# СЕЛЕВЫЕ ПОТОКИ: катастрофы, риск, прогноз, защита

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# DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

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# A multi-parameter simulation framework for debris flow hazard assessment using environmental and hydrological inputs

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**Abstract.** Mandakini River originates from the Chorabari Glacier. Coursing through the Garhwal Himalayas in Uttarakhand, India, has been the epicenter of multiple natural disasters over the past decade. These events, primarily driven by extreme weather patterns and exacerbated by human activities, have profoundly impacted the region's ecology and communities. This study introduces a computational framework designed to assess debris flow hazards by integrating environmental and hydrological parameters. The model calculates a Debris Flow Index (DFI) by normalizing and weighting factors such as precipitation, flow rate, slope, soil saturation, vegetation cover, and debris volume. Additionally, it estimates Expected travel time and distance to evaluate potential impact zones. An interactive interface allows for both real-time data input and predefined scenarios, facilitating rapid hazard assessment across multiple stations. The framework aims to enhance early warning systems and support disaster risk reduction strategies.

***Key words:*** *Mandakini River, debris flow, extreme weather, disaster risk reduction strategies*

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# Многопараметрическая структура моделирования для оценки опасности селей с использованием экологических и гидрологических данных

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**Аннотация.** Река Мандакини берет начало от ледника Чорабари. Протекая через Гархвалские Гималаи в Уттаракханде, Индия, за последнее десятилетие она стала эпицентром множества стихийных бедствий. Эти события, в первую очередь вызванные экстремальными погодными условиями и усугубленные деятельностью человека, оказали глубокое влияние на экологию и сообщества региона. В этом исследовании представлена вычислительная структура, предназначенная для оценки опасности селей путем интеграции экологических и гидрологических параметров. Модель рассчитывает индекс селевого потока (DFI) путем нормализации и взвешивания таких факторов, как осадки, скорость потока, уклон, насыщенность почвы, растительный покров и объем мусора. Кроме того, она оценивает ожидаемое время и расстояние в пути для оценки потенциальных зон воздействия. Интерактивный интерфейс позволяет вводить данные как в реальном времени, так и по заранее заданным сценариям, что облегчает быструю оценку опасности на нескольких станциях. Структура направлена на улучшение систем раннего оповещения и поддержку стратегий снижения риска бедствий.

***Ключевые слова:*** *река Мандакини, сель, экстремальные погодные условия, стратегии снижения риска стихийных бедствий*

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## Introduction

Debris flows are common phenomenon in landslide susceptible regions throughout the world, casing rapid mass movements of water-saturated soil and rock, often triggered by intense rainfall or rapid snowmelt. These events pose significant risks and losses to infrastructure and human life, particularly in mountainous regions [*Geertsema et al., 2009; Alimohammadlou et al., 2013*].

In Asia, India is considered the most landslide-affected nation, whose 12.6% of the land is prone to landslides worldwide [*Froude and Petley, 2018*], the scenario is more alarming in the Himalayan states, due to the diverse topography, intense and variable climatic conditions, and high anthropogenic activities which make it highly vulnerable to landslides [*NDMA, 2019*].

Uttarakhand lies in the Himalayas, with 93% land as a hilly region [*Khali et al., 2023*], prone to landslides due to its complex geology, climate, seismo-tectonic setting, and geomorphological condition [*Gupta et al., 2022; Chauhan and Dixit, 2023*]. Uttarakhand has undergone a considerable major natural disaster in Uttarakhand include of 1970, 1986, 1991, 1998, 2001, 2002, 2004, 2005, 2008, 2009, 2010, 2012, 2013, 2016, 2017, 2019, 2020, and 2021 [*Das et al., 2006; Dimri at al., 2017*]. Several studies have been conducted on landslide susceptibility in Uttarakhand [*Pham et al., 2015, 2016, 2017, 2022; Sangeeta and Maheshwari, 2019; Ram et al., 2020; Batar and Watanabe, 2021; Khali et al., 2023; Singh et al., 2023*].

