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Increasing Risk of Silent Disaster in Uttarakhand Himalaya: An Example from Higher Himalaya

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Abstract
Land subsidence is an abrupt and silent disaster worldwide caused by various factors such as tectonics, nature of rocks and climatic variability etc. It is directly triggered by anthropogenic activities. The Uttarakhand Himalayan province in India has witnessed several earthquakes, landslides, avalanches, droughts, and flash floods/floods in the recent past. Among these incidences landslides frequently occurs in the Himalayan region, particularly during the monsoon season. Seismically, this region falls in seismic zones V and IV due to which area witnesses frequent earthquakes. An attempt was made for preparation of an inventory of land subsidence across the state of Uttarakhand to determine the key factors that are responsible for land subsidence. Previous studies and field evidences suggests that land subsidence events mainly occur due to several factors such as carbonate rocks, topography, tectonics, seismicity, climate, flash floods/floods and reservoir drawdown effect in this region. Furthermore, anthropogenic activities such as mining, underground water, unscientifically civil constructions, inadequate drainage, heavy load on ground/slope, and modification of slope for infrastructure developments aggravates the problem. This study also highlights the problem of ongoing chronic land subsidence in Joshimath town which is situated over an old landslide mass as well as its proximity to Vaikrita Thrust.

Keywords: Central Himalaya, Joshimath, Key Contributing Factors, Land Subsidence, Inventory, Risk Reduction

1. INTRODUCTION

Land subsidence is a commonly occurring phenomenon in the mountains as also coastal areas across the world and is caused by consolidation related to sediment loading, tectonics, and the presence of carbonate rocks which are directly influenced by human activities and climatic variability (Galloway et al., 2016). This causes considerable damage to property and infrastructure as also loss of cultivated fields and landforms along with natural resources. There exists no simple tool for assessing the risk of land subsidence in the field, which limits the expertise and applicability of the design (Park et al., 2017).

Land subsidence induced by groundwater extraction is a man-induced geological hazard affecting many cities in the world, particularly in Northern Greece, Turkiye, Northern Italy, China, Mexico, and Japan (Stiros, 2001; Carminati and Martinelli, 2002; Hu et al., 2002; Pacheco et al., 2006; Zhou

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and Esaki, 2003; Martinez et al., 2015; Arık, 2018; Yıldız and Sarıfakıoğlu, 2022). A major land subsidence incidence was reported from California in 1969 wherein about 8 m settlement was noticed due to the uncontrolled exploitation of groundwater for agricultural use (Poland, 1981) and till 1994 this land subsidence increased about 10 m owing to 50 m water level dropping (Larson et al., 2001).

According to USGS, land subsidence is a gradual settling or sudden sinking of the earth's surface due to the removal or displacement of subsurface earth materials. It is one of the most diverse forms of ground failure, ranging from small or local collapses to broad regional lowering of the earth's surface. The principal causes include i) aquifer-system compaction associated with groundwater withdrawal, (ii) drainage of organic soils, iii) underground mining and, (iv) natural compaction or collapse, such as with sinkholes or thawing permafrost.

According to Colorado Geological Survey, the land subsidence process is characterized by a natural phenomenon as the downward displacement of surface material caused by the removal of underground fluids, natural consolidation, or dissolution of underground minerals, or by the man-made phenomenon as underground mining. More infrequently, subsidence may occur abruptly as dangerous ground openings that could swallow any part of a structure that happens to lie at that location, or leave a dangerous steep-sided hole.

2. LAND SUBSIDENCE-PRONE UTTARAKHAND PROVINCE

The Uttarakhand province in the Indian subcontinent is situated in the Central Himalaya (Figure 1) and is routinely devastated by natural hazards and the increasing frequency of extreme precipitation attributed to change in climate enhanced their devastating potential (Mukherjee et al., 2018; Kumari et al., 2019). During the financial years 2018-2023, fatalities incurred mainly due to landslides and flash floods instead of other disasters in this region are confirmed by Table 1.

The province has witnessed major disastrous incidences that include Asiganga flash flood of 2012, Kedarnath flash flood of 2013, Mangti flash flood of 2017, Mori flash flood of 2019, and Rishiganga flash flood of 2021, and these have caused enormous loss of lives, property, infrastructure and geo-environment (Gupta et al., 2013; Dobhal et al., 2013; Bhambri et al., 2016; Khanduri et al., 2018a; Khanduri and Sajwan, 2019; Sain et al., 2021). In the recent two decades, increased abrupt or concentrated rainfall patterns and associated flash flood events have caused a number of landslides and land subsidence in the region (Khanduri, 2020).

Similarly, in July 2003 heavy rains enhanced pore water pressure that decreased the shear strength of debris material over which Naitwar Market rests. This aggravated the bulging of ground in Naitwar Market and a number of civil structures were badly damaged due to this (Uniyal, 2006).

On Rishikesh-Gangotri National Highway, downhill side to Agrakhal many houses exhibited signs of distress due to land subsidence. The structural data showed the presence of an unfavorable discontinuity plane as also highly fractured and weathered phyllitic rocks, which allowed easy seepage of underground water (Ghosh et al., 2009).

The Bhatwari town witnessed frequent land subsidence initially after 2006 whereas, till 2009 the presence of frequent slope instability and massive damages were noticed (Sati et al., 2020). Similarly, Wariya village faced serious slope instability when a stretch of the National Highway (NH 94) sinking during the monsoon of 2012 (Khanduri and Rautela, 2012).

Table 1. Specific nature of disaster-wise fatalities incurred in Uttarakhand during the financial years 2018-2023 (Source: State Emergency Operations Center, Government of Uttarakhand).

Sl. No.	Nature of disaster	2018-2019	2019-2020	2020-2021	2021-2022	2022-2023
1.	Flood	7	4	6	1	5
2.	Flash Flood	47	27	223	19	23
3.	Landslide	38	59	47	88	45
4.	Lighting	2	9	5	2	4
5.	Cyclone	0	0	0	0	0
6.	Earthquake	0	0	0	0	0
7.	Cloudburst	0	3	0	0	8
8.	Hailstorm	5	3	3	2	4
9.	Thunderstorm	4	1	5	0	2
10.	Avalanche	0	0	1	27	29
11.	Forest Fire	1	2	4	1	2
Total		**104**	**108**	**294**	**140**	**122**

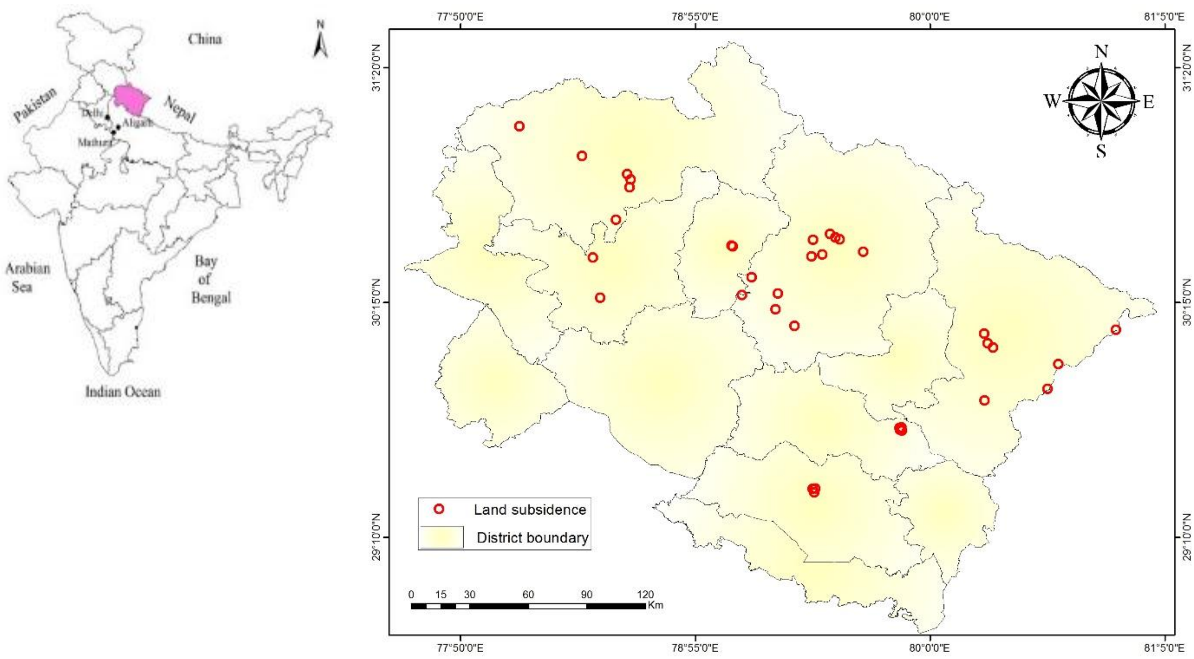

Figure 1. Distribution map of land subsidence in Uttarakhand Himalaya

A stretch of the Lower Mall Road between the Grand Hotel and HDFC Bank in Nainital town gradually subsided and fell into the Naini lake on August 18, 2018 and again on August 25, 2018. The combined effect of seepage from the upslope, periodic recharge and drawdown of lake water, and the cumulative dead loads on the hill slope exerted by existing buildings in the surrounding area and vehicular traffic were held responsible for this (Khanduri, 2019).

