analysis, foothill agriculture

INTRODUCTION

The purpose of this study is to assess the extent and intensity of soil erosion and gully formation in the foothill agricultural lands of East Kazakhstan using remote sensing and GIS methods. This includes the analysis of morphometric terrain parameters using DEM data, identification of erosion-prone areas based on the LS-factor and topographic wetness index, estimation of gully volumes and erosion rates, and the development of land management strategies aimed at reducing erosion risks and supporting sustainable agricultural practices.

The modeling in this study is based on the Revised Universal Soil Loss Equation (RUSLE), derived from the classical USLE by Wischmeier and Smith, which includes factors like rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover (C), and conservation practices (P). SAGA GIS was employed for the computation of morphometric indices, and erosion modeling was supported by the methodology of [Pásztor et al., 2016], using DEM-based elevation data to calculate gully volumes.

This article explores the integration of remote sensing (RS) and geographic information systems (GIS) in evaluating erosion dynamics across foothill croplands in East Kazakhstan. The study utilizes high-resolution satellite imagery and geomorphometric analysis, focusing on terrain attributes such as slope, aspect, and valley depth. Key indicators for erosion assessment

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include the LS-factor, the Topographic Wetness Index (TWI), and surface runoff parameters [Apshikur et al., 2024].

Before the use of satellite imagery, the quantitative assessment of soil erosion in foothill agricultural lands relied on direct field measurements, such as sediment tracking and monitoring of surface runoff [Bruno et al., 2008; Kunyapiyeva et al., 2023]. Nowadays, remote sensing and GIS provide enhanced capabilities to monitor and analyze the temporal and spatial dynamics of erosion processes [Golubev, 2023].

Soil erosion is one of the most critical environmental and economic issues for agricultural lands, particularly in foothill regions where intense water flows contribute to the degradation of fertile topsoil [Salumbo, 2020; Zhang et al., 2023]. According to the soil and climatic conditions, the agricultural lands of the East Kazakhstan region are classified into mountainous, foothill, and plain areas [Nazarenko et al., 2023]. These regions are distinguished not only by their geographical location and soil-climatic conditions but also by their unique natural resource potential [Sadenova et al., 2023].

These results can be instrumental in developing strategies for sustainable land use, the conservation of agricultural resources, and the prevention of further land degradation in erosion-prone areas of East Kazakhstan. They offer practical recommendations for land planning based on spatial erosion modeling, which is critical for improving agricultural sustainability in foothill regions.

In addition to gully erosion, this study acknowledges the occurrence of sheet erosion across the foothill croplands. While not as visually prominent as gully formation, sheet erosion contributes to the gradual loss of fertile topsoil and significantly affects agricultural productivity. The modeling approach based on RUSLE implicitly incorporates both gully and sheet erosion through parameters such as the LS-factor and rainfall erosivity. Therefore, the results presented in this study reflect a combined impact of different erosion types for a more comprehensive evaluation.

RESEARCH MATERIALS AND METHODS

Study Area

Fig. 1 illustrates the location of the study area on both banks of the Irtysh River. The selected area is situated in the foothill region of the Glubokoye district, specifically in the Beryozovka village, encompassing the arable lands of the “ERZHAN” farming enterprise.

The study area belongs to a mountainous region characterized by unique features such as a fragile ecosystem and a highly sensitive environment [Wen, Changbiao, 2018], which significantly constrain the sustainable use of arable lands in these areas.

The majority of the region is classified as a mountainous, arid zone with harsh winters characterized by heavy snowfall and severe frost. Summers are predominantly dry in June and July, while May, as well as early August and September, experience periodic rainfall and fluctuating temperatures, alternating between warm and hot conditions. Annual atmospheric precipitation ranges from 100 to 650 mm [Yapiyev et al., 2018].

The study focuses specifically on the agricultural lands of the “ERZHAN” farming enterprise, located within the Beryozovka village area. This farm was selected as a representative case due to its pronounced topographic variability, documented erosion issues, and the availability of relevant spatial and field data. All subsequent analyses, including morphometric modeling and erosion risk assessment, were conducted based on the land plots operated by “ERZHAN”.

Research data

Satellite imagery used for the analysis was obtained from open-access platforms, including USGS EarthExplorer and Sentinel Hub. The resolution and suitability of these datasets were evaluated prior to processing [Ogorodnikov, 2022].

