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# Analysis of Land Subsidence in Joshimath Township using GIS and Remote Sensing

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## Abstract

In this expansive study, a thorough analysis of land subsidence in the Joshimath area has been conducted, exercising remote sensing (RS) and Geographic Information System (Civilians) tools. The exploration encompasses colourful pivotal parameters including annual rainfall, geology, geomorphology, and lithology, rounded by the integration of different indicators. Joshimath, a fascinating city nestled within the rugged geography of the Indian state of Uttarakhand, stands out for its unique geographical features and its vulnerability to environmental vulnerabilities. The disquisition is carried out with the backing of ArcMap software, a technical Civilians tool, while exercising data sourced from the recognized Indian Space Research Organisation (ISRO) and the National Remote seeing Centre (NRSC). This comprehensive approach aims to give inestimable perceptivity into the dynamic processes associated with land subsidence in the region, offering critical data for disaster mitigation strategies and sustainable land operation in the area. It's noteworthy that the region endured a significant case of land subsidence in late December 2022, emphasizing the punctuality and applicability of this study. This event not only emphasizes the urgency of comprehending land subsidence in Joshimath but also underscores the necessity for ongoing monitoring and mitigation sweats. The integration of these different data sources and logical ways promises to enhance the understanding of land subsidence dynamics and inform decision-makers in the pursuit of flexible and sustainable land use practices in Joshimath and other also vulnerable regions.

## 1. Introduction

Land subsidence is the gradual sinking or settling of the Earth's surface, often due to excessive groundwater extraction, causing land to lower and potentially leading to infrastructure damage. Geological and hydrological data were employed to examine land subsidence in California's San Joaquin Valley, with a specific emphasis on the impact of subsurface fluid extraction on subsidence [1]. The capabilities and fundamental principles of Synthetic Aperture Radar Interferometry (InSAR) and have utility in monitoring land subsidence [2]. The utilization of InSAR for tracking land subsidence resulting from groundwater extraction, with a specific emphasis on California's Central Valley, provides insights into the geological and hydrological elements influencing subsidence in this region [3]. The InSAR technology was used to observe land subsidence in the French Paris Basin, demonstrating the capability of InSAR for investigating subsidence in areas marked by complex geological features [4]. SAR interferometry was used to assess land subsidence in the Kanto Plain, Japan, with a focus on the causes and consequences of subsidence in an urbanised area [5]. The importance of investigating changes in land shapes to gain a deeper understanding of the relationship between subsidence and annual precipitation is highlighted by conducting a geomorphological analysis of land subsidence in an agricultural region [6]. It is important to monitor geological characteristics and land subsidence in areas that are vulnerable to geological hazards. Remote sensing techniques can be utilised to assess land subsidence in geologically precarious zones [7]. Accurate remote sensing

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applications depend on the radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors as well as critical calibration parameters [8]. A strategy to reduce atmospheric effects and raise the accuracy of land subsidence monitoring is to mitigate tropospheric delays in Synthetic Aperture Radar (SAR) interferometry [9]. Remote sensing (RS) and Geographic Information System (GIS) tools can be used to perform a geology-driven analysis of land subsidence using global atmospheric models. The results highlight the role that geology plays in explaining and preventing land subsidence [10]. The relationship between annual rainfall and land subsidence in an urban area can be investigated using remote sensing and GIS techniques. There is a direct correlation between increased annual rainfall and land subsidence, highlighting the importance of monitoring the impact of changing precipitation patterns on land movements [11]. Urban sprawl can be evaluated using Landsat data, and changes in land cover can be tracked using remote sensing methods. These tools provide important information for environmental management and urban planning in cities that are growing quickly [12]. The dynamics of ground deformation and volcanic activity in volcanic regions can be better understood by using radar interferometry to measure surface deformation and coherence [13]. By utilising cutting-edge SAR data processing techniques, the "SqueeSAR" algorithm may be implemented to process interferometric data-stacks and improve the accuracy of land deformation monitoring [14]. Radar interferometry can be used to look into uplift and subsidence, exposing intricate patterns of deformation in this urban area [15].