Mandakini River Valley in Rudraprayag district of the state experienced maximum destruction caused by rainfall, followed by cloudbursts and flash floods. Landslide tragedy in August 1998 around Madhmaheshwar and the Kaliganga sub-watersheds; Phata cloudburst (2001), Lwara slide and Basukedar slide (1992) and cloudburst in Ukhimath (2012) are some examples of important devastating events in Mandakini Valley that caused large-scale loss of lives, damage to resources and associated environmental–social hazards. Landslides triggered due to extreme rainfall during the 15–17th of June 2013 around Kedarnath destroyed more than 250 villages and killed an estimated 6074 people [*Martha et al., 2015*].

Flood risk management is crucial as it provides optimal utilization and exploitation of land and water resources that bring prosperity and sustainable development to a nation [*Wheater and Evan, 2009*]. In India, flood risk management in hilly regions is still in the infancy stage, particularly due to complex and tough terrain with limited accessibility and a low level of monitoring [*Tullos et al., 2016; Li et al., 2019*].

In last few decadal floods and disasters event has shown that the structural measures alone could not ensure adequate security against such disasters and an effective strategy to safeguard these disasters is essential. Traditional assessment methods may not adequate to tackle the complex environmental factors influencing debris flow initiation and propagation. This study presents a simulation framework that integrates multiple parameters to assess debris flow hazards, aiming to improve predictive capabilities and inform mitigation efforts.

## Materials and methods

*Study area*

Uttarakhand, a Northern state of India, is located between 28° to 32° N and 77° to 81° E, as shown in Fig. 1 [*Chauhan et al. 2024a*]. It occupies approximately 53,400 km$^2$ region of India lies majorly in the Himalayas, with elevation values above mean sea level ranges from 169 to 7795 m. It is surrounded by two international borders (China in the North and Nepal in the East).

Mandakini Valley, an upstream part in Rudraprayag district , an area of about 1982.09 km$^2$ lies between lat. 30°12' 58.132–30°48' 27.642N and long. 79°2' 58.649–79°2' 0.952E , comprises two separable major litho-stratigraphical units, i.e. the Garhwal Group and the Central Crystalline Group, Survey of India topo sheets No. 53J /14, 53J/15,53N/1, 53N/2, 53N/3, 53N/4 and 53N/6. These groups are separated from each other by a major tectonic contact known as the Main Central Thrust (MCT). The Valley appears to have undergone several phases of tectonic movements, which are depicted by local folds, faults and thrusts. The zone between Rudraprayag and Kund consists of quartzite, slate, schist, crystalline limestone, dolomite, marble, gneiss and occasionally intruded by meta-volcanic rocks of the Garhwal Group. Upstream of Mandakini River from Kund to Kedarnath and Kund to Mandal, and beyond, various. The altitude of Mandakini River catchment extends from 670 to 6000 m a msl (Fig. 1).