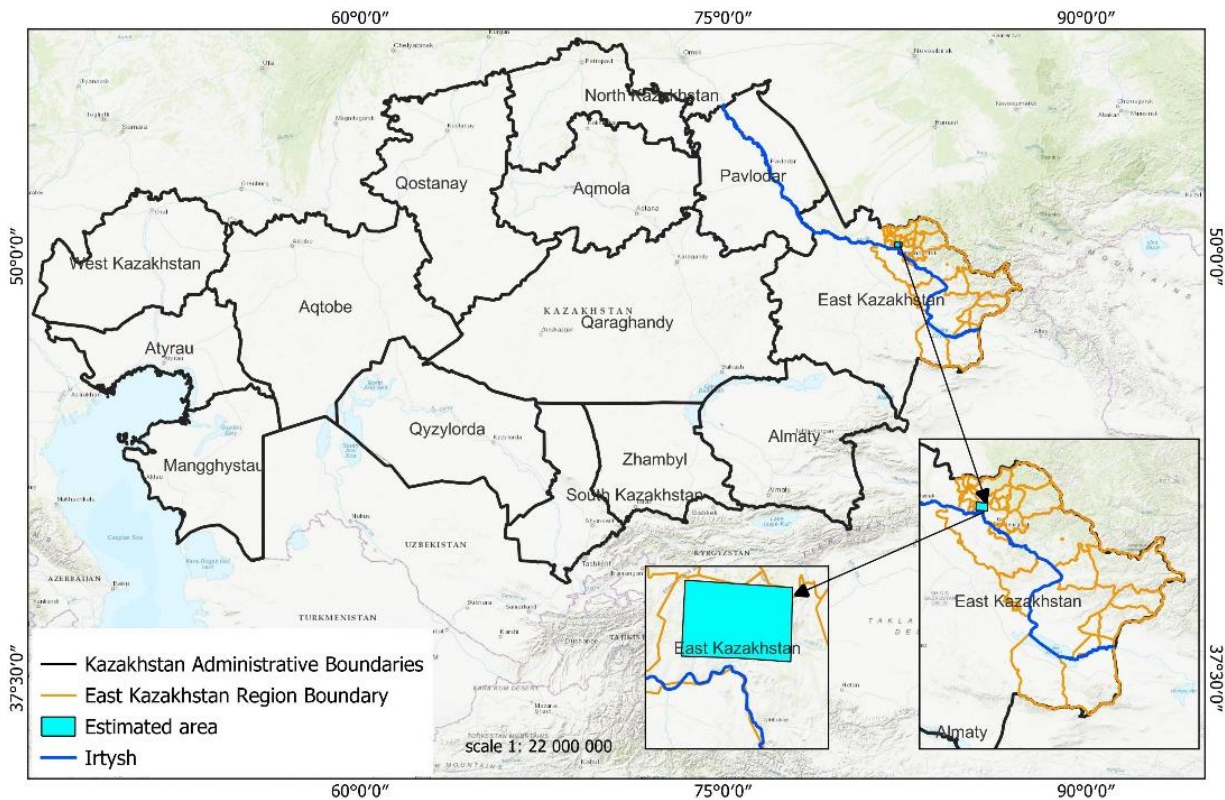


Fig. 1. Location of the Study Area

In this study, the arable lands of the Berezovka settlement in the East Kazakhstan Region were taken as the basis. The analysis area encompasses foothill regions located on the right bank of the Irtysh River, in the direction of its flow. Its geographical location is above 82° East Longitude and 50° North Latitude [Krasnoyarova et al., 2019]. The elevation values of the terrain range from 245 m, at the Irtysh River estuary to 300–400 m, in the croplands located on the riverbanks, while the mountainous heights, which serve as the primary water source, reach up to 1 261 m, (Fig. 2). In mountainous regions, extensive forest cover is present, which increases the natural soil moisture and complicates water infiltration into the ground. The use of remote sensing (RS) data is becoming increasingly widespread in studies of the region’s forest resources [Asangaliyev et al., 2024].

The study area, located between 49° and 52° N in East Kazakhstan, is predominantly characterized by chernozem (humus) soils, which significantly influence erosion dynamics and runoff behavior.

Due to its location in a foothill latitude, the studied area is frequently affected by surface erosion and related erosional processes. The two primary types of soil erosion in this region are wind and water erosion [Telkar et al., 2024]. The predominant concern is water-induced soil erosion, which involves the removal of the upper, most fertile soil layer by surface runoff.

As indicated by the location map of the studied area (Fig. 2a), soil erosion in this region is a pressing issue, given that its rate depends on precipitation, topographic features, soil composition, and vegetation cover [Sun et al., 2013]. A 3D map, constructed based on the elevation map of the local area and its water drainage systems (Fig. 2b), allows for a visual assessment of the high level of fertile topsoil erosion in arable lands inclined towards riverbeds in mountainous regions, as illustrated by the longitudinal profile (Fig. 2c) [Surinov, 2023].

The profile in Fig. 2c was deliberately drawn across several watercourses to reflect the hydrological structure of the terrain and illustrate the potential for gully formation and moisture

accumulation. This route allows for a better understanding of erosion-prone depressions and runoff pathways typical of foothill landscapes, even if it does not directly follow cultivated slopes.

During periods of precipitation and snowmelt, water does not fully infiltrate the soil and instead flows downward along slopes. This process intensifies particularly in foothill areas, leading to the formation of deep gullies in agricultural fields and resulting in the degradation of fertile lands. One of the key factors affecting agriculture in mountainous regions is soil erosion and surface runoff from slopes. In this regard, numerous fundamental and applied studies on soil erosion and surface runoff from cultivated slopes, as well as the development of countermeasures [Jenčo et al., 2020], have demonstrated that investigating the issue using modern methods enables rational and timely decision-making. In the decision-making process, the utilization of experimental and applied research in this field, along with the accurate analysis of contemporary satellite imagery using appropriate software, has yielded positive outcomes in many countries. This is evidenced by published studies [Tucci et al., 2021; Toguzova et al., 2022].