Land subsidence in coastal regions can be assessed using geomorphological analysis, highlighting the importance of incorporating geomorphic factors into subsidence estimation. The relationship between coastal landforms and instances of subsidence can be examined using GIS [16]. An approach based on lithology can understand land subsidence in arid environments. When discussing subsidence phenomena, lithological variations are important to take into account [17]. It is possible to use lithological variations to look into land subsidence in an arid area. Variations in the area's geological composition, which affect subsidence patterns, can be quantified by using remote sensing and GIS techniques [18]. Land subsidence can be analysed using Persistent Scatterer Interferometry (PSI) with ALOS PALSAR data. With implications for infrastructure management and urban planning, the application of PSI may offer insightful information about patterns of urban subsidence [19]. The assessment of the risks and vulnerabilities associated with land subsidence can be related to the application of GIS and remote sensing. Additional information can shed light on the vital goals of comprehending and reducing the risks connected to subsidence in vulnerable areas [20]. To investigate land subsidence, InSAR and GPS data can be combined, supplying more information about the patterns of ground deformation in volcanic regions [21].

Remote sensing data can be combined with geomorphological analysis to assess land subsidence, providing important new information about how landforms change as a result of subsidence and how these changes relate to geological features [22]. Geological considerations may be made in order to obtain a thorough grasp of urban land subsidence. Understanding and reducing land subsidence in urban areas depends on the kinds of sediment present and the underlying geology [23]. InSAR data may undergo spatially variable tropospheric correction, especially when monitoring land deformation surrounding volcanoes. This technique improves the InSAR analysis's accuracy, which is essential for studying volcanic eruptions and land subsidence [24]. In an agricultural region, land subsidence can be assessed using remote sensing and geomorphological analysis. It can shed light on the connection between changes in landforms, geological features, and subsidence in rural areas [25].

It is possible to monitor land subsidence and evaluate its effects on urban development by using InSAR. It sheds light on how subsidence and urban planning interact in a metropolis that is expanding quickly [26]. Land subsidence can be monitored and analysed using Persistent Scatterer Interferometry (PSI). This can provide insights into patterns of urban subsidence, which has important implications for urban planning [27]. The impact of geology on land subsidence in coastal cities can be investigated using GIS. It emphasises the critical role of geological factors, particularly sediment types, in understanding and mitigating land subsidence in these areas [28]. It is possible to assess the effects of land subsidence and sea level rise on coastal communities. This could help with the challenges of dealing with subsidence in the context of climate change [29]. The application of PSI and Sentinel-1 data can be used to analyse land subsidence. Underscoring the importance of PSI in monitoring subsidence in urban areas, with a particular emphasis on infrastructure stability [30]. Using the SRTM satellite dataset, slope aspect, slope degree, curvature, lithology, land use/land cover, and drainage density in GIS, the weighted overlay method (WOM) can be used to designate landslip danger zones [31]. Land subsidence assessment can be done with Sentinel-1 InSAR time series analysis. Sentinel-1 data can be used to monitor ground deformation in urban areas [32]. Urban land subsidence and its significance for adapting to climate change can be investigated using remote sensing and geographic information systems (GIS). Emphasising how important it is to keep an eye on subsidence, particularly in light of evolving precipitation patterns [33]. GIS-multi-criteria decision analysis (MCDA) techniques are increasingly employed in landslide susceptibility mapping for predicting future hazards, informing land use planning, and enhancing hazard preparedness [34]. In tropical regions, land subsidence can be evaluated by combining remote sensing data with geomorphological analysis. It advances our knowledge of how landform modifications brought on by subsidence affect regions with a variety of climates [35].

This paper aims to comprehensively explore the factors contributing to land subsidence in the study area. This investigation encompasses multiple aspects including the annual average rainfall, geology, geomorphology, and lithology of the region. The study seeks to establish correlations between these factors and various remote sensing indices. Ultimately, the research culminates in identifying potential causes of land subsidence instances, substantiated by the findings of the study.

