INTERNATIONAL CONFERENCE Dehli, India, 2026
https://eijmr.org/conferences/

SPATIAL ASSESSMENT AND ANALYSIS OF MUDFLOW HAZARD ZONES IN THE SURKHANDARYA RIVER BASIN USING GIS AND REMOTE SENSING-BASED STATISTICAL MODELS

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https://doi.org/10.5281/zenodo.20396190

Abstract

Mountainous and foothill regions of Surkhandarya Province (Uzbekistan) are increasingly affected by mudflow events driven by climate change, glacier retreat and intense seasonal rainfall. This study presents a spatial assessment of mudflow hazard zones in the Surkhandarya River basin (13 500 km²) using an integrated GIS and remote sensing approach. A geospatial database of 115 mudflow inventory points (2022-2024) was compiled and seven conditioning factors (TWI, SPI, rainfall, drainage density, lithology, NDVI and slope aspect) were standardized at 30 m resolution. Hazard zonation was carried out using the Frequency Ratio (FR) model, validated with ROC/AUC analysis (AUC=0.856). The study area was classified into five hazard categories. Results indicate that the very high hazard zone covers 265.17 km², of which 60% lies in Tajikistan (Tursunzoda district, 124.17 km²) and 40% in Uzbekistan (Sariosiyo district, 77.98 km²). Land cover analysis revealed that 163.05 km² of very high hazard areas overlap with cropland and 82.42 km² with settlements, highlighting the urgent need for risk reduction measures along the Karatag-Tupalang river confluence.

Keywords: mudflow hazard, GIS, remote sensing, Frequency Ratio, ROC/AUC, Surkhandarya, Uzbekistan.

1. Introduction

Mudflows are among the most destructive natural hazards in mountainous and foothill regions, threatening human lives, agricultural lands, settlements and infrastructure. According to the EM-DAT database, between 2000 and 2024 more than 472 major mudflow events were recorded worldwide, causing over 20 000 deaths and approximately USD 7 billion in economic losses [1]. Central Asia, characterized by complex terrain, rapid glacier retreat and intensifying rainfall variability, has experienced a marked increase in mudflow frequency over the past two decades [2,3].

Surkhandarya Province, located in the southernmost part of Uzbekistan, is one of the most mudflow-prone regions in the country. Between 2018 and 2024, a total of 268 mudflow events were officially registered, with the most extreme years being 2022 (78 events) and 2024 (62 events). The province lies within the southern foothills of the Hissar Range, where steep slopes, fragmented lithology, sparse vegetation and concentrated spring-summer precipitation create favorable conditions for mudflow initiation [4].

Hazard zonation is a fundamental component of disaster risk reduction. Modern approaches combine GIS-based spatial analysis with statistical models such as the Frequency Ratio (FR), Statistical Index (SI) and Certainty Factor (CF), which establish quantitative relationships between historical hazard events and a set of conditioning factors [5,6]. The Frequency Ratio model, in particular, has been widely applied due to its mathematical simplicity, intuitive interpretation and proven effectiveness in data-scarce environments [7].

The present study aims to delineate and analyze mudflow hazard zones in the Surkhandarya River basin using the FR model, integrated with high-resolution remote sensing data. The specific objectives are: (i) to classify the study area into five hazard categories; (ii) to assess the spatial distribution of very high hazard zones across districts and across the Uzbekistan-Tajikistan border; and (iii) to quantify the exposure of land cover classes (cropland, settlements, vegetation-free areas) to very high mudflow hazard.

2. Materials and Methods

2.1. Study Area

The Surkhandarya River basin covers approximately 13 500 km² in southern Uzbekistan and partly extends into the Tursunzoda and Sharinav districts of Tajikistan. Elevations range from 300 m in the southern plains to over 3 500 m in the Hissar Range. The basin is formed by the confluence of the Karatag (originating in Tajikistan) and Tupalang (originating in Uzbekistan) rivers. The climate is continental semi-arid, with mean annual precipitation varying from 130-400 mm in the plains to 600-1 000 mm in the high mountains. Intense convective rainfall in spring (April-May) is the primary trigger of mudflow events.

2.2. Data Sources

A geospatial database of 115 mudflow inventory points was compiled from the Hydrometeorological Service Center for the period 2022-2024. The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (30 m) was used to derive topographic factors. NDVI was computed from Landsat 9 imagery, and land use / land cover (LULC) was obtained from the ESRI Sentinel-2 10 m Global Land Use dataset. Hydrographic features were extracted from OpenStreetMap. Rainfall data were obtained from the CHIRPS satellite product, validated against six local meteorological stations ($R^2 = 0.87$-0.91).

