GIS-based assessment of soil erosion risk in a post-nuclear landscape: A morphometric approach using ALOS PALSAR DEM

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Abstract. Morphometric analysis of terrain is widely recognized as one of the most effective approaches to investigating soil erosion processes. This study examines the relationship between terrain morphometry and soil erosion susceptibility within the Semipalatinsk Test Site (STS), Kazakhstan, using the ALOS PALSAR digital elevation model (DEM) at 12.5 m spatial resolution processed within ArcGIS 10.4. A series of thematic morphometric maps – including hypsometric, slope gradient, and slope aspect layers – were generated and used to develop a three-level hierarchical classification of theResults indicate that flat and very gentle terrain (slopes below 6°) accounts for approximately 51% of the STS territory; gentle to moderate slopes (6° – 25°) cover 44%; and steep slopes (above 25°) occupy only approximately 5% of the total area, concentrated within the Degelen Mountain Range. The dominant slope aspect is north-facing, contributing to pronounced microclimatic asymmetry. Integration of GIS-based morphometric parameters with land cover and soil data revealed distinct erosion-prone zones correlated with slope steepness and relative relief. The findings confirm that high-resolution DEM-based morphometric analysis is a reliable and efficient tool for landscape assessment, soil erosion monitoring, and sustainable land management planning in semi-arid regions with complex topography.

1 Introduction

Relief is universally acknowledged as one of the primary factors governing landscape differentiation and driving geomorphological processes [1, 2]. The quantitative characterization of terrain-known as morphometric analysis-provides a systematic basis for identifying and mapping landform types, and for assessing their role in controlling hydrological and erosional dynamics [3, 4]. With the rapid development of digital elevation model (DEM) technologies and geographic information systems (GIS), morphometric analysis has become increasingly automated and spatially comprehensive, allowing

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researchers to derive topographic parameters—including slope, aspect, curvature, and hypsometry—with high accuracy and efficiency [5].

Soil erosion is a widespread environmental problem that threatens agricultural productivity and ecosystem stability, particularly in semi-arid regions where climatic variability and sparse vegetation amplify the vulnerability of soils to degradation [6, 7]. Topographic parameters-primarily slope steepness and aspect-are among the most influential drivers of erosion intensity, as they determine runoff velocity, sediment transport capacity, and moisture distribution across the landscape [8].

The Semipalatinsk Test Site (STS), located in eastern Kazakhstan, represents a unique and scientifically significant territory covering approximately 18,500 km². Formerly used as the primary nuclear weapons testing ground of the Soviet Union, the STS encompasses a diverse range of geomorphological environments, from flat steppe plains to low-mountain massifs, under an arid to semi-arid continental climate [9]. Despite the environmental legacy of nuclear testing, the territory has been the subject of increasing geoecological research; however, systematic morphometric characterization coupled with soil erosion risk assessment remains insufficiently addressed in the existing literature.

Previous studies have employed various approaches to assess soil erosion in semi-arid and degraded landscapes. Morphometric indices derived from DEMs have been applied to delineate erosion-prone watersheds, with ALOS PALSAR DEM data proving particularly effective for morphometric analysis in areas of complex topography due to its superior spatial resolution [1]. GIS-based integration of slope, aspect, and land cover data with RUSLE-type models has been demonstrated as an effective method for producing spatially explicit erosion risk maps in dryland and Mediterranean environments [4, 7]. In the context of ecologically sensitive and disturbed territories, GIS-based spatial modelling combining terrain analysis with satellite-derived indices has been used to assess soil erosion alongside other natural hazards [8]. However, comparatively few studies have applied high-resolution SAR-derived DEMs specifically to post-nuclear landscapes, where surface disturbance, restricted access, and heterogeneous soil conditions create particular challenges for conventional field-based assessment methods. The present work addresses this gap by applying ALOS PALSAR DEM data, which offers superior spatial resolution (12.5 m) compared to globally available alternatives, to characterize the morphometric structure and erosion susceptibility of the STS.

