TECHNICAL REPORT

Assessment of Soil Erosion Along Intensively Used Hiking Trails in Djerdap National Park (Serbia)

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ABSTRACT

This technical report presents an assessment of soil erosion along intensively used hiking trails in Djerdap National Park, Serbia. The study aims to identify spatial patterns of trail degradation and evaluate the influence of natural processes and human activities on soil erosion.

Field data were collected during a terrain survey conducted in spring 2026 using the Avenza Maps mobile GIS application. The collected data were subsequently processed and analysed in ArcGIS Pro, enabling spatial visualization and identification of erosion hotspots. Additional geomorphological analyses, including slope and flow accumulation, were applied to better understand terrain-related erosion dynamics.

The results reveal significant spatial variability in erosion intensity across the study areas. Higher levels of degradation were observed in locations affected by intensive tourism, vehicular access, and concentrated surface runoff, particularly in the Golubac and Lepenski Vir sections. In contrast, trails located in protected zones and along ridge lines exhibited minimal erosion.

The findings highlight the importance of sustainable trail management, appropriate infrastructure planning, and the application of geospatial technologies for environmental monitoring. The study also contributes to broader regional initiatives by emphasizing the role of cross-border cooperation between Serbia and Romania within the Danube region and the European Green Belt framework.

Keywords: Soil erosion; hiking trails; GIS; Avenza Maps; Djerdap National Park; sustainable tourism; Danube region; cross-border cooperation; European Green Belt

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1. Introduction

Soil erosion represents one of the key environmental challenges affecting protected areas with intensive tourist use. Hiking trails are highly vulnerable to degradation due to the combined effects of natural processes such as surface runoff and slope dynamics, as well as anthropogenic pressures including trampling, infrastructure development, and vehicular access.

Djerdap National Park, located along the Danube River in northeastern Serbia, is a prominent example of a protected landscape where tourism and environmental conservation must be carefully balanced. As one of the most significant natural areas in the Danube region, the park attracts a growing number of visitors, which increases pressure on its trail network and contributes to soil degradation processes.

Despite the importance of this issue, detailed spatial analyses of soil erosion along hiking trails in Djerdap National Park remain limited. Existing research has primarily focused on tourism development, environmental protection, and regional planning, while localized assessments of trail conditions and erosion dynamics are still insufficient.

The main objective of this study is therefore to assess soil erosion along intensively used hiking trails in Djerdap National Park and to identify key factors influencing trail degradation. The research combines field-based data collection with Geographic Information System (GIS) analysis to provide a comprehensive evaluation of erosion patterns across selected study areas.

In addition to its local relevance, the study contributes to broader regional and European contexts. Djerdap National Park forms part of a transboundary ecological system shared with Romania's Iron Gates Natural Park and is associated with the European Green Belt initiative. These frameworks emphasize the importance of sustainable tourism, environmental protection, and cross-border cooperation in the Danube region.

2. Background of the Study Area

2.1. Djerdap National Park

Djerdap National Park represents one of the most significant protected natural areas in Serbia and the wider Danube region. Established in 1974, the park stretches along the right bank of the Danube River in northeastern Serbia and covers approximately 637 km². It encompasses the Iron Gates Gorge, one of the most prominent fluvial landforms in Europe, forming a natural border between Serbia and Romania. Due to its exceptional natural and cultural values, the park holds national and international importance for conservation, tourism, and scientific research (Stanković, 2003; National Park Djerdap, 2023).

The area is renowned for its remarkable geological, geomorphological, and ecological diversity, including limestone cliffs, karst formations, deeply incised valleys, and forested mountain slopes. These features contribute to its outstanding geoheritage and environmental sensitivity. The Djerdap region has been recognized as part of the UNESCO Global Geopark Network, highlighting its significance for geoconservation, education, and sustainable regional development (Maran Stevanović, 2017).