Located on the Northern side of the reservoir of Tehri Dam, Okhala village is affected by land subsidence because of Reservoir Drawdown Effect (RDE) wherein subsidence is noticed in the agriculture fields and the houses have developing cracks. Similarly, another village Payal near the Koteshwar dam reservoir area has suffered from land subsidence due to the release of reservoir water (Sati et al., 2020).

During the monsoon period of 2020, land subsidence occurred due to heavy rains that caused damages in Josha and Malupati villages in Munsiyari tehsil as also Gwalgoan and Khela villages in Dharchula tehsil of Pithoragarh district (Khanduri, 2022).

2.1. Objective

Geology, tectonic, geomorphology, seismicity, dissected topography and hydro-meteorological characteristics make the Uttarakhand Himalayan region more prone to natural hazards like slope instability and land subsidence. Furthermore, human interference enhances this problem in the region. It was therefore felt necessary to study the geo-environmental conditions in the state of Uttarakhand with particular reference to land subsidence. The main objectives of this study are as specified below:

- To identify potential land subsidence areas on the basis of previous records and interaction with local people as also ground observations,
- To assess the effects of land subsidence upon the geo-environment together with local inhabitants,
- To make the inhabitants of the region aware of the threat of land subsidence and suggest possible remedial measures for community risk reduction,
- To prepare a working research methodology on the present state of affairs in the state of Uttarakhand including assessing the scenario in areas that could be witnessed in near future.
- To study the land subsidence situation in Joshimath town, with the ultimate aim of land subsidence hazard assessment, based on the ground observations undertaken to understand the dynamics of land subsidence and interactions carried out with local inhabitants to understand the history and present state of affairs so as to suggest appropriate mitigation measures

2.2. Procedure, Data, and Tools

For the purpose of the present study, the general information and data are mainly obtained from ground observations, as also available records from 1880 to 2022. All thematic maps have been prepared using Survey of India (SoI) toposheets on 1:50000 scale with the help of ArcMap 10.8 software along with Google Earth Pro image. Fieldwork undertook in the affected area in Joshimath to observe and demarcate land subsidence in different pockets in the month of August 2022. An attempt was also made to find out the possible causes of land subsidence and suggest risk reduction measures.

Table 2. Incidences of land subsidence incurred in Uttarakhand Himalaya, India

Sl. No.	Year of occurrence	Location	Contributing factors	Impacts
1.	1880	Sher-Ka-Danda, Nainital town, Nainital district	Excessive rains, poor quality rocks, and steep slopes (Rautela and Khanduri, 2011)	Hotel and temple were destroyed whereas cracks in houses
2.	1898	GIC ground at Harinagar, Nainital town, Nainital district	Baliyanala Fault, thick overburden, underground seepage and steep slopes (Kumar et al., 2017)	Cracks in houses of the Harinagar area
3.	1976	Lata-Malla, Uttarkashi district	MCT, the flood of 1976, and toe erosion by Bhagirathi River (Sati et al., 2020)	A portion of Gangotri Road (NH- 108)
4.	1976,	Joshimath town, Chamoli district	Vaikrita Thrust, thick overburden, erosion by local streams and toe erosion by Alaknanda River (USDMA, 2022)	Cracks in houses of Sema, Sunil, Marwari, Gandhi Nagar and Devgram localities
5.	1980	Narayanbagar, Chamoli district	Narayanbagar Thrust, seepage and toe erosion by Pinder river (Valdiya, 1980)	Road subsided
6.	1987	Garbyang, Pithoragarh district	Proglacial lake sediments, seismicity and toe erosion by Kali river (Rautela, 2005)	The devastation of prosperous inhabitation
7.	1991	Bagi, Uttarkashi district	Uttarkashi earthquake 1991, 1998 monsoon rains (Rautela, 2005)	Houses destroyed and cultivation lands damaged
8.	1995	Talla Dhumar, Pithoragarh district	Old rock fall debris, tectonic discontinuity, and toe erosion by the Goriganga river (Rautela, 2005)	Agriculture fields rendered unfit for cultivation
9.	2000	Ganai, Chamoli district	Cloudburst, loose materials (Khanduri, 2020)	Cultivated lands, houses
10.	2000	Okhala, Tehri district	Reservoir Drawdown Effect (Sati et al., 2020)	Fissures in agricultural fields and cracks in houses
11.	2003	Naitwar market, Uttarkashi district	Naitwar Thrust, loose materials and toe erosion by the Tons river (Uniyal, 2006)	Shops, houses, road
12.	2007	Chai, Chamoli district	Loose materials, heavy rains (Disaster Mitigation and Management Centre (DMMC), 2007)	Houses, electric poles, pedestrian routes
13.	2008	Bhatwari market, Uttarkashi district	Heavy rainfall, toe erosion by the Bhagirathi river (Sati et al., 2020)	NH-109 and shops, public property
14.	2010	Payal, Tehri district	Effects of the release of reservoir water of Koteshwar dam (Sati et al., 2020)	Cracks in houses, water canal
15.	2011	Thala band, Chamoli district	The thick pile of loose materials, heavy rainfall (Khanduri, 2018)	Pokhri-Mohankhal road
16.	2011	Barginda tok, Chamoli district	Heavy rains, loose soils, and toe erosion by the kalpganga river (Khanduri et. al., 2018)	Temple destroyed, agriculture lands and cracks in houses
17.	2012	Sansari, Rudraprayag district	Cloudburst, Nala erosion, loose materials (DMMC, 2012a)	Agriculture fields
18.	2012	Barsu, Uttarkashi district	Loose overburden and toe erosion by the stream (Source: DMMC)	Cracks in houses
19.	2012	Wariya, Uttarkashi district	Vaikrita Thrust, loose soils, seepage and toe erosion by the Yamuna River (Khanduri and Rautela, 2012)	Yamunotri road (NH 134)