The present study aims to: (1) conduct a morphometric analysis of STS relief using the ALOS PALSAR DEM; (2) develop a hierarchical terrain classification based on elevation, slope, and aspect parameters; and (3) evaluate the spatial relationship between morphometric characteristics and soil erosion susceptibility across the study area.

2 Study area

The Semipalatinsk Test Site is located in the eastern part of the Kazakh Uplands (Saryarka), spanning the administrative boundaries of East Kazakhstan, Pavlodar, and Karaganda regions. The site covers approximately 18,500 km² and includes three principal sub-polygons: Degelen, Balapan, and Telkem. The territory is bounded to the northeast by the Irtysh River and is characterized by a diverse mosaic of geomorphological units, including structural-denudation uplands, undulating ridge plains, alluvial lowlands, and low-mountain massifs (Figure 1).

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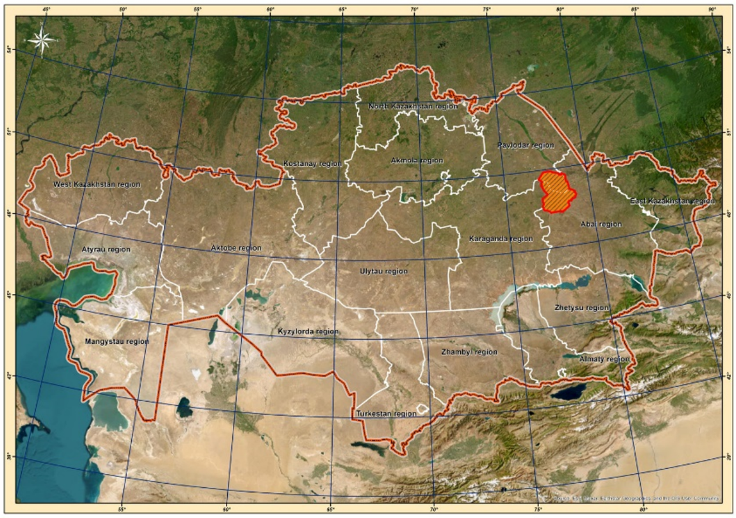

Fig. 1. Location map of the Semipalatinsk test site.

The climate is strongly continental, with mean July temperatures of +19 °C to +22 °C and mean January temperatures of −14 °C to −18 °C. Annual precipitation ranges from 250–300 mm on the steppe plains to 400–600 mm in the hilly and mountainous sectors. Prevailing winds shift seasonally, with southeasterly winds in winter and northerly winds in summer, contributing to the aridity and thermal instability of the region (Figure 2). The Degelen Mountain Range, the most prominent elevated feature, forms a dome-shaped massif approximately 17–18 km in diameter, with absolute elevations reaching 1,085 m.

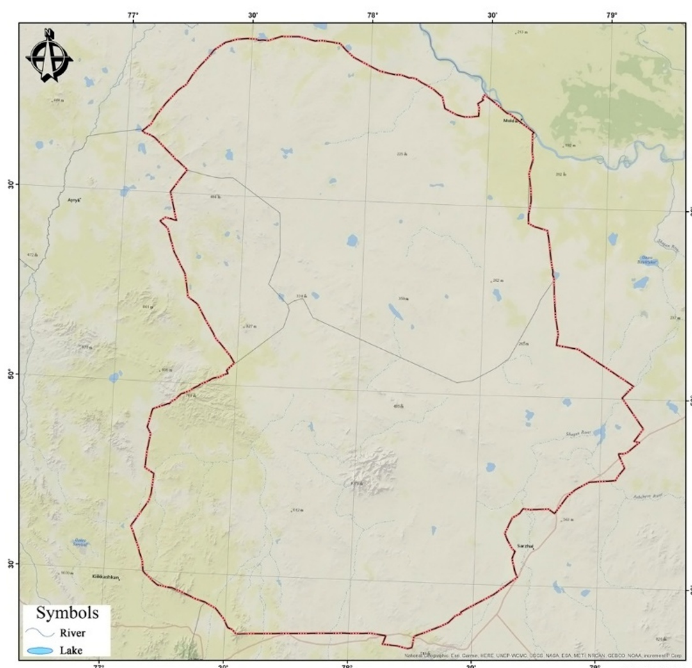

Fig. 2. Location and hydrographic features of the Semipalatinsk test site.

