Unstable slopes and threatened livelihoods of the historical Joshimath town, Uttarakhand Himalaya, India

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This study analyses the causes and consequences of slope instability around the historical Himalayan town of Joshimath, Uttarakhand, India. The town is in the Higher Himalaya near the Main Central Thrust. The lithology constitutes fissile, shattered and sheared gneiss. Consequently, the slopes are prone to land subsidence and mass wasting. In the last few decades rise in population has led to a surge of infrastructure development, thus causing immense pressure on the finite resources and limited accommodation space on precariously balanced vulnerable slopes. Particularly, the unplanned infrastructure development, lack of adequate drainage and excavation of roads through unstable debris slopes are some of the reasons that seem to have accelerated the ongoing slope instability and land subsidence.

Keywords: Geological fragility, higher Himalaya, historical town, land subsidence, slope instability.

THE Himalaya is the youngest mountain chain in the world, and instability is inherent to the Himalayan ecosystem. The geological fragility of the Himalaya was well appreciated by our ancestors, as demonstrated in the traditional architecture, natural resource utilization and religious practices. For example, multi-storied houses in the Yamuna and Bhagirathi valleys are hundreds of years old and have withstood several earthquakes, including the 1991 Uttarkashi and 1999 Chamoli events[1–3]. Similarly, the traditional irrigation system in the hills is based on small canal networks which are diverted from small to moderate streams without obstructing them. This type of irrigation is still in practice[4]. In the last few decades, Uttarakhand Himalaya has witnessed large-scale infrastructural developmental activities, particularly the proliferation of urban towns driven by the increase in urban population up to 20 times between 1901 and 2011 (ref. 5). Such a rapid rate of urbanization, if executed in an unplanned manner, is likely to create an additional burden on existing resources and infrastructure, adversely impacting the mountain ecology and terrain instability[6]. Therefore, it is important to assess the emerging risks and vulnerabilities associated with growth of infrastructure on precariously stabilized slopes, particularly in the Higher Himalaya. Compared to the Lesser Himalaya (LH), the Higher Himalaya is extremely vulnerable due to (i) a high rate of crustal deformation and seismicity[7,8] and the occurrence of extreme weather events[9], (ii) a high concentration of old landslides which reactivate during extreme events and (iii) presence of paraglacial sediments[9–11]. Considering that the Higher Himalaya has limited safe accommodation space for infrastructure growth (including domestic houses), the growing urbanization has compelled people to occupy relatively unstable/unsuitable sites that historically were never occupied. The classic example is the Kedarnath disaster of 2013, where maximum destruction of houses took place, which were constructed close to the river bed/flood plain[9,12]. One major threat to the habitation sites is the obstruction of stream courses and the lack of an efficient domestic wastewater drainage system. Thus, during monsoon, urban towns in Uttarakhand are frequently affected due to debris flow; for example, Uttarkashi (2006), Bhatwari (2010), Gopeshwar (1993), Agastyamuni (2009) and Kedarnath (2013)[9,12]. Additionally, the unscientific road alignment, construction of barrages and underground tunnels in the proximity of urban towns without due consideration of the geological fragility are amplifying the terrain instability[13,14]. Urban growth with development is inevitable as urban areas are the most proximal locations for generating local employment, and have better health and education facilities. Hence the legitimate scientific endeavour is to devise a viable plan for sustainable urban development in ecologically fragile areas that minimize environmental degradation and ensures ecological security.

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The present study examines the strategically located (near the border) Joshimath town in the upper Alaknanda (Ganga) valley. Recently, the town has been experiencing persistent problems of slope creeping, depletion of natural water springs, subsidence of roads, and consequent damage to the houses[15]. This study aims to understand the causes of ongoing subsidence and provide plausible remedial steps to prevent the slopes from further destabilization and save the infrastructure around this town. The study also has implications for other towns in the Himalaya, which are in near-identical geological and geomorphological settings and witnessing similar pressure of population growth and urbanization. The study is based on surface water hydrology and geomorphological observations of the area between 2018 and 2021, supplemented with remote sensing data from Google Earth imagery. Details of the slope, cross-sectional profiles and drainage are extracted from the Digital Elevation Model (ALOS PALSAR 12.5 m) (www.asf.alaska.edu) using ArcGIS 10.8. The drainage network is verified using the topographical sheet (1 : 50,000 published by the Survey of India, 1986).

