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A Geospatial and Socio-Economic Assessment of Land Subsidence in Joshimath, Uttarakhand: Drivers, Vulnerability and Resilience

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Abstract - Land subsidence in Joshimath, Uttarakhand, represents a severe Himalayan crisis, with cracks reported in over 850 houses, damage to nearly 700 buildings, and the displacement of more than 200 families during the 2022–23 event. Using satellite imagery, GIS mapping, and field surveys, this study measured subsidence rates of up to 6–9 cm per year and identified both natural and human drivers. Fragile geology, water seepage, and seismic activity, combined with unregulated construction (cited by 84.87% of respondents) and hydropower tunnelling (92.44%), accelerate instability. Vulnerability analysis shows that 72.44% of households reported property damage, while 95.68% of schools and health facilities suffered damage, reducing attendance by 94.06%. These cascading impacts highlight socio-economic fragility. To build resilience, strategies such as slope stabilisation, eco-sensitive planning, rainwater harvesting, and early warning systems are recommended. The Joshimath crisis underscores the urgent need for regulated construction and climate-resilient infrastructure to safeguard Himalayan towns.

Keywords: Joshimath, Himalayan land subsidence, Vulnerability assessment, Resilience strategies, Remote Sensing and GIS

INTRODUCTION

The Himalayas, the world's largest and youngest mountain range, formed as a result of the Indian-Eurasian continental collision, hosts thousands of landslides each year related to tectonic and anthropogenic activities *(Shrestha et al., 2025)*. It is important to characterise landslide kinematics, especially for slow-moving landslides in rapidly developing Himalayan urban centres, to support hazard assessment *(Solanki et al., 2026).* Subsidence of land is included in the United Nations' Sustainable Development Goal (SDG) 11, "Sustainable Cities and Communities". This goal aims to create safe, resilient, and sustainable urban environments. It includes a target to reduce the number of deaths and people affected by disasters, such as landslides and land subsidence. The International Consortium on Landslides (ICL) launched the Kyoto Landslide 2020 Commitment (KLC2020) to promote understanding and reduce the risk of landslide disasters *(Sassa & Sassa, 2026).* The KLC2020 provides tools, information, and incentives to help stakeholders reduce landslide risk. A prominent example of land subsidence in the world is the San Joaquin Valley in California, USA where excessive groundwater pumping for agriculture has caused the land to sink significantly, *(Matthew L.,2021)* with some areas dropping over 30 feet in the past few decades; other notable examples include Jakarta, Indonesia, Mexico City, and parts of the Po Plain in Italy, all experiencing major subsidence due to groundwater extraction. Similar to the land subsidence in the San Joaquin Valley, land subsidence has also been observed in the Chenab River Valley of the Jammu and Kashmir Union Territory in India, primarily affecting the Ramban, Kishtwar, and Doda districts *(Haq et al., 2019).* The town of Joshimath in the NW Himalaya experienced a crisis between 27th December 2022 and 8th January 2023, causing damage to ~700 buildings and leading to mass evacuation *(ISRO,2023)*. The primary concern is identifying the root causes of this subsidence, whether due to excessive groundwater extraction, unplanned construction, seismic activity, or a combination of these factors. Additionally, there is an urgent need to assess the socio-economic impact on displaced communities, the effectiveness of government response

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measures, and long-term mitigation strategies. This research seeks to analyse the contributing factors, examine the extent of damage, and propose sustainable solutions to prevent further land degradation. Addressing these challenges is crucial to safeguarding Joshimath's future and developing policies that can prevent similar disasters in other ecologically fragile regions. The objectives of this research work are (i) to identify geological and anthropogenic causes of land subsidence, and (ii) to assess socio-economic impacts on local communities.

AREA OF THE STUDY

Joshimath, also known as Jyotirmath, is located at 30°33'21.2" North latitude and 79°33'41.5" South longitude, with a total area of 4408.72 km² *(Sati, 2026).* falls in Toposheet No 53 N/10 and comes under the Alaknanda Basin (Figure 1). River Alaknanda makes the northern boundary of the study area. The Dauliganga river confluences with the Alaknanda at Vishnuprayag. Mostly, a dendritic pattern is observed in the area. High peaks, cliffs, steep slopes, and deep and narrow valleys are characteristic of the study area *(Rai P., 2023)*. Joshimath is better known for its religious significance, ancient temples, and proximity to Himalayan pilgrimage sites. Along with this, it is also an important military station. Auli, located very close to Joshimath, is known for its beautiful and adventurous sports. In winter, adventurous sports are organised in Auli, which becomes a tourist attraction.

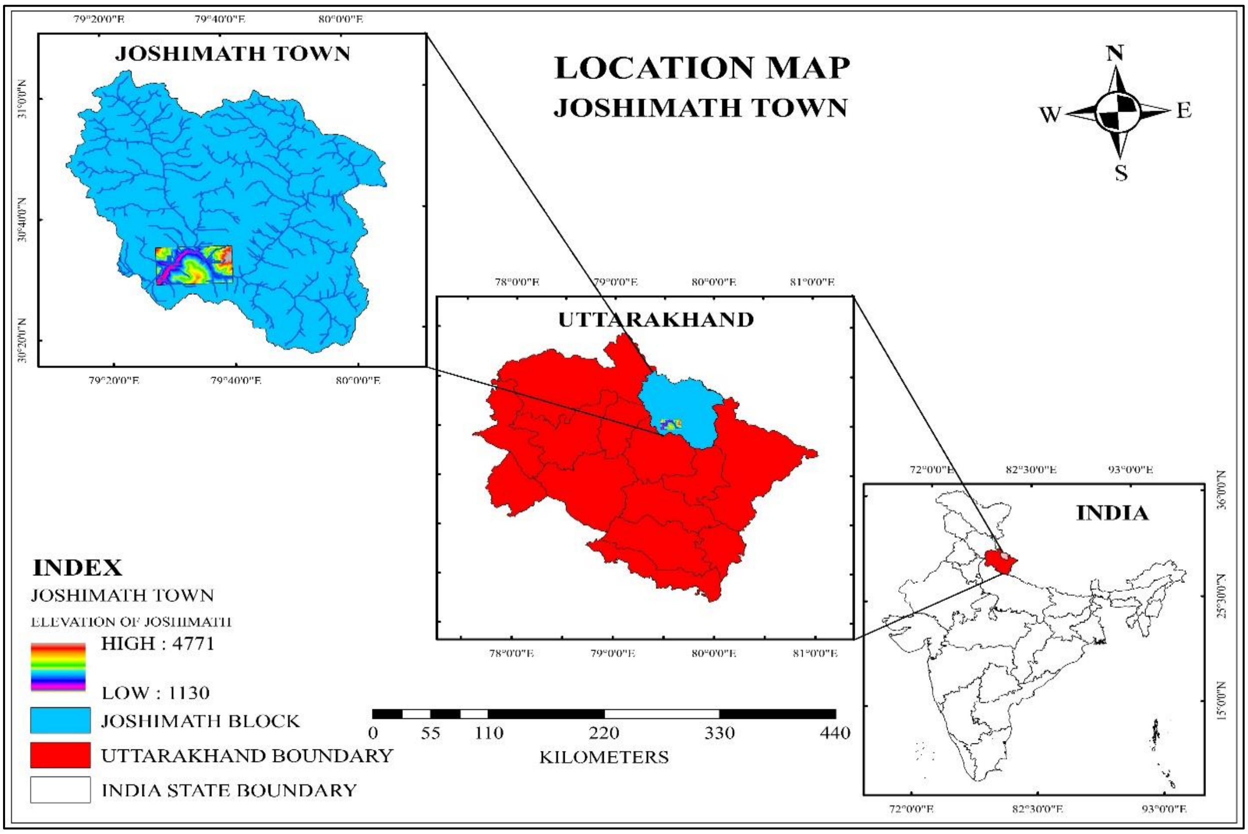

Figure 1: Location Map of Study Area

Data Collection and Methodology

For this research work, both primary and secondary data have been used. For primary data, sources included various government websites and reports. In the secondary data, both qualitative and quantitative data have been used. After acquiring the data, it was organised, compiled, analysed, and mapped using various software tools.