20.	2013	Kamera, Chamoli district	Heavy rains, seepage and thick overburden material (Khanduri et al., 2018)	Badrinath road (NH 7)
21.	2013	Near Bargaon, Chamoli district	Rains, seepage and a thick pile of loose soils (Khanduri, 2018)	Tapovan-Malari road
22.	2013	Bansoli, Chamoli district	Flash flood of 2013 in Bansoli Gad, loose materials/old slide mass (Khanduri, 2020)	Agricultural fields
23.	2013	Jalgwar, Chamoli district	Alaknanda flash flood of 2013, loose materials (Khanduri, 2018)	Cracks in houses, NH 7 and Gurudwara
24.	2013	Semi, Rudraprayag district	Flash flood of 2013 in the Mandakini River, loose materials (Khanduri et al., 2018)	Some houses were destroyed, cracks in houses, roads and cultivated lands subsided
25.	2013	Jal Talla, Rudraprayag district	Heavy rainfall, flood in the Kaliganga river, and loose materials (Khanduri et al., 2018)	A stretch of road and a number of cultivated lands subsided
26.	2013	Kunjethi, Rudraprayag district	Heavy rainfall, loose materials, and toe erosion by the Kaliganga river (Khanduri et al., 2018)	Road and cultivated lands subsided
27.	2013	Bedanu, Chamoli district	Loose overburden, seepage (Khanduri et al., 2018)	Badrinath road (NH 7)
28.	2016	Didihat town, Pithragarh district	Weathered rock and soil material, thick overburden (Khanduri, 2017)	Cracks in some houses
29.	2016	Dhanauli, Almora district	Toe erosion by the seasonal rivulet (Pande, 2016)	Cracks in 03 houses and agriculture lands
30.	2016	Sandani, Almora district	Toe erosion by Ghuniyoli Gad (Pande, 2016)	Damaged agricultural terraces and fissures in the houses
31.	2016	Bari, Almora district	Severe toe erosion by Jalia Gad (Pande, 2016)	Agriculture terraces collapsing
32.	2016	Jaduri, Almora district	Severe toe erosion by Jalia Gad (Pande, 2016)	The houses got cracks and collapsed agricultural fields
33.	2016	Thala, Almora district	Severe toe erosion along Jalia Gad. Unscientific anthropogenic interferences (Pande, 2016)	The whole village was subsiding due to which the houses got cracked
34.	2016	Dankhali, Almora district	Heavy rains and steep slopes (Pande, 2016)	Collapsing of agricultural terraces
35.	2018	Lower Mall road, Nainital town, Nainital district	Heavy rains, overburden material and dead load exerted by heavy Vehicular Traffic (DMMC, 2018)	Road subsided and consequently washed away
36.	2020	Josha, Pithoragarh district	Heavy rains, toe erosion by the local stream (Khanduri, 2022)	07 houses were destroyed
37.	2020	Malupati, Pithoragarh district	Heavy rains, loose materials, and toe erosion by the stream (Khanduri, 2022)	02 houses were destroyed, cracks in houses
38.	2020	Gwalgoan, Pithoragarh district	Heavy rains, loose soil, sink holes (Khanduri, 2022)	02 houses were destroyed and 02 houses hanging on
39.	2020	Khela, Pithoragarh district	Excessive rains, creep, steep slopes, and gully erosion (Khanduri, 2022)	Cracks in houses
40.	2021	Reni, Chamoli district	Vaikrita Thrust, Rishiganga flash flood of 2021 and loose overburden (USDMA, 2021)	Cracks in houses

3. DISTRIBUTION OF LAND SUBSIDENCE IN UTTARAKHAND HIMALAYA

Land subsidence can occur due to the sudden sinking of sub-surface rock/soil materials attributable to interplay of geological, geomorphological, and meteorological factors influenced by human activities and climatic variability. Earthquakes, heavy concentrated rains, overburden materials, flash floods/floods, and tectonic activities are generally responsible for land subsidence in the region. The entire region has witnessed land subsidence that was recorded earlier in years 1880, 1987, 2000, 2003, 2009, 2010, 2012, 2013, 2016, 2020 and recently in the year 2022. The same incidences have been collected on the basis of previous archives and interaction with local inhabitants, as also ground observations which are summarized in Table 2 and shown in Figure 1. It was observed that most incidences of ground subsidence in the region have occurred due to bank/toe erosion by the river/stream though other factors including heavy rains induced flood, seismicity, cloudburst associated flash flood, Thrust/Fault, thick overburden, and underground water have also contributed to the same.

3.1 Influence of Structural Discontinuities

The entire state of Uttarakhand has an influenced by several Thrusts/Faults such as HFT, MBT, MCT, T-HF as delineated in Figure 2. These are major tectonic discontinuities which are seismically active, this adds to the vulnerability of the region for land subsidence. Moreover, the presence of carbonate rocks in the Higher Himalaya, Lesser Himalaya, and Siwalik Himalaya makes the region more prone to erosion and chemical action due to the presence of water. The formation of sinkholes and cavities and their subsequent slumping has given these areas their peculiar geomorphic characteristics. Most land subsidence affected areas are located in proximity of major Thrust/Fault zones (Figure 2).

The problem is however aggravated by heavy rains, earthquakes, and flash floods/floods. Tectonic activities resulting in uplift or subsidence generally influence the flow characteristics of the rivers and depending on the interaction with new topography, the river might either aggrade or erode (Devrani and Singh, 2014). The areas in proximity of tectonic boundaries are generally covered with large fans and cones of landslide debris. Apart from landslides, subsidence zones are also observed in proximity to tectonic discontinuities (Khanduri et al., 2018).

The fault observed in varve deposits at Garbyang is, however, the manifestation of the palaeo-seismicity in the region and is related with the movement along the Tethyan Fault that forms the distal boundary of the proglacial lake (Rautela, 2005).

The area around Joshimath has been intermittently sinking for a long time due to the activeness of the Vaikrita Thrust that passes in its close proximity (Valdiya, 2014). Similarly, the slopes in and around the Main Central Thrust (MCT) zone along the Bhagirathi valley, delineate the evidence of ground subsidence, cracks in the buildings, and tilting of trees (Devi et al., 2022). Slumping of rock masses witnessed in the Kali and Gori valleys in the East, implies continuing movement at present on some of the faults of the MCT zone (Valdiya, 2014).

The Naitwar area is bounded by Chail and Mutaur Thrusts in the East and North whereas further East the MCT truncates all other tectonic units (Jamwal and Siddiqui, 1993) where the market town with a floating population of around >= 300 is witnessing landslide, subsidence and debris flow (Uniyal, 2006).

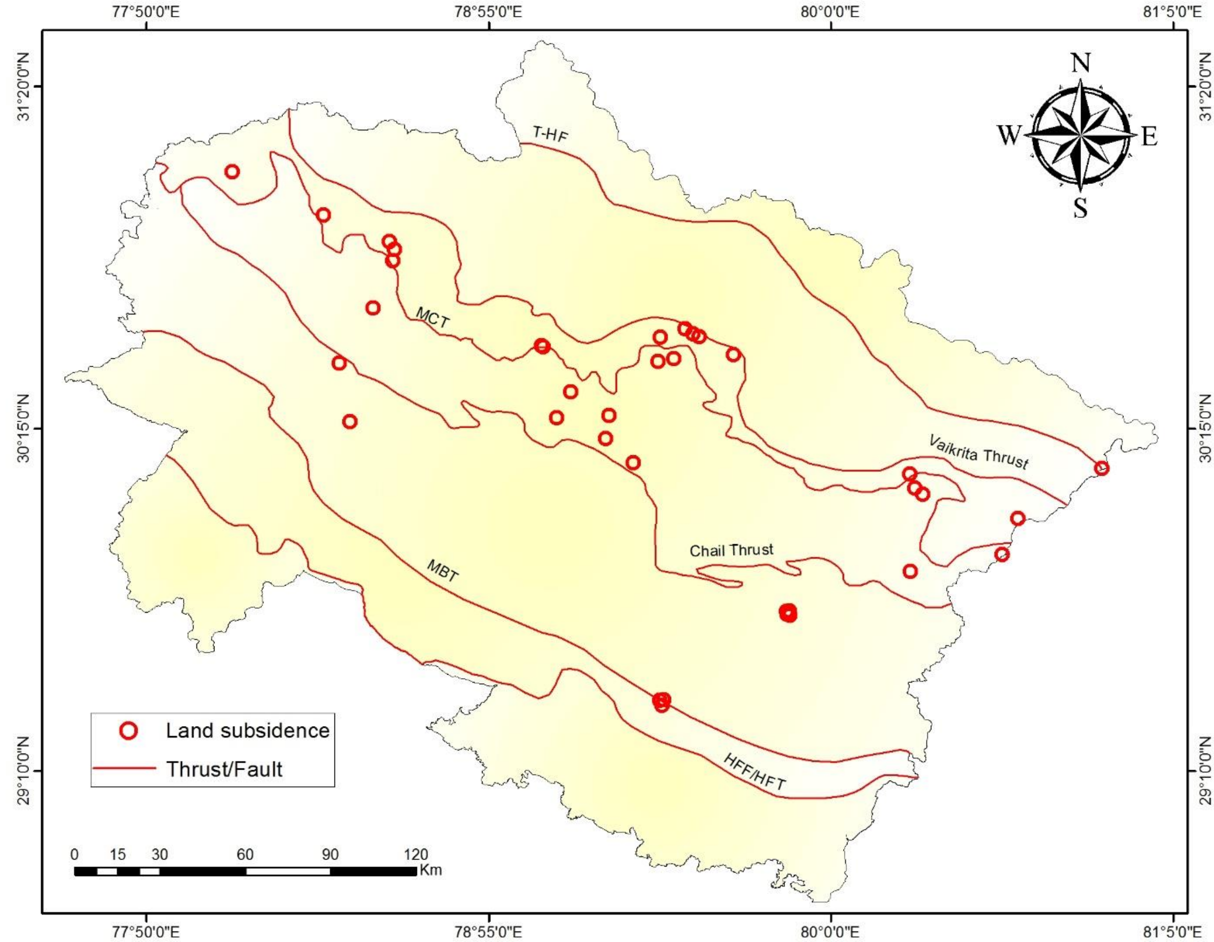

Figure 2. Map depicting major tectonic features along with distribution of land subsidence in the Uttarakhand Himalaya

