# Assessment of Landslide Susceptibility in the Himalayan Region: A Case Study of Rishikesh-Yamunotri Corridor

**Madhuri Meena ***
Research Scholar, Department of Geography, Delhi School of Economics, University of Delhi, New Delhi, India
**Seema Sahdev**
Professor, Department of Geography, Kalindi College, University of Delhi, New Delhi, India.
**Corresponding Author Email: madhurimeena16@gmail.com*

**Abstract:** *The findings of the statistical models based on geographic information systems (GIS) for creating landslip susceptibility maps utilising remote sensing data and geographic information systems for the Rishikesh to Yamunotri corridor of Uttarakhand are presented in this study. Cartosat, Landsat, IMD, and India water resources data were used to extract ten factors: slope, aspect, soil, lithology, NDVI, LULC, distance to stream, precipitation, distance to road, and elevation. Using GIS-based statistical models, such as the analytical hierarchy process (AHP), which assigns ranks and weights to various factors to determine which factors are more responsible for landslides, the relationships between the detected landslide locations and these ten related factors were identified. The three landslide zone categories, high, medium, and low, on the landslip inventory map were developed using various like field surveys and digital aerial photos. Regional planning and hazard mitigation would benefit from these landslip susceptibility maps.*

**Keywords:** Landslide, Susceptibility, AHP model, Inventory, Regional planning.

## INTRODUCTION

Landslides are natural disasters that primarily occur in mountainous regions, involving the downward movement of debris, rocks, and soil. This movement is triggered by various factors, including geological conditions, rainfall patterns, soil type, slope steepness, aspect, vegetation, land use, land cover, and anthropogenic activities. In recent times, numerous landslides have impacted India's mountainous regions, damaging infrastructure, causing loss of lives, and creating transportation challenges ranging from minor inconveniences to significant economic and social crises (Negi et al., 2013).

Landslide susceptibility refers to the likelihood of landslide events occurring at a specific location, irrespective of time, and is determined by the area's topographical features (Guzzetti et al., 1999). This probability can be evaluated through multiple analytical techniques, such as expert-based (heuristic), data-driven (statistical), and physically-based (deterministic) methods (Sarkar et al., 2023). During the rainy season, landslides remain one of the most severe hazards affecting India's hilly terrain. Every year, vast mountainous regions of the Himalayas, Northeast India, the Nilgiris, the Eastern Ghats, and the Western Ghats suffer from this threat, leading to significant losses in lives, infrastructure, and property (Sharda, Y.P., 2009). Landslides manifest in various forms across different geographical areas, highlighting the importance of analysing their potential risk and vulnerability. Debris flows are fast-moving landslides that have the potential to severely impact both human life and property due to their rapid movement, destructive force, and sudden onset. Similarly, mudflows, also known as mudslides, refer to the swift movement of liquefied debris and soil, triggered by the addition of water. These flows can travel at speeds ranging from 3 meters per minute to 5 meters per second.

Landslide Susceptibility Zonation (LSZ) has been widely carried out to pinpoint areas at risk of landslides by employing remote sensing and Geographic Information System (GIS) technologies. Remote sensing proves to be an effective resource for analysing and understanding surface landform characteristics, owing to its broad spatial reach, consistent temporal data, and ability to capture repeated observations over time. Numerous interconnected natural processes, including tectonic activity, slope failure, and volcanic events, along with various human-induced factors such as environmental degradation, land-use expansion, unregulated settlement growth, road construction, hydropower projects, unplanned tourism, and resource extraction, are significantly altering and impacting landform terrain (Taloor et al., 2021).

The Himalayan region is one of the most affected areas by landslides, making it crucial to study their types, causes, and the most vulnerable zones. This can be achieved through landslide identification, susceptibility mapping, and slope stability analysis. Various studies have considered factors such as slope aspect, proximity to roads and streams, soil type, geology, land use and land cover, vegetation, rainfall patterns, relief, and, in some cases, slope length and steepness as causative or instability factors (Myronidis et al., 2016). However, these factors do not all contribute equally to landslide occurrence (Sujatha et al., 2012). Human-induced landslides (HIL) have become increasingly significant in both frequency and damage, particularly in the Himalayan region. One of the primary contributors is the undercutting of slope base sections for road construction, which is strongly linked to landslides in the area (Barnard et al., 2021).

