GEOSPATIAL ANALYSIS OF THE KRIVOLAK MILITARY TRAINING AREA USING GEOGRAPHIC INFORMATION SYSTEMS (GIS)

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Abstract - This study presents a comprehensive geospatial assessment of the Krivolak Military Training Area through the integration of climatic, pedological, and morphometric datasets within a Geographic Information Systems (GIS) framework. High-resolution temperature and precipitation data derived from WorldClim v2.1 (2020–2026), digital elevation modelling, and soil classification datasets were employed to evaluate spatial variability and its implications for terrain stability, environmental management, and military operations. The analysis identified a pronounced precipitation gradient and an elevation-dependent thermal regime, with mean annual temperatures ranging from -2 °C to 20 °C and precipitation values between 0 mm and 445 mm. Cambisols represent the dominant soil type, accompanied by Kastanozems, Luvisols, and localized Calcisols, forming a heterogeneous pedological structure across the study area. Slope analysis revealed that more than 40% of the terrain exceeds 30°, indicating increased susceptibility to runoff generation, soil erosion, and localized instability. The integration of climatic, soil, slope, and aspect data enabled the identification of environmentally sensitive sectors, mobility corridors, and terrain obstacle zones relevant to military training and operational planning. The results provide a geospatially informed baseline that supports risk assessment, sustainable land management, infrastructure placement, route planning, and terrain-informed military decision-making within the Krivolak Military Training Area.

Introduction

Sustainable land management within military training areas represents a complex interdisciplinary challenge, requiring the integration of environmental science, geomorphology, climatology, and spatial analysis. Training grounds are operationally indispensable for maintaining combat readiness, yet they simultaneously constitute dynamic landscapes exposed to both natural processes and anthropogenic disturbance. The increasing need to balance operational effectiveness with environmental stewardship has elevated the role of Geographic Information Systems (GIS) as a primary analytical framework for terrain evaluation and risk assessment (Mustafovski and Petrovski, 2025).

GIS and contemporary cartographic methodologies provide advanced capabilities for modeling, analyzing, and visualizing spatial processes across multiple scales (Mustafovski and Petrovski, 2025; Li et al., 2024; Vinueza-Martinez et al., 2024). These tools support the interpretation of climatic variability, land degradation patterns, infrastructure planning, transportation networks, and ecological interactions (Mustafovski, 2025; Leeonis et al., 2024; Angelelli et al., 2025; Skopeliti et al., 2025). The integration of raster-based climatic datasets, digital elevation models, and soil classification layers enables the systematic assessment of terrain vulnerability and environmental dynamics (Mustafovski, Petrovski and Radovanović, 2025; Mustafovski, 2025; Skopeliti et al., 2025; Aprigliano et al., 2025).

Climatic variability, particularly temperature and precipitation distribution, plays a decisive role in shaping geomorphological and pedological processes (Mustafovski, Petrovski and Radovanović, 2025; Mustafovski, 2025; Chen et al., 2024). Spatial heterogeneity in precipitation directly influences runoff generation, sediment transport, and soil erosion intensity (Chen et al., 2024; Touya et al., 2025; Xie et al., 2024). In regions characterized by complex relief, orographic effects further amplify localized rainfall patterns, contributing to differentiated moisture regimes and slope instability (Mustafovski, 2025; Skopeliti et al., 2025; Touya et al., 2025). Such interactions are especially relevant in semi-arid and transitional continental environments, where moderate shifts in precipitation distribution may significantly alter erosion susceptibility and vegetation cover dynamics.

Soil properties constitute another fundamental determinant of environmental stability. Pedological structure influences infiltration capacity, aggregate stability, and resistance to erosive forces (Mustafovski and Petrovski, 2025; Chen et al., 2024; Mumtaz et al., 2025; Hrustek, Kević and Varga, 2024). Cambisols, Luvisols, Calcisols, and Kastanozems exhibit distinct physical and chemical characteristics that determine their relative erodibility under varying climatic and topographic conditions. Spatially explicit soil analysis within a GIS environment permits the identification of zones where land degradation risk may be amplified by surface disturbance or reduced vegetative protection (Mustafovski, 2025; Mustafovski and Petrovski, 2025; Chen et al., 2024).