2.3. Conditioning Factors

Seven conditioning factors were selected based on literature review and local relevance: Topographic Wetness Index (TWI), Stream Power Index (SPI), annual rainfall, drainage density, lithology, NDVI and slope aspect. All factor layers were resampled to a uniform 30 × 30 m grid in the WGS 1984 UTM Zone 42N projection. Continuous variables were classified using the Natural Breaks (Jenks) method, while categorical variables (lithology, slope aspect) were grouped according to thematic classes.

2.4. Frequency Ratio (FR) Model

The Frequency Ratio is a bivariate statistical model that compares the proportion of mudflow occurrences within each class of a conditioning factor to the proportion of the total area occupied by that class [5]. The FR value is computed as:

$$FR = (Si / \Sigma Si) / (Ni / \Sigma Ni)$$

where Si is the number of mudflow events in class i, Ni is the number of pixels in class i, and ΣSi and ΣNi are the totals across all classes. An FR value greater than 1 indicates a positive correlation between the factor class and mudflow occurrence, while values below 1 indicate a negative correlation. The Mudflow Susceptibility Index (MSI) was obtained by summing the FR values of all factor layers in a raster calculator, then reclassified into five hazard categories (very low, low, moderate, high, very high) using the Natural Breaks method.

2.5. Model Validation

The performance of the FR model was assessed using the Receiver Operating Characteristic (ROC) curve and the Area Under the Curve (AUC) metric, computed in the ArcGIS Desktop environment using the ArcSDM extension. AUC values were interpreted as follows: 0.7-0.8 acceptable, 0.8-0.9 excellent and above 0.9 outstanding.

3. Results and Discussion

3.1. Hazard Class Distribution

The FR model produced a hazard susceptibility map with a prediction accuracy of AUC = 0.856, confirming the reliability of the approach. The basin was classified into five hazard categories, whose areas are summarized in Table 1.

Table 1. Distribution of mudflow hazard classes based on the FR model

Hazard class	Area (km²)	Share (%)	FR range
Very low	619.96	4.63	< 0.50
Low	5 043.23	37.63	0.50-1.00
Moderate	4 621.00	34.49	1.00-1.50
High	2 849.90	21.27	1.50-2.00
Very high	265.17	1.98	> 2.00
Total	**13 399.26**	**100.00**	—

Moderate and low hazard classes together cover 72.1% of the basin, while the very high hazard class occupies only 1.98% (265.17 km²). Despite its small spatial extent, this class is of primary concern because it coincides with densely populated and economically important areas.

3.2. Spatial Distribution by District

The very high hazard zone is unevenly distributed between Uzbekistan and Tajikistan. Of the total 265.17 km², 158.12 km² (60%) lies in Tajikistan and 107.05 km² (40%) in Uzbekistan. At the district level, the largest very high hazard areas were recorded in Tursunzoda (124.17 km²) and Sariosiyo (77.98 km²), followed by Sharinav (33.94 km²) and Uzun (9.83 km²). Smaller but significant exposures were identified in Oltinsoy (4.49 km²), Denov (4.23 km²), Shurchi (3.35 km²), Bandihon (2.82 km²), Kumkurgan (2.38 km²) and Boysun (1.35 km²).

This spatial pattern indicates that the highest mudflow hazard concentrates around the confluence of the Karatag and Tupalang rivers, which collect runoff from the steep southern slopes of the Hissar Range. High orographic precipitation, steep gradients and rapid runoff concentration combine to produce favorable conditions for mudflow initiation in this transboundary corridor.

3.3. Exposure of Land Cover Types

Sentinel-2 LULC data were overlaid on the very high hazard class to quantify exposure (Table 2). Cropland represents the largest exposed category (163.05 km², 61.5% of the very high zone), followed by settlements (82.42 km², 31.1%) and bare land (16.66 km²). Water bodies, tree cover and pastures together account for less than 2% of the exposed area.

Table 2. Land cover exposure within the very high mudflow hazard class (km²)

Land cover type	Uzbekistan	Tajikistan	Total
Cropland	60.44	102.60	163.05
Built-up / settlements	31.13	51.29	82.42
Bare / vegetation-free	13.76	2.90	16.66
Pasture	1.23	0.07	1.30
Water	0.46	0.56	1.02
Tree cover	0.03	0.69	0.72
Total	**107.05**	**158.12**	**265.17**

The dominance of cropland and settlements within the very high hazard class is a clear signal that mudflow risk in the Surkhandarya basin is not only a natural hazard issue but also a socio-economic vulnerability problem. Agricultural production losses and damage to residential infrastructure can significantly affect local livelihoods, particularly in Sariosiyo and Uzun districts where the population density along river corridors is high.