The Hedakhan landslide lies in the vicinity of the Main Boundary Thrust (MBT) causing fractures and budging on the ground, road subsidence and cracks in buildings are some of the indications of its activeness (Kothyari et al., 2012).

Neotectonic activities along Baliyanala Fault caused subsidence of ground is common at GIC ground at Harinagar in Nainital (Kumar et al., 2017). On the other hand, the Narayanbagar subsidence zone located on the left bank of the Pinder river is lying in proximity to the boundary of Almora and Berinag Nappe (Gupta et. al., 2004). The boundary of these two Nappes is marked by the Easterly dipping Thrust (Valdiya, 1980).

The Himalaya is being thrust over the alluvium of the Ganga Plain by the Himalayan Frontal Thrust (HFT) and has its southern limit Piedoment Zone. Land subsidence and uplift related to movements along various faults strongly influence landforms in the area proximity to HFT (Goswami et al., 2009).

3.2 Influence of Seismicity

The Northern drift of the Indian plate and its collision with the Eurasian plate over the last >=50 million years resulted in the evolution of Himalayan orogen. The rapid convergence of the Indian Plate and ensuing strain buildup causes frequent earthquakes in the region (Bilham et al., 2001; Feldl and Bilham, 2006) resulting in the same region is highly susceptible to earthquakes (Paudyal and Panthi, 2010). Though, an earthquake causes not only human and property losses, but it may also cause slope instability and land subsidence.

Being a seismically active mountainous belt, Uttarakhand region lies in both Zone IV and V according to Earthquake Zonation Map of India (IS 1893, Part 1, 2002) and has witnessed devastating earthquakes in 1720 (Kumaun Earthquake), 1803 (Garhwal Earthquake), apart from the Uttarkashi and Chamoli earthquakes in 1991 and 1999 (Rautela, 2015).

Figure 3 illustrates major tectonic features along with the occurring past earthquake of 1803 and earthquakes from 1935 to 2022 in the Uttarakhand Himalaya. One of the major occurring earthquake was M ≥=7.0 during the past year 1803 is marked by a red circle. The magnitudes of occurring five major earthquakes were between M > 6.1 to M 7.0 during the past years 1935, 1945, 1958, 1991, and 1999 are shown by red stars. The green circles indicate that the magnitudes of occurring earthquakes were M > 5.1 to M 6.0 whereas occurring earthquakes of M 4.1 – M 5.0 and M <=4 were indicated by blue circles and purple circles respectively, during the past years in the region. All these earthquake epicenters indicate that most of the earthquakes are concentrated in proximity to Main Central Thrust (MCT) zone.

3.3 Factors Contributing to Land Subsidence

Five major tectonic discontinuities as Himalayan Frontal Thrust (HFT), Main Boundary Thrust (MBT), Main Central Thrust (MCT), Vaikrita Thrust (VT) and Trans Himadri Fault (T-HF) traverse across the Uttarakhand Himalaya from South to North respectively (Auden, 1949; Heim and Gansser, 1939; Valdiya, 1980; Valdiya, 1889; Valdiya and Goel, 1983). Apart from many local Thrust/Fault traces which are accountable for land subsidence and environmental degradation in the region.

Geomorphologically, U and V-shaped valleys, high rocky cliffs, highly dissected ridges, meandering channels, and river terraces are present in the region. This region has also been dissected by ridges and massifs whose altitudes are between 400 to 8000 m amsl (Sati, 2020) where the Nanda Devi west peak at an elevation of 7817 m amsl, the second highest massif in India (Maikhuri et al., 2001; Bosak, 2008). The valley floors are covered with thick piles of glacier sediments while the higher parts of the mountains are covered with glaciers. To the middle and lower reaches, most of the valley slopes are covered by colluvium due to high degradational process while the valleys possess alluvium by the aggradational process of rivers/streams.

Based on ground observations and a review of available records, it was noticed that heavy precipitation, bank erosion/toe erosion by the rivers/streams, overburden material, heavy loading on the ground, and thrusts/faults are common factors whereas carbonate rocks and draw down effects of the reservoir of dams or water bodies are other contributing factors of land subsidence in this region. Some of the most important factors are given below:

- Localised precipitation oversaturates the overburden material which removes the fine particles beneath the ground surface,
- Carbonate rocks which are influenced by natural and artificial means result in sinkholes in the ground surface,

- A thick pile of overburden material in front of the valley slopes are influenced by erosion of streams, infiltration of rainwater into the subsurface, and anthropogenic activities like unscientific construction for property and infrastructure, blockade of natural rivulet paths, and improper drainage for household wastewater and sewage lines etc.,
- Loosening of the rocks and soils mass by severe earthquakes and flood/flash flood,
- Construction of heavy loading of civil structures over the natural ground which is more than its carrying capacity,
- Increased Drawdown in the Reservoir is a key factor for the occurrences of land subsidence,
- The zones of active Thrust/Faults consists of deformed and fractured rock mass that is prone to move downwards when excavated or shaken by earthquakes and artificial explosions.