3 Data and methods

The primary data source for morphometric analysis was the ALOS PALSAR DEM (Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar), characterized by a spatial resolution of 12.5 m and a root mean square error (RMSE) of approximately 12.5 m in the vertical dimension [10]. This dataset (Figure 3) was selected for its superior spatial resolution relative to globally available alternatives such as SRTM (30 m) and ASTER GDEM (30 m), and for its improved accuracy in terrain with moderate relief complexity [10].

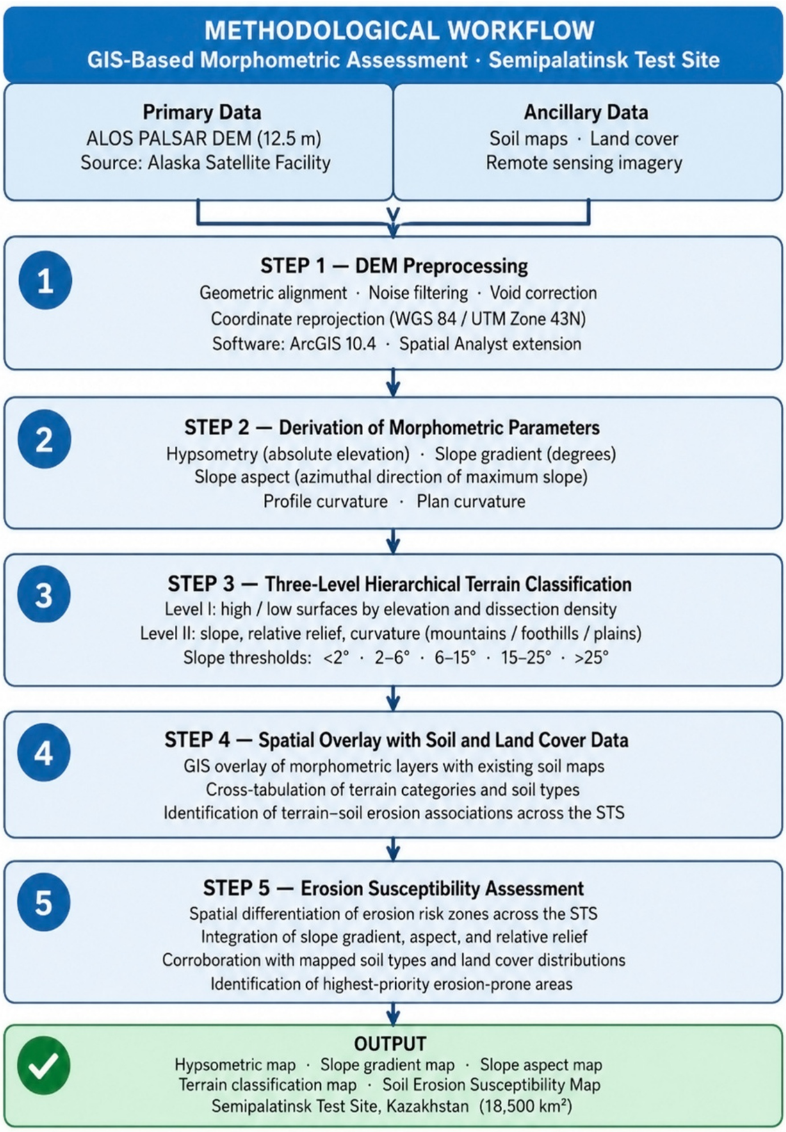

Fig. 3. Methodological workflow of the GIS-based morphometric soil erosion susceptibility assessment at the Semipalatinsk Test Site.

All DEM preprocessing-including geometric alignment, noise filtering, and error correction-was performed using the Spatial Analyst extension within ArcGIS 10.4. The following morphometric parameters were derived from the DEM: (1) hypsometric distribution (absolute elevation); (2) slope gradient (degrees); (3) slope aspect (azimuthal direction of maximum slope); and (4) surface curvature (profile and plan). These layers formed the basis for terrain classification and erosion susceptibility mapping.