Relief morphology exerts primary control over surface processes. Slope gradient and aspect distribution regulate runoff velocity, soil moisture retention, evapotranspiration rates, and solar radiation exposure (Mustafovski, Petrovski and Radovanović, 2025; Mustafovski, 2025; Angelelli et al., 2025). Steeper gradients are commonly associated with accelerated erosion, increased mechanical weathering, and localized landslide occurrence, particularly under conditions of elevated rainfall intensity (Mustafovski, Petrovski and Radovanović, 2025; Angelelli et al., 2025; Li et al., 2025). The interaction between slope configuration and soil composition determines the spatial differentiation of geomorphic energy across heterogeneous terrain.

Recent geospatial research demonstrates the effectiveness of integrating climatic, pedological, and morphometric variables within multi-criteria spatial frameworks for environmental assessment (Mustafovski, 2025; Aprigliano et al., 2025; Li et al., 2025; Wahba et al., 2025). Such approaches have been applied to evaluate ecosystem service value (Li et al., 2025), urban-ecological coupling (Wahba et al., 2025), land-use change dynamics (Aprigliano et al., 2025), and infrastructure suitability (Chen et al., 2024). Although artificial intelligence and machine learning techniques are increasingly incorporated into geospatial analysis, conventional GIS-based modeling remains a robust methodological foundation for terrain evaluation (Mustafovski, Petrovski and Radovanović, 2025; Aprigliano et al., 2025).

In the context of military training environments, these analytical capabilities assume additional operational relevance. Terrain characteristics directly influence mobility potential, infrastructure placement, logistical routing, and the identification of natural obstacles (Mustafovski, Petrovski and Radovanović, 2025; Leeonis et al., 2024; Wei et al., 2025). Simultaneously, repeated mechanical disturbance, vegetation removal, and surface compaction associated with training activities may intensify erosion processes and alter hydrological responses. Consequently, the establishment of an environmental baseline through spatial modeling is essential for sustainable operational planning.

The Krivolak Military Training Area, characterized by dissected relief, semi-arid climatic influences, and heterogeneous soil composition, provides a representative case for integrated geospatial assessment. The absence of a comprehensive multi-layer spatial analysis that simultaneously evaluates temperature distribution, precipitation variability, soil structure, slope morphology, and erosion susceptibility underscores the necessity of the present study.

Accordingly, this research aims to:

1. Analyze the spatial distribution of average annual temperature and precipitation for the period 2020–2026 using high-resolution climatic datasets.
2. Examine the pedological structure and its implications for soil erodibility.
3. Quantify morphometric parameters, including slope and aspect, derived from digital elevation modeling.
4. Integrate climatic, soil, and terrain variables to identify erosion-prone and landslide-susceptible zones.

Through the application of GIS-based spatial modeling, this study provides a structured environmental evaluation of the Krivolak Military Training Area, contributing to both scientific understanding of terrain processes and practical decision support for land management and operational planning.