Collection of data

Primary data were collected through field surveys, questionnaires, interviews, and direct observations in the study area. These methods helped gather first-hand information on local conditions, community perceptions, and water resource issues. The data formed the basis for analysing the study objectives and supporting the research findings. For the secondary data, location maps were obtained from the Survey of India website, and land-use and land-cover data were obtained from the USGS website. Elevation data was obtained from ESRI, and drainage pattern

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data was obtained from HydroSHAD. After downloading all the data, maps were created and displayed using ArcGIS.

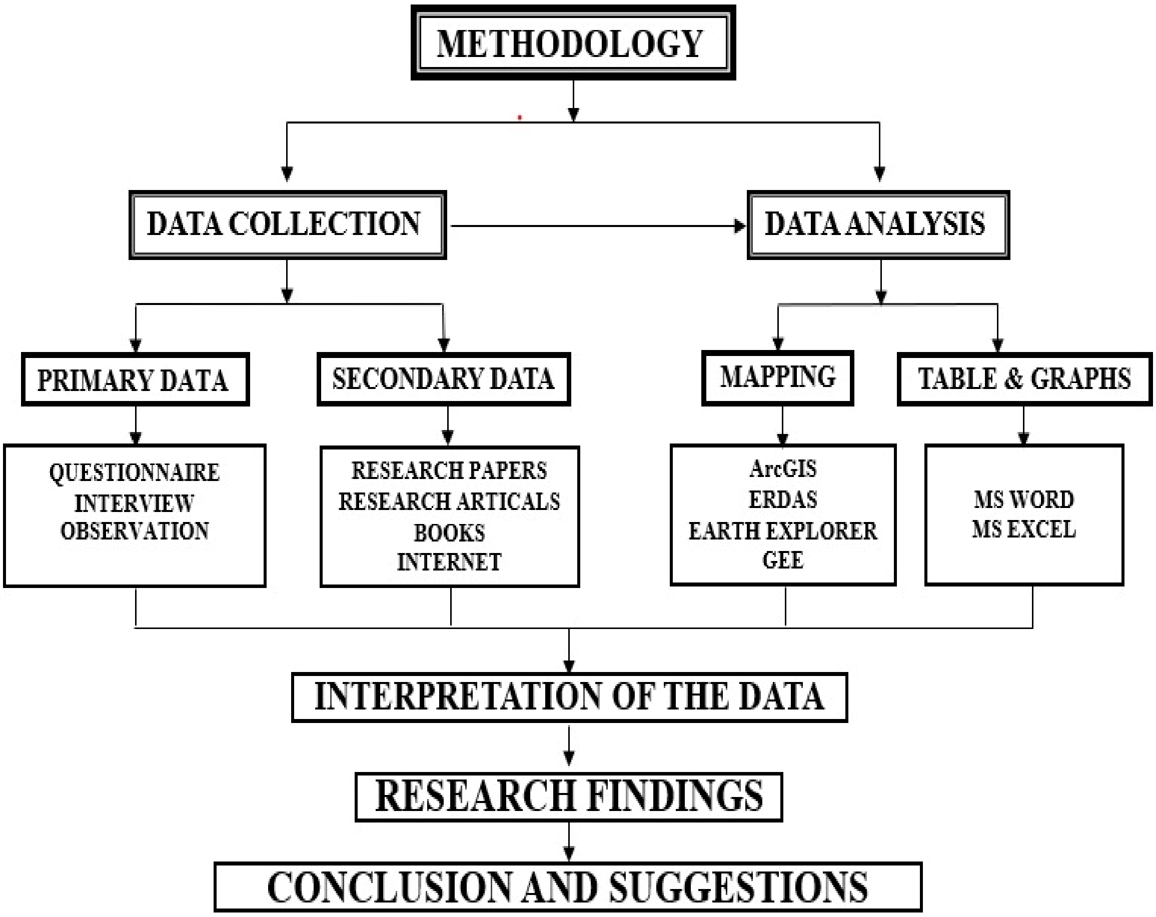

Figure 2: Methodology Flow Chart

Result and Discussion

Causes and Effects of Land Subsidence in Joshimath

Natural causes: The primary drivers of land subsidence in Joshimath are the region's geology and environment. Given that Joshimath is situated in the Himalayan region, a tectonically active area, the natural forces at work are complex and multifaceted. Here are the key natural causes contributing to subsidence in Joshimath:

Lithological Set-up: The lithology map shows that Joshimath comprises various rock types, including gneiss, schist, quartzite, granite, limestone, shale, and unconsolidated sediments. Lithology is an important natural factor influencing land subsidence because different rock types have varying strengths and weathering characteristics. Hard rocks such as granite and quartzite are generally more stable, whereas shale, weathered schist, and loose sediments are weaker and more susceptible to water infiltration, weathering, and ground deformation. These variations reduce slope stability and increase the area's susceptibility to land subsidence, particularly in the fragile Himalayan terrain *(Dolma,2025)*.

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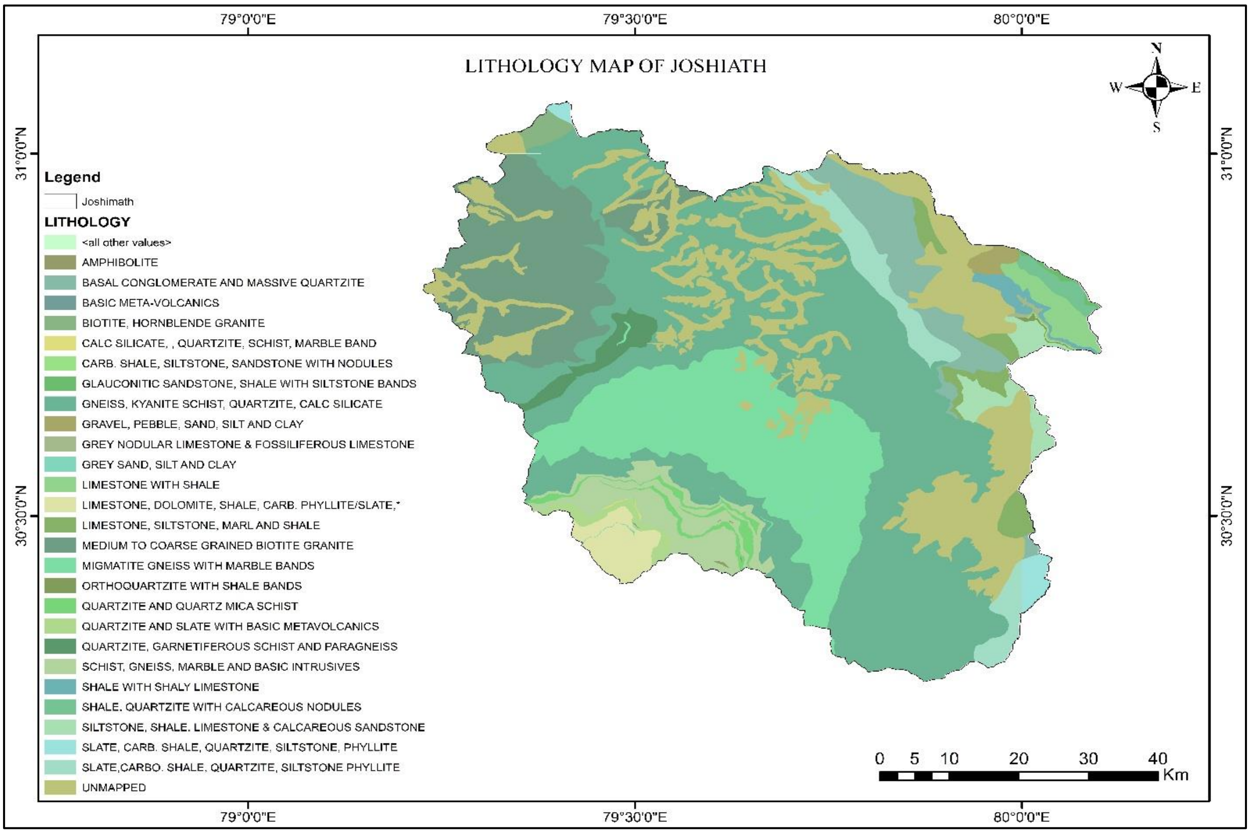

