

CASCADE RISK MODELING IN MOUNTAINOUS REGIONS: THE CASE OF THE 2023 SHOVI TRAGEDY IN GEORGIA

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Abstract

Mountainous regions are highly susceptible to natural hazards due to the interplay of geological instability, extreme climatic events, and infrastructural vulnerability. Such hazards often evolve into cascading risks, where an initial event triggers a sequence of secondary processes with far-reaching social, economic, and environmental consequences. This study examines the 2023 Shovi landslide in Georgia as a case of cascading risk development, integrating meteorological, glaciological, and geological data through hybrid forecasting models and semantic network analysis. Multi-level risk assessment is employed to map the progression from initial triggers, through direct and indirect impacts, to systemic disruptions affecting tourism, transport, and local communities. Expert-based evaluations supplement data gaps, enhancing model accuracy and reliability. The study further demonstrates how hybrid modeling and semantic network approaches can inform decision-making frameworks, enabling early warning protocols, infrastructure planning, and community preparedness. Findings underscore the importance of integrating diverse data sources and analytical approaches to improve disaster resilience, offering insights applicable to other mountainous regions with high variability in precipitation and glacial activity.

Keywords: cascading risks, landslide, hybrid forecasting, semantic networks, multi-level risk assessment, Shovi, disaster resilience, mountainous regions.

I. Introduction

Mountainous regions are among the most disaster-prone environments globally, where the interplay of geological instability, climatic extremes, and infrastructural vulnerability generates elevated risks of catastrophic events. Such regions frequently experience natural hazards including landslides, debris flows, avalanches, and floods, often resulting in substantial human and economic losses. These hazards are particularly dangerous due to their potential to develop into cascading risks, in which a single triggering event initiates a sequence of secondary processes, producing profound impacts across multiple systems. Understanding and modeling these cascading dynamics has thus become a critical task in disaster risk research and management.

Cascading risks are defined as those risks that, once initiated, lead to the emergence of other interconnected risks, functioning according to a “chain reaction” principle. That is, a single hazard or failure can set off a series of events that propagate across different systems or sectors. Key characteristics of cascading risks include:

- Chain effect: One event acts as a triggering factor for other risks.
- Interdisciplinary impact: Effects may extend across social, economic, technological, and ecological domains.
- Unforeseen consequences: An initially minor risk can escalate into a global or systemic crisis.

On August 3, 2023, a devastating disaster struck the Shovi mountain resort in Georgia's Racha region. Massive landslides and debris flows, triggered by a combination of geomorphological and hydrometeorological factors, destroyed infrastructure and claimed dozens of lives. This tragedy shocked the nation and attracted international attention, not only due to the scale of destruction but also because it illustrated the complex nature of cascading processes in fragile mountainous environments.

The objective of this study is to examine the Shovi tragedy as a case of cascading risk development and to propose a conceptual framework for its analysis. The research employs systemic and semantic network approaches to reconstruct event sequences and highlight the interactions between natural and anthropogenic factors. By doing so, the study contributes to a deeper understanding of how cascading risks originate, propagate, and culminate in large-scale disasters. This paper presents a theoretical framework applied to the Shovi tragedy, encompassing hybrid forecasting models, semantic and network-based approaches, multi-level risk assessment, and integration with decision-making systems.

II. Theoretical Framework: The Shovi Landslide Case Study

A. *Hybrid Forecasting Models in the Shovi Context*

Hybrid forecasting models integrate statistical techniques, machine learning, and expert-based approaches to improve predictive accuracy in complex systems. In the case of the Shovi landslide, a hybrid model could combine meteorological data (e.g., precipitation intensity), glaciological observations (e.g., glacier melt rates), and geological assessments (e.g., slope stability) to provide a comprehensive risk evaluation. For instance, integrating deep learning techniques with physical models has shown promising results in enhancing flood prediction accuracy [1].