In addition to its natural assets, Djerdap National Park possesses rich cultural and historical heritage. Notable sites such as Lepenski Vir and the Golubac Fortress contribute to its attractiveness as a major tourist destination in the Danube region. The park also represents an important component of a transboundary ecological system connected with the Iron Gates Natural Park in Romania, emphasizing its role in cross-border cooperation and sustainable landscape management (BăbăȚ and Pavel, 2022).

2.2. Environmental and Geomorphological Characteristics

The environmental and geomorphological characteristics of Djerdap National Park have been shaped by long-term geological and fluvial processes associated with the Danube River. The Iron Gates Gorge, which extends for approximately 100 km, represents a composite valley system characterized by narrow channels, steep slopes, and prominent limestone massifs (Stanković, 2003). This unique geomorphology creates a highly dynamic landscape with significant scientific and environmental value.

The park's geological structure consists predominantly of sedimentary and metamorphic rocks, including limestone and dolomite, which have facilitated the development of karst relief and rugged terrain. Elevations range from the Danube lowlands to mountainous areas exceeding 800 meters above sea level. These conditions, combined with thin soils and steep gradients, contribute to increased susceptibility to erosion and slope instability.

Climatically, the region is influenced by a moderate continental climate with sub-Mediterranean elements, supporting diverse ecosystems and high biodiversity. Extensive forest cover plays a crucial role in stabilizing soils and mitigating erosion processes. Nevertheless, natural factors such as precipitation, weathering, and runoff, together with human activities, contribute to landscape transformation and environmental vulnerability (Dragićević et al., 2013).

Hydrological processes associated with the Danube River significantly influence the evolution of the landscape. Human interventions, including hydropower development and river regulation, have altered sediment dynamics and river morphology throughout the Danube Basin. These changes have affected sediment transport, erosion, and deposition patterns, emphasizing the need for sustainable river basin management (Habersack et al., 2019).

2.3. Previous Research on Soil Erosion

Previous research conducted in Djerdap National Park and the broader Danube region has primarily addressed sustainable tourism, environmental protection, and natural hazards, with limited focus on localized soil erosion processes. The park has been widely recognized as a multifunctional tourist region, combining natural, cultural, and scientific values (Stanković, 2003).

Studies on tourism development highlight the importance of sustainable management in preserving the park's natural resources while supporting regional economic growth. Research indicates that Djerdap represents a significant ecotourism destination, where environmental protection and responsible tourism play a central role in long-term development (Veličkovska et al., 2017; Brankov et al., 2015). Furthermore, analyses of visitor behaviour confirm the park's importance as a recreational and ecosystem service provider (Poduška et al., 2014).

From a transboundary perspective, the Iron Gates Gorge constitutes an important cross-border tourism region between Serbia and Romania. Its development is influenced by political, economic, and infrastructural factors, highlighting the significance of international cooperation in regional planning and environmental management (BăbăȚ and Pavel, 2022).

Environmental studies have also examined natural hazards affecting protected areas in the Serbian Danube region. These include erosion, landslides, and floods, which pose risks to both natural ecosystems and cultural heritage sites. Such findings underscore the importance of systematic monitoring and sustainable land management within national parks (Dragićević et al., 2013).

At the European level, international initiatives and projects support coordinated environmental protection and sustainable tourism across the Danube Basin. Networks such as DANUBEPARKS and transnational projects emphasize cooperation among protected areas and highlight the need for harmonized conservation strategies (DANUBEPARKS, 2012). Similarly, the Danube GeoTour project promotes sustainable tourism

and the valorisation of geoheritage within geoparks, including Djerdap (Interreg Danube Transnational Programme, 2018).

Despite the growing body of literature, detailed studies focusing specifically on soil erosion along hiking trails in Djerdap National Park remain limited. This research gap highlights the need for spatially explicit analyses based on Geographic Information Systems (GIS) and remote sensing. The present technical report aims to address this gap by providing a comprehensive assessment of erosion processes in relation to tourism pressure and environmental conditions.