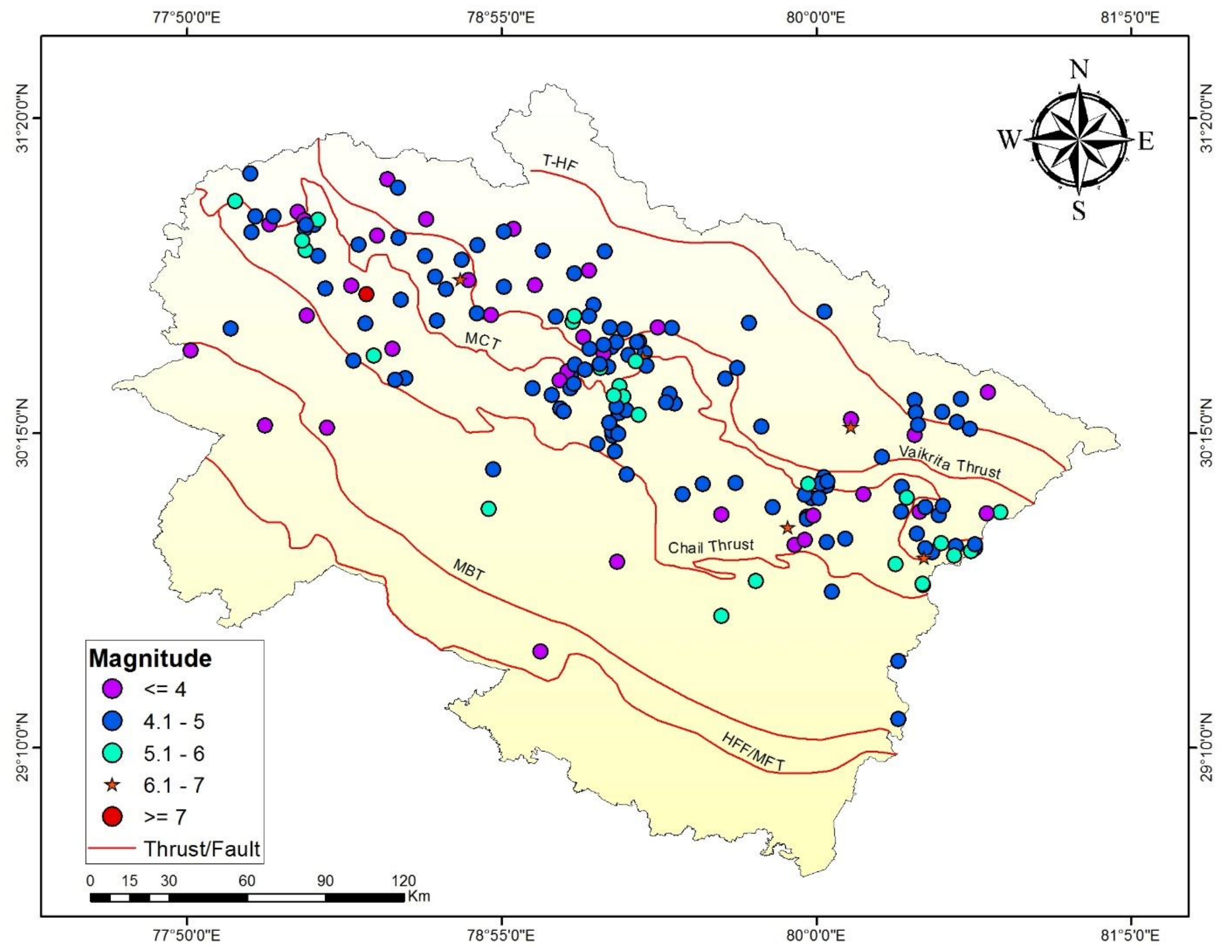

Figure 3. Map showing major tectonic features and earthquake epicenters of 1803 and continue from 1935 to 2022 of Uttarakhand Himalaya (Source: USGS)

4. GROUND OBSERVATIONS IN JOSHIMATH TOWN

Joshimath town is located in the hilly terrain of Higher Himalaya and enjoys good road connectivity and can be approached by Rishikesh – Badrinath Road (NH- 7) falls in parts of Survey of India toposheet number 53 N/10 (Figure 4). Located at an altitude of 1875 m amsl, it is an entrance to several mountaineering and trekking expeditions while famous Hindu and Sikh pilgrimage sites respectively Shri Badrinath and Shri Hemkunt Sahib. The population of Joshimath generally witnesses a manifold increase due to the same (Bisht and Rautela, 2010).

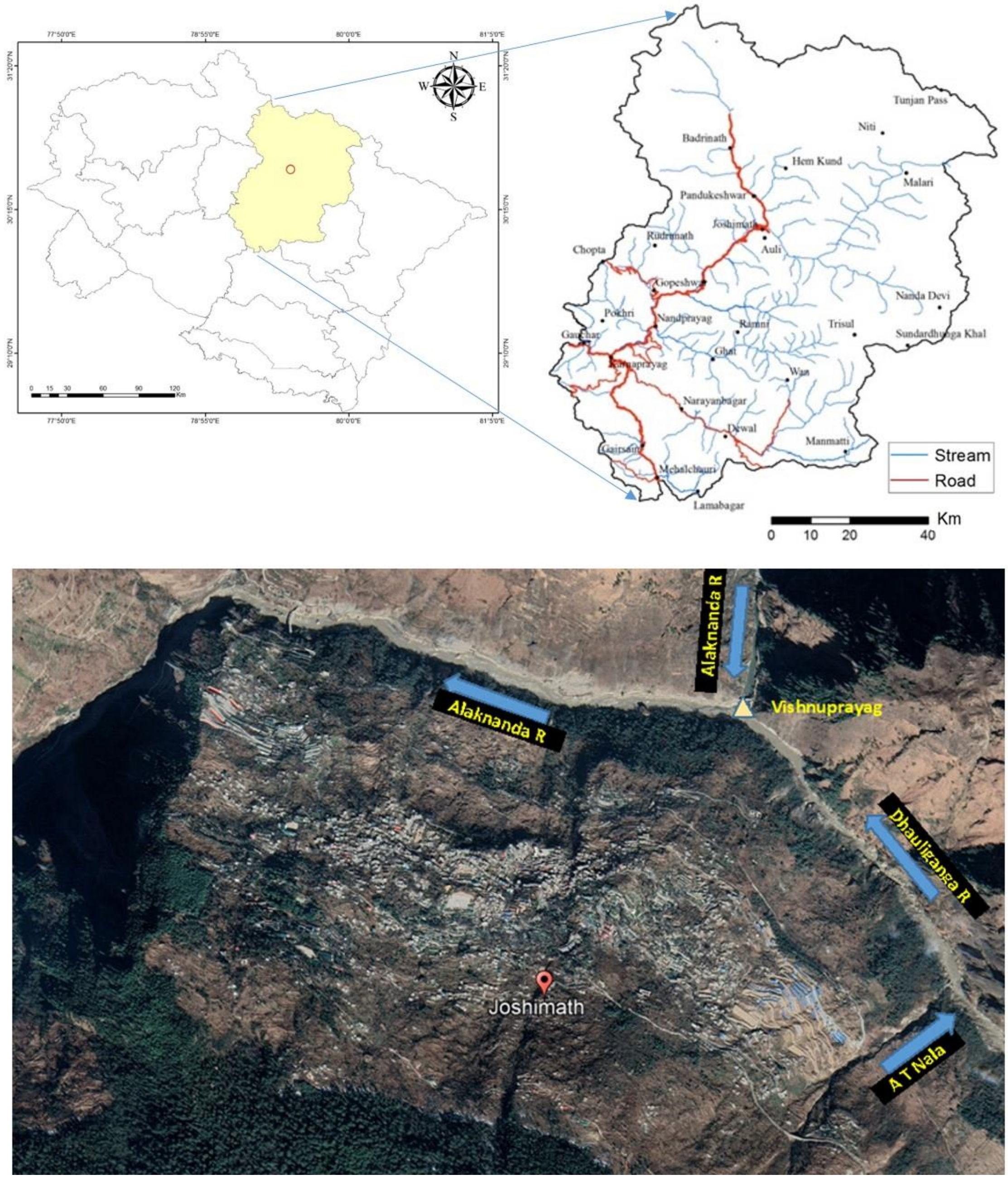

Figure 4. Map illustrates location of the study area on where upper left in Uttarakhand map Chamoli district is highlighted on which red colour circle showing location of the Joshimath town. Below Google Earth Pro image depicts the entire Joshimath town (Last Access: 07.12.2022)

Joshimath is one of the tehsil headquarter of Chamoli district and is a famous hill station that comes under Nagar Palika Parishad and is divided into 9 wards. Joshimath has a population of 16,709 of which 9,988 are males while 6,721 are females according to the Census of India 2011.

The town is situated on E-W running ridge to the SW of Vishnuprayag which is the confluence of the Alaknanda and Dhauliganga rivers. The ground elevations vary from about 1460 m and 3000 m amsl in this area. It is bounded by mainly three streams one is A T nala flows from SW-NE direction and meets with the Dhaulignaga river at Ravigram village whereas two other streams to the East and West of Shri Narshing Temple which are flowing in NNW directions and finally join the Alaknanda river at the right angle in this region. The Alaknanda river flows through the area from the WNW-ESE direction.

However, Joshimath town is facing the problem of land subsidence for a long time ago. Recently, the aftermath of the Rishiganga-Dhauliganga flash flood of 2021 and heavy rainfall events between October 17-19, 2021 have aggravated the problem of land subsidence in the same area. Research has been undertaken to find possible causes of mass movements and land subsidence and recommend mitigation measures for these disasters with due consideration to local residents

4.1 Geological Set Up

The studied region is occupied by rocks of the Joshimath Formation of the Central Crystalline of Vaikrita Group that consists of streaky, banded and augen gneisses. The VT separates low to medium-grade rocks of greenschist facies of the Helang Formation from medium to high-grade rocks of amphibolite facies of the Joshimath Formation. To the ENE of Joshimath town, major tectonic discontinuity as MCT separates the rocks of Helang Formation of Central Crystalline from Garhwal Group passing across the Alaknanda river at Helang in this region (Heim and Gansser, 1939; Valdiya, 1980; Jain et al., 2014). The Garhwal Group of rocks of Lesser Himalaya comprises of low-grade meta-sediments intruded with acidic and basic igneous rocks.