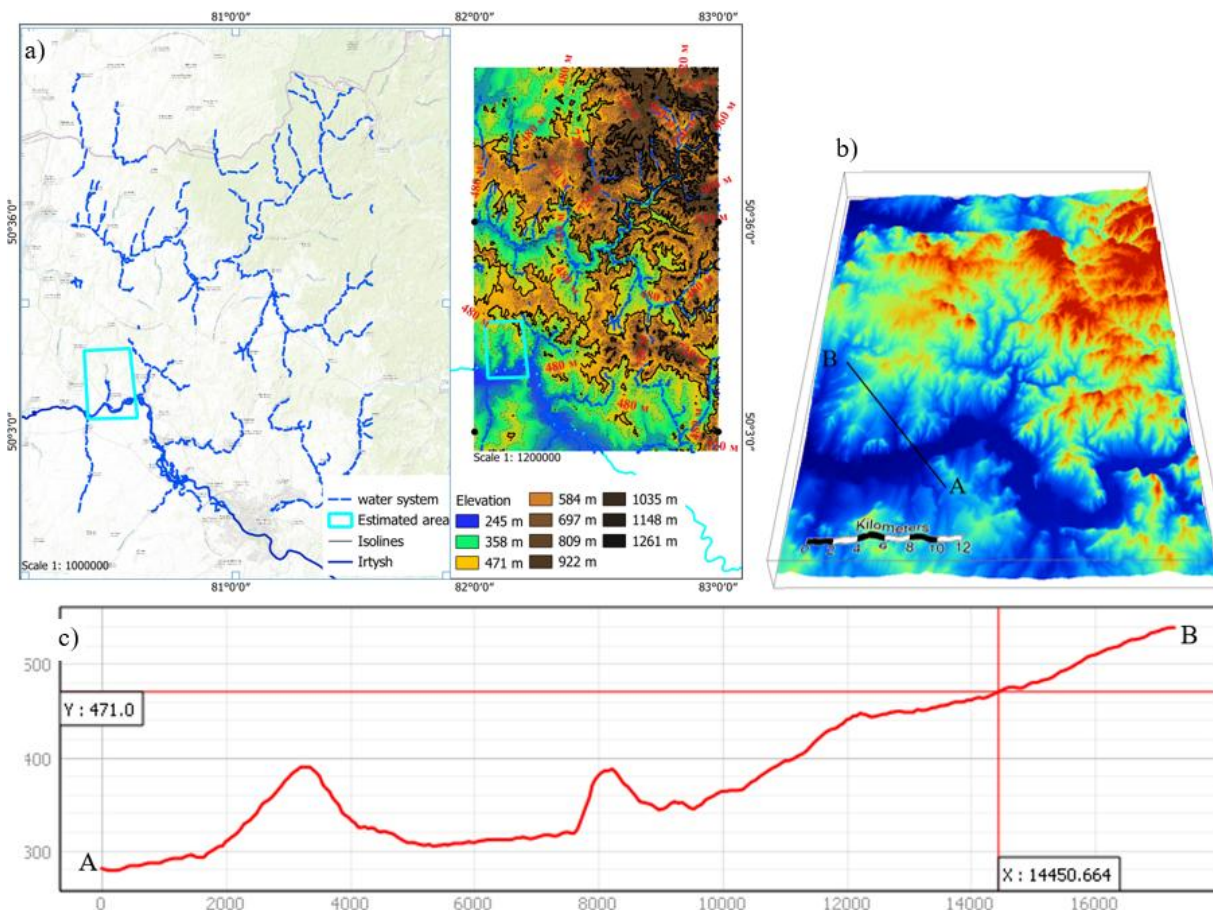


Fig. 2. Map of the study area: a) Hypsometric-hydrographic map; b) 3D map; c) Slope profile

Accordingly, the primary objective of this study is to assess the extent of soil erosion in arable lands inclined towards riverbeds in mountainous regions by utilizing remote sensing (RS) data and cartographic analysis methods [Apshikur et al., 2023]. This research aims to identify erosion-prone areas and propose preventive measures. The findings of this study are crucial for effective agricultural planning, soil resource conservation, and the development of sustainable land use strategies [Hoang et al., 2022].

RESEARCH RESULTS AND DISCUSSION

To comprehensively explore the research topic, the geomodelling method for determining the most functional structure and the morphometric approach to analyzing the functioning of basin geosystems have proven to be highly effective [Shinde et al., 2011; Apshikur et al., 2024].

The morphometric analysis of the basins within the arable lands of the “ERZHAN” farm, selected as the study site, included the following:

- the stage of creating the Digital Elevation Model (DEM), as well as the statistical analysis of the distribution of key morphometric parameters within the basins, based on the formal computational procedures of SAGA GIS modules;
- the slope characteristics of the studied area were processed using the SAGA (System for Automated Geoscientific Analyses) software, and the slope gradient and aspect indicators were determined.

The analysis revealed that slope angles range from 0.02 to 0.32 radians (Fig. 3a), while the relative values of aspect compared to the azimuth range from 0.4 to 6.0 radians (Fig. 3b). The slope angle directly influences soil erosion by water. On steeper slopes (0.16–0.32 radians), water infiltration is limited, leading to an increase in runoff velocity and, consequently, a higher likelihood of fertile soil layer erosion.

Fig. 3–5 collectively illustrate the key geomorphometric parameters — slope characteristics, valley depth, wetness index, and LS-factor — that influence erosion processes in the study area. These visualizations form the analytical foundation for identifying erosion-prone zones and support the spatial erosion modeling conducted in this research.

Conversely, as shown in Fig. 3b at the level of watercourse channels (0.02–0.08 radians), the high rate of water infiltration slows down flow processes, leading to the formation of algal growth along the banks. Consequently, prolonged exposure to stagnant water, which recedes into adjacent areas, may alter the soil structure and reduce its fertility.

The aspect (slope orientation) of the study area also influences the degree of soil erosion by water [Wang et al., 2024]. Slopes facing the sun (south and southwest directions) experience higher evaporation, leading to soil drying, which weakens its structure and makes it more susceptible to erosion. In contrast, shaded slopes (north and northeast directions) retain more moisture, resulting in softer soil that becomes prone to erosion during heavy rainfall. Since the study area predominantly consists of sun-facing slopes, soil erosion is more pronounced following seasonal drying, when intense rainfall or surface runoff occurs.

In the GIS-based study, one of the geosystem analysis methods applied to correspond with field measurements of arable lands was the Valley Depth function (Fig. 4a). Valley Depth is a GIS tool used to determine the relative depth of gullies and valleys in the lower parts of the terrain [Trofimetz, Panidi, 2016]. This method enables a quantitative assessment of the lower-lying landforms, specifically the depth of valleys and ravines.

The study revealed that the average gully depth in the investigated area ranges from 2 to 15 m. Agricultural fields with steeper slopes and those located near gullies exhibit a significantly higher level of soil erosion. In areas with lower topographic elevations, moisture accumulation processes intensify, increasing the risk of waterlogging [Maltsev, Yermolaev, 2019]. Based on the conducted modeling, it was established that, in most cases, the boundaries of areas identified as potential water accumulation zones correspond to large-scale field-based landscape cartography data.

For field measurements of water accumulation slopes in agricultural fields, as well as for analyzing agrochemical soil research results from the past two years, the Topographic Wetness Index (TWI) (Fig. 4b) was utilized to determine the mechanisms of soil moisture distribution within the geosystem. Humidification processes in the geosystem were analyzed based on the potential moisture index (Wetness Index), which essentially represents the potential water

accumulation index or the corresponding landscape condition that defines the “effective hydrological characteristics of water collection” [Zhang et al., 2023].