3. Methodology

3.1. Study Area and Research Design

The research was conducted in Djerdap National Park, Serbia, with the aim of assessing soil erosion along intensively used hiking trails. The study focused on three representative locations: the Golubac, Lepenski Vir, and Veliki Štrbac sections. These sites were selected based on their geomorphological diversity, accessibility, and varying levels of tourist pressure. The spatial distribution of the study areas is presented in the thematic maps prepared for this report.

Field surveys were carried out between 28 March and 1 April 2026 as part of a terrain-based research exercise. The methodology was designed to ensure standardized, accurate, and reproducible data collection suitable for GIS-based environmental assessment.

3.2. Field Data Collection

Primary data were collected directly in the field using the Avenza Maps mobile GIS application, which enabled georeferenced recording of observation points and associated attributes. All selected trail sections were surveyed on foot to ensure precise identification and assessment of erosion features and environmental conditions.

Field equipment included measuring tapes, GPS-enabled mobile devices, and digital cameras. Trail characteristics such as width and erosion depth were measured in situ, ensuring objective and comparable results across all surveyed locations. Additional observations included slope conditions, vegetation cover, surface type, and the presence of erosion rills or exposed roots.

To ensure systematic and consistent data collection, hiking trails were divided into individual segments ranging from 50 to 100 meters. A new segment was defined whenever a significant change in slope, surface type, vegetation cover, or erosion intensity was observed.

3.3. Soil Erosion Classification

The intensity of soil erosion was evaluated using a standardized classification system developed specifically for this study. The classification was based on field measurements and visual assessments of trail degradation, ensuring consistency and comparability across all surveyed locations. The detailed categorization of erosion levels is presented in *Table 1*.

Table 1: Soil Erosion Classification System

Level	Description
0 – No Erosion	Stable trail surface with no visible degradation; natural width and intact soil structure.
1 – Slight Erosion	Minor surface disturbance with shallow incision and slight widening of the trail.
2 – Moderate Erosion	Noticeable soil loss, visible erosion rills, and measurable trail incision.
3 – Severe Erosion	Significant degradation with deep incisions, exposed roots, and pronounced trail widening.
4 – Destroyed Trail	Complete loss of the original trail morphology; the trail is impassable or functions as a drainage channel.

The classification criteria were derived from field observations, including measurements of trail width and erosion depth, as well as indicators such as runoff channels, exposed roots, and the presence of parallel informal trails. This approach ensured objective and reproducible evaluation of erosion intensity across the study sites (Appendices).

3.4. GIS Processing and Spatial Analysis

The collected field data were processed and analyzed using ArcGIS Pro. Georeferenced points recorded via the Avenza Maps mobile GIS application were exported into GIS-compatible formats, including Shapefile (SHP), GeoJSON, and geodatabase structures. These datasets were subsequently used for spatial analysis, visualization, and the production of thematic maps supporting environmental assessment and decision-making.

To evaluate terrain characteristics influencing soil erosion, a Digital Elevation Model (DEM) derived from the Copernicus programme was utilized. Based on this dataset, two key geomorphological analyses were performed: slope and flow accumulation. These analyses enabled the identification of areas susceptible to erosion and enhanced the interpretation of field observations.

The slope analysis was conducted to determine terrain steepness and classify gradients according to their susceptibility to erosion. Steeper slopes are generally associated with increased surface runoff, reduced soil stability, and a higher risk of trail degradation.

The flow accumulation analysis was applied to identify potential runoff pathways and zones of concentrated water flow. This method highlights areas where water converges and accelerates erosion processes, particularly along hiking trails and natural drainage lines.

The integration of these raster analyses with field-collected erosion data allowed for the identification of erosion hotspots and improved the accuracy of spatial interpretation. The resulting thematic maps illustrate erosion intensity, slope gradients, and hydrological dynamics within the study areas.

The maps were generated using datasets from Copernicus DEM, OpenStreetMap contributors, the European Environment Agency, AEBR project data, and field surveys conducted in spring 2026.