## OBJECTIVES

1. To identify landslide prone zone based on the hydrological factor.

2. To evaluate the effects of road-building activities on slope stability and landslide occurrence

## STUDY AREA

Rishikesh, one of Uttarakhand's most well-known cities, is renowned for its cultural and tourism significance. The holy Ganga River flows through this city, which is situated in northwest India and is surrounded by the Himalayas on three sides. Geographically, Rishikesh is located at approximately 30.103368°N latitude and 78.294754°E longitude, with an average elevation of 372 meters (Fig. 1). Numerous villages have developed along the riverbanks, extending toward the eastern bank. The city is bordered by the districts of Dehradun, Pauri-Garhwal, and Tehri-Garhwal in Uttarakhand and has a population of approximately 102,000.

The Yamunotri Valley has an average elevation of 3,200 meters above mean sea level. The upper Yamunotri Valley, which forms the study area in Uttarkashi district, spans approximately 161 square kilometers, between latitudes 31º2´25´´ North and longitudes 78º20'58´´ to 78º29'41´´ East. Yamunotri, one of the four sacred sites of India's Char Dham pilgrimage, is the source of the Yamuna River and the westernmost shrine in the Garhwal Himalayas. Its true source is the Champasar Glacier, a lake and glacier covered in ice, located atop the mountain at an elevation of 4,421 meters above mean sea level. (Fig 01)

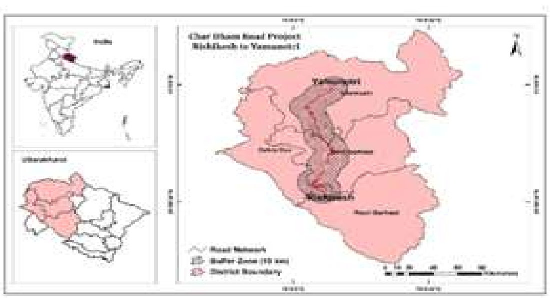

**Figure 1: Study Area**

## METHODOLOGY

In the dataset precipitation of the study area has been taken from Indian Meteorological department, New Delhi. The dataset was taken for recent periods in order to observe latest conditions in the study area except landslide inventory locations (entire period of dataset) since terrain changes are not significant on this temporal scale.

## RESULTS AND DISCUSSION

### RAINFALL INDUCED LANDSLIDE SUSCEPTIBILITY

Rainfall is a crucial factor influencing landslide susceptibility, particularly in the mountainous terrain between Rishikesh and Yamunotri. The given table categorizes rainfall into five subclasses based on annual precipitation levels, with a corresponding area percentage and ranking for overlay analysis. The majority of the study area (44.63%) falls within the 1,251–1,500 mm rainfall range, receiving a moderate susceptibility rank of 2. Similarly, 33.47% of the area experiences 1,501–1,750 mm of rainfall, while 17.91% falls within the 1,751–2,000 mm range, both of which hold a slightly higher rank of 3 due to increased precipitation and subsequent slope instability. The highest rainfall category (2,001–2,250 mm), covering only 1.08% of the area, is assigned the highest rank of 4, indicating a stronger influence on landslide occurrences. (Fig 02)

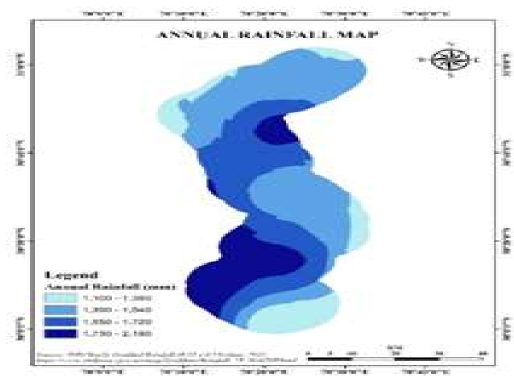


**Figure 2. Rainfall map of the study area**

Rainfall directly affects soil saturation, leading to reduced cohesion and increased pore water pressure, which trigger slope failures. Areas with higher precipitation are more prone to landslides, particularly when combined with steep slopes and weak geological formations. The overlay analysis assigns a weighted influence factor of 10.9, highlighting rainfall as a significant determinant in landslide susceptibility mapping. Such assessments aid in risk mitigation, guiding infrastructure planning and disaster preparedness in the Rishikesh-Yamunotri corridor. Rainfall is a major cause of landslides, and studies frequently examine the connection between the frequency, intensity, and length of rainfall and landslides. Slopes become unstable and more likely to fail when heavy rainfall saturates the soil, weakens it, and raises pore water pressure. Pre-existing groundwater conditions, slope angle, and soil type all have an impact on the impact of rainfall. But nowadays due to climate change we can witness the changing pattern of the rainfall in these highly fragile mountainous areas which also needs to be taken into consideration. Whole region comes within high to very high rainfall region which makes the corridor more vulnerable.