3.4. Practical Implications

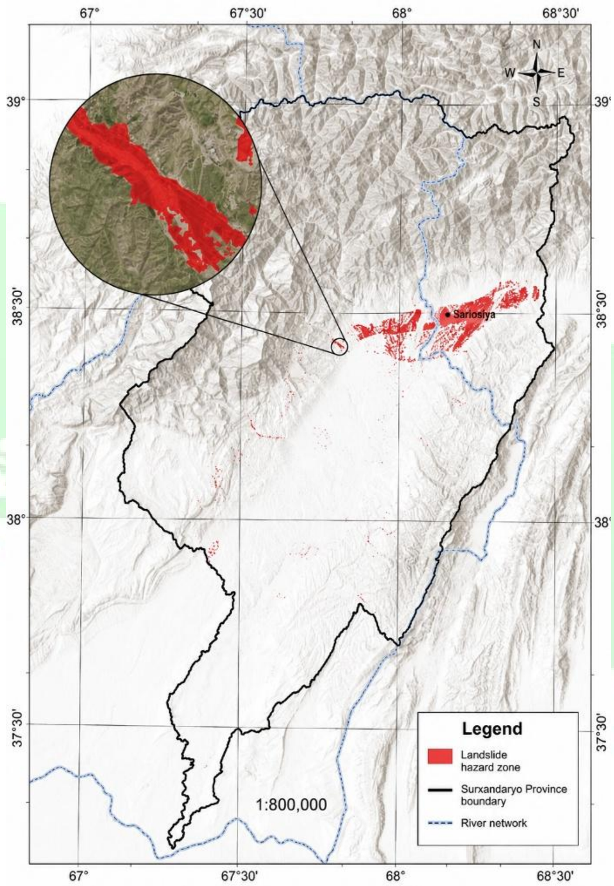

Figure 1. Very high mudflow hazard zones identified using the Frequency Ratio (FR) model

The hazard maps generated in this study can support several practical applications. First, they provide a science-based foundation for local authorities and the Ministry of Emergency Situations to prioritize early warning, evacuation planning and public awareness campaigns in the highest risk districts. Second, the identified very high hazard areas along the Karatag-Tupalang confluence justify targeted investment in bank protection structures, debris-retention dams and improved drainage networks. Third, the maps can inform land-use planning, helping to restrict new construction in exposed zones and to design crop diversification strategies for cropland under recurrent mudflow stress (Fig1).

It is also important to acknowledge methodological limitations. The 30 m SRTM resolution may underrepresent micro-scale topographic features critical for mudflow initiation, and the three-year inventory window (2022-2024) does not yet capture long-term climate variability. Future work should expand the inventory to at least a decade, integrate higher-resolution DEMs (e.g., ALOS PALSAR 12.5 m or Copernicus GLO-30) and apply ensemble approaches that combine FR with the Statistical Index (SI) and Certainty Factor (CF) models for improved robustness.

4. Conclusion

This study delineated and analyzed mudflow hazard zones in the Surkhandarya River basin using a GIS- and remote sensing-based Frequency Ratio model, validated with ROC/AUC analysis (AUC = 0.856). Five hazard classes were mapped, revealing that 1.98% of the basin (265.17 km²) falls within the very high hazard category, predominantly along the Karatag-Tupalang river confluence.

The transboundary character of mudflow hazard was clearly demonstrated, with 60% of the very high hazard zone in Tajikistan (Tursunzoda, Sharinav) and 40% in Uzbekistan (Sariosiyo, Uzun and others). Land cover analysis revealed that 92.6% of the very high hazard zone overlaps with cropland and settlements, exposing local communities and agricultural production to significant risk.

The hazard maps produced in this study have been transferred to the Surkhandarya provincial branches of the Hydrometeorological Service Center and the Ministry of Emergency Situations for operational use. Future research should focus on transboundary cooperation with Tajikistan, integration of climate change projections under CMIP6 RCP scenarios and the development of an early warning system that combines Sentinel-1 SAR-based real-time monitoring with the static hazard maps presented here.

Acknowledgments

The authors gratefully acknowledge the National Research University "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" for supporting this study within the framework of the international applied research project AL-8424012339 ("Climate-smart agriculture: integrating remote sensing, meteorological data and Geo-AI methods") and the applied project No. 1.13 (2023-2025). Special thanks are due to the Surkhandarya Hydrometeorological Service Center and the Provincial Department of Emergency Situations for providing inventory data and validating the results.

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