Detailed results for each study area are presented in the following figures:

- **Golubac Section**
- **Lepenski Vir Section**
- **Veliki Štrbac Section**

3.5. Methodological Documentation and Limitations

A comprehensive description of the field data collection procedures, classification criteria, and GIS-based analysis is provided in Appendices*: Methodology of Field Data Collection and GIS-Based Assessment.* This ensures transparency, reproducibility, and scientific rigor of the study.

Despite its effectiveness, the methodology has certain limitations. The field survey was conducted during a single campaign, and GPS accuracy depended on terrain and vegetation cover. Additionally, slope gradients were estimated visually, and seasonal climatic conditions may influence erosion intensity. Nevertheless, the applied approach provides a reliable framework for rapid field assessment and spatial analysis of soil erosion in protected areas.

(see Appendices A)

4. Results

4.1. Spatial Distribution of Soil Erosion in Djerdap National Park

This study evaluates the spatial distribution of soil erosion along intensively used hiking trails in Djerdap National Park. The overview map provides geographical context and highlights the main areas affected by trail degradation.

As shown in *Figure 1*, the surveyed locations are situated within the Golubac, Lepenski Vir, and Veliki Štrbac sections. The map illustrates the varying intensity of soil erosion across the park and identifies areas most susceptible to degradation.

Higher erosion levels are primarily associated with steep terrain and increased tourist pressure, whereas lower levels occur in more stable and vegetated environments. The inclusion of elevation, hydrography, protected zones, and transportation networks provides essential context for interpreting the results.

This overview serves as a basis for the detailed analyses of the individual study sites presented in the following sections. The overall spatial distribution of soil erosion in Djerdap National Park is presented in *Figure 1*.

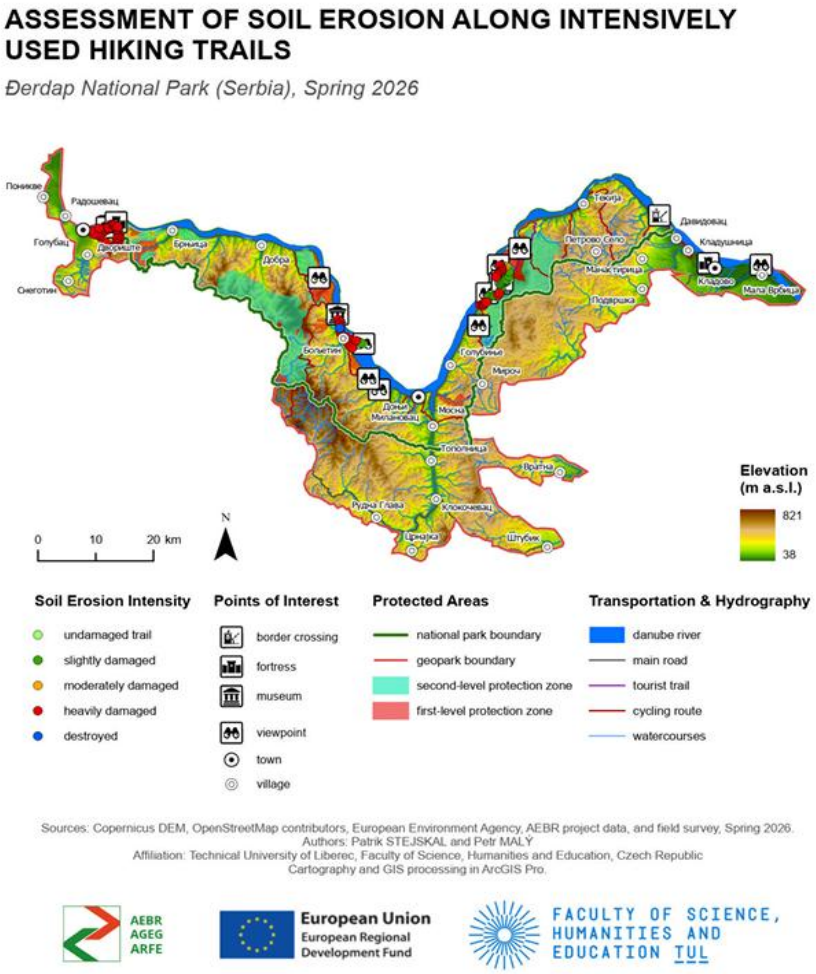

Figure 1: Assessment of Soil Erosion along Intensively Used Hiking Trails in Djerdap National Park (Serbia), Spring 2026.