## 2. Studied area

Joshimath, also known as Jyotirmath, is a picturesque town situated in the Garhwal Himalayas of Uttarakhand, India. Nestled at an elevation of 1,875 meters (6,152 feet) above the sea level, it serves as a vital starting point for journeys to various religious and tourist destinations in the region. One of its most prominent attractions is the Badrinath Temple, part of the Char Dham pilgrimage sites, which holds immense significance for Hindus. Pilgrims flock to Joshimath to visit this revered temple dedicated to Lord Vishnu, with the belief that completing the Char Dham pilgrimage will lead to moksha, or liberation from the cycle of birth and death. Besides the Badrinath Temple, the town is home to other essential Hindu temples like the Vasudeva Temple, Narsingh Temple, and the Shankaracharya Math, one of the four cardinal pithas established by Adi Shankara, a renowned Hindu philosopher. Joshimath's natural beauty is equally remarkable, with snow-capped peaks and lush forests surrounding the town. It is home to numerous glaciers and is traversed by the Alaknanda River, offering opportunities for white water rafting and kayaking. Its proximity to other tourist attractions enhances its appeal. The Valley of Flowers, a UNESCO World Heritage Site, is a mere 13 kilometres away, attracting trekkers and nature enthusiasts with its diverse flora and fauna. Auli, a hill station located 16 kilometres from Joshimath, is famous for its scenic beauty and skiing opportunities. The town serves as a base for trekkers and adventure enthusiasts, offering access to trekking routes like the Valley of Flowers and the Kuari Pass. It also provides opportunities for activities such as camping and white-water rafting. Joshimath's economy revolves around tourism, with a range of accommodations, restaurants, and shopping centres offering traditional handicrafts and woollen products. However, the town faces a pressing issue of land subsidence due to fragile geological terrain, extensive infrastructure development, and the impact of climate change.

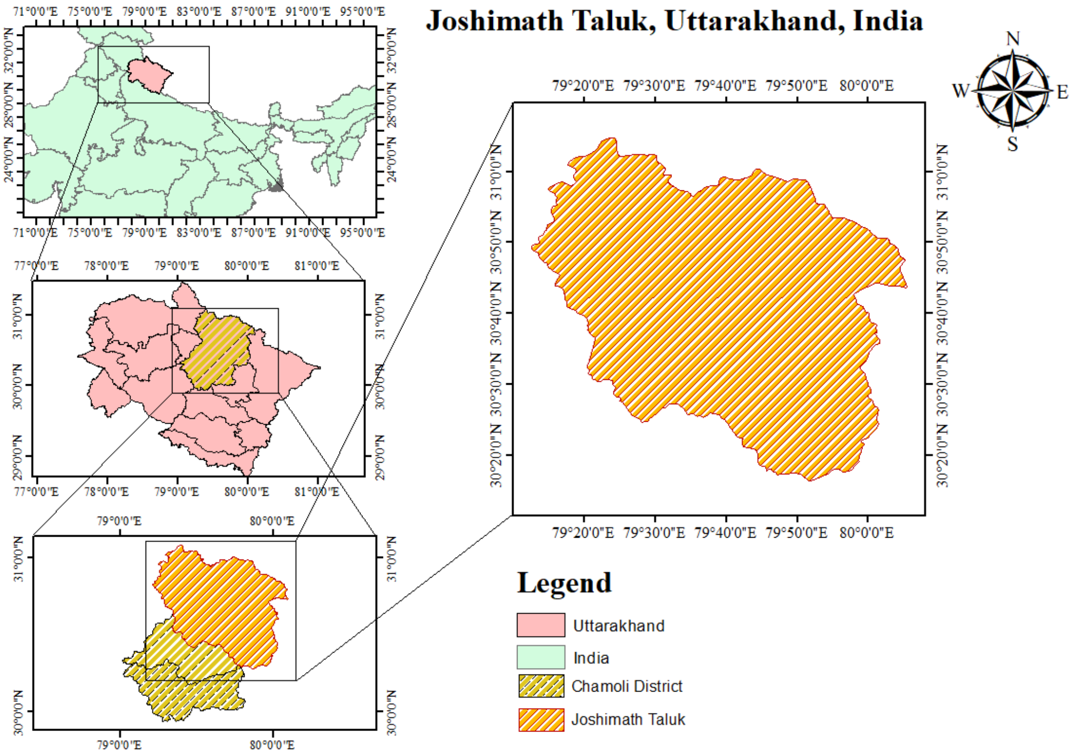


**Figure 1. Studied area: Joshimath Taluka.**

In December 2022 and January 2023, the Indian Space Research Organisation (ISRO) reported alarming land subsidence in Joshimath, Uttarakhand. Satellite images revealed that this picturesque town sank by 5.4 cm in just 12 days, following a slower subsidence of 8.9 cm between April and November 2022. The sudden acceleration of this sinking phenomenon has led to a crisis, causing the local administration to declare Joshimath a land-subsidence zone.

