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GUEST EDITORIAL

Geo-hazards in the Himalaya and remedial measures: some observations in the light of recent developments at Joshimath

The mighty Himalaya is one of the world's youngest and roughest mountain chains that was formed by collision tectonics during the early Eocene age. The Himalayan environment is fragile and is stressed by several subsurface processes such as crustal shortening, complex geodynamics, convergence, palaeo and neo-tectonics, rock deformation, rising or exhumation as well as surface processes like weathering, erosion, solid (snow) or liquid (rain) precipitation, elevation-dependent warming, etc. The vulnerability has been aggravated further by climate-induced extreme events, such as excessive rainfall leading to flash floods and landslides, and heavy snow precipitation leading to avalanches. It is also affected by anthropogenic activities. The surface and subsurface processes are still going on and are responsible for changes to the landscapes and geomorphology of the mountainous region, which can be detected by remote sensing, satellite data and by ground-based observations. These changes, in turn, control the damage pattern during a catastrophe, and the people living in the Himalayan states are under threat or risks due to geo-hazards caused by landslides, avalanches, earthquakes, flash floods, glacial lake outburst floods (GLOF), landslide-induced lake outburst floods (LLOFs) and flash floods of different magnitudes. The most affected state in the Indian Himalayan region is Uttarakhand, where disastrous events like landslides, earthquakes, avalanches and flash floods have all been recorded. Examples of tragic landslide events are the 1998 Pithoragarh landslide, the 2003 Varunavrat landslide and the 2012 Chamoli landslide. Of the earthquakes, the examples are the 1991 Uttarkashi earthquake (6.8 *M*), the 1999 Chamoli earthquake (6.6 *M*) and the 2017 Rudra Prayag earthquake (5.7 *M*). Of the flash floods are the 2013 Kedarnath flash flood caused by GLOF and the 2021 ice-rock avalanche that led to the Dhauliganga deluge. Around one-third of the world's landslides occur in the Himalaya due to natural processes, environmental degradation and anthropogenic activities. During the last few decades, the frequency and intensity of landslides have increased under the influence of the present climate change scenario, as witnessed in the Uttarakhand and Himachal Pradesh (HP), Himalaya.

It is to be noted that landslides are triggered by rainfall, earthquakes, reservoir drawdown, human intrusion, etc. The landslide susceptibility, vulnerability or risk maps can be prepared based on slopes, gradient, curvature, direction, elevation, lithology, structures, geomorphology, rock strength, forest cover and built-up area. These maps can be used by city planners for the developmental activities and preparation of the land-use map. The impact of catastrophic events influenced by natural phenomena on lives, livestock, properties and structures can be reduced by developing an alert system through establishing a network of multiple sensors of different kinds at multiple stations in the field; real-time transmission of data to a centralized monitoring centre; processing, analysis and integration of data; and developing an integrated warning system (IWS) to alert against such disasters. With the dense network of stations, availability of a fast computing system, advancement of modelling approaches and integration of data using AI/ML, it is possible to achieve the goal of developing an alert system against landslides or avalanches, and precursory studies for earthquakes. The investment in monitoring and development of the warning system would be much more cost-effective than the cost we pay towards the damage of properties and loss of lives in the event of a casualty.

The glaciers, snow fields, river waters, sediments, hot and cold springs, medicinal herbs, woods, minerals and ore bodies have all promoted the growth of many places along the Himalayan arc as hill towns towards the socio-agro-economic development, cultural growth, tourism, pilgrimage centres, and several other societal projects. Joshimath is one such growing town in the Chamoli district of Uttarakhand. In the beginning (2/3 January) of 2023, parts of the Joshimath town in and around the Manohar Bagh, Singdhar and Marwari wards witnessed development and widening of cracks in the houses, roads and ground surfaces, along with gushing out of water in the J. P. Colony. The Uttarakhand State Disaster Management Authority (USDMA) immediately constituted a committee by involving several state and central government agencies and organizations to comprehend the causes through the geoscientific investigation and suggest immediate remedial measures.