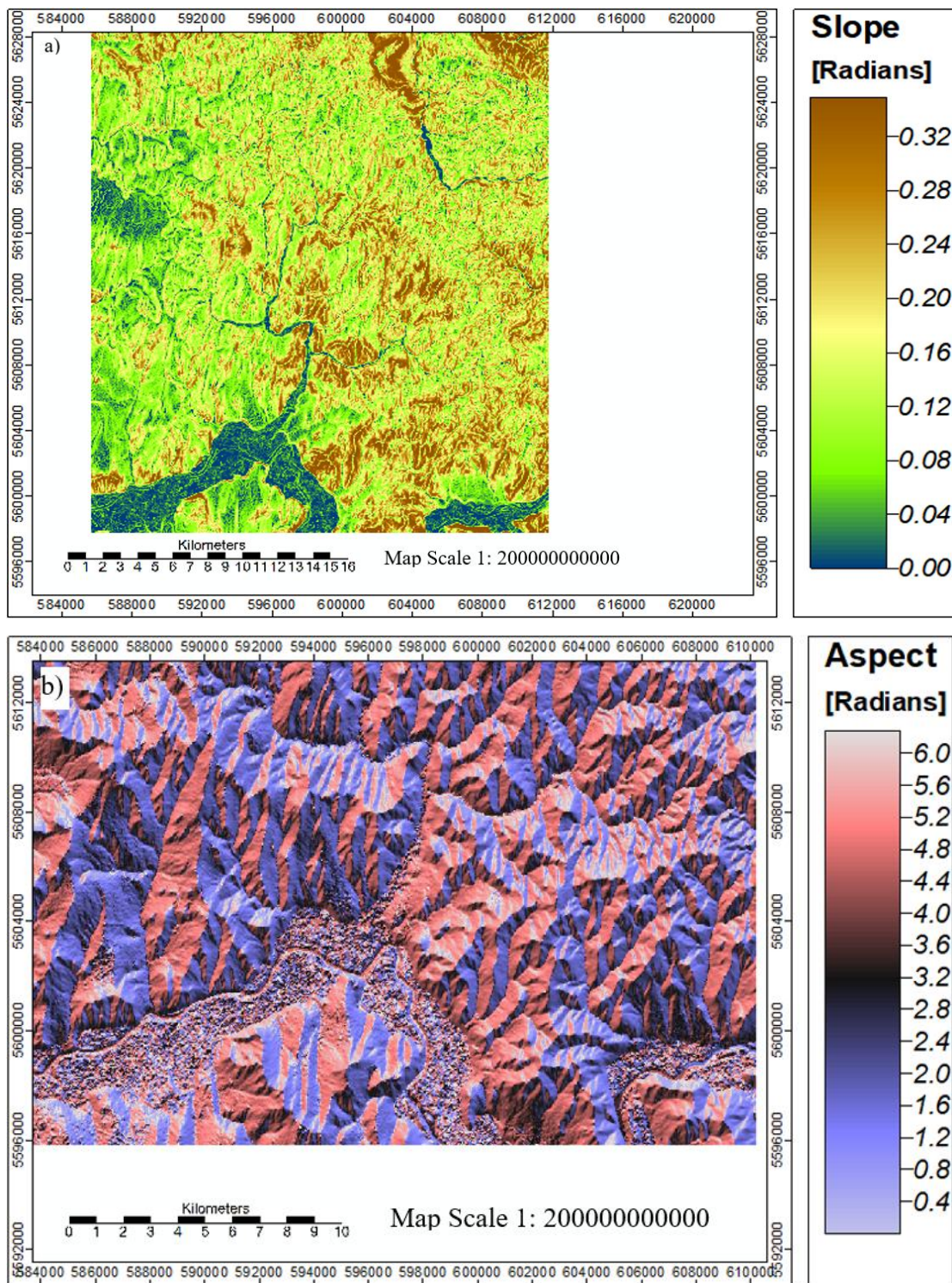


Fig. 3. Slope characteristics of the study area: a) Slope gradient (radians); b) Slope aspect

Higher values of this index correspond to increased moisture accumulation and a higher water content in the soil, which, in turn, influences other landscape characteristics such as microclimate, water balance, and the ecological conditions of soil formation. Several studies

include this index among the indicators used for predicting soil properties. According to the research of some scholars, this model accounts for approximately 65 % of the spatial variation in soil characteristics [Kopecký et al., 2021].