Fig. 1. Mandakini River vie from Google Earth

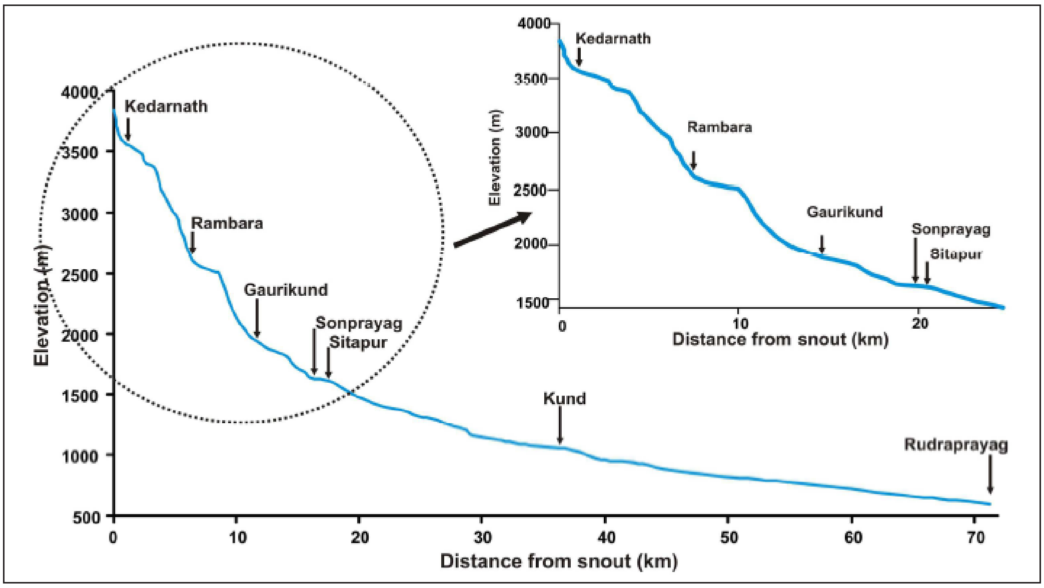


Fig. 2. Longitudinal profile of Mandakini River. Discontinuities show the depocenters for the sediment transport [*Sundriyal et al., 2015*]

The flow chart explains the full procedure of debris flow simulation model development (Fig. 3).

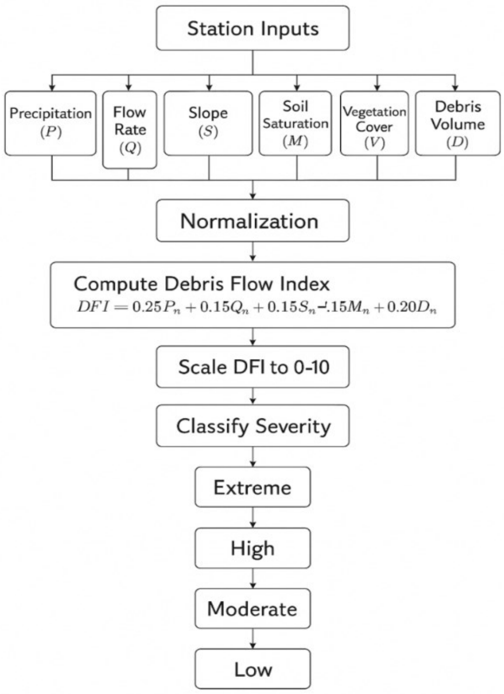


Fig. 3. Flow diagram of modeling process

Table 1 defines the input Parameters and their role in debris flow management. Each station in the simulation takes the following primary inputs obtained from secondary sources (Table 2). A simulation model was developed using python programming.

Table 1. Input parameters and their mathematical representations

| Variable | Symbol | Unit | Role in Debris Flow |
|---|---|---|---|
| Precipitation | PPP | mm | Triggers surface runoff and potential landslides |
| Flow Rate | QQQ | $m^3/s$ | Indicates water discharge which contributes to material movement |
| Slope | SSS | degrees | Controls gravitational force and flow velocity |
| Soil Saturation | MMM | % | Influences pore pressure and slope stability |
| Vegetation Cover | VVV | % | Acts as a stabilizer; less cover increases risk |
| Debris Volume | DDD | $m^3$ | Determines potential mass and impact severity |

Table 2. Input parameters for risk management model

| Station | Precipitation, mm | Flow, Cumec | Slope, % | Saturation, % | Vegetation, % | Debris Volume, cum |
|---|---|---|---|---|---|---|
| Custum-1 | 250 | 150 | 90 | 10 | 10 | 900 |
| Custum-2 | 300 | 270 | 60 | 40 | 20 | 1500 |
| Custum-3 | 400 | 900 | 30 | 90 | 80 | 3900 |

## Modeling

*Data Normalization*

Each parameter is normalized using min-max scaling based on predefined minimum and maximum values to ensure comparability across different units and scales.