Figure 3: Lithology Map of Joshimath

Morphological Elements: The morphological map indicates that most of the Joshimath area is mountainous, with glaciers and active river channels present in some parts. These landforms have an important role in land subsidence. The steep mountain slopes are more likely to become unstable due to weathering and rainfall. At the same time, glacier-fed rivers and active channels increase erosion and remove support from the lower slopes. This weakens the ground, making the area more prone to cracks and land subsidence. Therefore, the morphology of Joshimath is a natural factor that increases the risk of ground instability *(Awasthi et al.,2024).*

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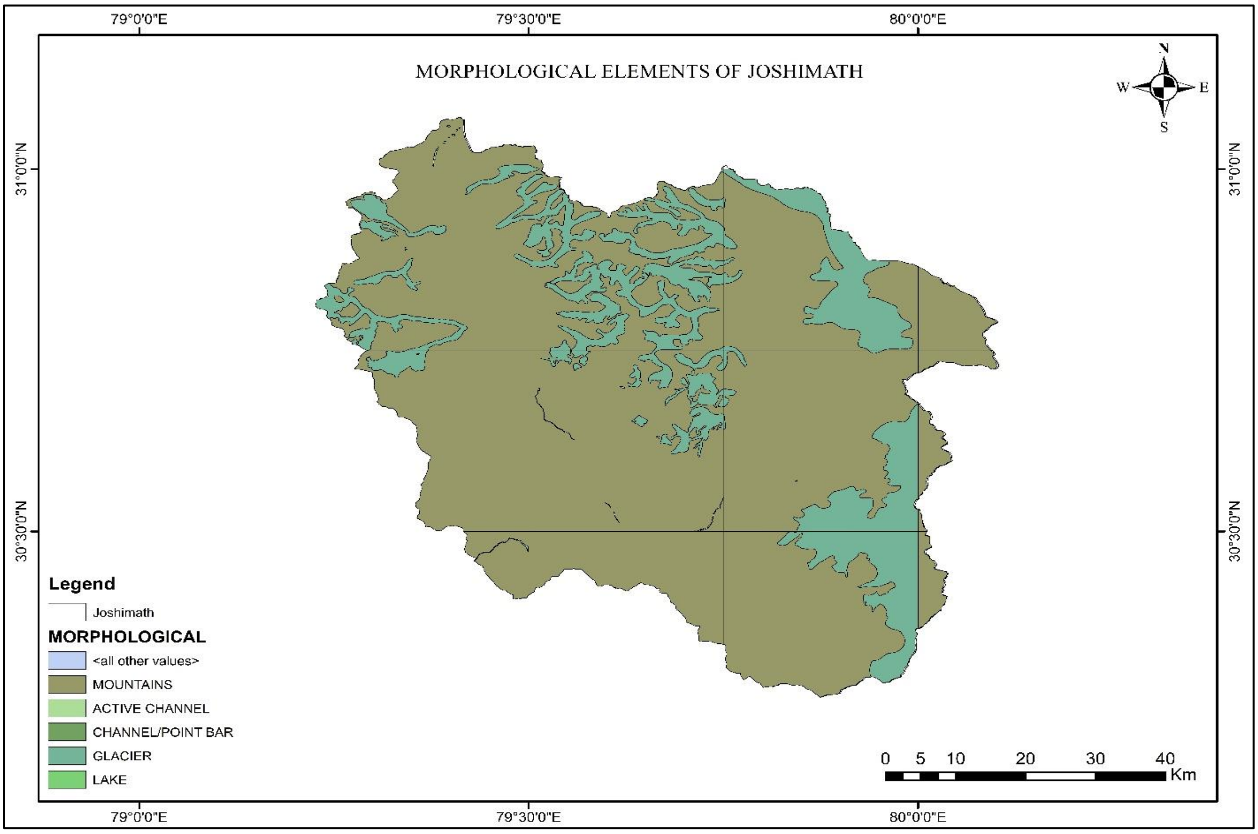

Figure 4: Morphological Elements of Joshimath

Geological Set-up: The geological map shows that Joshimath is mainly underlain by high- and medium-grade schist and gneiss, which are highly fractured and weathered. The town lies between the Main Central Thrust (MCT) and the Pandukeshwar Thrust (PT) and is also influenced by the Tapovan Fault. These major geological structures have weakened the rock mass by creating fractures and cracks over time. Water can easily move through these weak zones, reducing rock strength and destabilising the ground.

As a result, the area becomes more prone to ground movement and land subsidence. Natural geological conditions, along with human activities such as road construction and excavation, further increase the risk of slope instability and ground settlement in Joshimath *(Modified After Valdiya, K. S.,1998).*