Geological setting

Joshimath town (30°30′–30°35′N and 79°30′–79°40′E) is in the Higher Himalayan Crystalline (HHC), which is differentiated from LH by a regional north-dipping Main Central Thrust (MCT) that traverses the Alaknanda River near Helong village (~10 km southwest of Joshimath town)[16]. The MCT zone is defined by a 5–20 km wide shear zone[17] (Figure 1 *a*). Recent studies also indicate crustal shortening and high seismic activity in this zone[18,19]. Geomorphologically, the terrain between Joshimath town and Tapovan encompasses glacial and glacio-fluvial landforms. The slopes are precipitous and covered with alluvial fans and cones of active and stabilized landslide debris[20]. Glaciological studies in the Alaknanda and Dhauli Ganga river valleys have shown that glaciers descended around 3000 m (refs 21, 22). Considering the morphology of the terrain, it can be suggested that during the late Quaternary, glacial and periglacial activities were widespread in the area between 3000 and 4500 m (the upper slopes).

Slopes

The northern part of the study area is dominated by steep slopes (>50°) compared to the southern part with moderate slopes (<30°). The villages from Helong to Tapovan are mostly located on hill slopes ranging from 40° to 50° (Figure 1 *b*). Concave slopes dominate the middle (~2500 m) and lower (~1800 m) valleys, particularly between the two rock spurs located west and east of Joshimath town (Figure 1 *a–d*). The dominance of concave slopes suggests significant removal of colluvial material from the upper part of the slopes, which in the present case could be a combination of solifluction (in the middle slope) and gravity slide (in the lower slope)[23]. Besides the old landslide, frost shattering along the east–west trending ridge (>3500 m) is the major process responsible for generating debris at higher elevations (>3000 m).

Drainage

A number of perennial and seasonal streams drain through the mountain slopes on both flanks of the Alaknanda and Dhauli Ganga rivers. Around Joshimath town, the streams emanate from the NW–SE trending ridge and meet the Alaknanda/Dhauli Ganga at right angles. These streams (between Joshimath and Tapovan) emerge from the Himalayan pastures and probably relict cirques located ~4000 m on the NE-facing slope and drain through the unconsolidated debris-laden slopes (Figure 1 *c*). The streams are the lifeline of the villages, which are recharged by the precipitation and snow melt at higher elevation.

The stream hierarchy was analysed based on the method suggested by Strahler[24]. The overall drainage pattern of the study area is dendritic. The hillslopes along Joshimath town to Tapovan are dominated by first-order streams (~58%; Figure 1 *c*). Field observations indicate that these streams are eroding the unconsolidated debris, thus transporting a large number of sediments along their course.

Climate

Due to the abrupt rise in relief, the slopes around Joshimath town act as an orographic barrier to the northward penetration of the Indian summer monsoon (ISM). The average annual precipitation is ~1500 mm, of which ~80% is contributed by ISM (Figure 1 *e*). During ISM, cloud bursts on the precipitous slopes demarcated by the MCT zone are common[25]. Studies from the Himalayan region observed that rainfall shows a linear relationship with erosion[26], implying that the MCT zone, including the Joshimath town, receives high and focused rainfall (Figure 1 *e*) witnessing high erosion rate[27,28].

Vegetation is governed by altitude and dominated by the oak mixed forest between 2000 and 3000 m. Above 3500 m lies the Himalayan pasture, followed by perpetual snow above 5000 m. The cultivated and build-up area are located below 2500 m.

