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Ecology

Spatial Analysis of the Sediment Transport Index Using GIS – a Case Study of Ambrolauri Municipality, Georgia

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Abstract. The Sediment Transport Index (STI) is a crucial parameter for assessing erosion processes and predicting debris flow occurrences in mountainous regions. This study presents GIS-based STI modeling to identify areas with high sediment transport dynamics for the Ambrolauri Municipality (Georgia). A Digital Elevation Model (DEM) was used as the primary dataset, from which hydrological indices, such as flow direction, flow accumulation, surface slope, and STI were derived. The application of GIS technologies enabled a spatial analysis of erosion processes and the identification of areas with increased probability of sediment transport and deposition. The results indicate that the highest STI values are observed in the lower parts of the Rioni and Krikhula river basins, highlighting intensified water erosion and sediment accumulation in valley zones. The analysis confirms the effectiveness of the STI in assessing debris flow risks and developing watershed management strategies. *© 2025 Bull. Georg. Natl. Acad. Sci.*

Keywords: sediment transport index, GIS, soil erosion, hydrological indices

Introduction

Water erosion and sediment transport processes significantly impact landscape formation and ecosystem stability in mountainous regions. With the increasing frequency of extreme hydrometeorological events due to climate change, the need for accurate prediction of erosion process is becoming increasingly relevant [1-3]. One of the key methods for quantifying the spatial distribution of erosion and sediment accumulation is the Sediment Transport Index (STI), which is widely applied in watershed modeling [4,5].

Over the past decades, advancements in GIS-based STI modeling have enhanced the identification of high-risk erosion zones and the development of watershed management strategies [2,6]. The integration of GIS technologies into STI analysis allows for a detailed assessment of topographic influences on sediment dynamics, consideration of hydrological factors, and identification of areas prone to debris flow processes [7]. Specifically, STI incorporates parameters such as flow direction, flow accumulation, slope steepness, and river network morphology, making it a powerful tool for spatial erosion modeling [8].

Despite significant progress in STI modeling, numerous studies have focused on lowland and agricultural areas [9], while its application in mountainous regions, where debris flows are prevalent remains insufficiently explored. Therefore, applying STI to assess erosion processes in high-altitude watersheds, such as the Ambrolauri Municipality in Georgia, is of great scientific interest. This region is characterized by complex terrain, steep slopes, and high sediment transport dynamics, making it an ideal case for STI-based erosion risk assessment.

The objective of this study is to conduct GIS-based modeling of the STI in the Ambrolauri Municipality to identify areas with high erosion risk and forecast debris flow processes. To achieve this goal, the following tasks were undertaken:

- Processing a Digital Elevation Model (DEM) to derive hydrological indices [10].
- Analyzing the spatial distribution of STI and its correlation with topographic characteristics.
- Identifying areas with the highest risk of sediment accumulation and transport.
- Evaluating the applicability of STI for debris flow prediction.

Study Area

Ambrolauri Municipality is located in the north-western part of Georgia within the Racha-Lechkhumi and Kvemo Svaneti region. The area is characterized by a complex mountainous terrain, with elevations ranging from 550 m to 4000 m asl, resulting in significant landscape and hydrological variability. The main orographic structures of the region include the Racha and Lechkhumi mountain ranges, which are separated by deep river valleys.

The terrain of the Ambrolauri Municipality consists predominantly of steep slopes, with inclinations exceeding 30° in large areas, creating favorable conditions for intense water erosion and debris flow activity.

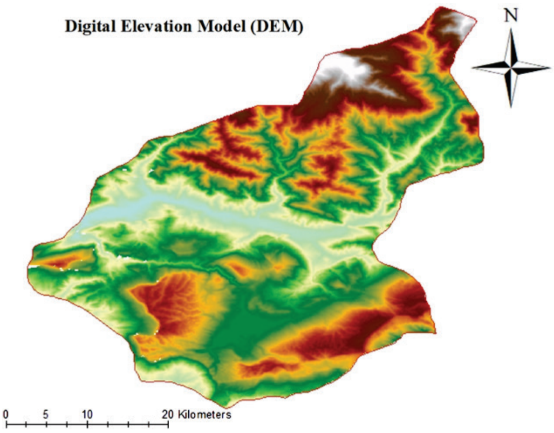

Fig. 1. DEM of the Ambrolauri Municipality.

Figure 1 illustrates elevation variations, with higher altitudes in the northern part and lower altitudes in the valley regions of the Ambrolauri Municipality.