4.2. Golubac Section

The Golubac section represents one of the most environmentally dynamic areas within Djerdap National Park, characterized by varying terrain conditions and significant anthropogenic influence. The detailed spatial distribution of soil erosion in this area is presented in *Figure 2*.

The results indicate that soil degradation in this area is strongly affected by human activities. Several trail sections were heavily impacted by tractor traffic and were used as access roads to nearby wind turbines. These interventions significantly contributed to trail widening, surface disturbance, and intensified soil erosion, particularly in lower-lying and more accessible areas.

In contrast, trail segments located on elevated and less disturbed terrain exhibited minimal or no signs of erosion. These sections, represented by green markers on the map, were typically situated on hilltops or in stable vegetated environments, where natural conditions limited surface degradation.

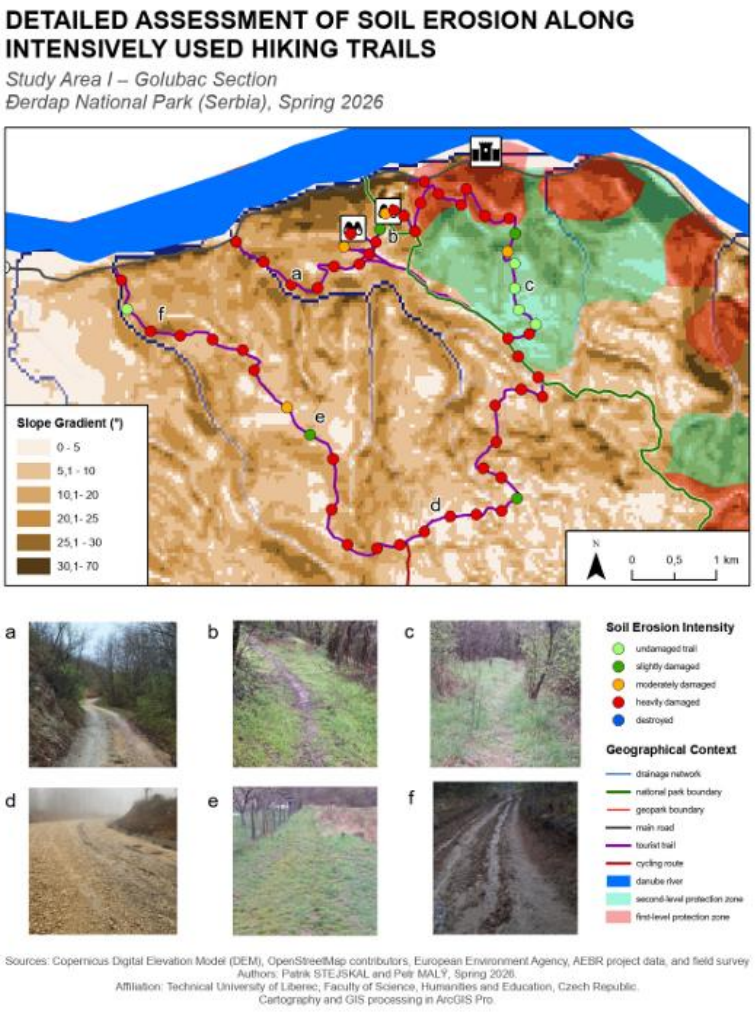

Figure 2: Detailed Assessment of Soil Erosion along Intensively Used Hiking Trails – Golubac Section, Djerdap National Park (Serbia), Spring 2026

A clear spatial pattern of erosion intensity was observed along the slopes descending toward the Danube River. As the trails approach the river, erosion becomes more pronounced due to increased slope gradients and the concentration of surface runoff. This trend is supported by slope and flow accumulation analyses, which identify zones of intensified water convergence and higher susceptibility to soil loss.