*Debris Flow Index Calculation*

The Debris Flow Index (DFI) is computed as a weighted sum of the normalized parameters:

DFI = (0.25 × Precipitation) + (0.15 × Flow Rate) + (0.15 × Slope) + (0.15 × Soil Saturation) - (0.10 × Vegetation Cover) + (0.20 × Debris Volume). (1)

The resulting DFI is scaled to a range of 0 to 10.

*Travel Time and Distance Estimation*

Travel time is estimated using the formula:

Travel Time = Travel Distance / Adjusted Velocity, (2)

where adjusted velocity accounts for slope and frictional losses. Travel distance is estimated based on terrain slope and empirical relationships.

*Severity Classification*

Based on the DFI and estimated travel time, debris flow events are classified into severity levels:

- **Extreme:** DFI ≥ 8.5 and Travel Time < 10 minutes;
- **High:** 6.5 ≤ DFI < 8.5;
- **Moderate:** 4.0 ≤ DFI < 6.5;
- **Low:** DFI < 4.0

**Results and discussion**

The Debris Flow Index (DFI) values, estimated travel times, and severity classifications, obtained simulation model, provided insights into potential hazard levels. Fig. 3. shows the DEM of Mandakini River, which has an inimitable topographical and climatic setting, making it prone to numerous hydro-meteorological disasters such as floods, cloudbursts, glacier lake outbursts, and landslides [*Lindell et al., 2019; Dash and Punia, 2019*]. In the last 30–40 years, the frequency and severity of natural hazards have risen due to various anthropogenic and changing climatic conditions [*Dimri et al., 2018*].

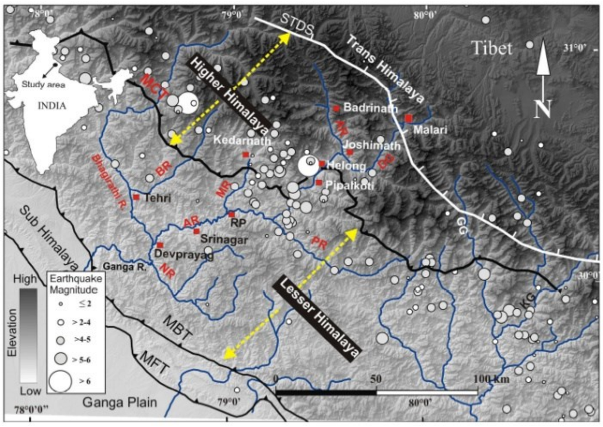


Fig. 3. DEM of Uttarakhand Himalaya. MFT – Main Frontal Thrust, MBT – Main Boundary Thrust, MCT – Main Central Thrust, STDS – South Tibetan Detachment System, BR – Bhilangana river, MR – Mandakini River, AR – Alaknanda River, NR-Nayar river, DG – Dhauliganaga river, PR – Pinder River, MCT is a zone of recurrent seismicity as indicated by the concentration of earthquake epicenters (Source: https://earthquake.usgs.gov/earthquakes/eqarchives/epic/) and physigraphic boundary between Lesser and Higher Himalayas)

*Debris Flow Index (DFI) and Severity*

Table 3 shows the debris flow index and severity for estimated travel distance and the time for three selected stations; the table shows the time taken by the debris to reach station two and three. The index integrates multiple physical and environmental parameters. Stations Custom_2 and Custom_3 fall into the "High" severity category, indicating increased risk to downstream aquatic systems, population and infrastructure.