A three-level hierarchical terrain classification was developed on the basis of the morphometric parameters described above [11]. The classification criteria follow established geomorphometric standards [3, 5], with slope angle thresholds applied as follows: <2° (flat surfaces and water bodies); 2–6° (very gentle slopes); 6–15° (gentle to moderate slopes); 15–25° (moderately steep slopes); and >25° (steep slopes). The spatial distribution of each slope category was quantified and correlated with corresponding soil types and erosion risk zones identified from existing soil maps and remote sensing data.

The overall methodological workflow followed a sequential, multi-stage structure: (1) acquisition and preprocessing of ALOS PALSAR DEM data (geometric alignment, noise filtering, void correction); (2) derivation of primary morphometric parameters (elevation, slope gradient, slope aspect, curvature); (3) hierarchical terrain classification using thresholds defined by established geomorphometric standards; (4) spatial overlay of morphometric layers with soil and land cover datasets; and (5) delineation and assessment of erosion susceptibility zones based on the integrated analysis of slope steepness, aspect, and relative relief. Each stage was implemented within ArcGIS 10.4 using the Spatial Analyst extension, ensuring full reproducibility of the geospatial processing workflow.

4 Results and discussion

4.1 Hypsometric characteristics and terrain classification

The morphometric interpretation of the ALOS PALSAR DEM revealed that the average elevation of the STS terrain is approximately 450 m above sea level (Figure 4). The three-level hierarchical terrain classification produced the following structural units:

Level I: Two major morphometric groups-“high” and “low” surfaces-were delineated. Low surfaces are characterized by minimal relative relief and low dissection density, while high surfaces display pronounced vertical differentiation and steeper slopes.

Level II: Classification was refined by incorporating slope gradient, relative relief, and curvature, yielding low and medium mountain systems and transitional foothill plains.

Level III: Distinguished medium and high mountain areas, hilly terrains, and broad plains exhibiting the most pronounced topographic contrasts and the strongest influence on erosional processes [12].

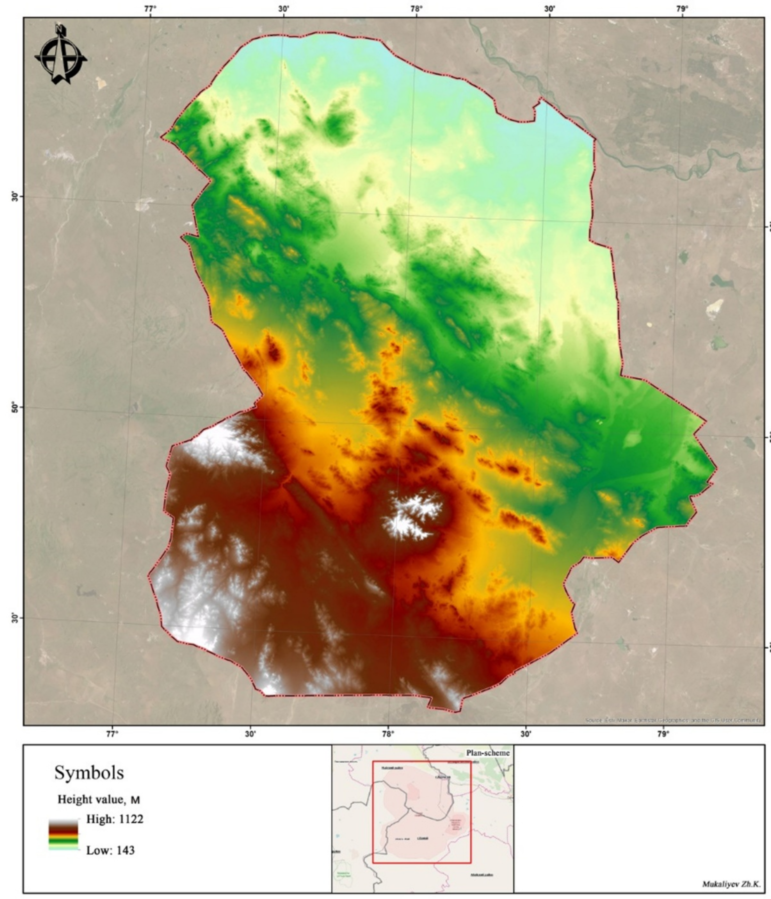

Fig. 4. Hypsometric map of the STS derived from ALOS PALSAR DEM (elevation range: 143–1122 m).