Exposures of Higher Himalayan Central crystalline gneisses of Vaikrita Group are to be observed near the Marwari bridge on both banks whereas continuously exposed in the opposite valley along the road having with rocky cliffs. These rocks are to be medium to coarse-grained, grey in color, slightly to moderately weathered, moderately jointed and thickly foliated. These dip towards the Northeast at moderate angles. The foliation plane is generally observed to be well developed and the dips angle varying from 35° to 45° in the Northeast direction. The joint sets are observed to dip at moderately steep angles towards S and NW (55° / 180° and 50° / 300°).

4.2 Damage to Property and Infrastructure

Joshimath town and surrounding are facing land subsidence problems since last >=100 years ago, but it is documented since the Mishra Committee Report of 1976. The flash flood of February 7, 2021 along the Rishiganga –Alaknanda rivers made significant changes in the area. This flash flood event caused severe toe erosion all along the Alaknanda river on its left bank, downstream of its confluence with the Dhauliganga river at Vishnuprayag (Figure 5f). This has an adverse impact on the stability of the slope on which Joshimath town is situated.

Additionally, during October 17-19, 2021 excessive rainfall aggravated the problem of land subsidence in the area. Apart from this, the infiltration of water and gully erosion by local streams to the East and West of Shri Narsing temple which flows through Joshimath town, and anthropogenic interventions in the form of heavy civil constructions of this fragile mountain slope created the situation worst. This results in differential land subsidence which aggravates the instability of the hill slope in the area.

Figure 5. Damage to property and infrastructure due to land subsidence events; (a) Wider cracks in walls of houses and courtyard at Sunil village, (b) detached column of a house at Gandhinagar, (c) transverse cracks on the wall of a house at Ravigram village, (d) road subsided just below NTPC colony near Marwari area, (e) a water supply line was observed to be dislocated caused road subsided in the Sunil village, and (f) severe toe erosion by Alaknanda river on its left bank

During the field investigations, it was observed that cracks in houses, and water supply lines were damaged, and roads subsided in the different pockets of vulnerable localities of the town. Active land subsidence events are observed to have occurred mainly in Sema, Sunil, near NTPC colony, Gandhinagar and Ravigram localities. Cracks in the houses are to be observed in Sunil and Ravigram villages indicating active land subsidence (Figures 5a and 5c). Poor quality of civil construction works was also noticed, particularly in Gandhinagar during the site inspection (Figure 5b). Apart from, a part of a stretch of the approach road of the National Thermal Power Corporation (NTPC) colony near the Marwari was subsided whereas a water supply line was observed to be dislocated due to the road subsiding in the Sunil village (Figures 5d and 5e).

It was observed that the Ravigram village is undergoing serious land subsidence during the field investigations. Most of the houses of this village were subsided resulting in cracks in the houses whereas some of the houses of this village were on the verge of damage. The mass movement process in the area is mainly due to rapid erosion by the A T Nala located to the East of the Ravigarm village. This Nala flows from the SW-NE direction and finally meets with the Dhauliganga river at a right angle in the area. On the other hand, toe erosion by the Dhauliganga river is also responsible for the active mass movement process in this area. Additionally, the aftermath of the Rishiganga-Dhauliganga flash flood of 2021 and rainfall on October 17-19, 2021 increased the problem of land subsidence in the area.

4.3 Key Contributing Factors

Around the Joshimath town, particularly towards the valley side, the slope was observed to be parallel to the foliations plane. The active landslide was observed all along the Alaknanda River on the left bank from Vishnuprayag to Marwari bridge whereas the right bank having with an almost vertical rocky cliff. This was deduced to adversely affect the stability of the town. The area is geo-dynamically active and lies in seismic Zone V. Some other important influencing factors of land subsidence are given below:

- Heavy rainfall and increasing heavy localised precipitation or heavy concentration rains in the region,
- The area comes under the cataclinal slope category,
- Impacts of the past earthquake of 1803 Garhwal and recent earthquakes of 1991 Uttarkashi and 1999 Chamoli ,
- The adverse impact of the floods/flash floods of 2013 and 2021 respectively in the Alaknanda river and the Dhauliganga-Rishiganga rivers,
- Seepages and leakages from natural and artificial means,
- Gully erosion by the local streams,
- Severe toe erosion by the Alaknanda river,
- The predominance of a thick pile of overburden material/deep-seated old landslide mass,
- Civil constructions in an indiscriminate manner as well as excess weight over ground/slope

4.4 Suggestive Measures

Based on ground observations and keeping in view of important geo-parameters like geomorphology, geology, and geo-environment conditions of the area, the following suggestive measures are recommended:

- Enforcing regulations for any type of construction activities in the area around the town.
- Managing seepages and leakages from natural and artificial means in this fragile mountainous slope.

- Relocating affected families who were residing in severely damaged houses while the same houses should be dismantled immediately and debris of these houses be removed helping with the guidance and advice of respective expertise agencies.
- Proper channelization of natural streams wherein nearby artificial drainages must be interconnected with each other. The entire drainage system must be lined with cascading from the bottom up to the top hill. This would also be protected against soil erosion as well as land subsidence.
- Constructing appropriately designed flood protection structures to check the severe toe erosion by the Alaknanda river on its left bank on which Joshimath town is situated.
- As the area falls in Seismic Zone V due to which it is considered high earthquake vulnerability, the houses that were on the verge of damage in different wards in the area around the town might have been completely damaged during the earthquake. It is therefore suggested that dismantling the same houses immediately for the safety of families living in the area,
- Physical monitoring of land subsidence in Joshimath town is the need of the hour, particularly in the pockets of different wards that were in a highly vulnerable state during the field visit. On the basis of continuous physical monitoring, the inhabitants can be warned before any mishappening or emergency situation,
- Special care must be taken during the rainfall, particularly during heavy spells of rain in the region. In such cases, the inhabitants of vulnerable localities must be made aware and immediately sifted to safe suitable places, if necessary

In addition to the aforementioned suggestive measures, detailed sub-surface investigations should be done to understand the actual overburden depth, groundwater table, and path of springs for checking the further threats of land subsidence zones in the town. Monitoring of land subsidence in Joshimath town should also be done with the help of State-of-art techniques as well as physical-basis to know the rate of sliding movements. This would help in reducing future threats of land subsidence within the town.

5. CONCLUSIONS

Erratic rainfalls due to climate change enhances the devastating potential of silent disasters not only locally but also globally (Trenberth, 2011). The Central Himalayan terrain of Uttarakhand province in India is more susceptible to numerous natural disasters like landslides, flash floods/floods, avalanches, and land subsidence etc. Apart from this, the area is earthquake prone and highly seismically zone. Falling in the geologically highly sensitive zone, a number of weak structural discontinuities namely HFT, MBT, MCT, VT, and T-HF are encountered in the entire region which results into highly fragile, fractured, jointed, and deformed rocks in this region. Geomorphologically, land subsidence events are rare but most frequent and widespread in the region attributed to a thick pile of overburden material, high relief, steep slopes, carbonate rocks, and tectonic discontinuities. Additionally, high-velocity streams play a key role in facilitating slope mass into landslides and land subsidence in the region.

Earlier, Nainital town, Joshimath town and Garbyang village were severely affected by land subsidence events whereas in the recent past, Naitwar market, Bhatwari market and Dharchula town along with several villages were also affected by land subsidence in the region. These caused a huge loss of property and infrastructure along with agricultural lands and geo-environment. Based on field evidence, it was observed that land subsidence is attributed to (i) thick pile of overburden material in the proximity of Thrust/Fault zones, (ii) unexpected discharge in the streams which erodes the toe of slope material, (iii) drawdown effect of natural and artificial lakes/water bodies, (iv) excessive rainfall which saturates the soils beneath the ground surface, (v) heavy construction over the soft ground without estimation of bearing capacity, (vi) unscientifically excavation of grounds/hill slopes for mining, underground water, property, and infrastructure developments, (vii) blocking of the course of natural streams and springs, and (viii) slaking potential of clay rocks and solution activities in carbonate rocks. Among these are mainly responsible for events of land subsidence in the region.