B. *Semantic and Network-Based Approaches*

Semantic networks represent relationships among concepts, enabling the modeling of complex systems through interconnected nodes and edges. Applied to disaster risk assessment, semantic modeling can identify causal chains and feedback loops. In Shovi, semantic modeling could clarify interactions among climatic factors, glacier dynamics, and human activity, providing insights into disaster progression. Research has demonstrated the utility of semantic approaches in vulnerability modeling and disaster management [2].

C. *Multi-Level Risk Assessment and Modeling*

Multi-level modeling in risk assessment accounts for factors across different spatial and temporal scales. In Shovi, a comprehensive understanding of risk required integrating micro-level factors (e.g., local soil saturation) with macro-level patterns (e.g., regional climate trends). A proposed three-tier framework for multi-level risk assessment considers interactions among hazards and their complex effects [3].

D. *Lessons Learned from Shovi*

The Shovi landslide exemplifies the challenges of disaster forecasting. Despite data availability, the absence of an integrated forecasting system contributed to the tragedy. A comprehensive hybrid model, incorporating semantic networks and multi-level risk assessment, could have supported earlier warnings and informed mitigation strategies. This study highlights the importance of integrating diverse data sources and analytical approaches to enhance disaster preparedness [4].

E. Decision-Making Implications

Effective disaster risk reduction requires translating predictive models into actionable strategies. In the Shovi context, integrating forecasting models into decision-making systems could facilitate timely evacuations and infrastructure planning. Enhancing disaster resilience necessitates a unified framework combining hybrid forecasting, semantic modeling, and multi-level risk assessment.

III. Analysis of the Shovi Tragedy

A. Risk Assessment and Multi-Factor Modeling

The Shovi case has been previously discussed in [5] as an example of multi-factor forecasting. However, it can also be analyzed in the context of cascading risks, as the sequence of events clearly illustrates the propagation of hazards:

- Initial Event: Collapse of a cliff mass.
- Direct Impact: Landslide and debris flow.
- Indirect Impact: River blockage, infrastructure destruction, and subsequent environmental destabilization.
- Cascading Consequences: Human fatalities, economic losses, and social and psychological crises.

Thus, the tragic event in Shovi exemplifies the mechanism of cascading risk escalation. The initial cliff collapse triggered direct consequences in the form of landslides and debris flows. Simultaneously, it generated indirect effects by obstructing the river flow and damaging local infrastructure. Both pathways led to systemic disruption, significantly affecting tourism, transportation, and the local economy. Ultimately, these disruptions culminated in cascading outcomes, including substantial human losses, social destabilization, and long-term economic challenges for the region.

This case (see Figure 1) demonstrates how a localized geophysical hazard can propagate through interconnected systems, amplify overall impacts, and create a chain reaction of risks.

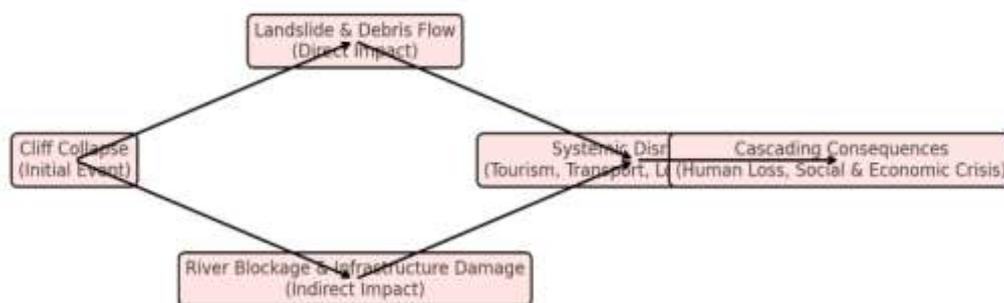


Figure 1: Cascading Risk Scheme Based on the Shovi Tragedy.