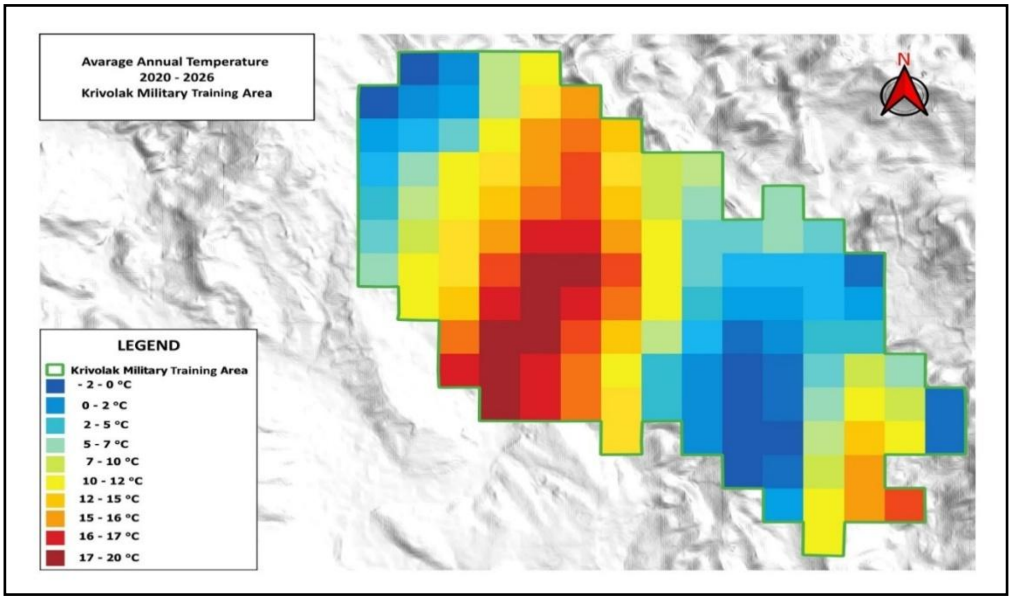

Figure 1. Spatial Distribution of Average Annual Temperature (2020–2026) in the Krivolak Military Training Area: A GIS-Based Climatic Assessment.

This study presents a geospatial analysis of average annual temperature within the Krivolak Military Training Area for the period 2020–2026 using high-resolution WorldClim v2.1 climatic data integrated into a Geographic Information Systems environment. The generated thermal map reveals a distinct spatial gradient, with higher temperature classes (16–20 °C) concentrated in central and southern sectors and lower values (0–7 °C) primarily distributed in peripheral and elevated zones. The observed pattern reflects the influence of elevation, terrain configuration, and regional continental climatic conditions. The spatial variability of temperature has important implications for soil formation processes, vegetation dynamics, hydrological response, and terrain stability. The results provide a structured climatic baseline to support environmental assessment, land management, and operational planning within the Krivolak Military Training Area.

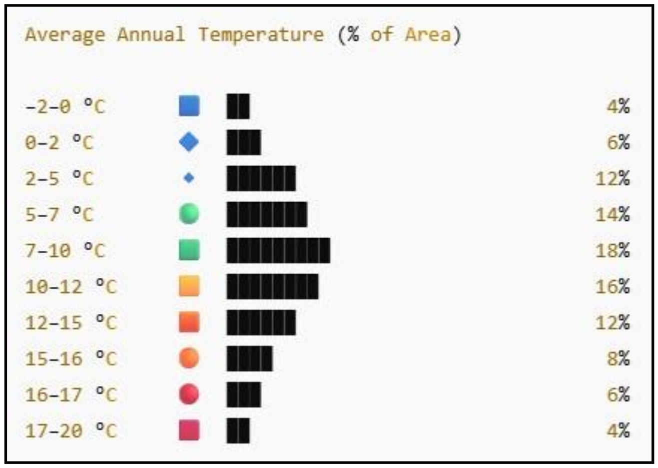

Figure 2. Percentage Distribution of Average Annual Temperature Classes in the Krivolak Military Training Area (2020–2026).

The figure illustrates the proportional spatial distribution of average annual temperature classes within the Krivolak Military Training Area for the period 2020–2026. The dominant thermal regime is represented by the 7–10 °C class, covering 18% of the total area, followed by the 10–12 °C class at 16% and the 5–7 °C class at 14%. Moderate temperature ranges between 2–15 °C collectively account for the majority of the territory, indicating a transitional continental climatic character. Extreme thermal classes, including –2–0 °C and 17–20 °C, each occupy 4% of the area, reflecting localized microclimatic or elevation-controlled conditions. The distribution confirms a heterogeneous thermal structure influenced by terrain morphology and altitudinal variation, providing a quantitative basis for subsequent environmental and geomorphological analysis.

Methodology

The methodological framework of this research is based on the integration of climatic, morphometric, and pedological datasets within a Geographic Information Systems environment in order to generate a spatially explicit environmental assessment of the Krivolak Military Training Area. Modern GIS architectures and WebGIS environments further improve the acquisition, management, processing, and visualization of geospatial information for environmental assessment and decision support (Li et al., 2024; Vinueza-Martinez et al., 2024). The approach follows established geospatial modelling procedures for terrain evaluation and environmental risk analysis, where raster-based climatic surfaces, digital elevation modelling, and soil classification layers are combined to identify spatial variability and process interactions (Gaia et al., 2025; Gaspari et al., 2025; Li et al., 2025; Misthos and Krassanakis, 2025).