The most influential factor, as intense precipitation increases soil moisture, reduces cohesion, and triggers landslides. As a trigger, rainfall raised the pore water pressure by soaking the soil and raised the pressure inside the pore spaces, which are tiny spaces in the soil. Because of this pressure, the soil's effective strength was decreased, which facilitated the slope's movement. Because saturated soil weighs more than dry soil, rainfall also increased the weight, which put more strain on the slope and increased the driving force for failure. Rainfall also made it simpler for the soil particles to glide down the hill by reducing friction between them. Rainfall raises the pore water pressure in the rock and soil. The slope becomes less stable as a result of this saturation since it lessens the binding and frictional forces between soil particles and rock. Instability is also exacerbated by the water's additional weight on the slope. By decreasing the effective stress inside the slope material, the rise in pore water pressure lowered the slope's shear strength, or resistance to sliding. The slope was more vulnerable to landslides as a result of this deterioration in its resistance to movement.

Rainfall raised the soil's pre-existing moisture content and enhanced its susceptibility to instability in the future, even if it doesn't immediately produce saturation. This is because a landslip could result from the extra rainwater more readily soaking the soil during later rainstorm episodes. Landslides occured when accumulated rainfall and rainfall intensity hit specific thresholds. Depending on variables including soil type, slope angle, and local climate, these limits may change. Rainfall changed a slope's stability by raising pore water pressure, reducing the slope material's effective strength, and perhaps inducing shallow erosion.

## LANDSLIDE SUSCEPTIBILITY ANALYSIS OF RISHIKESH TO YAMUNOTRI

As elevation changes affect slope stability, weathering, and hydrological processes, elevation plays a critical role in the likelihood of landslides along the Rishikesh-Yamunotri corridor. The elevation's role in landslip occurrences by classifying it into five subclasses with corresponding ranks for overlay analysis have been found. 23.72% of the research region is at the lowest elevation range (259–1,000 meters) in which Rishikesh and Dehra Dun districts are most prominent, which has the highest score of 4, suggesting increased susceptibility. The main cause of this is human activity that disrupts slope stability, such as building, deforestation, and road expansion. The majority of the region (48.31%) lies in the 1,001–2,000 m range in which Uttarkashi district falls, which is ranked 3 and has moderate slopes and more precipitation, which increase the risk of landslides.

Similarly, because rockfalls and debris flows can result from steep gradients and weathering processes at higher elevations which includes district of Tehri Garhwal, heights between 2,001 and 3,000 meters (17.34%), 3,001 and 4,000 meters (6.86%), and 4,001 and 6,100 meters (3.76%) are also ranked 3. Elevation has a moderate impact on the likelihood of landslides, with an influencing factor of 5.72. Higher elevations are more likely to experience natural slope failures, whereas lower elevations are subject to man-made causes like in Dehra Dun and Rishikesh where % of construction is much higher. Reducing the risk of landslides in this susceptible mountainous area requires careful development, vegetation control, and effective slope stabilisation.

Along the Rishikesh-Yamunotri corridor, slope plays a crucial role in landslip susceptibility because steeper slopes make slope failures more likely to occur as a result of surface runoff, soil instability, and gravity. The slope has been divided into five smaller groups and are rated according to how they affect the likelihood of landslides. The majority of the region (48.03%) is classed as being somewhat susceptible to erosion and unstable terrain since it sits within the 51–100° slope range. 32.80% of the land falls into the 26–50° slope category which includes Dehra Dun, Rishikesh districts and Tehri Garhwal districts, which is graded 2 and indicates a lesser risk but is still vulnerable to landslides during periods of intense rainfall or seismic activity. Likewise, 16.35% of the land is in the 0–25° slope range which includes some areas of Rishikesh district, which is graded 2, indicating comparatively stable terrain. However, the highest score of 4 is given to the steepest slopes (101–150° and 151–410°) within Uttarkashi district, which make up 2.51% and 0.31% of the area, respectively. This indicates how vulnerable these places are to rockfalls and debris flows. Slope has a major impact on landslip susceptibility, with an influencing factor of 17.98. More erosion, runoff, and structural instability occur on higher slopes. In this hilly area, reducing the risk of landslides requires the use of slope stabilisation techniques such as terracing, retaining walls, and afforestation.