Joshimath town, lying between the lat. of 30°33′15″ and 30°33′39.93″ and long. of 79°32′55.43″ and 79°34′59.2″, is a settlement on a palaeo-landslide deposit, which was reported to be subsiding (Misra Committee Report, 1976). The town has developed on a slope between altitudes 1400 m and 2388 m above the sea level (asl), and is at the entrance to the Himalayan destinations like the Badrinath, Hemkund Sahib shrine, Auli tourist place, Trekking area, UNESCO heritage site – picturesque valley of flowers, and one of the cardinal peethas established by Adi Shankara. During the last two decades, the region has witnessed growth related to culture, religion and infrastructure. Joshimath area falls in seismic zone IV/V and is thus seismo-tectonically active, as evidenced by the 1999 Chamoli earthquake (6.8 *M*). The Vaikrita thrust (VT) and Munsiari thrust (MT), which are tectonic/geological fault lines, also pass through the area near Joshimath. This zone divides the high-grade metamorphic rocks of the Higher Himalaya from the low-grade metamorphic rocks of the Lesser Himalaya.

The entire town of Joshimath is located on the dip slope covered with boulders, cobbles and pebbles of crystalline rocks – schists, gneiss and quartzite embedded in a loose matrix of fine micaceous sand and clay. Several rivers, like the Dhauliganga, flow from the east of Joshimath area and meet the Alaknanda flowing down from the north. Together, they flow as the Alaknanda river westward through the northern boundary of the Joshimath. Many nalas like the AT Nala near Parsari in the east, Kamet-Marwari drains in the west up to the NW ridge, a nala near Caukh, and other nalas flow down the slope of Joshimath hill up to the river-bed. Outcrops of *in situ* rocks are observed on the southern bank of the Alaknanda river. Solid *in situ* bed rocks are exposed in the Hathi Parbat on the northern bank of the Alaknanda river. All these, extending further south of Joshimath, beyond Auli, and up to the high mountain ridge, have formed the watershed into this region. Rivers and nalas may have played a role in the toe-cutting and erosion of soils/rocks, particularly along the lower slopes of Joshimath hill. The latest satellite data show that some of the nalas have expanded their channels on the slopes and changed their courses, which have created a more unstable ground for this fragile slope. There is plenty of water on the slopes in the form of surface flow through the nalas/drains, which might have percolated down into the slope, and washed away the fine sediments from the subsurface. All these processes might have weakened the Joshimath slope and hence accelerated the subsidence or sliding, which have led to flashing out of waters and development of cracks on the surface.

The geo-scientific investigations are in progress to discover the causes of subsidence or sliding in Joshimath, which have recently increased. The geophysical experiments consist of (i) Electrical Resistivity Tomography and Magneto-Telluric surveys (short-term) and (ii) establishment of a seismological network (both short- and mid-term) in and around Joshimath town. Real-time transmission of data is the need of the hour. The geophysical, geomorphological and hydrological data can be integrated to delineate subsurface features and/or processes that can be linked with surface observations to explain the recent phenomena. These studies also aim at measuring ground displacement (short-term) and monitoring of slope instability (long-term) that can be coupled to the rainfall threshold or tectonic movement, reservoir drawdown or human intervention to forewarn the landslides through web-based monitoring using sensors like rain gauges, piezometers, inclinometers, extensometers, InSAR, total stations, etc. To alleviate the situation in Joshimath, possible actions can be divided into three:

Immediate action:

(1) Regulation of constructions and developmental activities.
(2) Abandonment of houses which have developed cracks and become unsafe.

Short-/mid-term action:

(3) Assessment of load-bearing capacity of the ground rocks for sustainability.
(4) Restoration of natural flow of water through drains/nalas.
(5) Construction of drainage/sewage system with resistant materials to avoid percolation.

Long-term action:

(6) Micro-zonation of Joshimath town and preparation of land-use map.
(7) Install Web-based Monitoring and Landslide Early Warning System.

The Joshimath episode warns us to build a 'Centralized Council of Himalayan States' in the Indian Himalayan Region (IHR) to assess the geo-hazards that can be caused by natural processes, environmental degradation, or anthropogenic activities in several hill-stations and towns. These can be achieved by disaster management authorities of individual Himalayan states under the ambit of the Centralized Council. The main focus would be to gauge the impact of surface and subsurface stresses caused by (i) climate-induced phenomena; (ii) anthropogenic activities, and (iii) subsurface processes due to the convergence of the Indian plate beneath the Eurasian plate. All this information or knowledge must be disseminated and mutually shared among the Himalayan states for the effective and efficient formulation of strategies towards mitigating disasters or geo-hazards in the IHR. 'Comprehending and learning from the past, working in the present, foreseeing the future, and providing mitigation measures against the calamities' should be our motto for building a disaster-resilient and climate-adaptable future.

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