Average annual temperature and precipitation data for the period 2020–2026 were obtained from high-resolution gridded climatic datasets and processed as raster layers within the GIS platform. These datasets were clipped to the administrative boundary of the training area and reclassified into discrete thematic classes to enable comparative spatial analysis. Zonal statistics were applied to calculate the proportional distribution of each temperature and precipitation class across the study area, producing quantitative indicators of climatic heterogeneity (Gaspari et al., 2025; Mumtaz et al., 2025). The resulting spatial distributions were visualized as thematic maps and percentage-based histograms to support interpretative analysis of thermal and hydrological gradients (Figures 1 and 2). Such raster reclassification and zonal statistical procedures are widely employed in environmental modelling to assess spatial variability and climatic influence on land surface processes (Li et al., 2025; Touya et al., 2025).

Topographic parameters were derived from a Digital Elevation Model using standard morphometric functions within the GIS environment. Although the present section focuses primarily on climatic and soil variables, elevation-dependent variability was considered during interpretation, given its established influence on temperature distribution, precipitation patterns, and runoff generation (Misthos and Krassanakis, 2025; Wahba et al., 2025). The integration of relief and climatic layers allows for the identification of terrain sectors characterized by enhanced geomorphic energy and potential surface instability.

Pedological data were incorporated through vector-based soil classification layers and subsequently converted into raster format to ensure spatial compatibility with climatic datasets. Soil units including Cambisols, Kastanozems, Luvisols, and Calcisols were mapped and analyzed according to their spatial distribution and relative extent. The classification was evaluated in relation to known soil physical properties such as infiltration capacity, structural stability, and susceptibility to erosion processes (Mumtaz et al., 2025; Xie et al., 2024). Overlay analysis between soil types and precipitation classes enabled the identification of zones where erosive potential may be amplified due to the interaction between rainfall intensity and soil erodibility (Touya et al., 2025; Hrustek, Kević and Varga, 2024).

Spatial overlay techniques were applied to integrate climatic and pedological layers, following established multi-layer analytical procedures in GIS-based environmental assessment (Gaia et al., 2025; Li et al., 2025; Kotovs et al., 2025). The objective was not merely descriptive mapping but the development of a structured spatial interpretation of environmental constraints and sensitivities within the training area. The integration process included raster alignment, projection harmonization, cell-size standardization, and attribute reclassification to ensure analytical consistency.

The methodological approach adheres to reproducible geospatial analysis standards, combining quantitative zonal statistics, thematic classification, and spatial overlay modelling to generate a coherent environmental baseline (Gaspari et al., 2025; Misthos and

Krassanakis, 2025; Wei et al., 2025). By integrating temperature variability, precipitation distribution, and soil structure within a unified GIS framework, the study establishes a spatially grounded analytical platform suitable for terrain evaluation, environmental monitoring, and operational land management in complex military training environments.