Table 3. Debris Flow Index (DFI), severity class, Travel distance and time across three custom stations

| No. | Station | Debris flow index | Severity | Estimated travel distance, km | Travel time, min |
|---|---|---|---|---|---|
| 0 | Custom_1 | 5.733333 | Moderate | 5.715934e+16 | 1.337061e+17 |
| 1 | Custom_2 | 6.900000 | High | 6.060000e+00 | 9.100000e+00 |
| 2 | Custom_3 | 7.550000 | High | 2.020000e+00 | 1.580000e+00 |

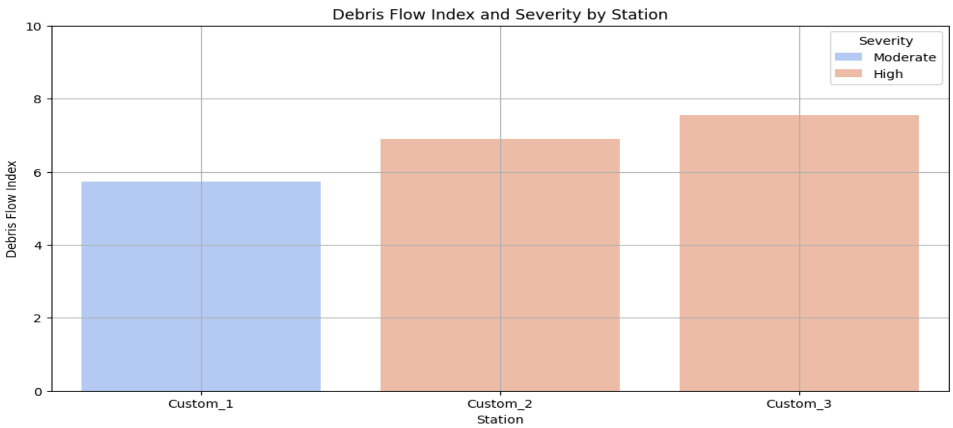


Fig. 4. Debris Flow Index (DFI) and severity class across three custom stations

The Debris Flow Index (DFI) presented in Fig. 4. and for their corresponding severity classifications, for three custom stations across the Mandakini River. Debris Flow Index (DFI), based on normalized inputs, ranging from 0 to 10, quantifying the hazard and pollution of debris in Mandakini River flows at each station. The DFI increases steadily from Custom_1 to Custom_3, indicating a rising debris flow hazard gradient, which may be possibly due to increasing slope, precipitation, or debris load.

It is evident from the results that water stress and quality would be low at the station Custom_1, due to low temperatures, high oxygen, and clear water. Although DFI is moderate (5.7), the resulting eco-impact remains relatively lower. This reflects healthy upstream water conditions, typical of glacial-fed Himalayan segments at the upstream. At Custom_2 (Midstream), the temperature was observed increasing and the decrease of DO begin to elevate water stress which increased the hazard impact. Degradation in water quality would lead to reasonable ecological amplification. Custom_3 (Lower Reach / Impact Zone) shows the high thermal and chemical stress, lowest DO, lowest WQI, high dustiness, triggers maximum ecological hazard magnification causing severe ecological vulnerability, especially in heavily sediment or polluted zones. Difference in DFI between Custom 1 and Custom 3, underscores the compound nature of debris hazards, where physical events and degraded water quality synergistically intensify risk.

The transition from moderate to high DFI across Custom_1 to Custom_3 showed that the hazard levels escalated spatially, probably due to terrain or hydrological factors such as slope steepness or recent rainfall. All respective stations fall in the High and moderate severity class and preemptive action such as slope stabilization, debris traps, or ecological monitoring is required. The clear separation of DFI values across severity thresholds supports the model's utility in classifying risk zones. Integrated watershed management practices are highly required, not only to check debris flow initiation but also to protect downstream water quality, which is crucial for maintaining overall ecosystem resilience.

The anthropogenic activities at lower reaches, such as the construction of dams, roads, deforestation, etc., aggravated the disasters and disrupted the Himalayan ecosystem in the various states such as Uttarakhand [*Geneletti and Dawa, 2009*]. The climate change in the Himalayas has resulted in irregular precipitation, temperature rise, drying up of perennial rivers, depletion of natural resources, and an increase in the frequency and intensity of flash floods [*Mishra et al., 2021*].