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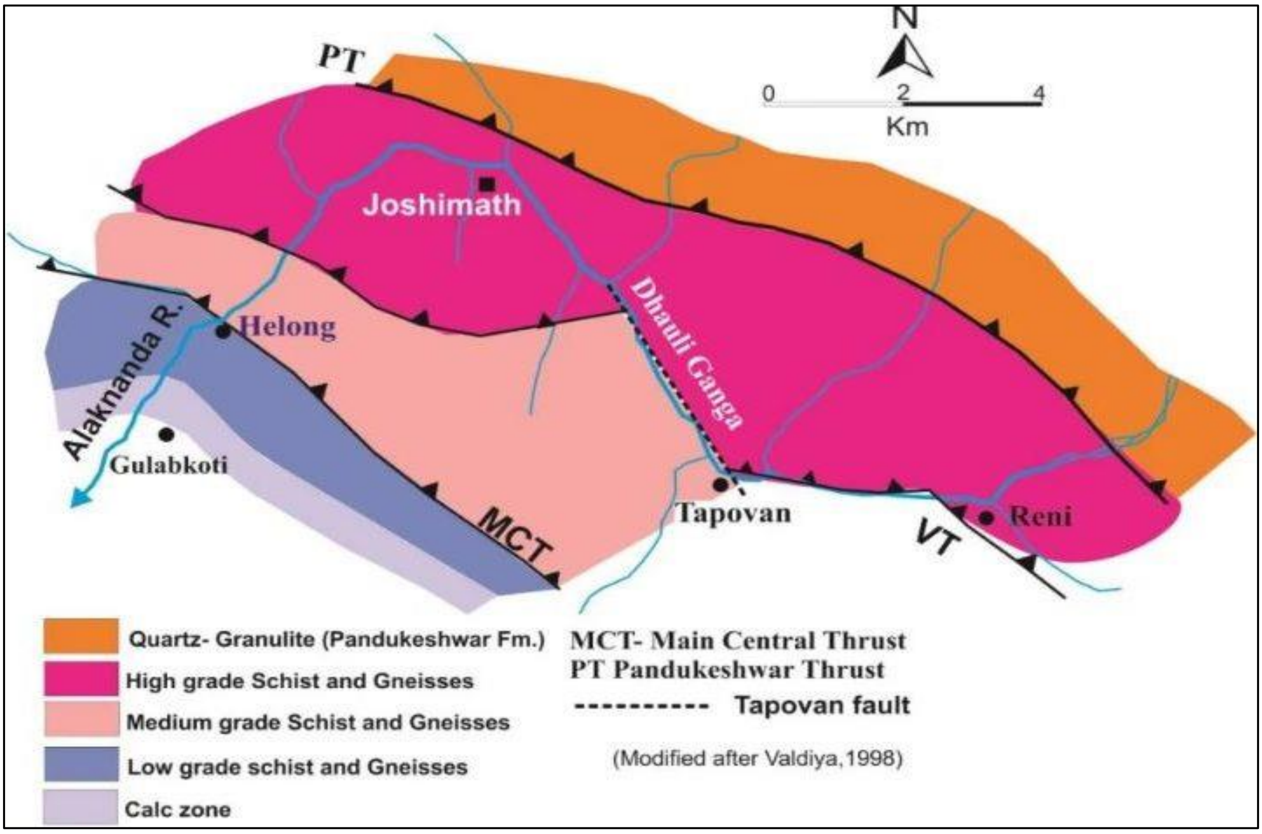

Figure 5: Geological Settings of Joshimath

Slope: The slope map shows that most parts of Joshimath have moderate to steep slopes, while gentle slopes are found mainly along river valleys. Steep slopes are naturally less stable because the force of gravity acts more strongly on them. During heavy rainfall, water enters the soil and cracks in the rock, reducing their strength and weakening the slopes. Joshimath is already located on old landslide material, so steep slopes increase the chances of ground movement and land subsidence. In addition, road cutting, construction work, and increased human activity on these slopes place additional pressure on the ground, which can lead to cracks in buildings and roads. Therefore, slope is an important factor that influences land subsidence in Joshimath *(Chadha, R. K., 2023; CGWB, 2023; Sati et al., 2023).*

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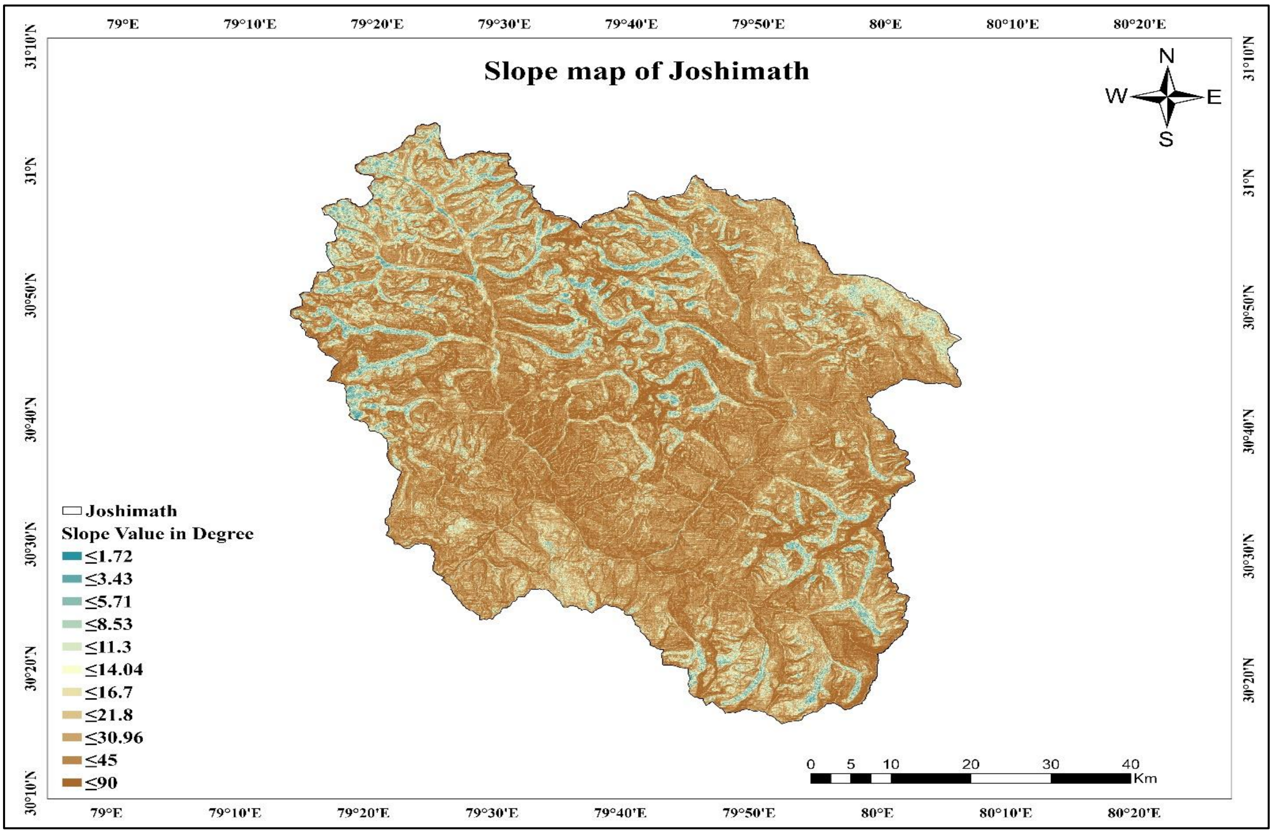

Figure 6: Slope Map of Joshimath

Drainage Pattern: The drainage map shows a dendritic drainage pattern, in which many small streams join larger streams, ultimately draining into the Alaknanda and Dhauliganga rivers. This type of drainage is common in mountainous areas with fractured rocks. In Joshimath, the stream network allows rainwater to move quickly over the slopes and through cracks in the ground. According to recent studies, continuous seepage of water through these fractures weakens the soil and rock mass, increases erosion, and reduces slope stability. The obstruction of natural drainage channels by unplanned construction further increases water infiltration into the ground. These conditions make the area more vulnerable to ground movement and land subsidence, especially during periods of heavy rainfall *(Bhatla et al., 2024)*.