In the year 2022, Joshimath town faced chronic land subsidence problems due to the Dhauliganga-Rishiganga flash flood of 2021, excessive rainfall of October 17-19, 2021 and presence of loose unconsolidated materials, moderately steep slopes as also seismo-tectonic activities and unscientific constructions resulting in numbers of properties and infrastructures were severely affected and some of these on the verge of damage. Presently, Joshimath town is facing serious slope instability and land subsidence problem and have already cracks observed in many houses as well as on the ground surface. In view of the high vulnerability of the area, it is therefore recommended that the dismantling of severely damaged structures and detailed monitoring along with sub-surface investigations should be done to determine the actual sub-strata conditions for reducing the future threats of land subsidence within the town. Additionally, families of highly vulnerable localities should also be relocated to safe suitable places.

Land subsidence events are sudden and abrupt phenomena that can be neither easily predicted nor easily treated. Once much displacement in civil structures is taken place, it is impossible to repair the same. As we knew that about 90 percent problem of slope instability as land subsidence happens due to water action in the form of heavy precipitation as well as household wastewater. It is therefore, this problem needs to be reduced by taking adequate water management. Keeping a view of geological, geomorphological, and hydrological conditions of the region, in order to minimize and control the adverse impacts of land subsidence in the region authors recommends (i) proper documentation of past land subsidence for better understanding of this phenomenon, (ii) detailed geological and geomorphological study to understand the nature of the ground before any planning activity, (iii) provision of adequate natural and wastewater management, (iv) Estimation of carrying capacity of natural ground before any establishment, (v) geo-environmental friendly developmental initiatives, (vi) regularly physical monitoring to observe the movement of critical groundmass, particularly in the proximity of habitations, and (vii) follow up of indigenous knowledge of traditional habitation practices. This would definitely reduce the impacts of land subsidence in the region. Last but not least, avoidance is a better-suited option for safeguarding against chronic land subsidence.

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Author contributions
SK undertook geological fieldwork in different land subsidence areas through interaction with different stakeholders, analysed the same, wrote the manuscript, edited and reviewed it. RDS reviewed the manuscript whereas BMC generated figures using available software.

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REFERENCES

Arık, F. (2018). Sinkholes, Sinkhole Formations in Central Anatolia and Suggestions for Solutions. Maden ve İnsan 3, 46-53 (in Turkish).

Auden, J.B. (1949). In Director's General report for 1939. Record of Geological Survey of India, 78, 74-78.

Bhambri, R., Mehta, M., Dobhal, D.P., Gupta, A.K., Pratap, B., Kesarwani, K., & Verma, A. (2016). Devastation in the Kedarnath (Mandakini) Valley, Garhwal Himalaya, during 16-17 June, 2013: a remote sensing and ground-based assessment. Natural Hazards, 80(3), 741-766.

Bisht, M.P.S., & Rautela, P. (2010). Disaster looms large over Joshimath. Current Science, 88(10), 1271.
Bilham, R., Gaur, V.K., & Molnar, P. (2001). Himalayan seismic hazard. Science, 293, 1442–1444.

Bosak, K. (2008). Nature, Conflict and Biodiversity Conservation in the Nanda Devi Biosphere Reserve. Conservation and Society, 6(3), 211–224.

Carminati, E., & Martinelli, G. (2002). Subsidence rates in the Po plain, northern Italy: The relative impact of natural and anthropogenic causation. Engineering Geology, 66, 241-255.

Devi, M., Gupta, V., Solanki, A., & Sarkar, K. (2022). Assessment of slope instability using Kinematic analysis and Finite Element Modelling in the Main Central Thrust zone, Bhagirathi Valley, NW Himalaya. Himalayan Geology, 43(1A), 51-60.

Devrani, R., & Singh, V. (2014). Evolution of valley-fill terraces in the Alaknanda Valley, NW Himalaya: its implication on river response studies. Geomorphology, 1, 10.

DMMC (2007). Ground subsidence in Chain Village of Chamoli district in Uttarakhand. Unpublished report of Disaster Mitigation and Management Centre (DMMC), Department of Disaster Management, 12.

DMMC (2012). Investigations in the Asi Ganga valley on the aftermath of flash flood / landslide incidences in August, 2012. Unpublished report of Disaster Mitigation and Management Centre (DMMC), Department of Disaster Management, 45.

DMMC (2012a). Investigations in the areas around Okhimath in Rudraprayag district on the aftermath of landslide incidences of September 2012. Unpublished report of Disaster Mitigation and Management Centre (DMMC), Department of Disaster Management, 37.

DMMC (2018). Report Note on land subsidence of Lower Mall Road in Nainital, Uttarakhand. Unpublished report of Disaster Mitigation and Management Centre (DMMC), Department of Disaster Management, 9.

Dobhal, D.P., Gupta, A.K., Mehta, M., & Khandelwal, D.D. (2013). Kedarnath disaster: facts and plausible causes. Current Science, 105(2), 171–174.

Feldl, N., & Bilham, R. (2006). Great Himalayan earthquakes and the Tibetan plateau, Nature, 444, 165–170.
Galloway, D.L., Erkens, G., Kuniansky, E.L., & Rowland, J.C. (2016). Preface: Land subsidence processes. Hydrogeology Journal, 24, 547–550.

Ghosh, A., Sarkar, S., Kanungo, D.P., Jain, S.K., Kumar, D., Kalura, A.S., & Kumar, S. (2009). Slope instability and risk assessment of an unstable slope at Agrakhal, Uttarakhand. Indian Geotechnical Society (IGC) 2009, Guntur, India, 783-785.

Goswami, P.K., Pant. C.C., & Pandey, S. (2009). Tectonic controls on the geomorphic evolution of alluvial fans in the Piedmont Zone of Ganga Plain, Uttarakhand, India. Journal of Earth System Science, 118(3), 245–259.

Gupta, V., Dobhal, D.P., & Vaideswaran, S.C. (2013). August 2012 cloudburst and subsequent flash flood in the Asi Ganga, a tributary of the Bhagirathi river, Garhwal Himalaya, India. Current Science, 105(2), 249-253.

Gupta, P., Mukherjee, D., Sikdar, P.K., & Kumar, K. (2004). Investigation and control of Narayanbagar landslide, District Chamoli, Uttaranchal, India- A case study. Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering New York, NY, April 13-17, 2004. 1-8.

Heim, A., & Gansser, A. (1939). Central Himalaya: geological observations of the Swiss expedition 1936. Memoir Society Helvetica Science Nature, 73, 1–245.

Hu, R.L., Wang, S.J., Lee, C.F., & Li, M.L. (2002). Characteristics and trends of land subsidence in Tanggu, Tianjin, China. Bulletin of Engineering Geology and the Environment, 61, 213-225.

IS 1893 (2002). Indian Standard (IS):1893, Part 1, Criteria for earthquake resistant design of structures, Bureau of Indian Standards, New Delhi.

Jain, A.K., Shreshtha, M., Seth, P., Kanyal, L., Carosi, R., Montomoli, C., Iaccarino, S., & Mukherjee, P.K. (2014). The Higher Himalayan Crystallines, Alaknanda – Dhauli Ganga Valleys, Garhwal Himalaya, India. In (Eds.) Chiara Montomoli, Rodolfo Carosi, Rick Law, Sandeep Singh and Santa Man Rai, Geological field trips in the Himalaya, Karakoram and Tibet, Journal of the Virtual Explorer, 47, 1- 38.

Jamwal, J.S., & Siddiqui, M.A. (1993). Delineation of Main Central Thrust across UP – HP border, Uttarkashi District, UP and Shimla District, H.P. Geological Survey of India, Records, 126(8), 255-257.

Khanduri, S. (2022). Rain-Induced Slope Instability: Case Study of Monsoon 2020 Affected Villages in Pithoragarh District of Uttarakhand, India. International Journal of Earth Sciences Knowledge and Applications, 4(1), 1-18.

Khanduri, S. (2020). Cloudbursts Over Indian Sub-continent of Uttarakhand Himalaya: A Traditional Habitation Input from Bansoli, District-Chamoli, India. International Journal of Earth Sciences Knowledge and Applications, 2(2), 48-63.