Landslides pose a significant challenge in mountainous terrains, especially along vital transport corridors. An assessment of landslide susceptibility along the Rishikesh–Yamamori route highlights specific hazard-prone zones influenced by topography, geomorphological features, and human activities. Based on the susceptibility mapping, the region has been categorised into three distinct risk levels: high, moderate, and low. The table indicates that 29.86% of the area falls under high susceptibility, 17.88% under medium susceptibility, and 52.27% under low susceptibility. The high susceptibility zones (red) are concentrated along steep slopes, riverbanks, and road networks, highlighting areas vulnerable to slope failures, particularly during heavy rainfall or seismic activity. The medium susceptibility areas (yellow) act as transitional zones, indicating moderate risk. These areas may be prone to occasional landslides depending on external triggers such as excessive rainfall, deforestation, or infrastructure development. On the other hand, low susceptibility zones (green) dominate the region, covering 52.27% of the landscape, representing relatively stable areas with gentle slopes and dense vegetation that minimize erosion. A critical observation from the map is the strong correlation between landslide-prone zones and road networks. The construction of roads through steep and fragile terrains often disturbs the natural slope stability, increasing the likelihood of landslides. Additionally, the proximity of high susceptibility areas to river channels suggests that hydrological factors like riverbank erosion and water saturation play a significant role in slope failures. Mitigation measures such as slope stabilization, afforestation, and proper drainage management are essential to reduce landslide risks in vulnerable areas. Understanding these susceptibility patterns is crucial for policymakers and infrastructure planners to develop sustainable and disaster-resilient strategies along the Rishikesh-Yamunotri route.

The high susceptibility zones (29.86%), marked in red on the map, align with steep slopes, road networks, and stream proximity, making them critical areas for intervention. Medium susceptibility zones (17.88%) are transition areas where external factors like deforestation and urbanization may increase landslide risks. Low susceptibility zones (52.27%) dominate stable areas with gentle slopes and dense vegetation.

## SPATIAL VARIATIONS OF THE LANDSLIDES SUSCEPTIBILITY

Yamunotri has hydrometeorological conditions that are somewhat comparable and is similarly prone to heavy rainfall. Extreme weather occurrences, such as protracted heavy rains, have occurred in the upper Mandakini and upper Yamuna valleys in recent decades. After a week of intense rains and landslides, Uttarakhand's normal life is still totally interrupted. Highways are impassable and rivers are overflowing due to the unremoved debris from landslides. Due to debris on the Rishikesh-Yamunotri national highway, the Uttarkashi district's Dharasu-band was closed. Following the road at Kalimati, close to Gairsain, being washed away, the Karnaprayag-Gairsain national highway was also closed. These incidents not only play havoc with the life of the residents but it also impacts the wildlife and vegetation within the area which gets disrupted due to landslides.

There are 44 identified landslide zones which obstruct the smooth flow of traffic every year especially during the monsoons (Fig 04). Landslides lead to the fall of boulders and debris which not only block the way but also threaten the life and safety of pilgrims. The areas like Bhatwadi, Chamdhar, Bacheli Khal, Ojari-Dabarkot and Atali Ganga. There are 12 landslide zones from Brahmapuri to Kodiala, 10 from Kodiala to Devprayag, 7 from Devprayag to Srinagar, 5 zones from Srinagar to Rudraprayag which are known to regularly obstruct the highway. Apart from this, 10 other small and big zones are active on the National Highway include Bacheli Khal and Singtali which are located in close proximity to Ganga and Yamuna river near Yamunotri. The extreme northern region of yamunotri which is snow covered mostly for 6 months is least susceptible area as we reach yamunotri through trek of 5 km so no motorable road is available hence no vehicles and as it is closed for 6 months due to snow so no major built up areas are available. The regions with higher susceptibility are mostly located close to streams, road networks and builtup areas.