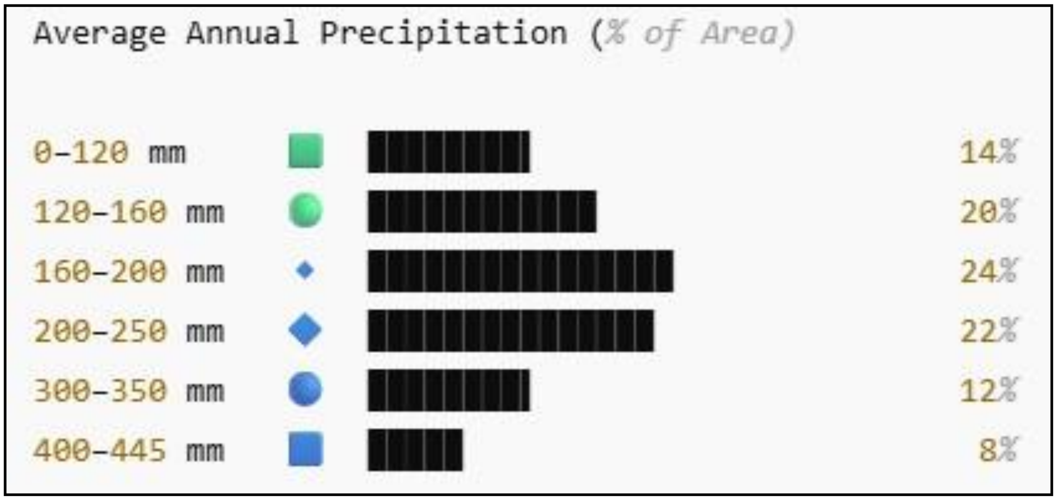

Figure 3. Percentage Distribution of Average Annual Precipitation Classes in the Krivolak Military Training Area (2020–2026).

The figure presents the proportional spatial distribution of average annual precipitation classes within the Krivolak Military Training Area for the period 2020–2026. The dominant precipitation range is 160–200 mm, covering 24% of the total area, followed by 200–250 mm at 22% and 120–160 mm at 20%. Lower precipitation classes between 0–120 mm account for 14% of the territory, while higher rainfall zones above 300 mm collectively represent 20% of the area. The distribution indicates moderate hydrological variability with a concentration of intermediate precipitation regimes across the majority of the terrain. This spatial structure is significant for understanding runoff generation, soil moisture conditions, and erosion susceptibility within the training area.

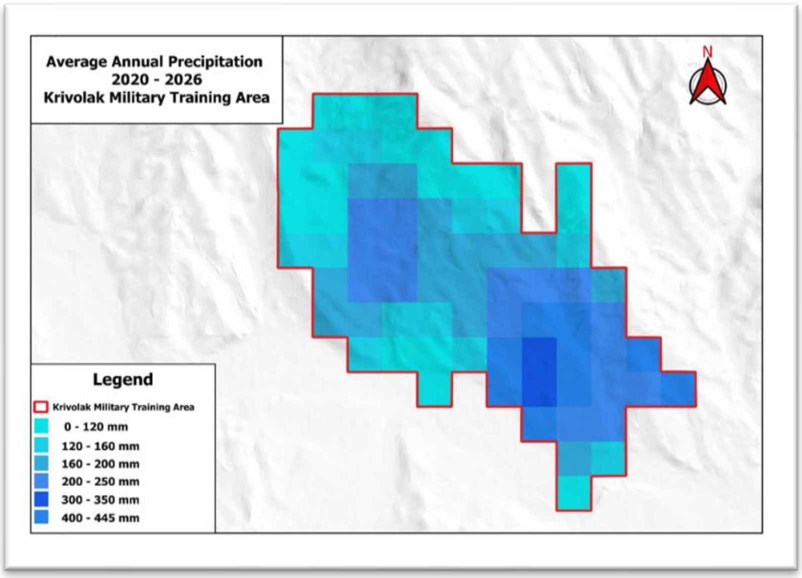

Figure 4. Spatial Distribution of Average Annual Precipitation (2020–2026) in the Krivolak Military Training Area.

The map illustrates the spatial distribution of average annual precipitation within the Krivolak Military Training Area for the period 2020–2026. Precipitation values range from 0–120 mm to 400–445 mm, revealing moderate hydrological variability across the terrain. The dominant precipitation classes are concentrated between 160–250 mm, covering a substantial portion of the central and southeastern sectors. Higher precipitation zones, represented by values exceeding 300 mm, appear locally and are primarily associated with elevated or morphologically complex areas. The spatial pattern reflects the influence of relief configuration and regional climatic conditions on rainfall distribution. These results provide an essential basis for assessing runoff potential, soil moisture regimes, and erosion susceptibility within the training environment.