Khanduri, S., & Sajwan, K.S. (2019). Flash floods in Himalaya with special reference to Mori tehsil of Uttarakhand, India. International Journal of Current Research in Multidisciplinary, 4(9), 10-18.

Khanduri, S. (2019). Natural Hazards in the township of Nainital, Uttarakhand in India. International Journal of Engineering Applied Sciences and Technology, 3(12), 42-49.

Khanduri, S., Sajwan, K.S., Rawat, A., Dhyani, C., & Kapoor, S. (2018). Disaster in Rudraprayag District of Uttarakhand Himalaya: A Special Emphasis on Geomorphic Changes and Slope Instability. Journal of Geography and Natural Disasters, 8(1), 1-9.

Khanduri, S., Sajwan, K.S., & Rawat, A. (2018a). Disastrous Events on Kelash-Mansarowar Route, Dharchula Tehsil in Pithoragarh District, Uttarakhand in India. Journal of Earth Science & Climatic Change, 9(4), 1-4.

Khanduri, S. (2018). Landslide Distribution and Damages during 2013 Deluge: A Case Study of Chamoli District, Uttarakhand. Journal of Geography and Natural Disasters, 8(2), 1-10.

Khanduri, S. (2017). Disaster Hit Pithoragarh District of Uttarakhand Himalaya: Causes and Implications. Journal of Geography & Natural Disasters, 7(3), 1-5.

Khanduri, S., & Rautela, P. (2012). Geological note on road subsidence on Yamunotri NH 94 below Wariya village in Barkot tehsil of Uttarkashi district in Uttarakhand. Unpublished report of Disaster Mitigation and Management Centre, Department of Disaster Management, 12.

Kothyari, G.C., Pant, P.D., & Luirei, K. (2012). Landslides and Neotectonic Activities in the Main Boundary Thrust (MBT) Zone: Southeastern Kumaun, Uttarakhand. Journal of Geological Society of India, 80, 101-110.

Kumar, M., Rana, S., Pant, P.D., & Patel, R.C. (2017). Slope stability analysis of Balia Nala landslide, Kumaun Lesser Himalaya, Nainital, Uttarakhand, India. Journal of Rock Mechanics and Geotechnical Engineering, 9, 150-158.

Kumari, S., Haustein, K., Javid, H., Burton, C., Allen, M.R., Paltan, H., Dadson, S., & Otto, F.E.L. (2019). Return period of extreme rainfall substantially decreases under 1.5°C and 2.0°C warming: a case study for Uttarakhand, India. Environmental Research Letters, 14, 1-10.

Larson, K.J., Basagaoglu, H., & Marino, M.A. (2001). Prediction of optimal safe Groundwater yield and land Subsidence in the Los Banos-Kettleman city area, California, Using a Calibrated Numerical Simulation Model. Journal of Hydrology, 242, 79-102.

Maikhuri, R.K., Nautiyal, S., Rao, K.S., & Saxena, K.G. (2001). Conservation policy–people conflicts: a case study from Nanda Devi Biosphere Reserve (a World Heritage Site), India. Forest Policy and Economics, 2(3-4), 355-365.

Martinez, J.P., Cano, E.C., Wdowinski, S., Marin, M.H., Lozano, J.A.O., & Leon, M.E.Z. (2015). Application of InSAR and Gravimetry for Land Subsidence Hazard Zoning in Aguascalientes, Mexico. Remote Sensing, 7, 17035–17050.

Mukherjee, S., Aadhar, S., Stone, D., & Mishra, V. (2018). Increase in extreme precipitation events under anthropogenic warming in India. Weather and Climate Extremes, 20, 45-53.

Pacheco, J., Arzate, J., Rojas, E., Arroyo, M., Yutsis, V., & Ochoa, G. (2006). Delimitation of ground failure zones due to land subsidence using gravity data and finite element modeling in the Queretaro valley, Mexico. Engineering Geology, 84(3), 143-160.

Pande, A. (2016). Assessment of slope instability and its impact on land status: a case study from Central Himalaya, India. Landform Analysis, 32, 27–43.

Park, J.Y., Jang, E., & Ihm, M.H. (2017). Study of Influence Factors for Prediction of Ground Subsidence Risk. Journal of Korean Society of Disaster & Security, 10(1), 29-34.

Paudyal, H., & Panthi, A. (2010). Seismic Vulnerability in the Himalayan Region. The Himalayan Physics, 1(1), 14-17.

Poland, J.F. (1981). The occurrence and control of land subsidence due to Groundwater withdrawal with special reference to the San Joaquin and Santa Clara valleys, California, Ph.D. Dissertation, Stanford University, Palo Alto, California.

Rautela, P. (2015). Traditional Genius and Earthquakes. Geography and You, 24-26.

Rautela, P. and Khanduri, S. 2011. Slope instability and geo-environmental issues of the area around Nainital. Publication of Disaster Mitigation and Management Centre, Department of Disaster Management, 92.

Rautela, P. (2005). Ground subsidence: a silent disaster in Himalaya. Disaster Prevention and Management, 14(3), 395-406.

Sain, K., Kumar, A., Mehta, M., Verma, A., Tiwari, S.K., Garg, P.K., Kumar, V., Rai, S.K., & Srivastava, K.S. (2021). A Perspective on Rishiganga-Dhauliganga Flash flood in the Nanda Devi Biosphere Reserve, Garhwal Himalaya, India. Journal Geological Society of India, 97, 335-338.

Sati, V.P. (2020). Vertical and horizontal distribution of forests in Uttarakhand Himalaya: A Geographical analysis. Turkish Journal of Forest Science, 4(2), 229-244.

Sati, S.P., Sharma, S., Sundriyal, Y.P., Rawat, D., & Riyal, M. (2020). Geo-environmental consequences of obstructing the Bhagirathi River, Uttarakhand Himalaya, India. Geomatics, Natural Hazards and Risk, 11(1), 887–905.

Stiros, S.C. (2001). Subsidence of the Thessaloniki (northern Greece) coastal plain, 1960-1999. Engineering Geology, 61(4), 243-256.

Trenberth, K.E. (2011). Changes in precipitation with climate change. Climate Research, 47, 123–138.

Uniyal, A. (2006). Disaster management strategy for mass wasting hazard prone Naitwar Bazar and surrounding areas in Upper Tons valley in Uttarkashi district, Uttaranchal (India). Disaster Prevention and Management, 15(5), 821-837.

USDMA (2021). Geological and Geotechnical Report over Reni village on Joshimath-Malari Road in Chamoli, Uttarakhand. Unpublished report of Uttarakhand State Disaster Management Authority, Department of Disaster Management, 16.

USDMA (2022). Geological and Geotechnical survey of land subsidence areas of Joshimath town and surrounding regions, Uttarakhand. Unpublished expert committee report of Uttarakhand State Disaster Management Authority, Department of Disaster Management, 28.

Valdiya, K.S. (2014). Damming rivers in the tectonically resurgent Uttarakhand Himalaya. Current Science, 106(12), 1658-1668.

Valdiya. K.S. (1989). Trans-Himadri intracrustal fault and basement upwarps south of the Indus-Tsangpo Suture Zone. Geological Society of America Special Paper, 153-168.

Valdiya, K.S., & Goel, O.P. (1983). Lithological subdivision and petrology of the great Himalayan Vaikrita Group in Kumaon Himalaya, India. Proceedings of the Indian Academy of Sciences - Earth and Planetary Sciences, 92, 141-163.

Valdiya, K.S. (1980). Geology of the Kumaun Lesser Himalaya. Wadia Institute of Himalayan Geology, Dehra Dun, India, 249.

Yıldız, M.S., & Sarifakioglu, E. (2022). Investigation in terms of soil characteristics of Inandik (Cankiri, Turkiye) sinkholes due to gypsum karstification. Proceedings of IKSTC 2022 - The 1st international Karatekin Science and Technology Conference, 1-3 September 2022, Çankiri, Turkey. 245-252.

Zhou, G.Y., & Esaki, T.J. (2003). GIS based spatial and predication system development for regional land subsidence hazard mitigation. Environmental Geology, 44, 665-678.