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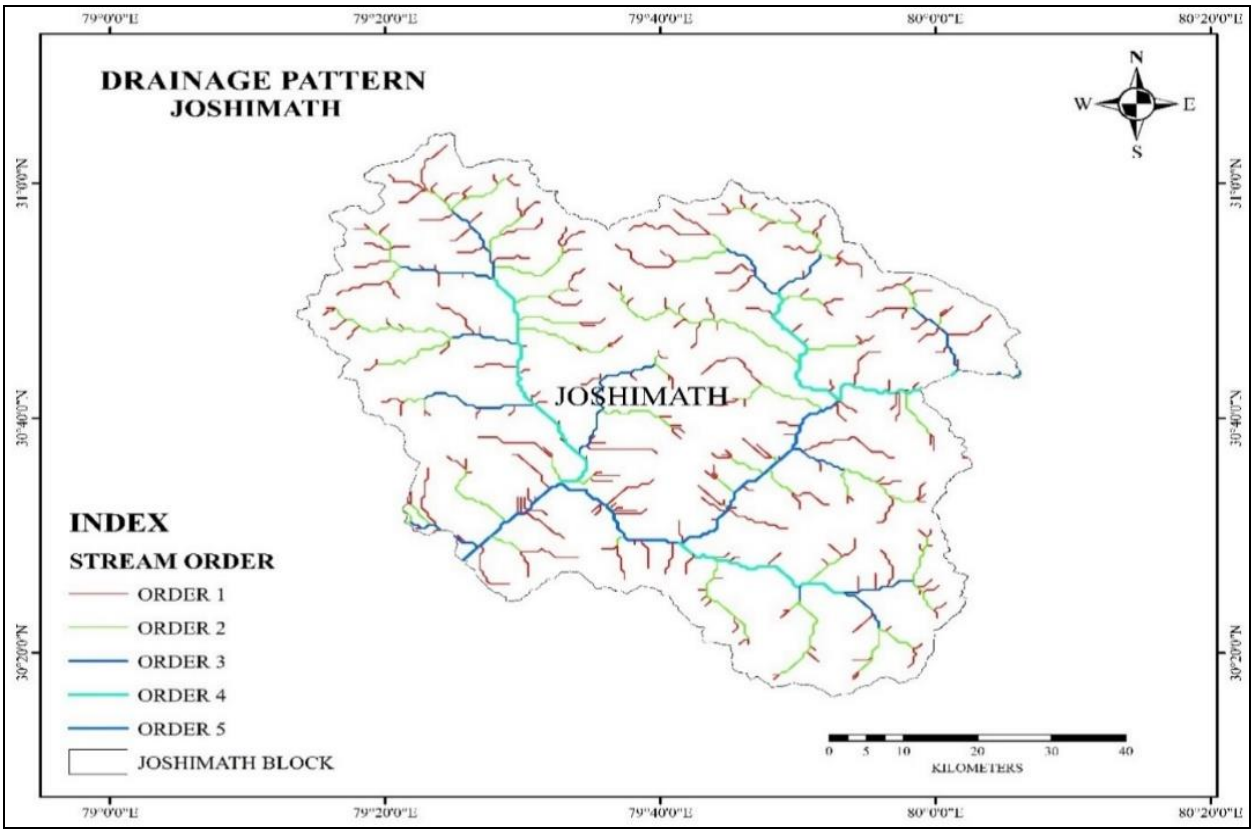

Figure 7: Drainage Pattern of Joshimath

Rainfall: The rainfall maps show that the overall spatial pattern remained largely similar from 2000 to 2020, but the distribution and intensity changed slightly over time. In all four periods (2000–2004, 2005–2009, 2010–2014 and 2015–2020), the south-western and southern parts of Joshimath received comparatively higher rainfall, while the northern and north-eastern areas experienced lower rainfall. The maps also indicate that the high-rainfall zone gradually became more concentrated in the southern part during the later years, suggesting changes in rainfall distribution rather than a major shift in the overall pattern. For a fragile Himalayan town like Joshimath, even small changes in rainfall distribution are important. Continuous rainfall increases surface runoff and allows more water to enter fractures, joints and old landslide debris. This raises pore-water pressure, weakens the soil and rock, and reduces slope stability. Recent studies have shown that extreme rainfall events can accelerate ground deformation and trigger slow-moving landslides in Joshimath. Therefore, rainfall acts as an important triggering factor that, together with weak geology and human activities, increases the risk of land subsidence and slope failure in the region *(Dalal et al., 2025; Sreejith et al., 2024).*

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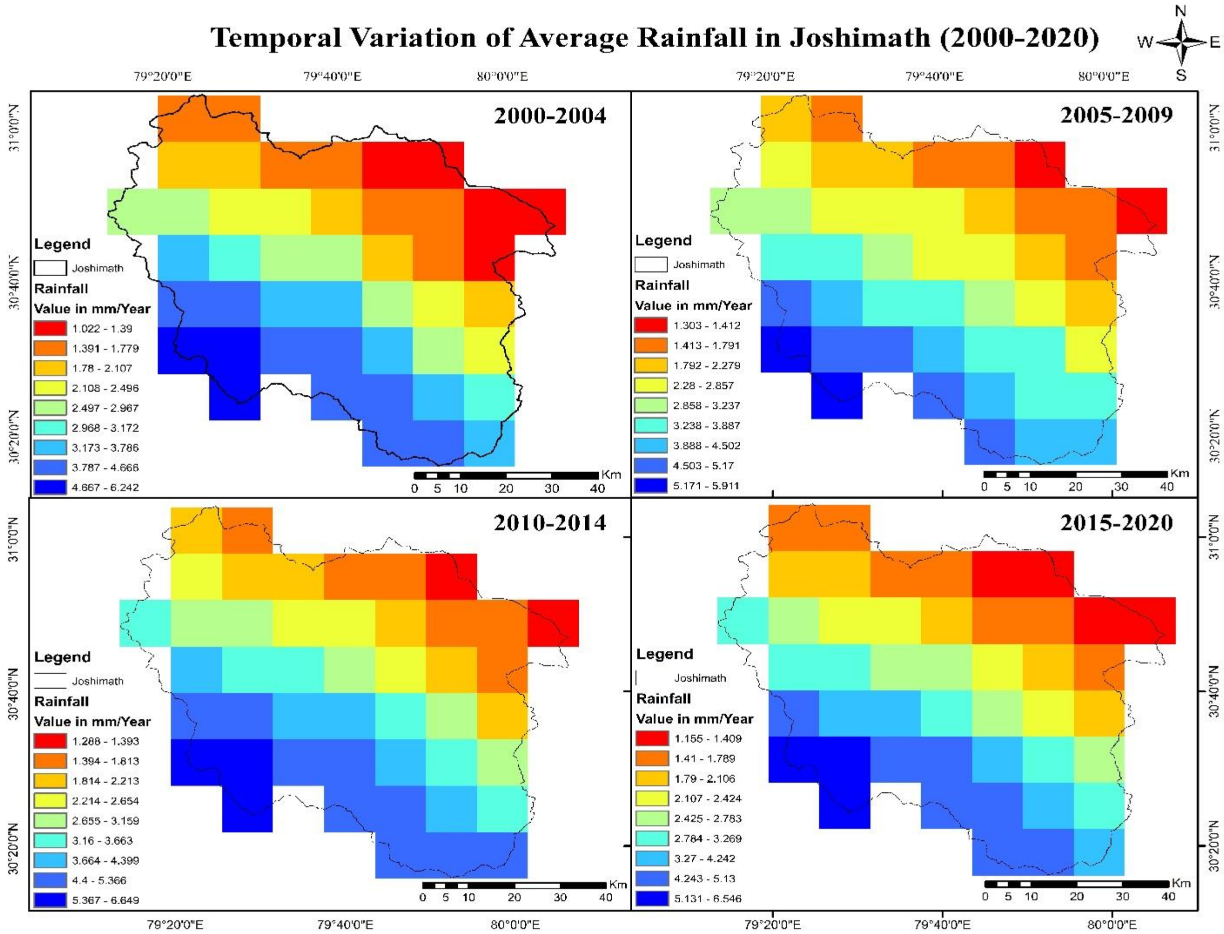