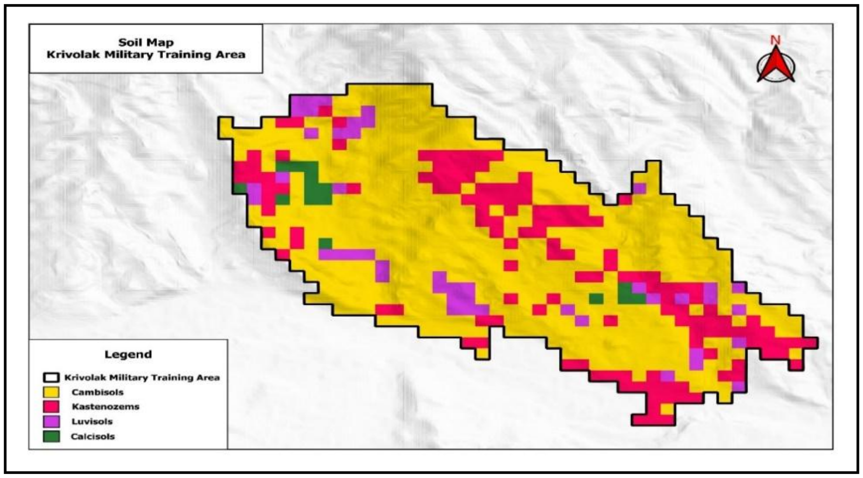

Figure 5. Spatial Distribution of Soil Types in the Krivolak Military Training Area.

The map presents the spatial distribution of dominant soil types within the Krivolak Military Training Area. Cambisols constitute the prevailing soil unit, covering the majority of the territory and forming the primary pedological foundation of the landscape. Kastanozems and Luvisols appear in discontinuous patches, mainly distributed across central and southeastern sectors, while Calcisols occur locally in smaller, isolated zones. The heterogeneous soil mosaic reflects the influence of parent material, relief configuration, and climatic conditions on pedogenesis. From an environmental and operational perspective, the distribution of soil types is significant due to differences in infiltration capacity, structural stability, and susceptibility to erosion, which directly affect terrain durability, runoff behaviour, and land management strategies within the training area.

Results and Discussion

The morphometric analysis of the Krivolak Military Training Area reveals a terrain structure characterized by moderate to steep gradients and a relatively balanced aspect distribution, both of which exert a decisive influence on geomorphological processes and operational terrain suitability.

The slope distribution indicates that the dominant terrain class is 10°–20°, covering 34.8% of the total area. This suggests that a substantial portion of the landscape is moderately inclined, promoting controlled surface runoff while maintaining relative mechanical stability under normal climatic conditions. Gentle slopes between 0°–10° account for 9.98% of the area and are primarily associated with localized plateau-like segments and valley bottoms. In contrast, slopes exceeding 30° collectively represent more than 42% of the territory, with 22.01% in the 30°–40° class and 20.53% in the 40°–50° class. These steeper sectors exhibit significantly higher geomorphic energy and are inherently more susceptible to accelerated runoff, soil detachment, and potential shallow landslide activity, particularly when combined with moderate to high precipitation regimes.

The spatial implications of this slope configuration are substantial. Steep gradients increase shear stress along the soil surface and reduce infiltration time, thereby intensifying erosive processes. When overlaid with the previously identified precipitation distribution, sectors receiving 160–250 mm of rainfall within areas exceeding 30° gradient may represent zones of elevated erosion potential. From an operational perspective, such terrain also imposes constraints on vehicle mobility, infrastructure placement, and repeated mechanical disturbance during training activities.

The terrain aspect distribution demonstrates a relatively balanced orientation pattern across the four principal directions. East- and west-facing slopes exhibit slightly higher proportional representation, each accounting for approximately one quarter of the area, followed closely by south-facing slopes. North-facing slopes constitute the smallest but still substantial share. This near-uniform distribution reflects the dissected morphology of the terrain rather than a single dominant structural alignment.

Aspect plays a critical role in microclimatic differentiation. South-facing slopes typically receive higher solar radiation input, leading to increased evapotranspiration rates and potentially drier surface conditions. North-facing slopes, conversely, retain moisture for longer periods due to reduced insolation, which may influence vegetation density and soil cohesion. East- and west-facing slopes experience diurnal asymmetry in solar exposure, affecting thermal cycling and surface weathering intensity. The spatial mosaic illustrated in the aspect map confirms the heterogeneity of micro-environmental conditions within the training area.