Landslides

Focused high rainfall during monsoon accentuates hillslope erosion by increasing pore water pressure causing slope destabilization[29]. Such failures are further enhanced due to the undercutting of slopes (toe erosion) by the Dhauli Ganga, which carries a large volume of paraglacial sediments, particularly during extreme rainfall. The Dhauli Ganga river

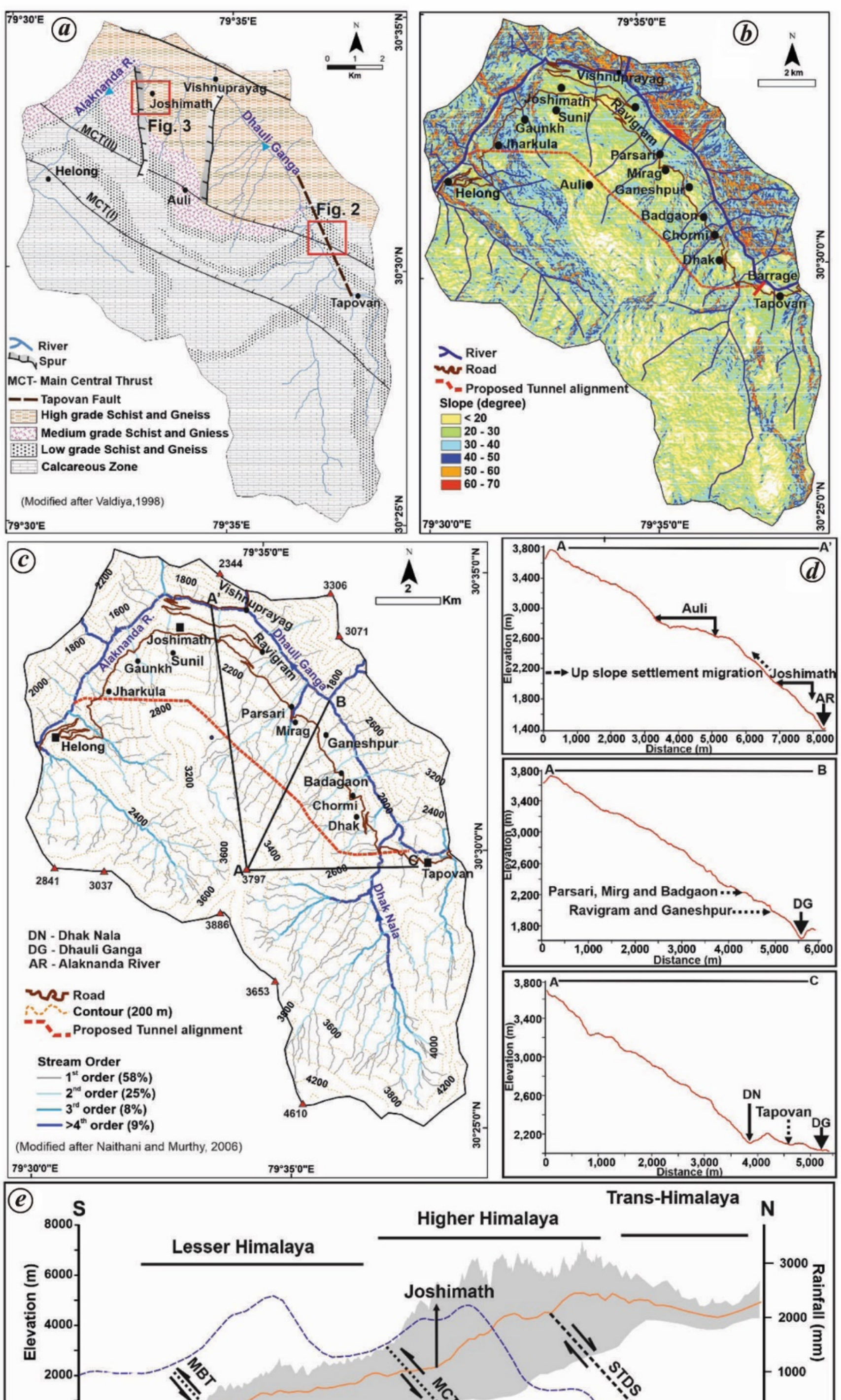

Figure 1. ***a***, Simplified geological map between Helong and Tapovan. MCT, Main Central Thrust. Majority of the houses are located between the rocky spurs. The locations of field photographs in Figures 2 and 3 are also marked. ***b***, Slope and drainage distribution map around Joshimath town. Note the relatively gentler slopes towards the southeast of Joshimath, southwest of Tapovan, and steeper slopes towards the north and northeastern parts of the study area. ***c***, Contours showing elevations, and drainage maps marked with first, second and third order streams. Location of the road (starting from 1600 m and varying through close contour intervals till Joshimath town) is also shown. The small stream traversing along the road stretch can be seen, which becomes a threat to the existing infrastructure during monsoon and extreme precipitation events. The cross-sectional profiles shown in (***d***) are drawn along *AA*, *AB* and *AC* transects. ***d***, Cross-sectional profiles of Joshimath town and the surrounding villages between 2200 and 1500 m. Compared to Joshimath town and the villages, Auli village is present on a relatively gentler slope of <20°. ***e***, Cross-section profile of the relief between Haridwar and north of Niti pass (South Tibetan Detachment System, STDS). Note that the discontinuities in relief and rainfall variability are dictated by the terrain boundary thrusts. High and focused rainfall is centred around the Main Boundary Thrust (MBT) and the southern slope of MCT. The north of STDS marks the low-precipitation zone.

Figure 2. ***a***, Panoramic view of Dhauli Ganga (facing east) taken in 2010. Nanda Devi forms the eastern boundary of the Rishi Ganga catchment. The location of Raunti Gad is shown which was responsible for triggering the February 2021 Rishi Ganga flood. Note the old landslide deposit along the right flank opposite the Tapovan barrage site (red dotted ellipsoid). ***b–d***, Upstream from the barrage site at Tapovan, the reactivated landslides (white dotted line) after February 2021 flash flood are shown.