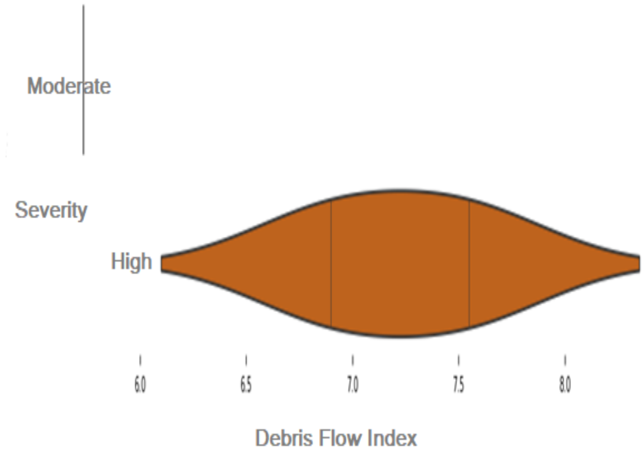


Fig. 5. Debris Flow Index (DFI) values according to severity class

Fig. 5 represents the distribution of Debris Flow Index (DFI) values categorized by severity Class, as part of your simulation results. The plot combines a boxplot and a kernel density estimate (KDE). It visually shows the distribution, range, and concentration of DFI values within each severity category. The plot shows the physical hazard from factors like precipitation, slope, debris volume, etc. The plotted DFI values range approximately from 6.0 to 8.1. The plot of severity category classified from simulation results shows high and a thin line appears for moderate, but no data is shown because there are zero cases in this range). Violin plot shows that all the custom stations are exposed to debris flows (DFI values ranging from 6.9 and 7.55), leading to "High" severity category. The study shows that even with the variation in environmental inputs the debris flow hazard remains persistently high across the modeled stations. The clustering around a DFI of ~ 7 shows debris-generating conditions (e.g., moderate slope, moderate precipitation, and moderate debris volume) and consistently contributing to high ecological stress.

Fig. 6a shows that there is linear increase in values, starting from 0.0 and reaching 2.0 by index 2. The graph suggests a uniform rate of change at every step forward along the x-axis corresponds to a fixed increase in the index value. DFI shows the linear increase in hazard severity and ecological impacts. The trend validates the index weighting system and confirms the comuted index changes with each input variation and verifies the scaling function. The controlled simulation scenario Shows uniform environmental degradation, as expected behavior by the normalized index function. It also shows the model's internal consistency, especially when testing with synthetic data or analyzing the scaling behavior of impact metrics.

Fig. 6b. Shows a monotonic increasing trend in DFI values across the stations. Rate of DFI growth decreases with the stabilization and saturation of environmental conditions. Progressive rise in DFI growth from custum_1 to Custom_3 shows spatial gradient in debris flow hazard along the Mandakini River watershed area caused due to due to increase in slope, sedimentation or less vegetation in downstream areas. Transition from moderate to high severity between station 1 to station 2 shows model's sensitivity to small changes in saturation or flow volume.

The steady but non-linear increase in DFI demonstrates that the index appropriately accounts for multiple compounding variables. The leveling off near Station 3 could indicate a saturation effect in hazard accumulation, suggesting that mitigation efforts could be more effective if focused upstream.