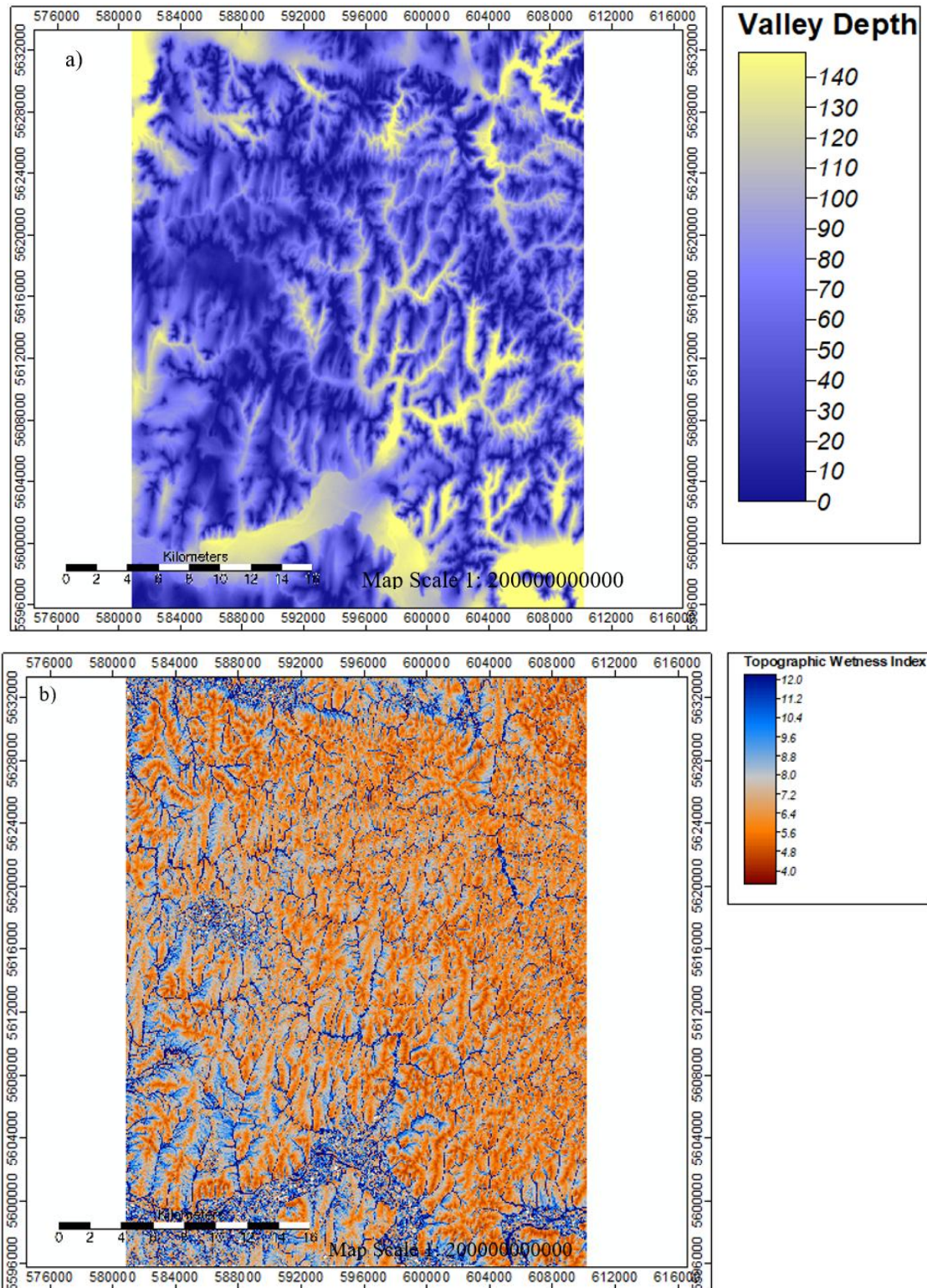


Fig. 4. Morphometric analysis of valley depth in the study area:
a) Valley Depth; b) Wetness index

In the analysis of satellite imagery within the SAGA geosystem, the LS-factor composite index was utilized based on the unit force theory, developed for assessing the erosional potential of the terrain [Panagos et al., 2015], (Fig. 5a) [Mashudi, 2023]. As water accumulates and flow intensifies in areas near river channels, the eroded fertile soil layer is transported into the river system, negatively impacting agricultural productivity. From this perspective, the channels of water systems within agricultural areas are assessed [Rakhymberdina et al., 2024], (Fig. 5b).

The LS-factor (slope length and steepness) was calculated using geomorphometric analysis in SAGA GIS based on a Digital Elevation Model (DEM). This factor, along with other coefficients, was then incorporated into the Revised Universal Soil Loss Equation (RUSLE) to estimate the average annual rate of soil erosion. The Universal Soil Loss Equation (USLE), originally formulated by [Wischmeier, Smith, 1978], is expressed as follows (1):

$$A = R \cdot K \cdot LS \cdot C \cdot P \quad (1),$$

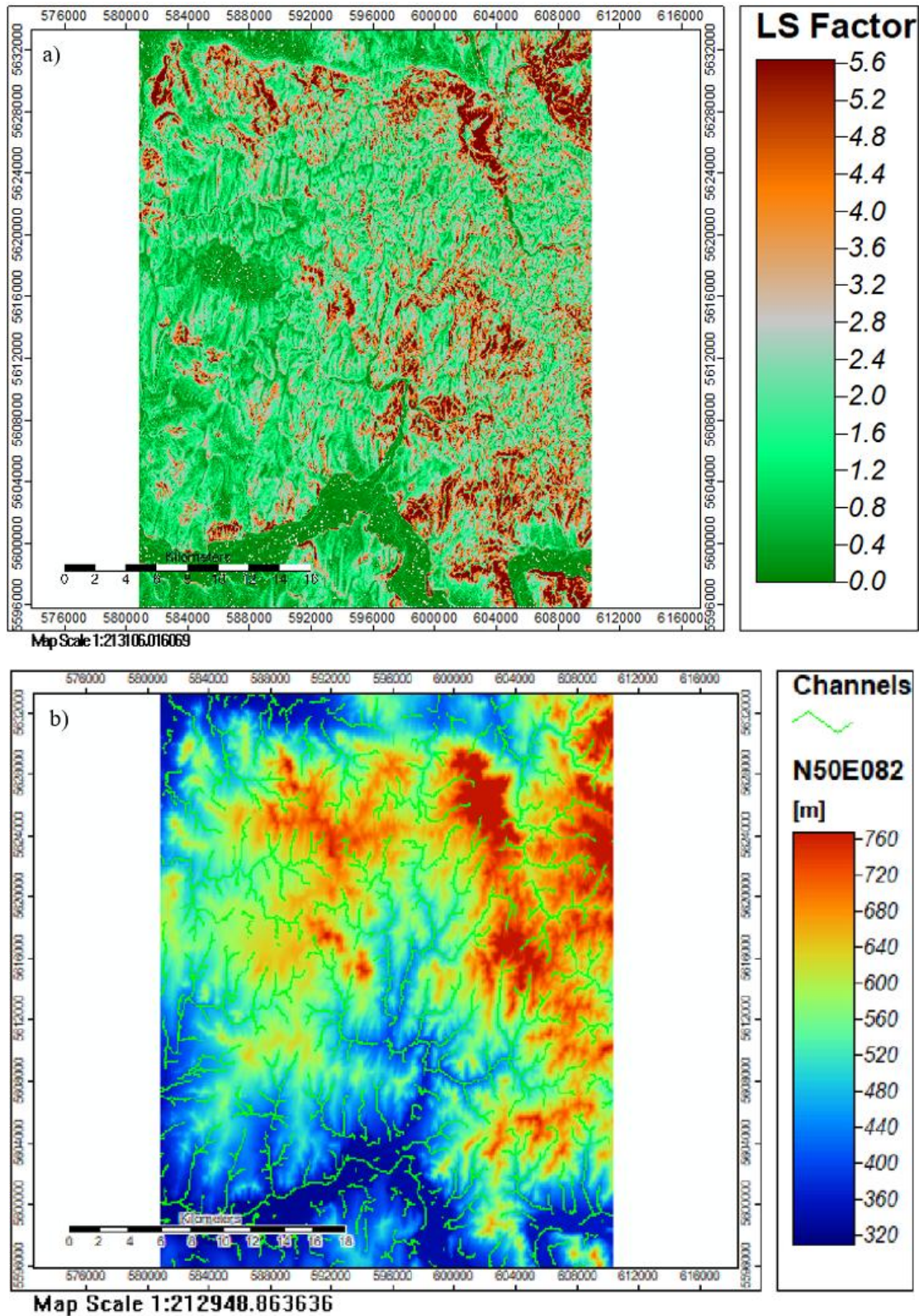
where: A — Average annual soil loss (t / ha / year),
 R — Rainfall erosivity factor (MJ · mm / ha · h · year),
 K — Soil erodibility factor (t · ha · h / ha · MJ · mm),
 LS — Slope length and steepness factor (dimensionless),
 C — Cover-management factor (dimensionless),
 P — Support practice factor (dimensionless).