Figure 8: Rainfall Map of Joshimath

Human-Made Causes: Human activities are major drivers of land subsidence in many parts of the world. Rapid urbanisation, unplanned construction, road cutting, tunnel excavation, poor drainage and changes in land use disturb the natural balance of the ground *(Bagheri-Gavkosh et al., 2021).* In the Himalayan region, including Joshimath, these human-induced factors become more serious because they interact with weak geology, steep slopes, and heavy rainfall. Therefore, land subsidence in Joshimath is not controlled by a single factor but by the combined effect of natural conditions and human activities *(Awasthi et al., 2024; Huning et al., 2024).*

Table 1: Causes of Subsidence in Joshimath (Primary Data)

Main Reasons for Joshimath land subsidence?		
Value	Frequency	Percentage
Tunnel boring and blasting from the Tapovan -Vishnugad hydropower project	171	92.44
Excessive and unregulated construction activities	157	84.87
Lack of proper drainage systems leading to water seepage	124	67.03
Urbanisation and Population Pressure	91	49.19
Seismic activity in a high-risk zone (Zone V)	31	16.75
Location on an ancient landslide deposit with low soil stability	8	4.33
Erosion caused by the Alaknanda and Dhauliganga rivers	3	1.63

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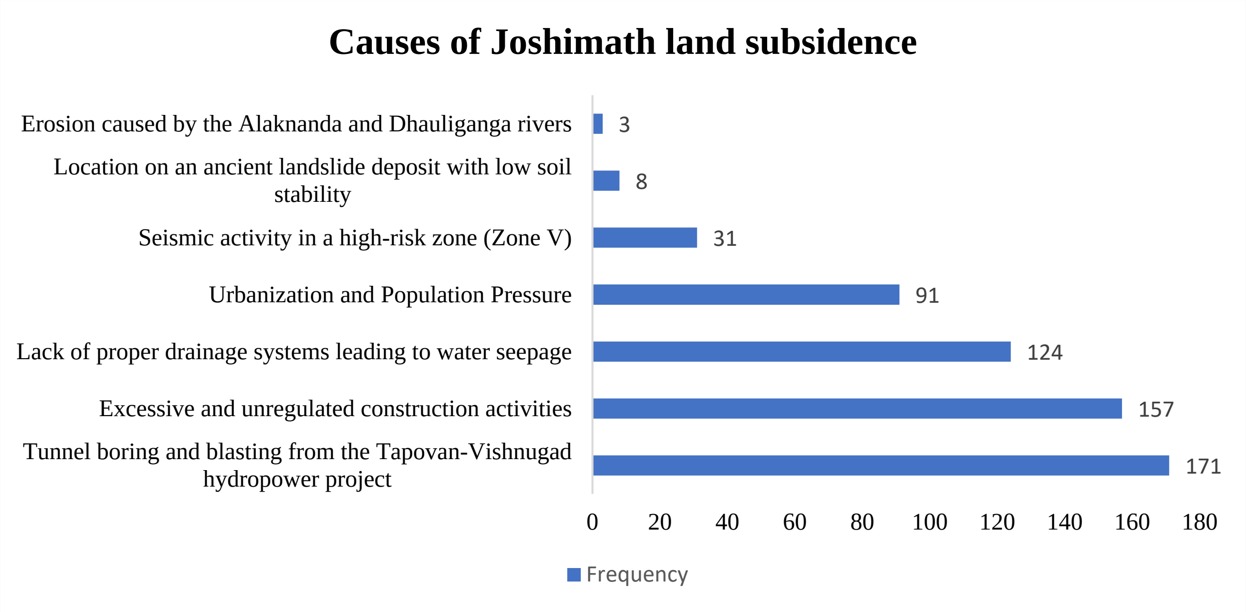

Chart 2: Bar Graph of Causes of Joshimath Land Subsidence

A total of 185 respondents were asked about the main reasons for land subsidence in Joshimath. The survey shows that 171 respondents (92.44%) believed that tunnel boring and blasting at the Tapovan-Vishnugad Hydropower Project are the main causes of land subsidence. Excessive and unregulated construction activities were reported by 157 respondents (84.87%), showing that many people also consider rapid construction as an important cause. Lack of a proper drainage system leading to water seepage was identified by 124 respondents (67.03%). Urbanisation and population pressure were reported by 91 respondents (49.19%). A smaller number of respondents believed that seismic activity (16.75%), the old landslide deposit (4.33%), and erosion by the Alaknanda and Dhauliganga rivers (1.63%) are the main reasons for land subsidence. Overall, the survey shows that most local people believe human activities are the main cause of land subsidence in Joshimath.

Changes in Land Use and Land Cover- The LULC maps of 2017 and 2024 show small but noticeable changes in land use across the Joshimath Block. The built-up area has slightly increased, mainly around the central and southern parts of the study area, indicating the expansion of settlements and infrastructure *(Awasthi et al., 2024).* At the same time, minor changes can also be seen in vegetation, barren land and rangeland.

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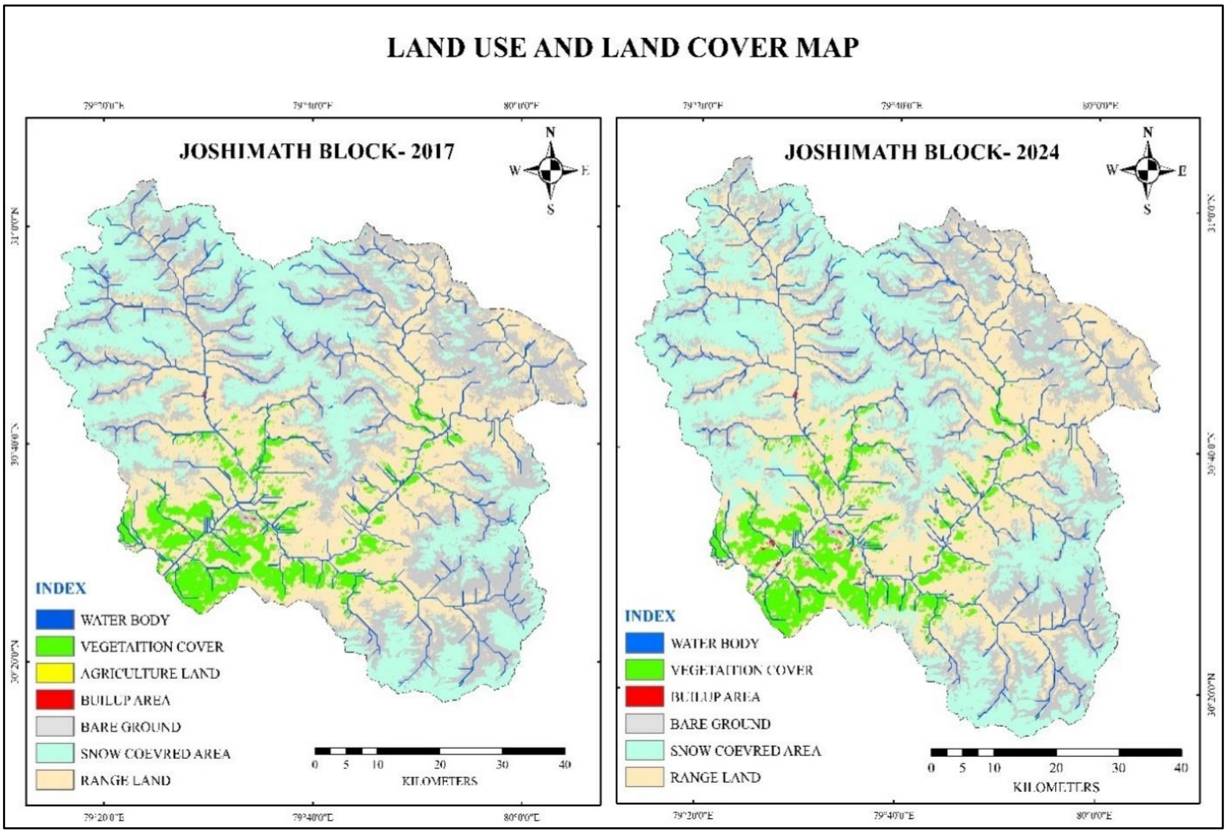