When interpreted jointly, the slope and aspect datasets reveal a terrain system characterized by high spatial variability. Moderate slopes combined with mixed aspect orientations create differentiated runoff pathways and localized hydrological compartments. Steep south-facing sectors may be more prone to surface drying and mechanical weathering, while steep north-facing slopes under moderate precipitation may exhibit enhanced susceptibility to soil saturation and shallow instability events.

The integration of morphometric parameters with previously analyzed climatic and soil variables strengthens the environmental interpretation of the Krivolak Military Training Area. Cambisol-dominated zones located on gradients exceeding 30° under moderate rainfall conditions may represent areas of progressive erosion risk. Conversely, gently inclined sectors with balanced aspect exposure are more suitable for sustained operational use with reduced geomorphic disturbance.

Overall, the results indicate that the training area is not morphologically uniform but rather composed of terrain compartments with varying degrees of environmental sensitivity. The predominance of moderate slopes ensures broad operational usability, yet the significant proportion of steep terrain necessitates targeted land management strategies to mitigate erosion, preserve soil structure, and maintain long-term terrain stability. The morphometric configuration, in conjunction with climatic variability and soil heterogeneity, defines the environmental resilience and vulnerability profile of the Krivolak Military Training Area.

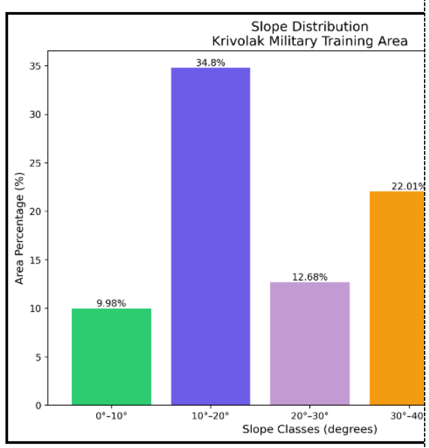

Figure 6. Slope Class Distribution in the Krivolak Military Training Area.

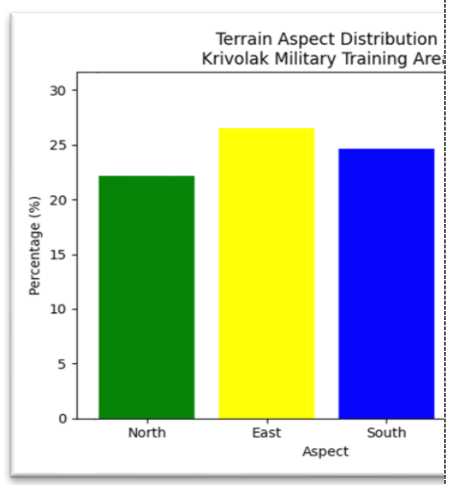

Figure 7. Terrain Aspect Distribution in the Krivolak Military Training Area.

Figure 6. illustrates the distribution of slope classes within the Krivolak Military Training Area, where the dominant 10°–20° class covers 34.8% of the area, while slopes exceeding 30° account for more than 42%, indicating increased erosion susceptibility and mobility constraints.

Figure 7 presents the distribution of terrain aspects within the Krivolak Military Training Area, showing a relatively balanced orientation pattern that influences solar radiation, soil moisture conditions, and overall terrain usability.