The map further integrates geomorphological and environmental data, including slope gradients derived from the Copernicus Digital Elevation Model. These findings confirm that soil erosion in the Golubac section results from a combination of natural factors—such as topography and hydrological processes—and anthropogenic pressures associated with infrastructure and tourism.

Overall, the Golubac section demonstrates moderate to severe levels of soil erosion, emphasizing the need for targeted management measures to mitigate trail degradation and support sustainable use within Djerdap National Park.

4.3. Lepenski Vir Section

The Lepenski Vir section is characterized by a diverse pattern of soil erosion influenced by both anthropogenic activities and natural geomorphological processes. The detailed spatial distribution of erosion intensity within this area is presented in *Figure 3*.

The highest concentration of heavily eroded segments is located near the Lepenski Vir archaeological site and along the main road. These trails primarily consist of gravelled tourist paths and cycling routes, which are subject to intensive use and surface disturbance. Consequently, these areas are represented predominantly by red points indicating severe erosion.

A notable exception is represented by a blue point classified as a destroyed trail. This location corresponds to a valley where surface runoff converges, as confirmed by the flow accumulation analysis. Due to heavy rainfall during the survey period, the trail was washed away and became impassable. This section poses

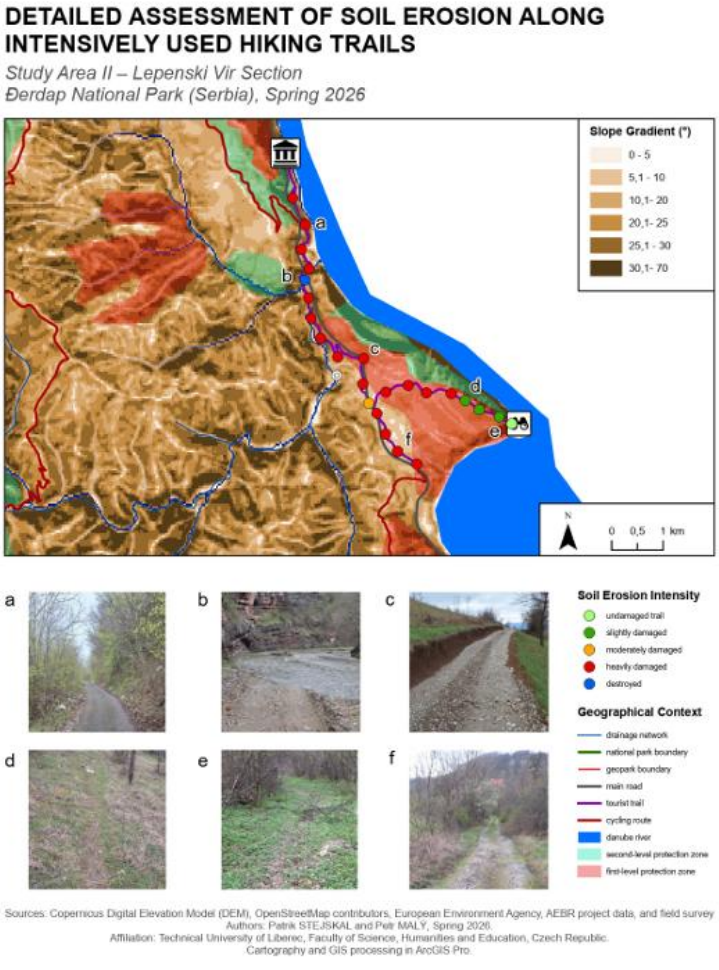

Figure 3: Detailed Assessment of Soil Erosion along Intensively Used Hiking Trails – Lepenski Vir Section, Djerdap National Park (Serbia), Spring 2026

a safety risk for visitors, who are required to cross fast-flowing water, and was therefore categorized as a special case of extreme erosion.