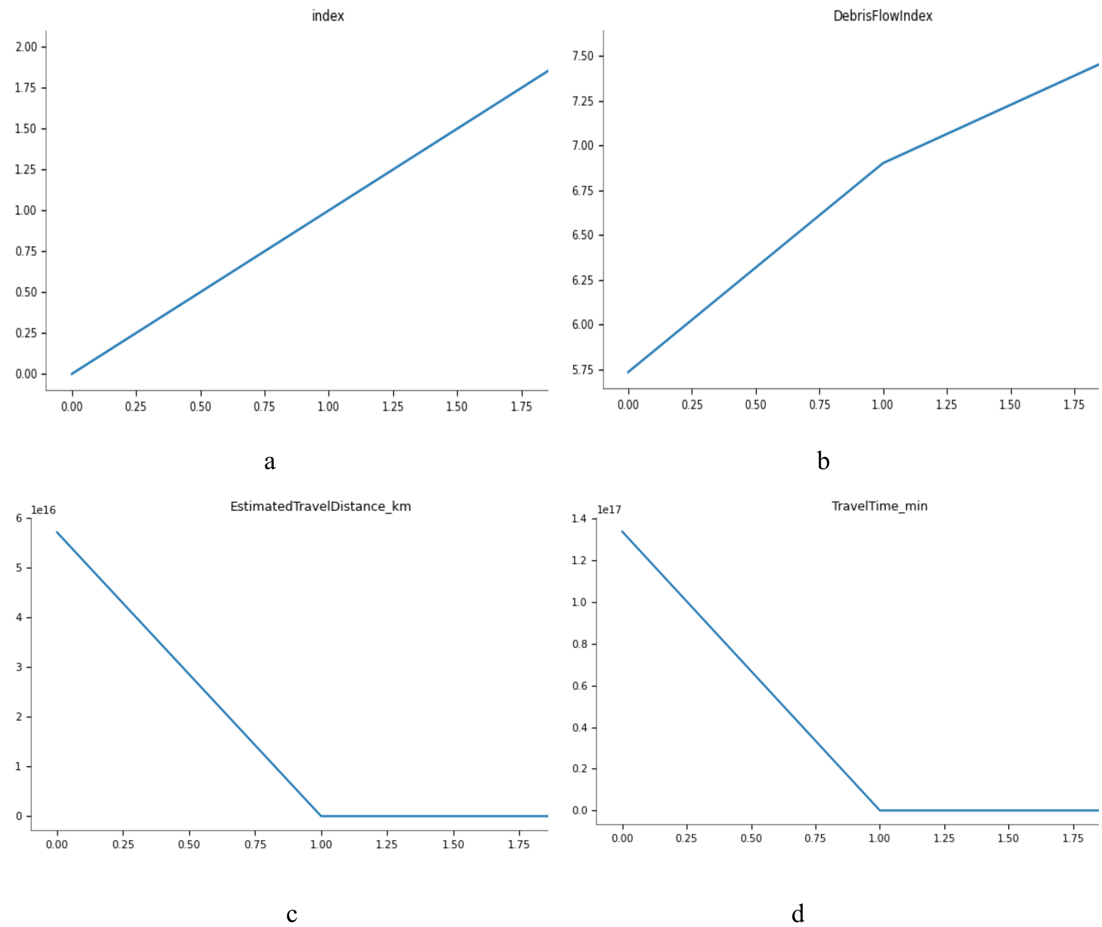


Fig. 6. Linearly increasing index (a); debris Flow Index (DFI) (b); estimated debris flow travel distance (c); estimated travel time (in minutes) for debris flow simulation across three sequential positions (d)

*Travel Time, distance and Hazard Zonation*

Fig. 6c shows the estimated debris flow travel distance at three stations. Due to a data anomaly (likely slope or depth = 0), Custom_1 shows a non-physical travel distance. This highlights the importance of slope and flow parameter validation in predictive hazard modeling. On the other side there may be possibility of collection of debris at the lower slope side causing velocity of flow to become extremely slow and spread of debris to wider area.

Fig. 6d estimated travel time (in minutes) for debris flow simulation across three stations. Anomalous values are observed at Station 0, suggesting input-related instability in the velocity calculation. Such cases reinforce the need for pre-validated input ranges to maintain numerical reliability in debris flow travel modeling. The values increase linearly, starting from 0.0 and reaching 2.0 by index 2. This suggests a uniform rate of change, every step forward along the x-axis corresponds to a fixed increase in the index value. This graph reflects a uniform increase in hazard severity across stations Custom_1 to Custom_3. A straight-line trend confirms the model's linear response to increasing input values, validating the weighting system used for index calculation. As a control or validation plot, the graph confirms that each increment in the input causes an equal increment in the computed index, verifying the scaling function.