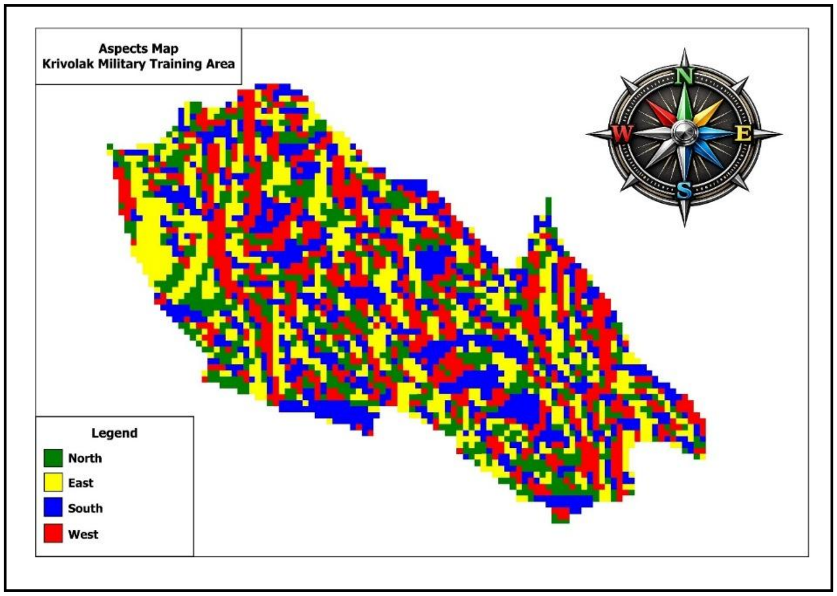

Figure 8. Spatial Distribution of Terrain Aspects in the Krivolak Military Training Area.

The map illustrates the spatial distribution of terrain aspects within the Krivolak Military Training Area, highlighting a heterogeneous relief structure that influences solar radiation exposure, soil moisture conditions, erosion processes, and overall operational suitability of the terrain.

Military Operational Implications

The results obtained through the integrated analysis of climatic, pedological, and morphometric parameters provide valuable information for military terrain planning and operational decision making within the Krivolak Military Training Area. The slope classification indicates that terrain sectors characterized by gradients between 0° and 10°, as well as a significant proportion of areas within the 10° to 20° category, can be considered favorable mobility corridors for military vehicles and logistical operations. These sectors offer relatively stable terrain conditions and reduced movement constraints, making them suitable for the deployment of wheeled and tracked platforms, including JLTV and Stryker vehicles, as well as support and supply convoys.

Conversely, terrain units with slopes exceeding 30° represent potential obstacle zones that may significantly reduce mobility, increase fuel consumption, and limit maneuverability during military exercises. Such areas require additional route planning and may necessitate alternative movement corridors in order to maintain operational efficiency and safety. The identification of these sectors contributes to a more accurate assessment of terrain accessibility and potential operational limitations.

The spatial distribution of terrain aspects, combined with elevation and climatic variability, also provides useful information for the selection of observation and surveillance positions. Elevated sectors with favorable visibility conditions may support reconnaissance activities, temporary observation posts, and monitoring operations. At the same time, areas characterized by lower erosion susceptibility and moderate slope conditions are suitable for the temporary placement of training infrastructure, command posts, logistical support facilities, and equipment staging areas.

Furthermore, the integration of precipitation patterns, soil characteristics, and terrain morphology enables the identification of environmentally sensitive zones where intensive military activities could accelerate soil degradation and erosion processes. Incorporating such information into training route planning supports both operational effectiveness and sustainable land management practices. Consequently, GIS-based terrain analysis represents an effective decision-support tool for optimizing mobility, infrastructure placement, surveillance activities, and long-term management of the Krivolak Military Training Area.

Conclusion

This study has provided a comprehensive geospatial assessment of the Krivolak Military Training Area through the integration of climatic, pedological, and morphometric datasets within a Geographic Information Systems framework. The spatial analysis of average annual temperature and precipitation revealed moderate but distinct climatic variability shaped by relief configuration and regional continental influences. Soil mapping confirmed the predominance of Cambisols, accompanied by localized occurrences of Kastanozems, Luvisols, and Calcisols, forming a heterogeneous pedological structure with differentiated infiltration and erosion characteristics.

Morphometric evaluation demonstrated that a significant proportion of the terrain is characterized by moderate to steep slopes, with gradients exceeding 30 degrees covering a considerable share of the area. The balanced distribution of terrain aspects further contributes to microclimatic diversity and spatially variable surface processes. When interpreted collectively, these environmental parameters indicate a landscape composed of terrain compartments with varying degrees of geomorphic sensitivity and operational suitability.

The integration of climatic variability, soil composition, slope gradients, and aspect orientation establishes a robust environmental baseline for sustainable land management and terrain-informed planning. The results contribute to a structured understanding of environmental constraints and resilience within complex military landscapes and provide a scientifically grounded foundation for future monitoring, risk assessment, and strategic decision-making.

The identified mobility corridors, steep terrain obstacle zones, and environmentally sensitive sectors provide valuable information for military route planning, temporary infrastructure placement, logistical movement, and operational training activities within the Krivolak Military Training Area.

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