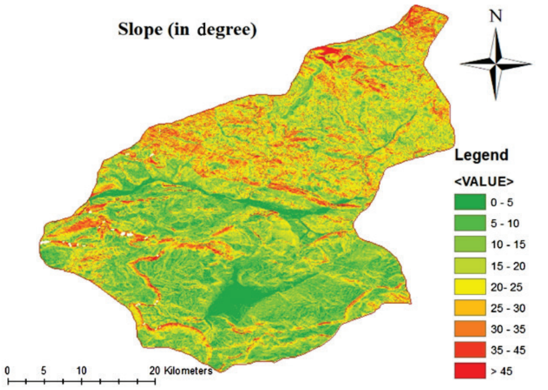

Fig. 2. Slope map for theAmbrolauri Municipality.

Figure 2 classifies slope gradients, highlighting steep slopes (>30°) that contribute to erosion and debris flow susceptibility.

The geomorphological structure includes a highly developed river network with valleys shaped by fluvial and glacial processes. A key feature of the region is its highly fragmented slope systems, which lead to frequent landslides, avalanches, and intensive formation of channel deposits. Sharp elevation differences and a dense network of temporary watercourses contribute to high values of the STI, particularly in the lower parts of slopes and near the main river channels.

Fig. 3. Field observation of erosion-prone areas in Ambrolauri Municipality.

Figure 3 illustrates sediment accumulation in a high-STI zone captured by Ph.D. student Dimitri Djandjalashvili on August 1, 2024.

Ambrolauri Municipality is situated in a moderately humid climate zone, but it experiences significant seasonal variability in precipitation. The annual precipitation ranges from 900 mm in valleys to 2000 mm in the high-altitude areas. The highest precipitation levels occur in the autumn and winter months, which intensify erosion processes and contribute to the formation of debris flows in small river basins.

The hydrological regime of the region's rivers is highly dynamic, with significant increases in water discharge during spring snowmelt and heavy rainfall events. The rivers in this area have high flow energy, leading to active bank erosion and the transportation of clastic material, including clay-sand deposits and alluvial sediments. The major rivers in the area are the Rioni and Krykhula, which serve as primary channels for sediment transport.

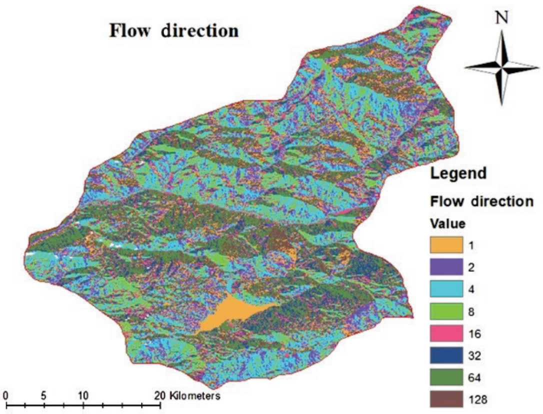

Fig. 4. Flow direction map of the Ambrolauri Municipality.

The map illustrates the direction of surface water flow across the terrain, highlighting primary drainage patterns and contributing areas.

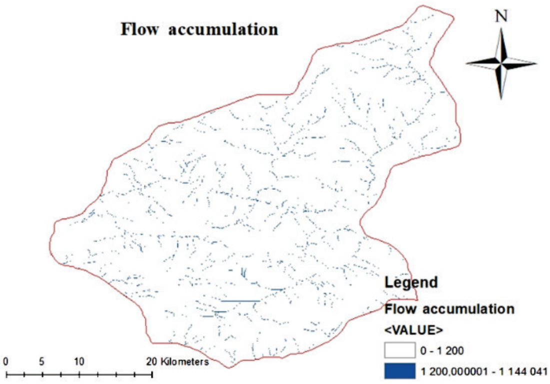

Fig. 5. Flow accumulation map of the Ambrolauri Municipality.

The map indicates areas of concentrated water flow, highlighting potential sediment transport pathways.

Ambrolauri Municipality is highly susceptible to debris flow activity, as evidenced by frequent destructive flows in the Rioni and Krykhula river basins. The key factors contributing to debris flow hazards include:

- Steep slopes (>30°), which facilitate rapid surface runoff.
- Intense rainfall events, leading to sudden increases in river discharge and bank erosion.
- Geological composition, dominated by loose sedimentary rocks and clastic material that are easily eroded.

- Anthropogenic impacts, such as road construction, deforestation, and river channel modifications.

The application of the STI in this region enables a quantitative assessment of zones with high sediment transport and accumulation potential. Areas with steep slopes and active erosion processes exhibit the highest STI values, highlighting locations prone to debris flow formation. This study aims to identify these high-risk zones and improve debris flow prediction through GIS-based modeling.