The Degelen massif, the dominant elevated feature, forms a dome-shaped structure approximately 18 km in diameter and covering approximately 331 km². It rises up to 500 m above the surrounding terrain and reaches a maximum elevation of 1,085 m. The foothill zone accounts for approximately 30% of the total STS area; low mountain terrain (600–1,000 m a.s.l.) covers approximately 20%; and medium mountain terrain (above 1,000 m) accounts for approximately 5%, concentrated mainly within the Degelen Range. The Irtysh River valley represents the lowest hypsometric tier, with elevations dropping below 200 m near the floodplain.

4.2 Slope gradient distribution

Analysis of the slope gradient map derived from the DEM revealed values ranging from 0° to 51°, with a mean slope of 8.55° across the study area (Figure 5). The areal distribution of slope categories is as follows: approximately 21% of the territory consists of flat surfaces and water bodies (slope <2°); approximately 30% is classified as very gentle slopes (2–6°); approximately 28% as gentle slopes (6–15°); approximately 16% as moderate slopes (15–25°); and approximately 5% as steep slopes (>25°). Steep slopes are almost exclusively confined to the Degelen mountainous sector (Table 1). These findings are consistent with the semi-arid steppe character of the STS, where flat to gently undulating terrain prevails.

Table 1. Areal distribution of slope gradient categories across the Semipalatinsk Test Site (STS). Mean slope: 8.55°; elevation range: 143–1,122 m a.s.l.

Slope class	Range (°)	Area (km²)	Share (%)
Flat / water bodies	<2	3,885	21
Very gentle	2–6	5,550	30
Gentle	6–15	5,180	28
Moderate	15–25	2,960	16
Steep	>25	925	5
Total	0–51	18,500	100

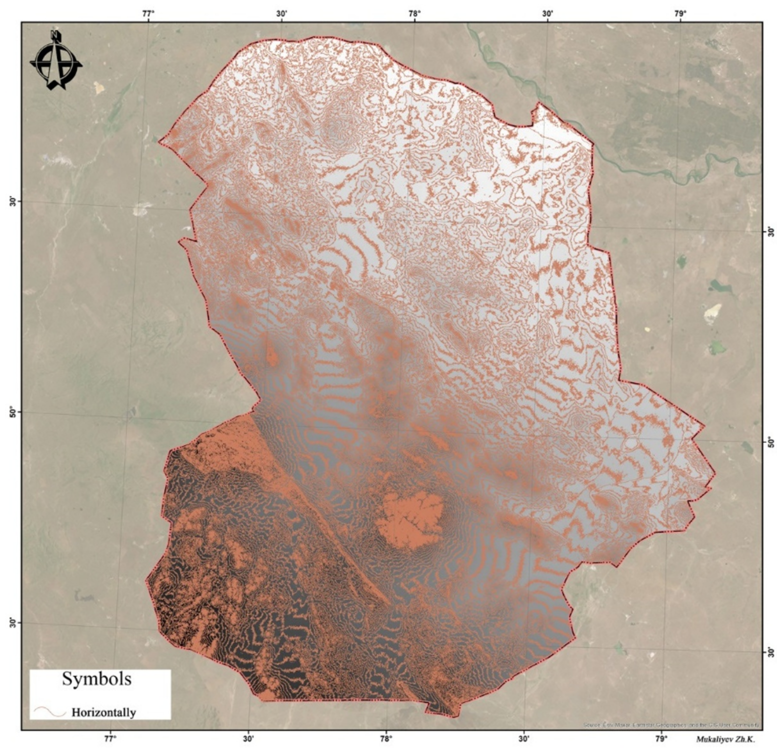

Fig. 5. Contour line map of the STS terrain derived from ALOS PALSAR DEM.