has high stream power due to the combination of discharge and over-steepened river gradient[30]. It was observed during the recent February 2021 Rishi Ganga disaster that multiple debris-laden stabilized slopes (old landslide deposits) were reactivated between Reni and Marwari (Figure 2 *b–d*).

Anthropogenic interventions

Joshimath town is located on an old landslide deposit which was first reported in 1939 (Figure 3)[16]. The study suggests that the landslide was triggered on the mountain crest at ~4000 m east of Kuari Pass, and the slopes between Joshimath town and Tapovan were burdened with massive boulders[16]. Subsequently, the slopes were inhabited during the historical period, which grew with time, particularly along two prominent depressions in the central segment. These are from Sunil to Marwari, and from the east of Chawani bazaar extending to the Alaknanda River. These depressions are occupied by the streams which follow the north–south trending fractures (Figure 3). Joshimath town, also known as ‘Jyotrimath’, was the capital of the Katyuri dynasty around the 7th-century AD, suggesting human occupation on these delicate slopes since historical times. The town is highly revered as it was established as one of the four ‘Mathas’ (Hindu monastic institution) by Adi Shankaracharya (first Vedic teacher) and is the winter seat (place of deity/worship during snowbound winter months) of Lord Badrinath. Thus, the town steadily grew with time from merely a small village with a temple and probably a dharmshala (rest house) around 1890 (Figure 4 *a*). At present, Joshimath town has been transformed into a concrete jungle with virtually no space left on the slopes (Figure 4 *b*). Besides the proliferation of settlements, a tunnel is being excavated through the same slope under Tapovan hydro-power project (Figure 1 *b* and *c*). On 24 December 2009, the tunnel boring machine (TBM) employed for excavating the head race tunnel punctured the water-bearing strata at about 3 km from Helong village[31]. The TBM was stuck due to a major rockfall followed by sudden ingression of water (600–700 litres/sec)