- Cliff Collapse (Initial Event) – collapse of cliff mass.
- Landslide & Debris Flow (Direct Impact) – landslide and debris flow.
- River Blockage & Infrastructure Damage (Indirect Impact) – river blockage and infrastructure damage.
- Systemic Disruption (Tourism, Transport, Local Economy) – systemic disruption in tourism, transport, and local economy.
- Cascading Consequences (Human Loss, Social & Economic Crisis) – final outcomes: human loss, social and economic crisis.

B. Risk Assessment and Multi-Level Modeling

Multi-level modeling for risk assessment has been proposed by the authors in [6,7]. This approach presents a three-tier semantic model that establishes causal relationships among events at different levels. A typical three-tier semantic model (see Figure 2):

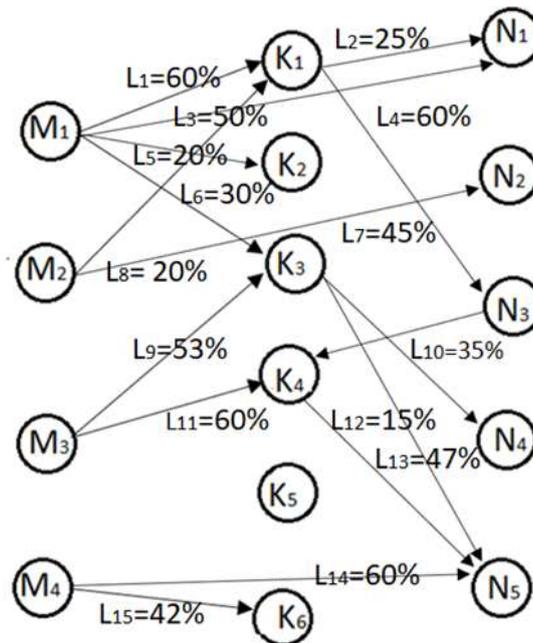


Figure 2: Three-Tier Semantic Network of Forecasting Models

Model consists of:

- Stage One Events (M): Initial driving factors, such as natural hazards or socio-political shocks.
- Stage Two Events (K): Transitional processes induced by Stage One events.
- Stage Three Events (N): Final outcomes, which are directly or indirectly affected by preceding stages.

This framework allows for the systematic mapping of cascading processes and facilitates multi-step risk prediction, highlighting the interplay between initial triggers, transitional dynamics, and ultimate consequences.

C. Involvement of experts in forecasting

While large volumes of data are required for accurate forecasting, in practice, statistical computation is often unavailable, and data are temporarily estimated using expert judgment. The use of experts is described in [8]. Initially, experts are selected for the predictive process, but following each event, expert selection is updated—some experts are removed from the core database, while others are added. Experts who repeatedly err two or three times are replaced, whereas consistently accurate experts have their reliability scores increased.

The new approach to forecasting assumes that there are at least two industry models that are different from event forecasting models, but if this is not the case, then we use experts. In general, the role of experts in predicting such events is very large, since the information obtained by automatic measurement sensors requires a great deal of knowledge and experience from the event specialist.

Article [9] discusses a hybrid forecasting model that initially evaluates “necessary” and “sufficient” models within the decision-making process, subsequently selecting optimal pairs or triplets of models, and finally engaging experts. The study outlines how to operate with a hybrid

model, determining when experts should be involved and according to which criteria. Algorithms are developed both for selecting new forecasting models and for determining the need to replace an expert. Importantly, expert selection is based on the accuracy of their predictions rather than solely on their competence.

IV. Detailed Data Integration: Meteorology, Glaciology, and Geology

The Shovi landslide resulted from a combination of meteorological, glaciological, and geological factors. Detailed integration of these datasets can substantially enhance the accuracy of predictive models.