Materials and Methods

The calculation of the STI in the Ambrolauri Municipality was based on remote sensing data and geoinformation technologies. The DEM with a 30 m spatial resolution, obtained from the Shuttle Radar Topography Mission (SRTM), served as the foundation for spatial analysis. The DEM was preprocessed, including depression filling and anomaly filtering, to improve calculation accuracy.

Hydrological parameters such as flow direction, flow accumulation, slope, and STI were derived from the processed DEM using ArcGIS (Spatial Analyst and Hydrology Toolbox). Additional supporting datasets, including climatic parameters (precipitation, temperature), geological maps, and land use data, were also integrated to enhance the erosion process assessment.

The STI is calculated using the formula [4]:

$$STI = (m+1) \times \left(\frac{A_s}{22.13}\right)^m \times \left(\frac{\sin B}{0.0896}\right)^n,$$

where A_s is specific catchment area (upslope contributing area), estimated using flow accumulation algorithms; B – surface slope in degrees, derived from the DEM; m – coefficient representing the influence of the contributing area on erosion processes (typically 0.4–0.6); n – coefficient characterizing the effect of slope gradient (1.3-1.4).

The calculations were performed in ArcGIS Raster Calculator, following these steps:

- Slope Calculation (Slope Tool) – converting the DEM into a slope raster.
- Flow Direction Analysis (Flow Direction Tool) – generating the flow direction network.
- Flow Accumulation Computation (Flow Accumulation Tool) – determining the upslope contributing area for each cell.
- STI calculation using the formula in Raster Calculator (RC).
- STI Normalization and Classification – categorizing the results into low, medium, and high-risk zones for sediment transport.

After computing the STI, thematic maps were generated to visualize the spatial distribution of erosion processes. A Natural Breaks (Jenks) classification was applied to distinguish areas of high, medium, and low sediment transport potential.

A crucial aspect of the analysis involved comparing the STI map with observed debris flow occurrences in the Ambrolauri Municipality. This validation was conducted using field observations and historical records of debris flows, ensuring the reliability of the results.

Results and Discussion

The STI results for the Ambrolauri Municipality reveal a strong spatial variation in sediment transport potential across the study area. The highest STI values are observed in the steep valley slopes and downstream sections of the major river basins, particularly along the Rioni and Krykhula rivers, indicating areas with intense sediment movement and accumulation.

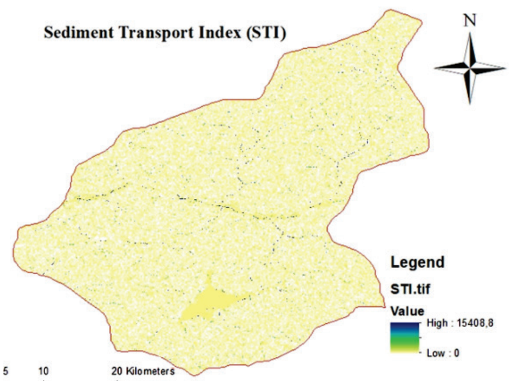

Fig. 6. The STI Map of the Ambrolauri Municipality.

In contrast, lower STI values are concentrated in areas with gentler slopes and higher vegetation cover, where sediment deposition predominates (Fig. 6).

The map visualizes the spatial distribution of sediment transport potential, with high STI values concentrated in steep slopes and high flow accumulation zones.

The spatial analysis confirms that steep gradients (>30°) and high flow accumulation zones correspond to the most erosion-prone areas. The STI classification identifies:

- **High-risk zones (STI > threshold)** – found in steep, unprotected slopes, typically associated with active debris flow processes.
- **Moderate-risk zones** – located in transition areas between steep slopes and valley floors, where partial sediment deposition occurs.
- **Low-risk zones** – found in flat terrain with dense vegetation cover, indicating low erosion potential and sediment retention.

These findings align with previous studies, where STI has been proven effective in identifying high-sediment transport areas in mountainous watersheds [6,7]. The regions classified as high-risk correspond to documented debris flow events, confirming the reliability of STI as an indicator of sediment transport intensity. In these areas, steep slopes enhance surface runoff, while seasonal precipitation patterns, particularly during autumn and spring, intensify erosion. The geomorphological characteristics, including loose sedimentary formations and fractured bedrock, further contribute to mass movements and debris flow initiation.

The practical application of STI modeling in watershed management is evident from these results. The high-risk zones identified in the analysis should be prioritized for erosion control strategies, including slope stabilization, check dams, and afforestation programs. Implementing riverbank protection measures and land-use planning policies based on STI analysis could significantly reduce sediment loads and mitigate erosion hazards.