The erosion volume calculated using this equation serves as a crucial landscape-ecological indicator for land-use planning, the organization of soil and water conservation measures, the prediction of erosion network distribution, and other essential environmental management applications. In our case, the index is directly correlated with the slope of geosystems and indicates the maximum surface runoff intensity within a given area. To accurately determine the actual volume of soil erosion, the LS-factor value must be integrated with other indicators representing erosion-related factors such as precipitation, soil properties, vegetation cover, and others [Zivotic et al., 2012].

The Digital Elevation Model (DEM) used in this study is based on SRTM 30-meter resolution data, sourced from the USGS EarthExplorer platform. All geomorphometric parameters, such as slope, aspect, and LS-factor, were derived using SAGA GIS and applied in spatial erosion modeling. Fig. 2 represents the general morphometric layout of the study area, highlighting water flow paths and terrain exposure zones that influence sheet erosion processes. In contrast, Fig. 6 focuses on a detailed segment of the same agricultural area, where visible gully formation is observed (right side), and the left part demonstrates zonal erosion intensity mapping based on sector-based modeling. These two visualizations collectively allow for both qualitative and quantitative interpretation of erosion severity.

The analysis of remote sensing imagery in the SAGA software enabled the assessment of the erosional potential of the terrain in foothill areas and its impact on the loss of fertile soil layers in agricultural lands. The red-colored regions indicate high LS-factor values, signifying areas with a very high risk of soil erosion. This phenomenon is particularly evident in mountainous and steeply sloped terrains. Statistical analysis of the distribution of satellite imagery results in geomodelling allows for the identification of several patterns [Rawat et al., 2016]. In particular, the number of facies units within potential water accumulation basins in the studied area amounted to 1 043 for Type A and 1 051 for Type B (flow direction), which were consolidated into 132 distinct categories.

To calculate soil erosion in the foothill area sloping towards the river channel, a region with a relatively high erosion rate and extensive gully formation was selected (Fig. 6a and Fig. 6b).



*Fig. 5. Major factors in identifying slope soil erosion and degradation:
a) LS-factor; b) Water channel systems*

The ERZHAN farm was selected as a representative site within the broader study area due to its topographical diversity and visible erosion impact. While the overall research encompasses

foothill agricultural lands in East Kazakhstan, the ERZHAN area enables a detailed quantitative assessment of erosion dynamics based on high-resolution modeling. The patterns observed in this location are indicative of broader regional processes and allow for practical validation of spatial modeling results.

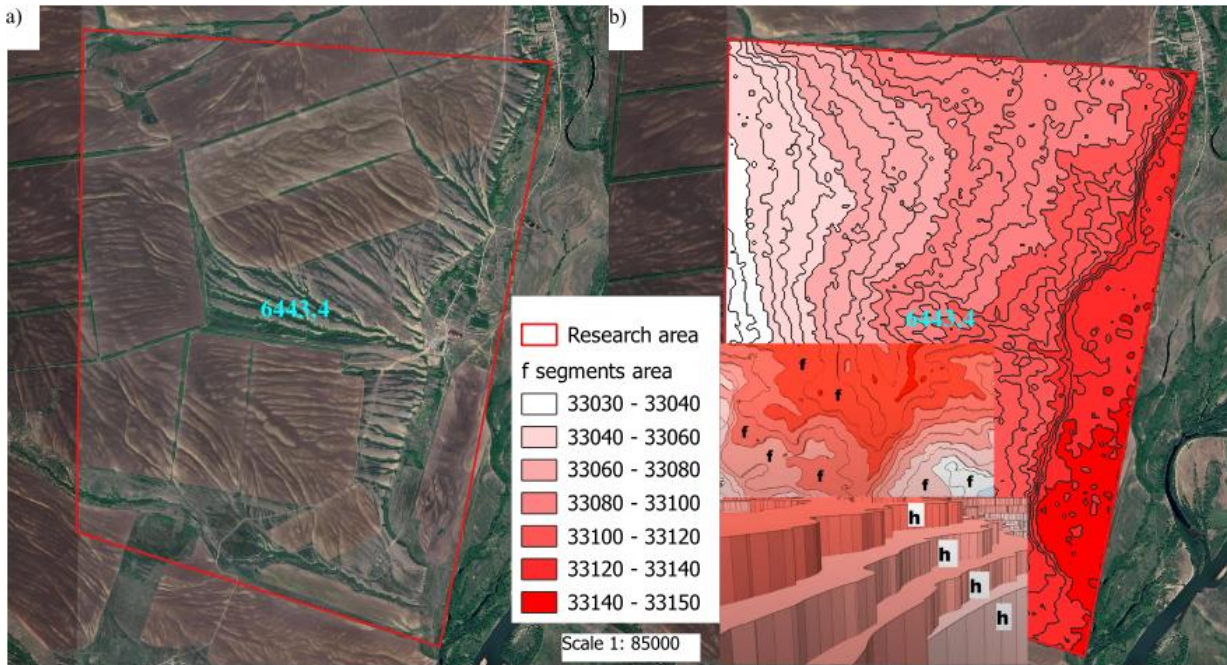


Fig. 6. Valley Depth in the Study Area: a) A fragment of the valley-affected area within the agricultural lands of the “Ernar” farm (Map-Google Hybrid); b) A fragment illustrating gully volume calculation