In contrast, the least affected segments are concentrated near the Greben viewpoint. These trails are situated along a low ridge and are located outside the built-up area. Represented by green points on the map, they exhibit minimal or no signs of erosion, reflecting stable terrain conditions and limited hydrological impact.

Overall, the Lepenski Vir section demonstrates varying degrees of erosion intensity, controlled by terrain morphology, hydrological processes, and visitor pressure. These findings highlight the importance of localized management measures to ensure both environmental protection and visitor safety.

4.4. Veliki Štrbac Section

The Veliki Štrbac section represents one of the most scenically significant areas within Djerdap National Park, characterized by steep terrain and panoramic viewpoints overlooking the Danube River. The spatial distribution of soil erosion in this locality is presented in *Figure 4*.

Higher erosion intensity is predominantly concentrated near the Danube and along trail segments originating from the main road. These routes often serve as forest access roads and supply paths to small settlements and facilities, including a restaurant located near the viewpoint. Consequently, these sections are represented by red points, indicating severe trail degradation caused by frequent vehicular use and intensive tourist activity.

In contrast, trail segments located within the first-degree protection zone exhibit minimal signs of erosion. These paths are generally well preserved and maintained, with only minor trampling observed in

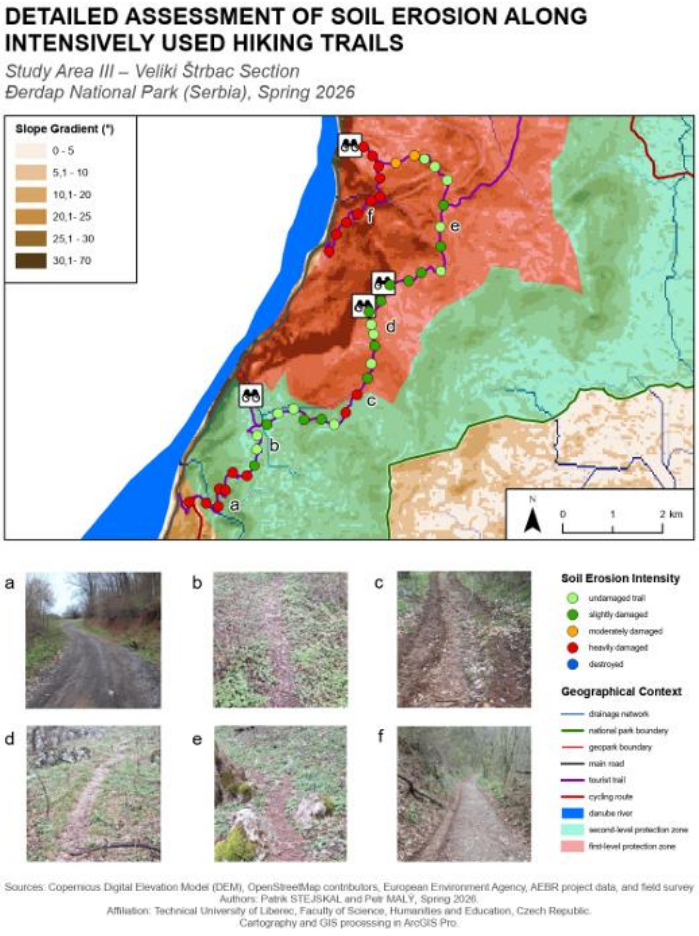

Figure 4: Detailed Assessment of Soil Erosion along Intensively Used Hiking Trails – Veliki Štrbac Section, Djerdap National Park (Serbia), Spring 2026

certain areas. Represented by green points on the map, they follow contour lines along the ridge, which significantly reduces the impact of slope and limits soil instability.