Figure 1: Land Use and Land Cover Pattern of Joshimath

These land use changes can affect land stability in a fragile Himalayan region like Joshimath. An increase in built-up areas adds extra load on the ground, while changes in vegetation and land cover can reduce soil protection and increase surface runoff. Together with weak geology and heavy rainfall, these changes may increase slope instability and contribute to land subsidence *(Glade, 2003; Huning et al., 2024).*

Socio-Economic Impact of the Joshimath Land Subsidence

Direct Impact: The survey shows that property damage was the biggest impact of land subsidence in Joshimath. Around 72.44% of the respondents reported damage to their houses, shops and other buildings. This shows that many people suffered financial losses due to property damage. Displacement or relocation was reported by 25.41% of respondents, indicating that many families had to leave their homes and move to safer places. Health problems, such as stress, anxiety and minor injuries, were reported by 10.28% of the respondents. No loss of life was reported during the survey. Around 20% of the respondents also mentioned other problems, such as loss of income, disruption to daily life, and other social and economic difficulties. Overall, the results show that land subsidence has affected the daily lives, property, and livelihoods of the people living in Joshimath.

Table No. 2 Direct Impact of Subsidence (Primary Data)

Impact on Humans of Land Subsidence		
Value	Frequency	Percentage
Property Damage (home, Business Buildings, etc)	134	72.44
Displacement or Relocation	47	25.41
Health Issues (Injury, Stress, etc)	19	10.28
Life Loss	0	0
Others	37	20

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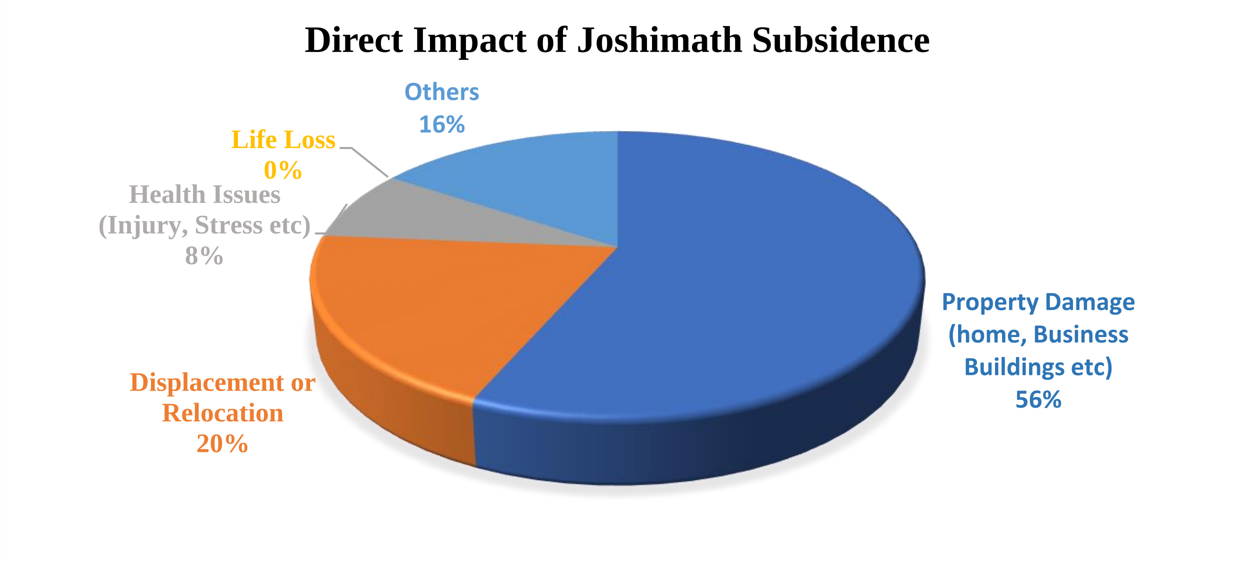

Chart 3: Pie Chart of the Direct Impact of Joshimath Subsidence

Change in Landscape- The survey shows that the most common changes after land subsidence were cracks and tilting in buildings. Both were reported by 100% of respondents, indicating that these changes were observed across nearly the entire affected area. Cracks and road damage were reported by 93.52% of respondents, indicating that transport and daily movement were also affected. In comparison, loss of vegetation or land erosion was reported by 28.65% of the respondents. Overall, the findings show that land subsidence has caused major damage to buildings and roads, while changes in vegetation and land surface were reported in some parts of the study area.
Table No. 3 Change in Landscape of Joshimath (Primary Data)

The change in Joshimath's landscape is most noticeable due to subsidence		
Value	Frequency	Percentage
Cracks in the walls or floors of buildings	185	100
Tilting of buildings	185	100
Cracks or Damage to Roads	173	93.52
Loss of Vegetation or Land Erosion	53	28.65

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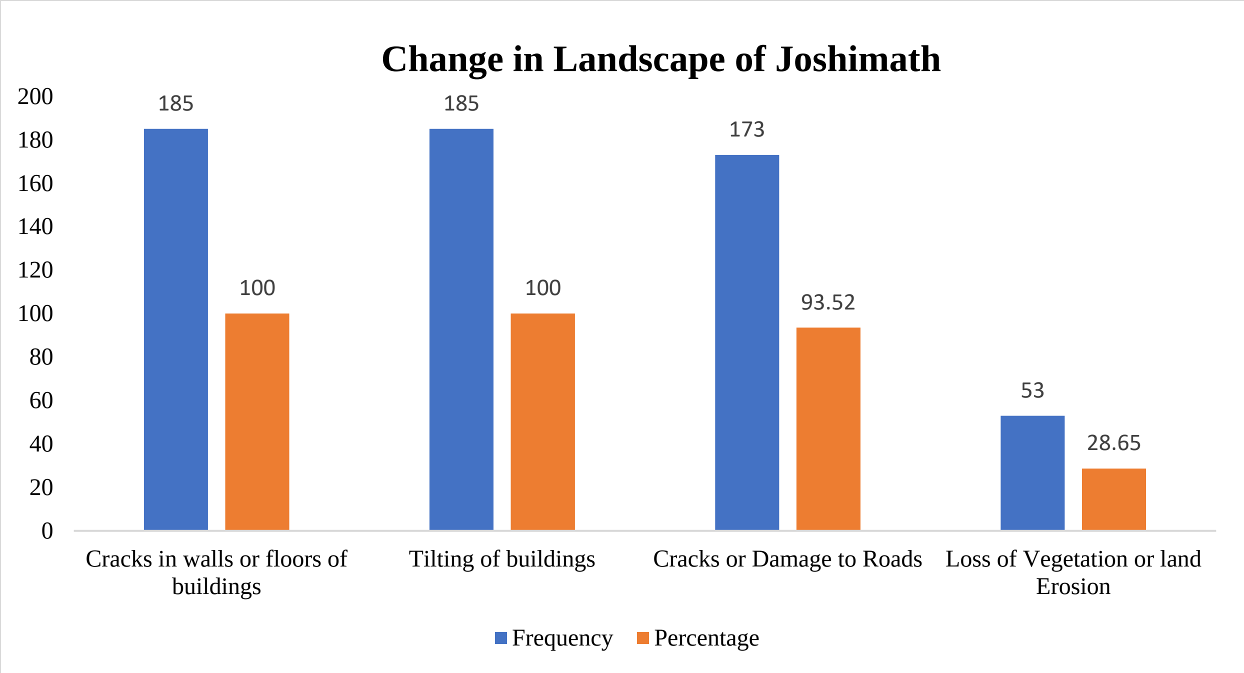