As a result of this alarming situation, over 700 houses developed dangerous cracks, prompting families to evacuate their homes. Moreover, numerous roads, hotels, and hospitals were also affected. The subsidence primarily impacted the central part of Joshimath including critical locations like the Army helipad and the Narsingh Mandir. The development of the Army Helipad can be visualised through Google Earth imagery, as illustrated in Figure 2.

ISRO identified the Joshimath-Auli road as the epicentre of this subsidence event. The overall shape of the subsidence zone resembled a typical landslide, with a tapered top and a fanned-out base. The National Remote Sensing Centre of ISRO, which released the satellite images, noted the stark contrast in sinking rates. In just 12 days, the town's subsidence reached 5.4 cm, compared to the slow 9 cm subsidence observed over seven months between April and November 2022. The rapid subsidence event took place between the last week of December 2022 and the first week of January 2023, causing widespread concern and necessitating immediate action. With houses cracking and the ground sinking rapidly, the local administration's decision to declare Joshimath a land-subsidence zone was a crucial step in ensuring the safety of the residents. The situation continues to be closely monitored, as experts work to understand and mitigate the causes and consequences of this troubling subsidence event.

**Figure 2. Google Earth Imagery depicting Expansion of Army Helipad.**

Land subsidence, as evidenced by the recent case in Joshimath, Uttarakhand, has significant implications for various aspects of society and the environment. The accelerated sinking of Joshimath, from a slow 9 cm over seven months to a rapid 5.4 cm in just 12 days, serves as a stark reminder of the potential consequences. One immediate concern is the severe damage to infrastructure including roads, buildings, and utilities, which can lead to substantial economic losses and disrupt daily life. Moreover, the safety of the affected population is at risk due to unstable ground conditions and the potential for accidents and injuries. In response, authorities must prioritize evacuation and relocation, as witnessed in Joshimath, to ensure human safety.

## 3. Analysis methodology

A comprehensive approach has been employed to investigate land subsidence in a specific region. This multifaceted analysis leverages several distinct data sources and tools. Firstly, annual rainfall data spanning from 1990 to 2020 was scrutinized, with information sourced from the Indian Meteorological Department (IMD) in Pune. This element of the study allows for a temporal examination of precipitation patterns and their potential influence on land subsidence. Additionally, the research incorporates various remote sensing indices, specifically the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Normalized Difference Built-Up Index (NDBI). These indices were derived from data obtained through the US Geological Survey's Earth explorer platform. By utilizing these indices, the study can assess changes in land cover, vegetation, and built-up areas over time.

Furthermore, the analysis extends to geology, geomorphology, and lithology by utilizing data sourced from the Geological Survey of India's Bhukosh database. This segment of the research delves into the geological characteristics of the area including its landforms and rock types. Such data is crucial in understanding the subsurface conditions that may contribute to land subsidence. All these analyses were conducted using ArcMap, a Geographic Information System (GIS) software developed by ESRI. This software serves as a powerful tool for integrating and visualizing spatial data, enabling researchers to map, analyse, and draw insights from the diverse datasets used in the study. In summary, this holistic approach amalgamates meteorological, remote sensing, and geological information within a sophisticated GIS environment to provide a comprehensive understanding of land subsidence dynamics in the region.

### 3.1. Annual rainfall analysis

The annual rainfall analysis process begins with the acquisition of NetCDF data from the Indian Meteorological Department (IMD) in Pune. This data is then imported into ArcMap, a Geographic Information System (GIS) software, using the Multidimensional Tools, specifically the NetCDF to Raster Layer function, to convert the multidimensional data into a raster format. The resulting raster data is further refined by extracting the relevant information for the desired geographic area through the export data function. To enhance the analysis, a band composition is performed using raster processing tools, combining various layers of data to generate meaningful insights. The spatial data is then corrected, to ensure spatial accuracy. To aggregate the data appropriately, spatial analyst tools are employed, applying cell statistics with the overlay statistic set to SUM. This step facilitates the summation of rainfall values over the desired region.