The geomorphological analyses further confirm that slope gradient and flow accumulation have a limited influence on erosion in this section. Due to the ridge-top location and well-drained terrain, surface runoff does not accumulate significantly, preventing the formation of severe erosion features.

Overall, the Veliki Štrbac section demonstrates a clear contrast between anthropogenically impacted access routes and well-preserved hiking trails situated within protected zones. These findings highlight the effectiveness of conservation measures in maintaining trail stability while emphasizing the need for sustainable management of access roads and tourist infrastructure.

4.5. Summary of Results

The assessment of soil erosion along intensively used hiking trails in Djerdap National Park revealed distinct spatial patterns influenced by both natural conditions and human activities. The results indicate that the highest levels of degradation occur in areas affected by intensive use, vehicular access, and concentrated surface runoff, particularly in the Golubac and Lepenski Vir sections.

In contrast, trails located within protected zones and along ridge-top alignments, such as those in the Veliki Štrbac section, exhibited minimal erosion and remained in good condition. These findings confirm that slope, hydrological processes, and tourist pressure are key factors influencing soil erosion dynamics within the park.

Overall, the integration of field surveys and GIS-based analyses proved effective in identifying erosion hotspots and evaluating trail conditions. The results provide a valuable foundation for sustainable trail management and environmental protection in Djerdap National Park.

5. Conclusion

This technical report assessed soil erosion along intensively used hiking trails in Djerdap National Park, Serbia, through an integrated approach combining field surveys and GIS-based spatial analysis. Utilizing ArcGIS and georeferenced data collected via the Avenza Maps mobile application, the study identified erosion hotspots and evaluated the environmental vulnerability of selected trail sections. The results provide valuable insights into the interactions between natural processes and human activities within a protected landscape.

The findings revealed clear spatial differences in erosion intensity across the study areas. The Golubac and Lepenski Vir sections exhibited higher levels of degradation, primarily due to concentrated surface runoff, intensive tourism, and vehicular access. In contrast, the Veliki Štrbac section showed generally stable conditions, particularly within the first-degree protection zone, where trails follow ridge lines and contour paths. These results confirm that terrain morphology, hydrological dynamics, and land-use practices are key determinants of soil erosion in Djerdap National Park.

The integration of field observations with GIS-based analyses, including slope and flow accumulation, proved to be an effective and replicable methodology for environmental monitoring. This approach enables accurate identification of vulnerable areas and supports evidence-based decision-making for sustainable trail management and conservation planning.

Based on the findings, several practical recommendations can be proposed. These include regulating vehicular access to sensitive areas, reinforcing erosion-prone trail sections, improving drainage systems, and implementing regular monitoring using geospatial technologies. Additionally, the installation of informative signage and the promotion of responsible tourism could enhance visitor safety while minimizing environmental impacts.

Beyond its local significance, the study contributes to broader regional and European initiatives. Djerdap National Park forms part of a transboundary ecological system shared with Romania's Iron Gates Natural Park, highlighting the importance of cross-border cooperation in environmental protection and sustainable tourism development. Furthermore, the area is associated with the European Green Belt, also known as the Iron Curtain Trail, which promotes biodiversity conservation, landscape connectivity, and cultural heritage across Europe. These frameworks align with European sustainability objectives and support the mission of AEBR Balkans.

Overall, this report provides a reliable scientific basis for improving trail management, preserving the natural values of Djerdap National Park, and fostering sustainable development in the Danube region. Future research should focus on long-term monitoring, seasonal variability, and the application of advanced geospatial technologies to support adaptive environmental management.

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7. Appendices

Appendix A – Methodology of Field Data Collection and GIS-Based Assessment

Stejskal, P. and Malý, P. (2026).

https://drive.google.com/file/d/15Cxr21o6z-nn3WFtI_EYbjBYUam_o0OO/view?usp=drive_link

Appendix B – Spatial Data from Avenza Maps

https://drive.google.com/file/d/1u7v4IzYi8fMPiXd0KrFT8d0r2Zyomi-r/view?usp=drive_link