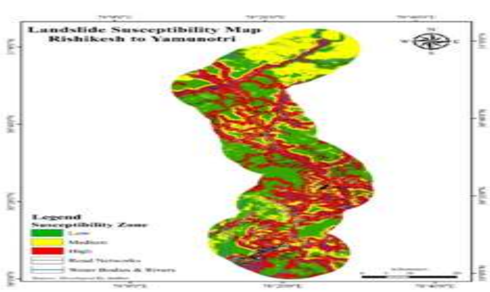


**Figure 3: Landslide susceptibility map of the area**

The snow covered valleys in the north show low to moderate susceptibility whereas the valleys in the northwest and southern region along river Ganga demonstrate high susceptibility. Moderate susceptibility was found in the valleys in the north-east with some areas with high susceptibility where merging valleys can be seen. In the southern region of the area which is covering areas near Rishikesh have comparatively moderate susceptibility as compared to the central and higher regions as we can see the steepness of the slope is increasing with the altitude. This determines that rainfall and roads are the major factors in higher susceptibility of landslides in the area.

Coupled with the climate change the incidents of the rainfall pattern change are being witnessed where some areas are reeling under the stress of rainfall and the other areas comes under the deluge of floods. Depending on the type of the soil and geology of the area coupled with increasing pressure of the rainfall the landslides are increasing over the time. In today's time in comparison to natural factors, man-made factors are more responsible for such natural hazards. As the footfall of the tourists are increasing over the time many incidents of the accidents due to landslides are generally seen which are very common specially in monsoons. As vegetation too is getting destroyed due to landslides the habitat of many wild animals and birds is also being destroyed which leads to their dwindling numbers over the period of time. Landslides are seen all over the route from Rishikesh to Yamunotri but as we move to higher reaches the landslides incidents also increases along with their impact because slope also plays its part. As the mountain height increases so is the slope which leads to landslides. The road construction under the Char Dham project leads to cutting of the mountains which makes their slope vulnerable leading to landslides as can be witnessed with many cliff hangers on the way. The hazard of landslide is very spontaneous and unpredictable, it leads to loss of life and destruction of the infrastructure too. Number of people's footfall decreases as we move from Rishikesh to Yamunotri so much impact can be seen in the southern region.

The trek from Janaki Chatti till Yamunotri region is almost 8 kms so there is no construction of road, hence no movement of traffic so less incidents of landslides are seen. There are V shaped valleys along with high slopes in yamunotri region which makes this region vulnerable to landslides. As the tourism is increasing, this leads to more haphazard construction in its nearby areas surpassing the carrying capacity of the region which leads to more incidents of landslides. This is leading to increasing vulnerability of the area. The Janki Chatti-Yamunotri region's geological composition is characterised by many types of the rocks like limestone, clay slate, shale, dolomite etc within bands which makes this area unsuitable for cutting of the slopes and ever increasing construction of the houses in the area. This region also receives heavy amount of rainfall during the monsoons which are the added factors coupled with other factors like soil, slope, and geology triggering landslides. High rainfall can also lead to Kedarnath like floods within the region and the risk is looming large within the region.

It is essential to employ a multifaceted strategy that includes both structural and non-structural interventions to lower the frequency of landslides in the Yamunotri region. This entails putting in place rockfall barriers, enhancing drainage systems, using retaining walls to stabilise slopes, and raising community knowledge and disaster readiness. Land-use planning, early warning systems, and hazard mapping are also crucial instruments for reducing risk. Temporary stores near the iron bridge over the Yamuna River at Yamunotri should be moved to a more secure location on the left bank of the river because they are vulnerable to landslides from the upslope hillside, flash floods, and toe erosion along the river. Structural measures like rockfall barriers can protect infrastructure and stop landslides by carefully placing them to intercept falling boulders and debris. Slopes can be stabilised by retaining walls, which keep them from collapsing under the weight of dirt and debris. Slope stabilisation is the process of stabilising slopes utilising a variety of methods, such as soil nailing, geotextiles, drainage enhancements, and draining Drainage systems are essential for directing excess water away from landslide-prone locations, lowering the risk of saturation and failure. They should be properly planned and maintained.

zone identification, and preparedness that allows

Zonation (LHZ) maps, should also be prioritised because they aid in identifying high-risk locations for landslides, facilitating improved land-use planning and mitigation initiatives. Land-use planning, where laws and policies can limit construction in high-risk areas and encourage sustainable land-use practices, and early warning systems, which assist in tracking weather patterns, slope movement, Non-structural measures, such as landslide Hazard and other indicators, can provide early warnings of possible landslides, enabling prompt evacuation and preparedness measures and building Awareness and Capacity which requires educating the public about landslip hazards, emergency protocols, and preparedness measures.