Figure shows a linearly increasing index across three sequential positions, suggesting uniform environmental degradation, a controlled simulation scenario, or the expected behavior of a normalized index function. This kind of linearity is useful in validating the internal consistency of model while analyzing the scaling behavior of impact metrics of the model.

The result shows that debris could reach critical zones within 1.5 to 9 minutes depending on flow velocity and channel geometry, the river hydraulics and slope gradients will play a major role.

Rapid movement of debris and the downstream areas shows the urgent need for real-time early warning systems, especially in the high risk or populated areas. Since the custum_1 is at higher slope, flow energy is high and travel time was to short i.e. 1.3 minutes, whereas Station Custom_2 had a much higher lead time (> 9 minutes) due to reduction in slope, thereafter Custum_3(< 1.5 minutes) has time with having the risk of spreading of debris in lager area.

*Model Behavior Breakdown*

The sudden drop from a huge value to zero in the next two stations is non-physical and indicates a computational logic issue, likely related to slope, flow width, or other input conditions. It should not be interpreted as physical behavior of debris flow.

The graph illustrates the estimated travel time (in minutes) for debris flows at three stations – likely Custom_1, Custom_2, and Custom_3 – but exhibits extreme and nonphysical values, indicating computational or data input issues.

Fig. 6d illustrates the estimated travel time (in minutes) for debris flows at three stations – likely Custom_1, Custom_2, and Custom_3 – but exhibits extreme and nonphysical values, indicating computational or data input issues. The figure shows Debris volume too high with very low flow is not a real pattern shows unrealistically slows debris and numerical instability and the values not constrained within physical or empirical ranges, further, it either supports a breakdown in the velocity computation logic under certain edge conditions which requires a enforcement of minimum value for flow depth and slope in the program or extremely slow velocity may be due to spread of debris in larger area taking more time to move down the slope. The event predicted by model needs a physical validation. It is suggested that if there is any input-related instability in the velocity calculation. It requires a pre-validated input ranges to maintain numerical reliability in debris flow travel modeling.

The Mandakini River system exhibits a high baseline hazard profile, especially in areas downstream of glacial valleys. This model confirms that natural topography combined with anthropogenic pressure (e.g., construction, deforestation) significantly increases both debris flow severity and its ecological consequences. Since the single debris flow index includes multiple environmental and hydrological parameters, the model provides much comprehensive assessment of debris flow hazards. Model's applicability may be enhanced to early warning systems, by providing real time data. However, the model's accuracy will depend upon quality of input data, formula used and the assumptions, if any. Model accuracy may be enhanced by calibrating it with historical debris flow events and incorporating additional input factors such as land use changes and soil types et.

## Conclusion

Simulation model successfully assesses debris flow hazards by combining key environmental and hydrological parameters for the Mandakni River watershed area. The model provides valuable information for risk assessment and mitigation planning and can be applied to any watershed area. The developed model is interactive and was found to be a versatile tool to support both, real-time monitoring and scenario analysis, and can provide reliable information for disaster risk assessment and mitigation to stakeholders. The debris flow simulation model integrates multiple environmental and hydrological parameters through mathematical normalization, weighting, and index-based classification to simulate debris flow risk and behavior.

The mathematical approach included in the model, enables flexibility, comparability, and scalability across varied terrain and conditions, makes it suitable for early-warning tools and risk assessments. Model evaluates various rainfall and debris scenarios and multi-station hazard profiles in real time and can be successfully used by the stakeholders, including disaster managers, ecologists, and local authorities

The proposed Model bridges the gap between hazard forecasting, risk analysis and ecosystem vulnerability analysis. Model provides a versatile decision-support system for disaster preparedness and response planning for Himalayan river systems.

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