Chart 4: Bar Graph of Change in Landscape of Joshimath

Impact on health and Education- The survey shows that land subsidence has affected both health and education in Joshimath. The greatest impact was on schools, colleges, hospitals, and clinics, where 95.68% of respondents reported infrastructure damage. Reduced attendance due to migration or displacement was reported by 94.06% of the respondents, showing that many students and families were forced to move. School closure or relocation was reported by 82.17%, indicating that educational activities were also disturbed. About 41.09% of the respondents said that financial problems made it difficult to continue their education. In addition, 12.44% reported health problems such as stress and other environmental issues. Overall, the results show that land subsidence has affected education, health services and the daily lives of people in Joshimath.

Table 2: Impact on Health and Education (Primary Data)

Impact on Health and Education		
Value	Frequency	Percentage
Damage to Infrastructure (Schools, Colleges, Hospitals & Clinics)	177	95.68
Reduced Attendance Due to Migration or Displacement	174	94.06
School Closures or Relocation	152	82.17
Limited Access to Education Due to Financial Constraints	76	41.09
Increased Health Problems due to Stress or Environmental Factors	23	12.44

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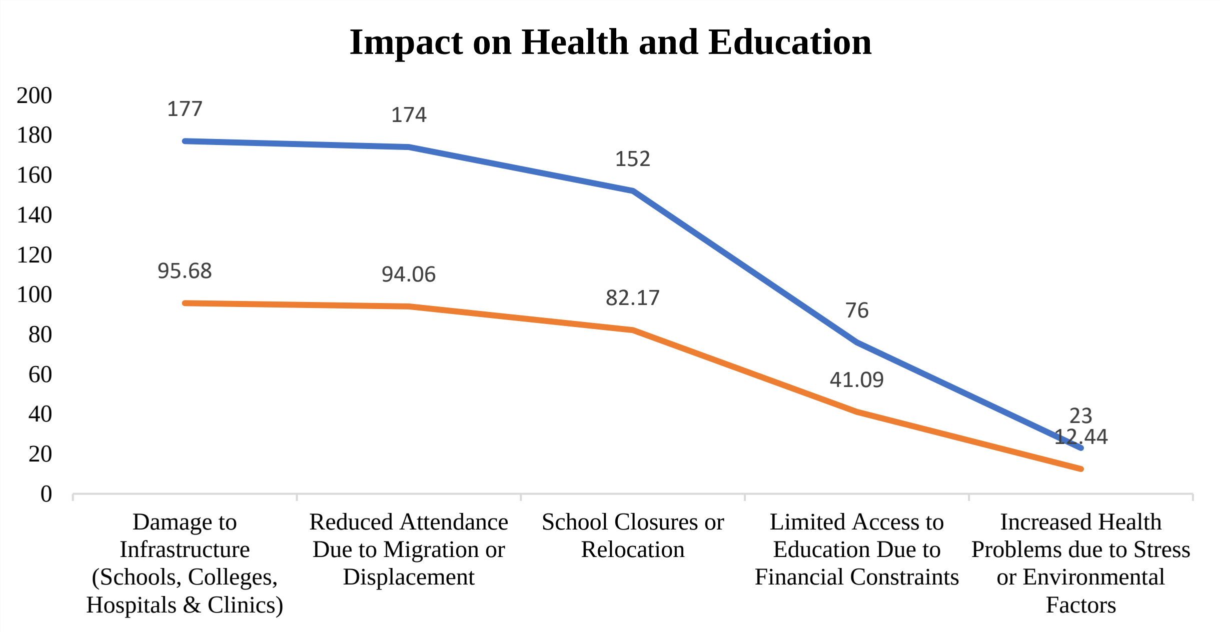

Chart 5: Line Graph of Impact on Health and Education

COMMUNITY ADAPTATION AND INSTITUTIONAL RESILIENCE STRATEGIES

Community-level adaptive strategies

- Temporary relocation, adjusting the location of household activities, and movement to comparatively safer areas adopted by the local communities.
- Residents have undertaken repair and strengthening of damaged houses, including treatment of cracks and other visible structural deficiencies, wherever continued occupation is considered feasible.
- Households have increasingly relied on family members, relatives, neighbours, and community networks for temporary accommodation, financial assistance, information, and other forms of support.
- Some households have adjusted their livelihood and expenditure patterns, including diversification of income sources and reduction of non-essential expenditure to cope with losses and uncertainty.
- Community awareness, local knowledge, mutual assistance, and willingness to relocate from highly affected areas have emerged as important components of local adaptive capacity.

Governmental strategies, policies and plans

- Government agencies have implemented structural safety assessments, damage evaluation, evacuation measures, and relocation of highly vulnerable households to reduce immediate exposure to subsidence-related risks.
- Financial assistance, compensation, rehabilitation and resettlement measures for affected households are important institutional mechanisms for supporting recovery and strengthening long-term resilience.
- Continuous geospatial and geotechnical monitoring, drainage management, and early identification of ground deformation should be strengthened to support risk-informed decision-making and reduce future exposure.
- Risk-sensitive land-use planning and regulation of construction and infrastructure development in unstable and highly vulnerable zones are essential for preventing the accumulation of future risk.
- Long-term resilience requires an integrated rehabilitation and development strategy combining safe housing, livelihood restoration, essential services, community participation, and coordination among local, district, state and scientific institutions.

CONCLUSION AND SUGGESTION

The land subsidence in Joshimath presents a significant challenge due to the combined effects of natural and human-made factors. The region's fragile geology, along with uncontrolled development and deforestation, has exacerbated the situation. To prevent further damage and protect the lives and livelihoods of the people of Joshimath, urgent and coordinated action is required. Addressing land subsidence in Joshimath will require a multi-faceted approach, including improved urban planning, sustainable water management, environmental conservation, and infrastructure reinforcement. The implementation of monitoring and early warning systems, along with effective disaster management strategies, can help mitigate the risks associated with land subsidence. Furthermore, promoting research and collaboration will enable the development of long-term solutions and policies that prioritise the region's safety, stability, and sustainable growth. In conclusion, while the challenges of land subsidence in Joshimath are significant, with concerted efforts, proper planning, and community engagement, the region can work towards minimising its impact and ensuring a safer and more resilient future for its residents. In this study, I suggested that improved urban planning and regulation, strengthened infrastructure, sustainable water management, control of deforestation and Afforestation, and Community relocation and support should be implemented to lead to a better, more sustainable future for the community.

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