Community actions, like catastrophe Community awareness and readiness can be raised through drills, safe for the establishment of clear evacuation protocols. Communities can be empowered to take appropriate action through programs that increase awareness of landslip risks, early warning signs, and prevention strategies. These programs can also encourage community members to keep an eye out for signs of instability on slopes and notify local authorities of any suspicious activity.

## CONCLUSION

This study highlights the effectiveness of the Analytical Hierarchy Process (AHP), a multi-criteria decision-making approach, in identifying areas prone to landslides. The AHP technique proved efficient in assigning appropriate weights to various factors and their respective categories. Analysis revealed that regions with steep slopes, particularly those falling under high and very high slope angle classes, are predominantly more susceptible to landslides. Similarly, zones with high and very high relative relief also exhibited greater vulnerability. The presence of numerous agricultural terraces on southwest-facing slopes contributes to increased instability in these areas. High susceptibility was also noted in locations near drainage channels, likely due to erosional processes such as gully formation and toe cutting caused by river action, which trigger landslides. Additionally, alluvial soils found at lower elevations along drainage paths lack sufficient compaction, making them prone to slope failure. This is reflected as high-risk zones on the landslide susceptibility map. Elevated risk levels were also found near roadways, where unregulated development and slope alterations near reservoirs intensify the likelihood of landslides, particularly during the monsoon season.

Although the available physical factors are responsible for the landslide occurrence, nowadays anthropogenic activities, including the building of roads like the Char Dham road project, along with other developmental infrastructure and projects, lead to major landslides in the region. As this hazard and its impacts are increasing over time, there is a major requirement to devise methods and policies to mitigate the impact of this deadly hazard. Although landslide-induced losses cannot be totally avoided, they can be lessened in frequency and impact intensity with careful planning. Therefore, before beginning any developmental projects, it is essential to do the proper geological and geotechnical investigations and put the recommended mitigation strategies for landslides into action. After a geological and geotechnical study of the area, corrective actions should be carried out in areas where instability has already been introduced into the slope material. This would tremendously assist in lowering the amount of the landslip losses that occur on a regular basis.

## REFERENCES

1. Barnard, P. L., Owen, L.A., Sharma, M.C., and Finkela, R.C. (2001). Natural and human induced landsliding in the Garhwal Himalayas of Northern India. *Geomorphology,* 40(1-2), 21-35. https://doi.org/10.1016/S0169-555X(01)00035-6

2. Guzzetti et al., (1999). Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy*, Geomorphology*, 31, pp. 181-216

3. Myronidis, D., Papageorgiou, C. & Theophanous, S. (2016). Landslide susceptibility mapping based on landslide history and analytic hierarchy process (AHP). *Nat Hazards* 81, 245–263. https://doi.org/10.1007/s11069-015-2075-1

4. Negi, I.S., Kumar, K., Kathait, A. *et al.* (2013). Cost assessment of losses due to recent reactivation of Kaliasaur landslide on National Highway 58 in Garhwal Himalaya. *Nat Hazards* 68, 901–914. https://doi.org/10.1007/s11069-013-0663-5

5. Sarkar et al., (2023). An event-duration based rainfall threshold model for landslide prediction in Uttarkashi region, North-West Himalayas, India, *Int. J. Earth Sci.*, 112, pp. 1923-1939

6. Sharda, Y.P., (2009). Landslide studies in India, glimpse of geoscience research in India, *the Indian report to IUGS*,2004-2008, Indian science academy, Silver Jubilee, (2009), pp. 98-101

7. Sujatha et al., (2012). Landslide susceptibility analysis using probabilistic certainty factor approach: a case study on Tevankarai stream watershed, India, *J. Earth Syst. Sci.*, 121 (5), pp. 1337-1350

8. Taloor et al., (2021b). Tectonic imprints of landscape evolution in the Bhilangana and Mandakini basin, Garhwal Himalaya, *India: a geospatial approach*, Quat. Int., 575–576, pp. 21-36, 10.1016/j.quaint.2020.07.021