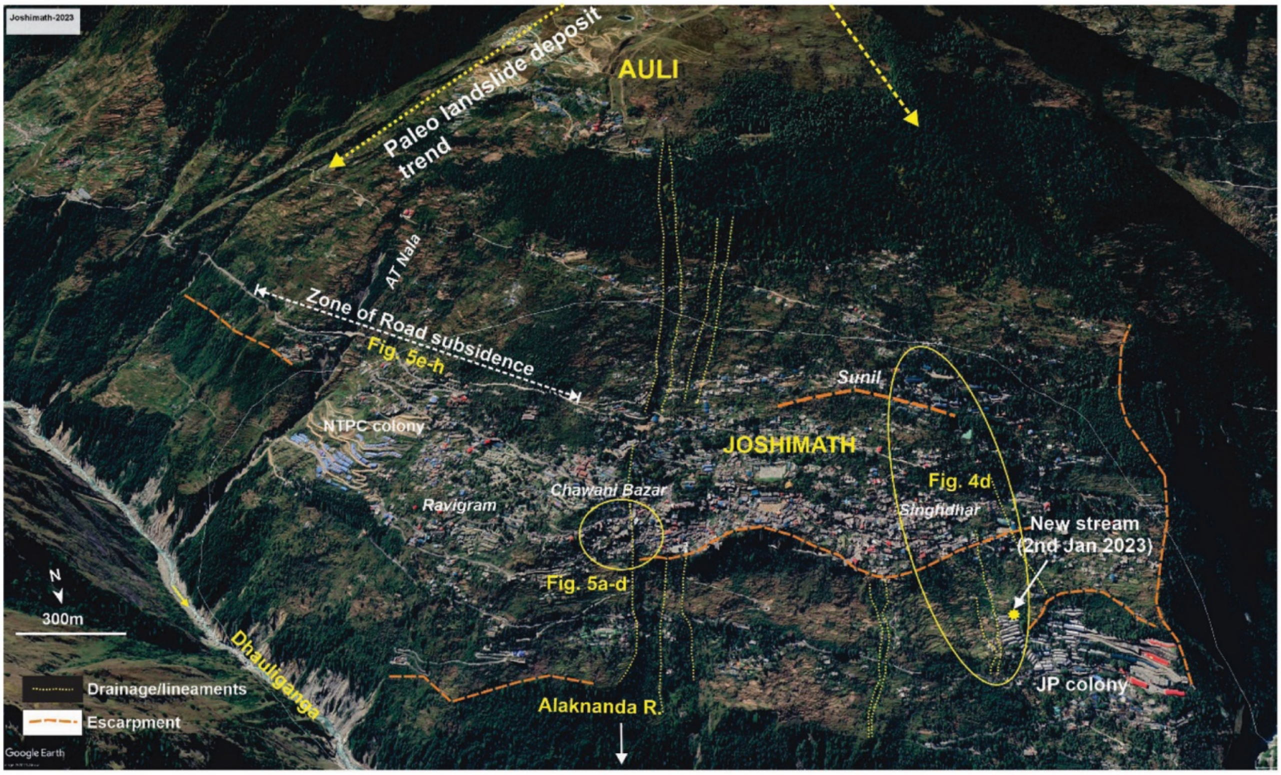

Figure 3. Google Earth imagery of Joshimath township marked with three breaks in slopes (orange dashed lines) that were verified in the field. Majority of the settlements are located behind these escarpments on relatively gentle slopes. The escarpments are dominantly developed on the landslide/avalanche debris probably representing pulsating gravity slides from the area above Auli (yellow dashed arrow), or can be the expression of bedrock topography. The streams which drain northward/northeastward (yellow dotted lines) seem to occupy major fractures/lineaments developed in the bedrock. Also note that the new stream that emerged on the surface on 2 January 2023 is located above the JP Colony (yellow star). The accelerated subsidence associated with creeping that occurred after 2 January 2023 is between JP Colony and Sunil locality in which the Singhdhar area is located on the middle slopes. The areas that witnessed maximum damage are marked by a yellow ellipsoid and a yellow circle. Houses constructed close to perennial and rainfed streams were also damaged.

through the jointed, fractured and probably faulted blocky quartzite rocks (Tapovan Formation)[32]. With continuous water flow, the fractures progressively widened and created 8–9 m long cavity (trending NE) having a width >12 m. A study suggested that following the incident, no change was observed in the spring/stream flows and surface subsidence[32]. The water discharge was ~700–800 litres/sec (60–70 million litres/day)[32]. Sudden and large-scale dewatering may have led to the initiation of ground subsidence. This is in agreement with local observations by the residents that many water springs either dried or significantly reduced their discharge with a concurrent increase in the incidence of land subsidence causing damage to the roads and houses.

During the late 1960s, the town began to show evidence of slope creeps associated with subsidence at many locations. As the threat increased, in 1976, the Government of Uttar Pradesh constituted the Mishra committee to examine the causes of land subsidence[33,34]. After a detailed study, the Committee made the following important recommendations:

(i) ‘Further construction in the area should be made only after examining the stability of the site and restrictions should be placed on the excavation on slopes.

(ii) No boulders should be removed by digging or blasting, and no tree should be cut in the landslide zone. Extensive plantation work should be launched in the area, particularly between Marwari and Joshimath towns, and the cracks, which have developed on the slopes, should be sealed.