To make the data more accessible and interpretable, a conversion tool is applied to transform the raster data into points. This allows for a more granular analysis of rainfall at specific locations within the studied area. Lastly, interpolation is carried out using the Inverse Distance Weighting (IDW) tool, with a specified cell size of 12.5 and a processing extent that is limited to the studied area. This interpolation method helps in estimating rainfall values at unsampled locations based on the known data points, creating a continuous surface of annual rainfall distribution. This comprehensive process enables a detailed and accurate analysis of annual rainfall patterns, vital for various applications including hydrology, agriculture, and urban planning and has been summarised in a flow diagram, as shown in Figure 3. The analysis of annual rainfall holds substantial significance in addressing land subsidence in a region. Land subsidence, the gradual sinking of the Earth's surface, is often linked to excessive groundwater extraction. Annual rainfall plays a pivotal role as it acts as a vital source of groundwater recharge. In areas where groundwater is a major water resource, low rainfall can lead to over-pumping of aquifers, causing subsidence due to the compaction of unconsolidated sediments. By monitoring and analysing annual rainfall patterns, authorities, and researchers can gauge the availability of this essential water source. Adequate rainfall serves to replenish aquifers and maintain groundwater levels, thereby reducing the need for excessive extraction and mitigating subsidence risks. Additionally, rainfall data aids in the management of water resources and allows for the development of sustainable groundwater management strategies. In essence, annual rainfall analysis provides critical insights for policymakers and hydrogeologists, aiding in the preservation of land integrity and the prevention of subsidence-related damage to infrastructure and the environment.

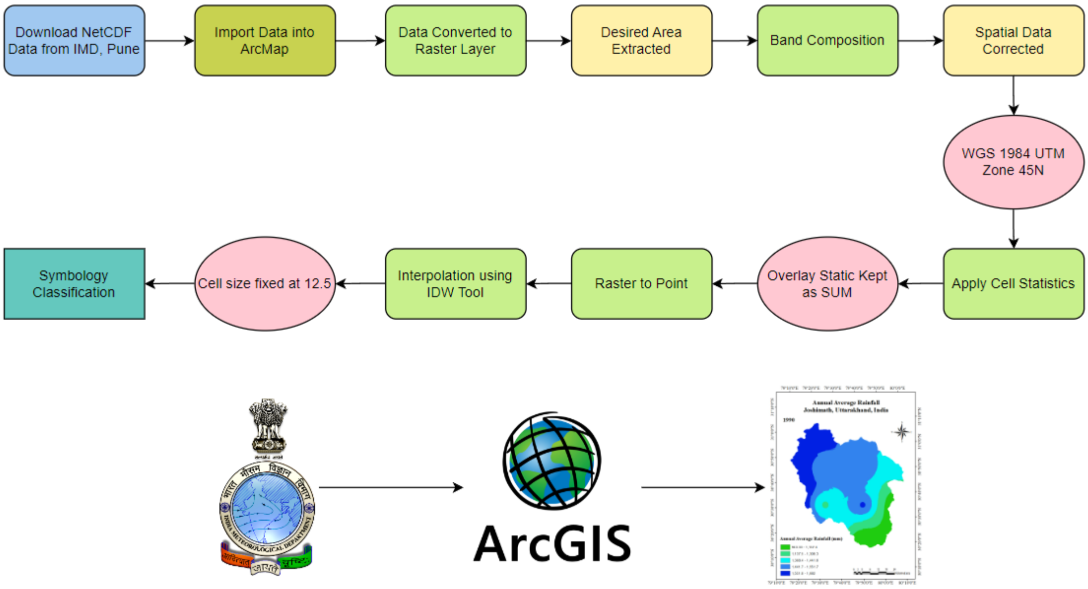


Figure 3. Flow diagram of annual rainfall analysis.