A. Meteorological Analysis

Historical data from the Shovi region indicate that in the 48 hours preceding the landslide, cumulative precipitation exceeded 120 mm, significantly above the regional May average. Peak intensities reached approximately 25 mm per hour, leading to soil layer saturation and increased slope instability (see Figure 3). Precipitation measurements from nearby automated meteorological stations, combined with satellite-derived rainfall data, can be integrated into hybrid forecasting models to determine critical thresholds for slope failure.

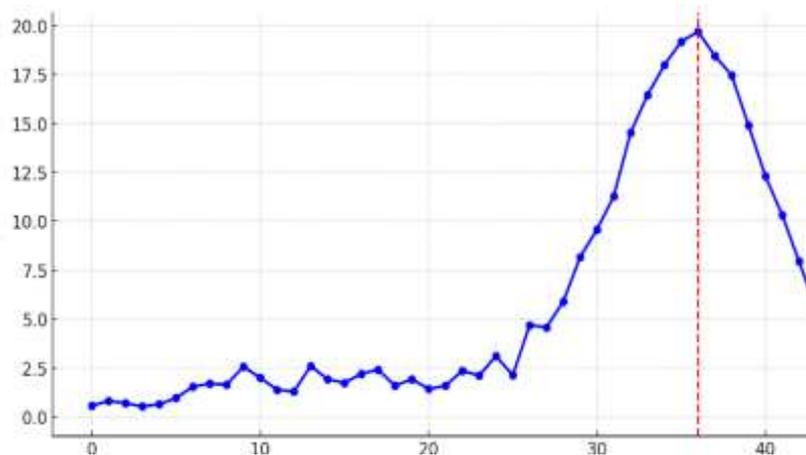


Figure 3: Precipitation Intensity Series (for Shovi)

The graph illustrates the precipitation dynamics leading up to the landslide. The red line marks the peak rainfall occurring 6–12 hours prior to the disaster.

B. Glaciological Observations:

The Buba Glacier, located above the Shovi settlement, experienced accelerated melt in the months preceding the catastrophe. Remote sensing imagery revealed approximately a 12% loss in glacier volume compared to the previous year. Subglacial water accumulation contributed to a sudden increase in river discharge, which, in turn, exerted additional stress on downstream slopes (see Figure 4). Incorporating glacial melt models into hybrid forecasting systems allows for the quantification of runoff contributions and flood potential.

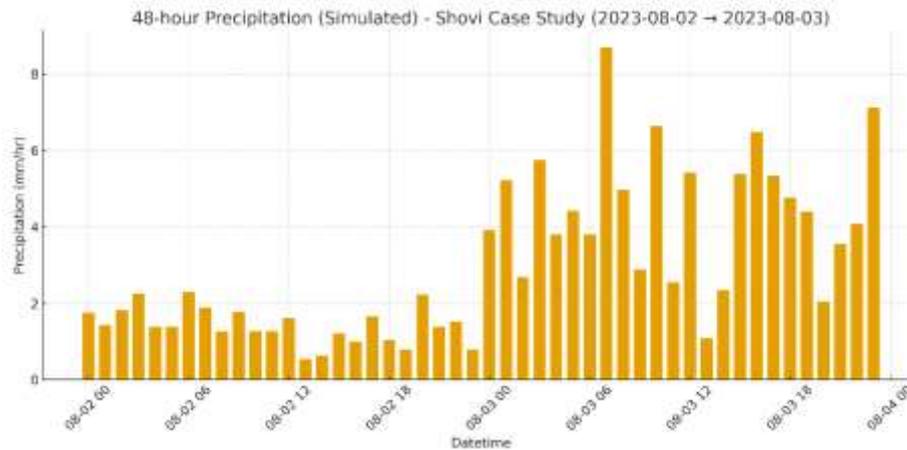


Figure 4: Glacial Melt Table (Hourly Water Discharge in m³/s or mm equivalent)

Example: Increased water discharge corresponding to rising temperatures (°C).