4.3 Slope aspect and microclimatic asymmetry

The slope aspect analysis reveals a clear dominance of north-facing exposures across the STS (Figure 6). This directional asymmetry has direct implications for soil moisture distribution, snow accumulation, and vegetation cover patterns, all of which influence the spatial organization of erosion processes. North-facing slopes receive less direct solar radiation, leading to reduced evapotranspiration and greater soil moisture retention [13, 14]. As a result, these slopes tend to support denser vegetation and exhibit lower erosion rates compared to south-facing counterparts, which experience more intense desiccation and a higher degree of surface degradation.

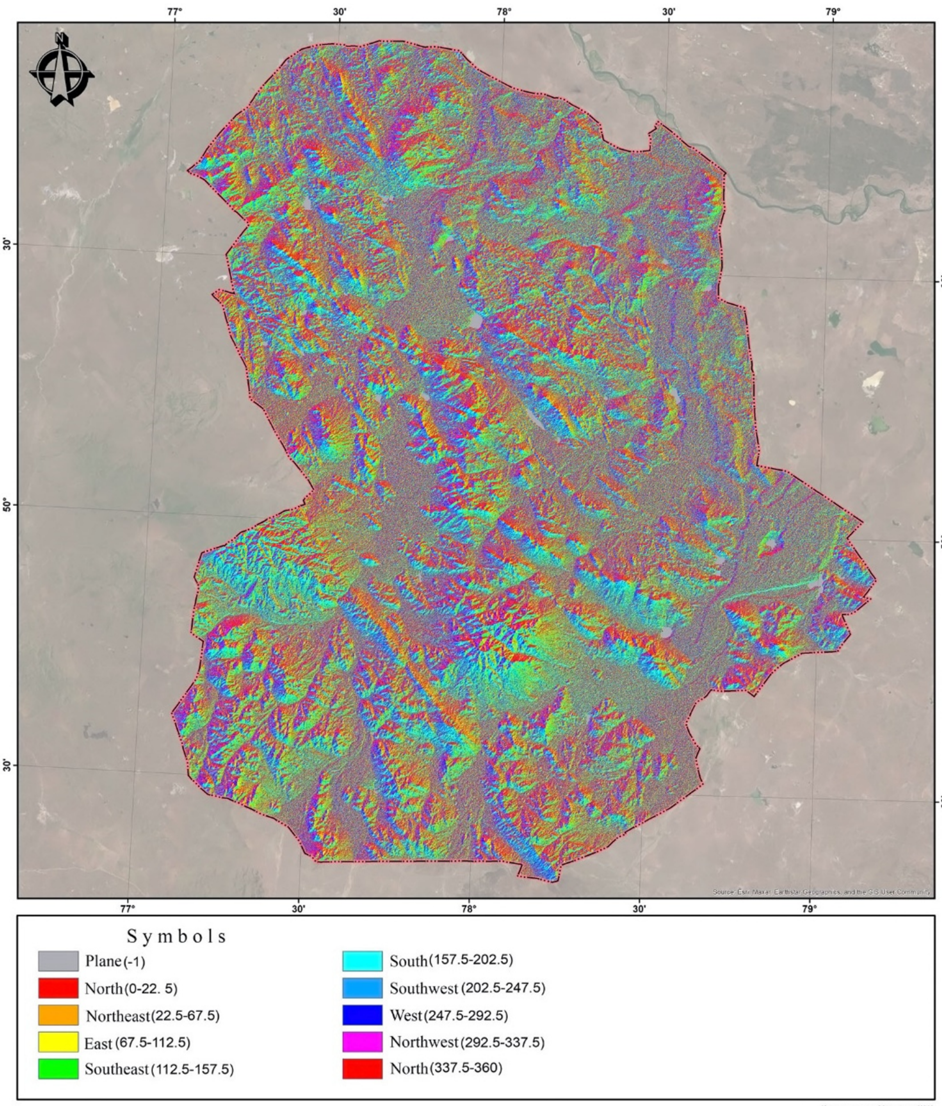

Fig. 6. Slope aspect map of the STS showing directional distribution of slope exposures.