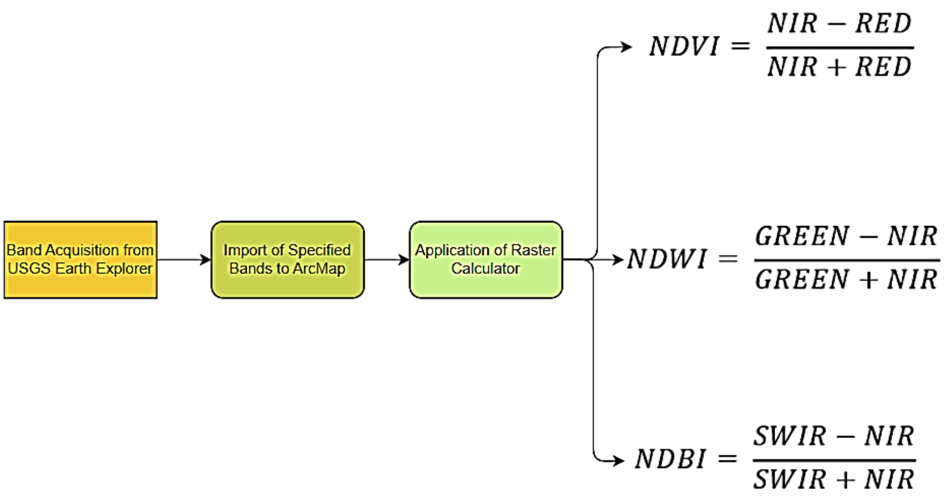
### 3.2. Remote sensing indices

Remote sensing indices play a crucial role in monitoring and analysing changes in land cover, vegetation, and water bodies over time. In this case, satellite imagery from the USGS Earth Explorer website was used to calculate NDVI (Normalized Difference Vegetation Index), NDWI (Normalized Difference Water Index), and NDBI (Normalized Difference Built-up Index) for the years 2000, 2010, 2015, and 2020. Figure 4 illustrates the equations used to calculate the indices. The choice of different satellite sensors such as LANDSAT 7 for 2000, LANDSAT 4-5 for 2010, and LANDSAT 8 for 2015 and 2020, is essential because it ensures consistency and compatibility of the data across these years, the acquisition details of the satellite imageries is summarised in Table 1. The NDVI quantifies the health and density of vegetation, with higher values indicating healthier and denser vegetation. NDWI identifies water bodies and their changes, while NDBI highlights built-up areas and urban expansion. By applying raster calculator tools, one can manipulate the satellite data to derive these indices, allowing for easy visualization of changes in land features over time.

The analysis of these indices is vital for land subsidence studies. Land subsidence is the gradual sinking or settling of the Earth's surface, often caused by human activities like groundwater extraction and urban development. Monitoring changes in NDVI, NDWI, and NDBI can help detect the impacts of these activities on the environment. For example, a decreasing NDVI might indicate deforestation or land degradation, while an increasing NDBI could signal urban sprawl. NDWI changes could reveal alterations in water bodies due to land-use changes or natural factors. In sum, the use of remote sensing indices and satellite imagery provides a powerful tool for tracking environmental changes and their impacts over time. It aids in making informed decisions related to land use, conservation, and urban planning, and it plays a critical role in addressing issues like land subsidence by identifying areas at risk and guiding mitigation efforts.

Table 1. Acquisition data of satellite imagery.

| Year | Satellite | Date of acquisition |
|---|---|---|
| **2000** | LANDSAT 7 | 10/05/2000 |
| **2010** | LANDSAT 4-5 | 16/05/2010 |
| **2015** | LANDSAT 8 | 28/05/2015 |
| **2020** | LANDSAT 8 | 10/06/2020 |