Despite its effectiveness, the STI model has inherent limitations. The DEM resolution (30 m) may not accurately capture localized erosion processes, and the exclusion of real-time precipitation variability limits its predictive capability. Future research should integrate higher-resolution topographic data, hydrological modeling, and direct sediment yield measurements to refine STI-based erosion assessments. Nevertheless, the findings demonstrate that STI is a valuable GIS-based tool for identifying erosion-prone areas and predicting debris flow risks in the Ambrolauri Municipality, providing essential insights for sustainable watershed management.

Conclusion

This study demonstrats the effectiveness of the STI as a GIS-based tool for assessing erosion risks and predicting sediment transport dynamics in the Ambrolauri Municipality. The results revealed a strong correlation between high STI values and areas prone to debris flows, particularly along the Rioni and Krykhula river basins, where steep slopes and intense hydrological activity contribute to sediment mobilization. The spatial analysis confirmed that regions with slopes exceeding 30°, combined with high flow accumulation, exhibit the greatest erosion potential, making them critical areas for watershed management and disaster mitigation.

The findings underscore the importance of integrating STI modeling into erosion risk assessments and land-use planning strategies. The identification of high-risk zones enables the implementation of targeted soil conservation measures, such as slope stabilization, check dams, afforestation, and riverbank protection, to mitigate sediment transport and reduce the impacts of debris flows. By utilizing STI in conjunction with hydrological modeling and real-time precipitation data, stakeholders can enhance the predictive accuracy of erosion assessments and improve the sustainability of mountainous watersheds.

Despite the model's robustness, several limitations should be acknowledged. The 30 m DEM resolution, while suitable for regional-scale analysis, may not capture finer-scale erosion features, necessitating the integration of higher-resolution LiDAR-based data for improved precision. Additionally, real-time hydrological parameters, sediment transport validation, and long-term monitoring should be incorporated into future studies to refine STI-based erosion assessments further. Overall, this study confirms that STI modeling is an effective approach for evaluating sediment transport potential and identifying erosion-prone areas in mountainous regions. The methodology presented can serve as a foundation for future research on debris flow prediction and erosion mitigation, contributing to sustainable watershed management and disaster risk reduction strategies in similar geomorphological environments.

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ეკოლოგია

მყარი ნატანის ტრანსპორტირების ინდექსის სივრცული ანალიზი გეოინფორმაციული სისტემების გამოყენებით ამბროლაურის მუნიციპალიტეტის მაგალითზე, საქართველო

დ. გურგენიძე*,, ი. ინაშვილი**, კ. ბზიავა**, ზ. ცინაძე**, დ. ჯანჯალაშვილი****

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მყარი ნატანის ტრანსპორტირების ინდექსი (STI) წარმოადგენს მთიან რეგიონებში ეროზიული პროცესების შეფასებისა და ღვარცოფული ნაკადების პროგნოზირების განმსაზღვრელ პარამეტრს. წინამდებარე კვლევა მიზნად ისახავს გეოინფორმაციულ სისტემაზე (GIS) დაფუძნებულ STI მოდელირებას ამბროლაურის მუნიციპალიტეტისთვის (საქართველო) მყარი ნატანის ტრანსპორტირების მაღალი დინამიკით გამორჩეული ტერიტორიების გამოსავლენად. ძირითად მონაცემთა ბაზის შესაქმნელად, ნაშრომში გამოყენებული იყო რელიეფის ციფრული მოდელი (DEM), რომლის დახმარებით მიღებულ იქნა ჰიდროლოგიური ინდექსები, მათ შორის, დინების მიმართულება, ნაკადის აკუმულაცია, ზედაპირის ქანობი და STI. GIS ტექნოლოგიების გამოყენებამ შესაძლებელი გახადა ეროზიული პროცესების სივრცული ანალიზი და მყარი ნატანის ტრანსპორტირებისა და დალექვის გაზრდილი ალბათობის მქონე ტერი-

ტორიების იდენტიფიცირება. მიღებული შედეგები ცხადყოფს, რომ STI-ის ყველაზე მაღალი მნიშვნელობები ფიქსირდება მდინარეების რიონისა და კრიხულას აუზების ქვემო წელში, რაც მიუთითებს მდინარეთა ხეობების ზონაში წყლისმიერი ეროზიის გააქტიურებასა და მყარი ნატანის აკუმულირებაზე. განხორციელებული ანალიზი ადასტურებს STI-ის გამოყენების ეფექტურობას ღვარცოფული ნაკადის რისკების შეფასებისა და წყალგამყოფის სააუზო მართვის სტრატეგიების შემუშავებაში.

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