4.4 Soil erosion susceptibility assessment

The integration of morphometric parameters-slope gradient, aspect, and relative relief-with soil and land cover data enabled spatial differentiation of erosion risk zones across the STS. Areas of complex relief, particularly those within the Degelen massif and foothill transitional zones, were identified as the most erosion-prone, due to the combination of steep slopes, coarse-grained granitic parent material, and sparse vegetation [13]. In contrast, flat and gently sloping steppe surfaces in the northern and central portions of the STS exhibit the lowest erosion susceptibility.

The soil cover of the STS reflects this geomorphological gradient: chestnut and light-chestnut soils dominate the Irtysh valley lowlands, which transition southwestward to saline and solonetzic soils in the Kazakh Uplands, and to dark-chestnut soils interspersed with stony and gravelly formations on the slopes of denudation plains and low hills. Such soil heterogeneity, conditioned by topographic position, reinforces the spatial coherence between morphometric parameters and erosion risk [15].

These findings are broadly consistent with results reported for comparable semi-arid and mountain landscapes. Studies applying morphometric analysis with ALOS PALSAR DEM data have consistently shown that slope, drainage density, and relief parameters are the most reliable predictors of erosion susceptibility, with the highest-priority sub-basins associated with steeper terrain and finer drainage texture [1]. In Mediterranean catchments, RUSLE-based assessments combined with morphometric parameter analysis have demonstrated that steep, sparsely vegetated slopes generate disproportionate sediment yields even when they occupy limited areal extents [4]. Annual soil loss rates estimated through RUSLE in semi-arid North African watersheds typically range from 22 to 55 t ha^{-1} $year^{-1}$ [7], considerably exceeding rates typical of steppe environments where gentle terrain and continuous vegetation limit erosive potential. GIS-based terrain modelling in mountain national park settings has further confirmed that erosion intensity is strongly governed by lithology and land use type, with the most erodible substrates concentrated on moderate rather than the steepest slopes [8]. The dominance of gentle to moderately undulating terrain in the STS (approximately 79% of total area) is consistent with inherently low erosion susceptibility observed in comparable semi-arid steppe settings. In contrast to RUSLE-based quantitative approaches, the present morphometric framework offers a logistically feasible alternative for large, inaccessible post-nuclear territories where calibration data for process-based models are unavailable. While the absence of field-measured erosion rate data precludes direct quantitative validation, the spatial consistency of erosion risk zones with independently mapped soil types and land cover patterns provides indirect corroboration of the classification scheme's reliability. Future work integrating rainfall erosivity data and multi-temporal satellite imagery will enable transition toward fully quantitative erosion modelling at the STS.

5 Conclusion

This study has demonstrated the effectiveness of ALOS PALSAR DEM-based morphometric analysis for characterizing terrain structure and evaluating soil erosion susceptibility across the Semipalatinsk Test Site. A three-level hierarchical terrain classification was developed, revealing that gently sloping to moderately undulating terrain dominates the STS (approximately 79% of total area), while steep, erosion-prone slopes are confined primarily to the Degelen Mountain Range (approximately 5%). The mean slope angle of 8.55° and the prevalence of north-facing exposures contribute to a distinctive pattern of microclimatic and pedological heterogeneity across the territory.

The spatial integration of morphometric indicators within a GIS framework proved to be a reliable method for identifying erosion-prone zones and for establishing quantitative linkages between topographic parameters and soil degradation risk. Remote sensing data, combined with GIS-based terrain analysis, represent a particularly valuable approach for large, poorly accessible territories such as the interior sectors of the STS, where field-based surveys are logistically constrained.

The results of this study provide a foundational dataset for further quantitative modeling of erosion intensity, runoff formation, and landscape dynamics at the STS. Future research should incorporate multi-temporal remote sensing data and field validation to refine erosion susceptibility maps and support evidence-based land management planning in this ecologically sensitive region.

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