$$NDVI = \frac{NIR - RED}{NIR + RED}$$

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR}$$

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR}$$

**Figure 4. Flow diagram for remote sensing indices and indices equations.**

### 3.3. Geological features analysis

In the context of geological and geomorphological mapping, the data obtained from the Geological Survey of India (GSI) Bhukosh database serves as a foundational resource for understanding the Earth's surface and subsurface features in a given studied area. This data encompasses a diverse range of information related to geology, geomorphology, and lithology, which can be crucial for numerous scientific and environmental applications. After downloading the data, the next step involves extracting relevant information specifically tailored to the studied area. This process is essential to focus on the specific geographical region under investigation and avoid unnecessary clutter in the analysis. Once the data extraction is completed, the classification of geological, geomorphological, and lithological features becomes pivotal. This classification involves categorizing the extracted information into distinct groups or classes, which can provide insights into the composition, structure, and history of the Earth's surface. Figure 5 shows the summary of the process involved in the analysis of these features. Such classification is vital for various purposes including land subsidence analysis. Geology and lithology data can help identify the types of rocks and sediments present in the subsurface, which, in turn, can influence land subsidence due to factors like groundwater extraction and natural geological processes. Meanwhile, geomorphological data helps in understanding the surface features and landforms, which can give clues about potential subsidence-prone areas. By combining these features, a comprehensive analysis of land subsidence can be conducted, allowing for better risk assessment, urban planning, and environmental management in the studied region.

In summary, the process of downloading, extracting, and classifying data from the GSI Bhukosh database is a fundamental step in understanding the geological, geomorphological, and lithological features of a given area. These features play a crucial role in the analysis of land subsidence, as they provide insights into the underlying geological conditions and surface features, which are essential for predicting and mitigating the risks associated with land subsidence in the region. This holistic approach to data utilization contributes significantly to informed decision-making and sustainable land management practices, ultimately safeguarding communities and their environments from the adverse effects of subsidence-related issues.

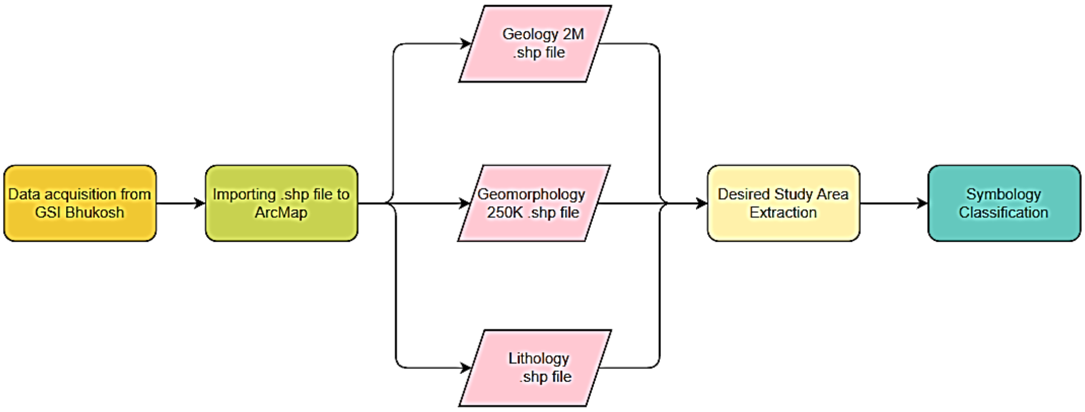


**Figure 5. Flow diagram for geological features.**

## 4. Results and discussion

### 4.1. Annual average rainfall

The annual average rainfall in a region is a critical environmental indicator, reflecting both natural climate variability and the potential impacts of climate change. In the case of the specific region under discussion, a significant change in rainfall patterns has been observed over the past few decades. To gain a comprehensive understanding, Data has been divided down into three main time periods: 1990 to 2005 and 2005 to 2020.

From 1990 to 2005, the region experienced a notable dip in the lowest bracket of annual rainfall. In 1990, the range was 943.33-1137.4 mm, whereas in 2005, it decreased to 689.41-850.03 mm. This decline can be attributed to several factors, including natural climate variability and meteorological phenomena. However, it's crucial to note that this is not necessarily indicative of a long-term trend. Climate patterns can exhibit substantial year-to-year variation, and one anomalous year does not necessarily represent a permanent shift.

The period from 2005 to 2020 tells a different story. The lowest bracket of rainfall rebounded to 1127.1-1437.4 mm by 2020, indicating a recovery from the lower values observed in 2005. This resurgence is more in line with a broader trend observed in many regions worldwide, where the overall trend has been an increase in annual precipitation due to climate change. The increase in rainfall, as indicated by the rising lower bracket, suggests that this region is now experiencing more frequent and heavier rainfall events compared to earlier years.