(iii) Most importantly, the foothill hanging boulders should be provided with appropriate support, and anti-scour or river-training measures should be taken. It was also emphasized that there should be a blanket ban on collecting construction material within a radius of 5 km of Joshimath town.’

Recent field observations

The presence of potholes and fissures in Joshimath town indicates unstable slope conditions due to the selective removal of fine sediments, which could be one of the reasons for observed subsidence and the development of cracks/fissures in the houses (Figure 5). According to the locals, subsidence and slope destabilization which was going on for the last few decades was exacerbated post-November 2021 (after the Rishi Ganga disaster). Prior to February

Figure 4. Joshimath town in (***a***) 1890 (photograph courtesy: Dr Kurt Boeck, Himalayan Album, 1894) and (***b***) May 2022 (photograph courtesy: Atul Sati). Note the change in the type of settlement from rural to urban, as thatched houses have been converted into dense and closely packed multi-storied concrete buildings. (***c***) The subsiding area east of Sighdhar. Note the Alnus forest at the bank of Dhauli Ganga (DG) – an ecological indicator of old landslide deposits. (***d***) Close-up of the settlements located in the subsiding Singhdhar area. (Inset) Fissured ground located immediately below the road. The white arrows show the subsidence and direction of creep which is towards the north (picture taken after January 2023).

2021 (before Rishi Ganga disaster), there are no time-series data on the rate of subsidence and magnitude of damage to the houses, hence we can neither support nor discount the observations made by the locals. However, during the disaster, sediment-laden peak discharge in the Rishi Ganga was ~1.1×10^5 m^3/s, which is a magnitude higher than the normal peak discharge with a flow velocity of 30 ± 3 m/s (ref. 35). Such flows are likely to dislodge boulders in the river banks causing accelerated bank erosion and hence destabilization of the debris-covered slopes (Figure 2 *c*). We observed that the hyper-concentrated flood discharge destabilized the old landslide deposits and created fresh landslide scars at multiple locations by toe erosion along the Dhauli Ganga till Marwari (located below Joshimath town) (Figure 2 *b*–*d*). Such landslide scars may progressively move upslope[36,37]. Additionally, if the toe erosion by the Dhauli Ganga and other tributaries continues, slopes may remain in a state of disequilibrium. Further, it can be speculated that an increase in anthropogenic interventions (e.g. road cutting/widening, tunnel excavation, inadequate drainage) could accelerate slope instability. However, considering the complexity of anthropogenic interventions coupled with natural causes, the factors responsible for the present crisis need more detailed scientific examination.

Summary and remedial measures

Joshimath town lies in earthquake hazard zone-V, implying that the terrain is seismically active and geologically fragile, where buildings require earthquake-resistant design according to the Bureau of Indian Standards guidelines[38]. Geomorphological and historical evidence also indicate unstable slopes (between 2200 and 1500 m), which make the entire ecosystem extremely vulnerable to slight natural or anthropogenic disturbance (Figure 1 *d*). The town is facing unprecedented anthropogenic pressure as well[31]. According to the 2011 census, the local population was about 20,000 (ref. 39). With the growing population, settlements are expanding

Figure 5. ***a–c***, Damage caused to houses in the Chawani Bazar area (Badrinath road) due to continuous soil creeping. ***d***, Potholes on the alluvium have become a regular feature, and are one of the reasons for eroding and transporting the fine matrix of the landslide deposits, thus creating caverns. ***e–h***, Few segments of Joshimath–Auli road which are undergoing subsidence (photograph courtesy: Atul Sati).

on the upper and lower unstable slopes (Figure 1 *d*), further accelerating the pace of instability (Figure 4). Additionally, more than 3 lakh pilgrims transit the town during summer on their way to Badrinath, requiring additional infrastructure. The nearby Auli skiing resort is also growing as a popular winter sports location in Uttarakhand. To sustain the stability of the terrain, there is a need to maintain a balance between the economy and ecology.