Geological Assessments: Field surveys indicated that the landslide occurred on a slope with an average inclination of 35–40°, composed of loose alluvial deposits and heavily weathered rock. Previous minor landslides in the area suggested a predisposition to slope failure. Geotechnical parameters, including soil cohesion, internal friction angle, and pore water pressure, are critical for deterministic slope stability modeling. Integrating these parameters into statistical and machine learning models significantly enhances predictive capabilities.

C. Semantic Network Diagram of the Shovi Landslide:

A semantic network can represent the cascading interrelations of precipitation, glacial melt, and their propagative effects in the Shovi case. A consolidated, layered approach may be structured as follows (see Figure 5):

- Initial Stimuli: Climatic triggers, historical antecedent conditions.
- Direct Events: Intense rainfall, glacier melt.
- Secondary Processes: Soil saturation → landslide initiation; glacial melt → debris and mudflows.
- Impacted Entities: Infrastructure, population.
- Mitigation and Response: Existing controls, monitoring, early warning systems.

V. Decision-Making Framework

Integrating hybrid forecasting and semantic network modeling into decision-making frameworks enhances disaster resilience. Key components include:

- Early Warning Protocols: Threshold-based alerts can trigger evacuations or protective actions. For example, if precipitation exceeds 100 mm within 24 hours combined with glacier runoff greater than 15 m³/s, local authorities may implement precautionary measures.
- Infrastructure Planning: Placement of retention walls, diversion channels, and monitoring stations can be optimized based on model outputs. Integration with Geographic Information Systems (GIS) allows for high-risk zone mapping.
- Community Engagement: Effective communication regarding hazard zones and risk levels is essential. Residents and local authorities must be trained to interpret warnings and implement mitigation strategies.

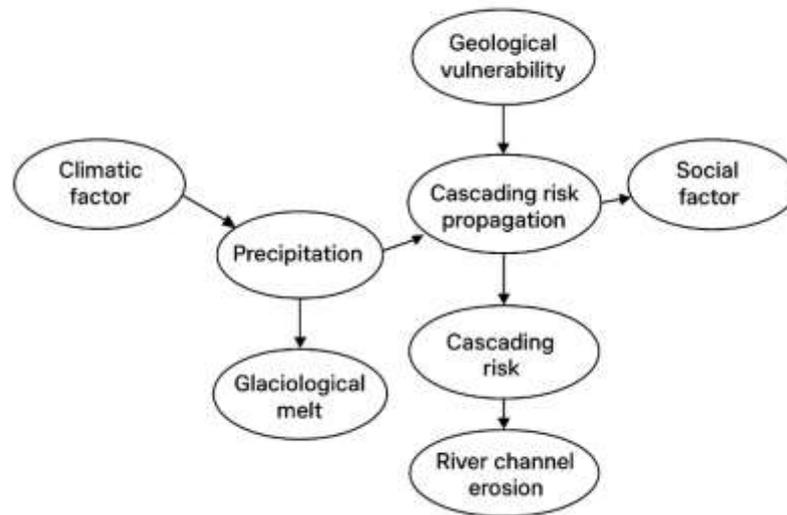


Figure 5: Hierarchical diagram with arrows (→) illustrating the cascading chain of events.

VI. Conclusion and Future Applications

The Shovi case underscores the importance of integrating multiple datasets and modeling approaches:

1. **Data Integration:** Single-source forecasting is insufficient for complex landslides; hybrid models that combine meteorological, glaciological, and geological data are more effective.
2. **Forecast Accuracy:** Incorporating semantic network analysis enables the identification of cascading effects and interdependent risk factors.
3. **Decision Support:** Real-time integration of forecasting outputs into decision-making processes facilitates timely mitigation and evacuation.

These lessons can be applied to other mountainous regions characterized by glaciers and highly variable precipitation, enhancing preparedness for large-scale disasters. The findings are expected to inform strategies for risk reduction, early warning mechanisms, and sustainable development practices in similar global mountainous contexts.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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