The obtained image is referenced to geographic coordinates “WGS 84 - EPSG 4326” with a pixel size of 0.00027, -0.00027. The smallest pixel covers an area of approximately 1” (arcsecond) in both longitude and latitude, which corresponds to a ground resolution of about 30 meters. This equals approximately 787 000 ha on the ellipsoid surface and about 1 235 500 ha in a rectangular coordinate system, representing a vast territory. Therefore, utilizing the software’s capabilities, a study area of 6 443.4 ha, was extracted (Fig. 6a). To calculate the volumetric loss of gullies within the land parcel, metric measurements are required. Hence, the selected area image was converted using the software’s transformation command into the “WGS 84/Pseudo-Mercator” rectangular coordinate system and saved accordingly.

In SAGA GIS, the depth of gullies located below a conditionally accepted flat reference surface is calculated using the “Valley Depth” function. In QGIS, the height of segments (“h”) and the area of segments (“f”) are assigned to the study area’s attribute data. Using the developed geoinformation model [Pásztor et al., 2016], contour lines are generated at equal intervals starting from $ELEV_{max} = 5$ m, and structured in a pyramidal form, where they overlap in a stepped manner, forming polygons of varying sizes. The volume of soil loss due to Ravines in the study area, derived from the equation, is presented in tabular form (Table 1).

These polygons are then converted into a vector format. The area of each segment is calculated using the program’s $f = \$$ area function in the field calculator (Fig. 6b). Thus, the volume of soil lost due to gullies in the study area is determined using the following formula (2).

$$V = \Sigma(f) * (\Sigma(h * f) / \Sigma(f)) \quad (2),$$

where: h — the thickness between each contour elevation level,
 f — the area of each segment formed by the contour lines,
 $h * f$ — the product of each contour elevation height and the corresponding segment area.

Table 1. The volume of soil lost due to gully erosion in the study area

| Segment Number (5 m interval) | ELEV_MIN | ELEV_MAX | h | f | h_f | V_m ³ |
|-------------------------------|-------------|----------|-------|-------------|-------------|------------------|
| 0 | -4294967295 | 33030 | 33030 | 93032,4639 | 3072862283 | 864467,4 |
| 1 | 33030 | 33035 | 33035 | 231578,7396 | 7650203664 | |
| 2 | 33035 | 33040 | 33040 | 615179,8575 | 20325542491 | |
| 3 | 33040 | 33045 | 33045 | 989750,9369 | 32706319709 | |
| 4 | 33045 | 33050 | 33050 | 925374,746 | 30583635354 | |
| 5 | 33050 | 33055 | 33055 | 988272,313 | 32667341306 | |
| 6 | 33055 | 33060 | 33060 | 977876,3747 | 32328592949 | |
| 7 | 33060 | 33065 | 33065 | 1045838,08 | 34580636108 | |
| 8 | 33065 | 33070 | 33070 | 1179252,754 | 38997888576 | |
| 9 | 33070 | 33075 | 33075 | 1178578,396 | 38981480459 | |
| 10 | 33075 | 33080 | 33080 | 1215856,401 | 40220529739 | |
| 11 | 33080 | 33085 | 33085 | 1305642,319 | 43197176118 | |
| 12 | 33085 | 33090 | 33090 | 1783966,019 | 59031435558 | |
| 13 | 33090 | 33095 | 33095 | 2025421,012 | 67031308378 | |
| 14 | 33095 | 33100 | 33100 | 1879302,907 | 62204926208 | |
| 15 | 33100 | 33105 | 33105 | 1651591,944 | 54675951317 | |
| 16 | 33105 | 33110 | 33110 | 1296758,683 | 42935679999 | |
| 17 | 33110 | 33115 | 33115 | 1137852,39 | 37679981885 | |
| 18 | 33115 | 33120 | 33120 | 893303,7829 | 29586221289 | |
| 19 | 33120 | 33125 | 33125 | 545274,8602 | 18062229744 | |
| 20 | 33125 | 33130 | 33130 | 498752,1566 | 16523658947 | |
| 21 | 33130 | 33135 | 33135 | 726713,9329 | 24079666166 | |
| 22 | 33135 | 33140 | 33140 | 1787204,041 | 59227941906 | |
| 23 | 33140 | 33145 | 33145 | 1129131,54 | 37425064887 | |
| 24 | 33145 | 33150 | 33150 | 20847,40016 | 691091315,4 | |

Machine-based calculations [Rukhovich et al., 2021] indicate that more than half of the 6 443.529-hectare study area is affected by gully erosion. The total volume of gullies in this area amounts to 864 467.4 m³. To approximately determine the annual volume of eroded soil, considering the factors in the LS-factor calculation, it is first necessary to establish the average soil loss per hectare. Assuming an average soil erosion rate of 15 t/ha/year (based on the region's mean erosion level), the total eroded soil mass is calculated as 15 × 4,000 = 60,000 t/year. Converting this into volume, given an average soil density of 1.3 t/m³ [Terekhov et al., 2023; Suleimenov et al., 2023], results in 60 000 / 1.3 ≈ 46 154 m³/year.

Based on this data, it is possible to compare the estimated annual soil erosion volume in agricultural lands with the total volume of gullies within the study area (Fig. 7).