As pointed out in the Mishra Committee report[34], the major threats posed to the fragile slopes of Joshimath town are the unregulated disposal of wastewater, removal of landslide boulders for construction purposes and lack of anti-scour or river-training measures. These still hold true for the safety, security and longevity of Joshimath town and surrounding villages. The first observation that Joshimath town is situated on an old landslide deposit suggests the fragility of the slopes[16]. The town proliferated, especially after the 1960s, mainly in response to strategic concerns. However, in the process, the stability of the surface on which Joshimath grew was largely ignored, threatening the very existence of the town.

Thus, based on our preliminary analysis, the following broad recommendations emerge to prevent/decelerate the pace of terrain instability, land subsidence and infrastructure damage.

(i) The existing studies on the geological setting and ecological diversity around Joshimath town are fragmentary in nature and require an integrated approach emphasising terrain stability and natural resource management. Specifically, a detailed multi-temporal mapping (multi-decadal) of geological, geophysical, ecological and anthropogenic interventions at the cadastral level should be carried out. The data thus generated can be assessed for the nature, magnitude and trend of landform and natural resource changes. The vulnerability of the slopes should be categorized based on categories of threat perception (severe, moderate and safe) for human intervention and habitation, as also for their rejuvenation planning.

(ii) As an immediate measure, there should not be any excavation activities, particularly of the precariously balanced crystalline boulders. The landslide deposits contain moderately fine grains (pebbly sand), which act as the filling material between the boulders. It has been observed that there are cavities (mimicking potholes) on the surface (Figure 5 *d*), which we speculate are caused due to the selective removal of fine sediments by unregulated domestic wastewater drainage. In recent times, these cavities are posing a serious threat to the stability of the built-up structures in Joshimath town.

(iii) Recent media reports indicate that the much-needed road widening work from Helong to Marwari via Joshimath town is going to be initiated soon, as the existing road is narrow and incapable of handling heavy traffic during a pilgrimage. However, for the ascent from Helong village, the road between Sailang and Paini passes through the old landslide deposits which are subsiding at multiple places and needs to be adequately addressed. Another similar location is between Chawani Bazar and Marwari. Except for a small stretch before Tushar Dhara and Chungi Dhar, where the road is being excavated through hard crystalline rocks, the majority of the ~20 km road stretch (between Helong and Marwari), passes through the old landslide deposits. We have already witnessed that the Chardham road widening work has created many new landslide zones, where a few have become chronic[14]. Therefore, engineering methods must provide stability to areas prone to subsidence by providing state-of-the-art slope treatment, such as rock bolting to pin the boulders along with tensioned rock bolts anchored to the substratum (*in situ*) rocks and wire netting on highly fractured and sheared lithology. Most importantly, since the road passes through a high-rainfall zone with many perennial streams, diversion drainage on the colluvium slopes must be mandatory to prevent/arrest the slope from creeping.

(iv) The roads in the periglacial zones, such as between Joshimath town and Tapovan, is undergoing subsidence at multiple places (Figure 5 *e–h*). This is because the slopes (20°–40°) are drained by the snow/groundwater-fed streams (Figure 1 *d* and *e*) and are subjected to winter snowing and summer thawing. This leads to solifluction (gradual downslope movement of the surface soil). Therefore, such areas require special engineering skills while excavating the slopes for road construction, which are currently lacking. Consequently, our response to maintaining the roads in such areas is reactive (repair following subsidence) and not proactive (providing long-term slope stability). One of the ways to circumvent this chronic problem of continuous creeping and subsidence is by making elevated corridors with pillars deeply anchored on hard rock substratum, as done for the ropeway in Joshimath town.

(v) The harnessing of hydropower potential is required in order to meet the current energy demand in India till more sustainable energy options become viable. However, in the process, geological and ecological constraints need to be considered for economic and ecological sustainability. For example, excavation of tunnels for hydropower projects in the rugged Himalayan terrain having variable lithology, along with unexpected encounters with the water bodies pose a challenge and require further precautions. Further, the Tapovan–Vishnuprayag project was affected by a short-lived flash flood triggered by a small Raunti Gad stream[10] in 2021 (Figure 2 *a*), which besides inflicting collateral damage to the valley flanks, reactivated stabilized landslides in this region (Figure 2 *b–d*). Therefore, taking lessons from Tapovan–Vishnuprayag project, we must recalibrate our strategy towards harnessing the hydropower potential in the Higher Himalayan terrain.

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