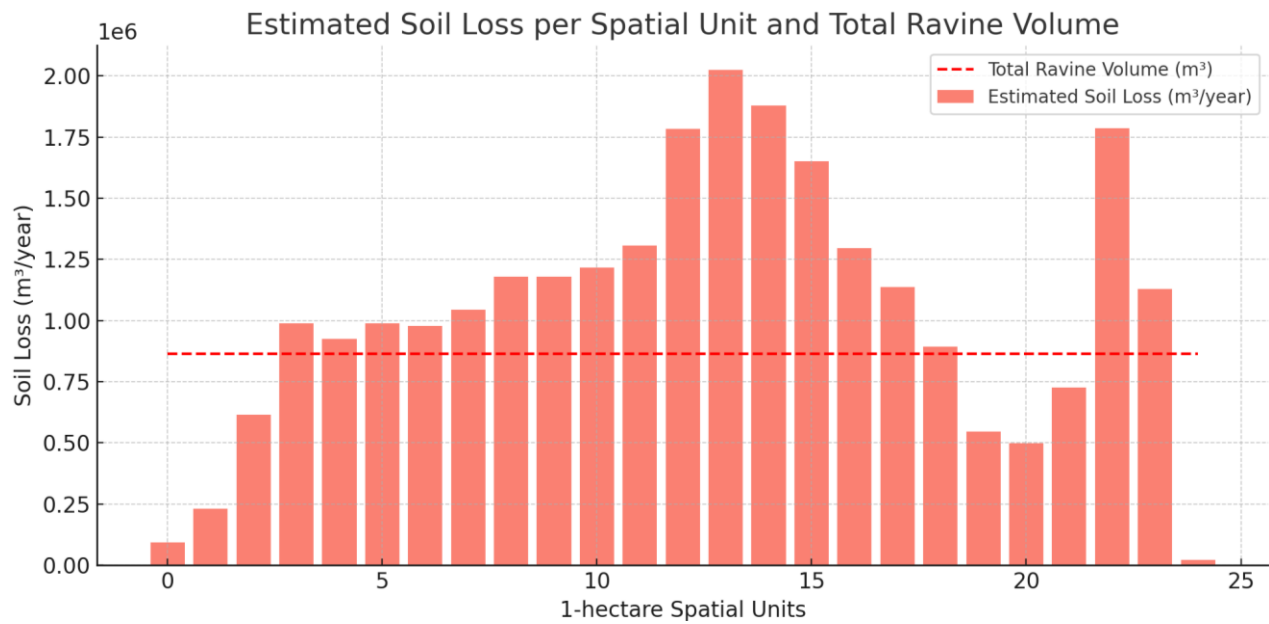


Fig. 7. Estimated annual soil loss compared to ravine volume

The analysis results indicate that the average soil loss per hectare is approximately 46 154 m³/year. However, the values vary considerably across the 1-hectare spatial units, as shown in Fig. 7, indicating that erosion intensity is not uniform throughout the study area. This variation reflects differences in slope, runoff accumulation, and terrain exposure. The calculated values are based on an assumed average soil density of 1.3 t/m³ and an erosion rate of 15 t/ha/year.

The red line in Fig. 7 represents the total volume of soil lost due to ravine formation — 864 467.4 m³ — highlighting the cumulative long-term impact of gully erosion. In contrast to annual erosion rates, ravine volumes suggest that these features have developed gradually over time and are continuously fed by surface runoff. This spatial erosion pattern is typical for agricultural lands in foothill regions along the Irtysh River, where topographic conditions contribute to active soil degradation.

Based on these findings, it is concluded that targeted erosion control measures are essential for sustainable agricultural land use in such environments.

CONCLUSIONS

This study was conducted to assess the potential for detecting soil erosion and degradation on sloping terrain in the investigated area using Remote Sensing (RS) satellite imagery analysis combined with the geosystem model (SAGA). The research incorporated all necessary comprehensive indices relevant to the topic and revealed that the most widespread and intensively developing process in mountainous regions is water erosion. Furthermore, the proximity of the Irtysh River basin was found to have a direct impact on the widespread occurrence of surface runoff and gully formation in agricultural lands.

The analysis demonstrated that the erosional potential of the geosystems' relief, determined by slope magnitude and the LS-factor index, is largely correlated with slope angles and exhibits significant erosion intensity. Based on geomodelling results utilizing LS-factor and Valley Depth indicators, it was estimated that the soil loss per hectare could exceed 46 154 m³/year. Additionally, an analysis of crop rotation maps indicated that in recent years, the investigated agricultural lands have predominantly been used for shallow-rooted crops, further exacerbating erosion risks.

Based on the morphometric and erosion modeling analysis, specific land management interventions are proposed for various topographic conditions. Contour plowing is recommended for gently sloping fields to reduce surface runoff, while terracing is suited for steeper gradients to minimize downslope erosion. Vegetative stabilization measures, such as planting grass cover or green belts, can protect gully edges and minimize sediment loss. In high runoff zones, drainage systems and engineered soil barriers should be implemented to regulate water flow and prevent erosion-related damage.

From an engineering perspective, terracing techniques should be applied to steep slopes, while specially designed soil barriers can help slow down water flow. Gullies can be stabilized by vegetative reinforcement, including grass cover and the establishment of green belts to curb soil displacement. Moreover, drainage systems should be installed to regulate excess water runoff and prevent uncontrolled erosion.

Among biological measures, planting perennial vegetation and shrubs in gullies and on steep slopes, as well as cultivating crops with robust root systems, is highly effective. Additionally, hydrotechnical interventions, such as constructing temporary or permanent check dams, filtration channels, and water flow retardation structures, can help control erosion processes. By integrating these measures, the expansion of gullies can be curtailed, and the degradation of fertile topsoil can be significantly reduced.

Thus, the application of advanced geo-information technologies in the assessment and visualization of this complex, multi-factorial process enabled the processing of extensive datasets, yielding highly detailed quantitative parameters. The obtained results provide a solid foundation for the development of a comprehensive erosion prevention strategy for the region.

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