The highest recorded rainfall values also demonstrate this trend. From 1990 to 2020, the highest annual rainfall values increased from 1682 mm to 2445.8 mm. While these extreme values may not be indicative of average conditions, they illustrate the potential for heavy rainfall events in the region. These trends could have significant implications for the local environment, particularly in terms of land subsidence.

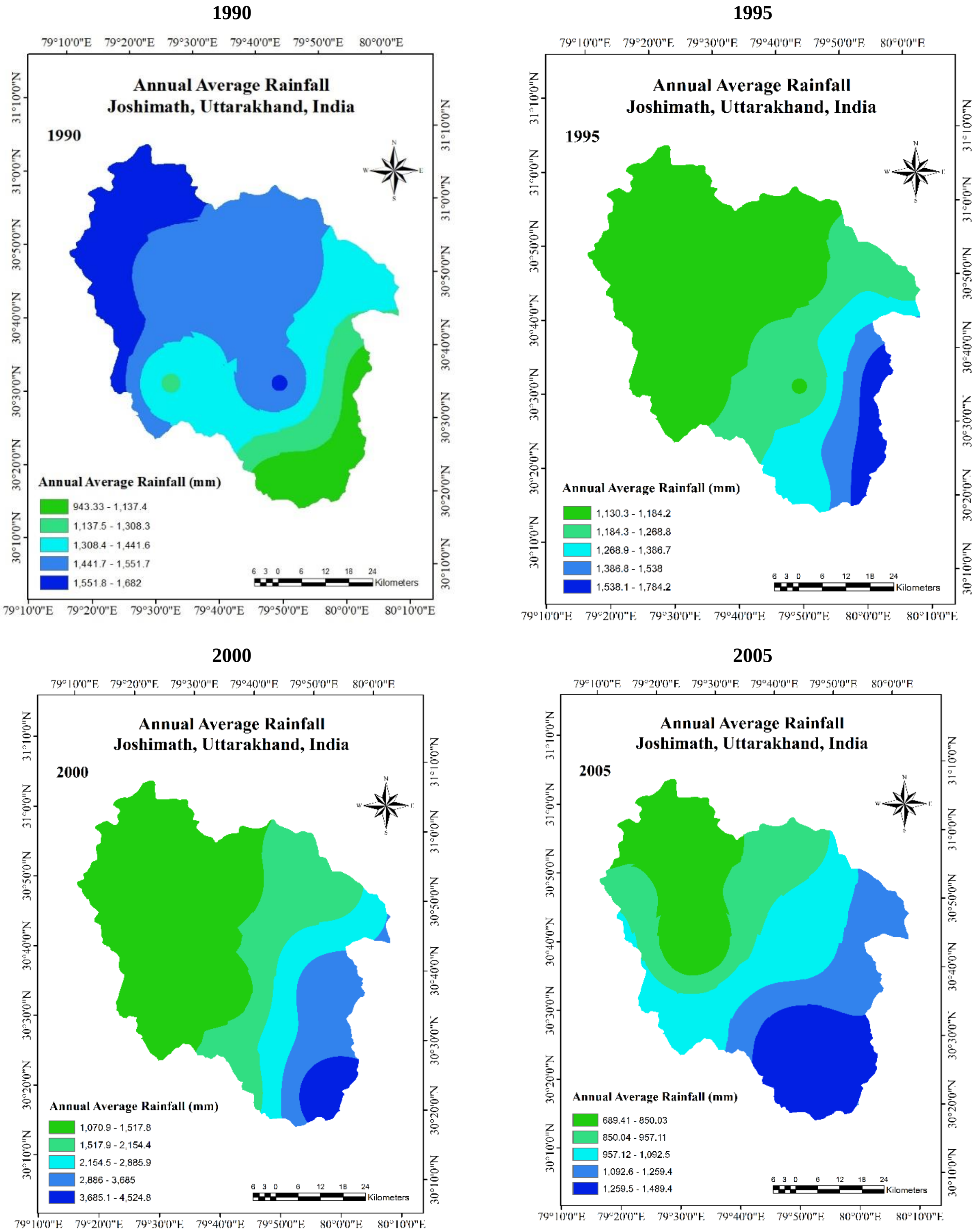


**Figure 6. Annual average rainfall maps.**

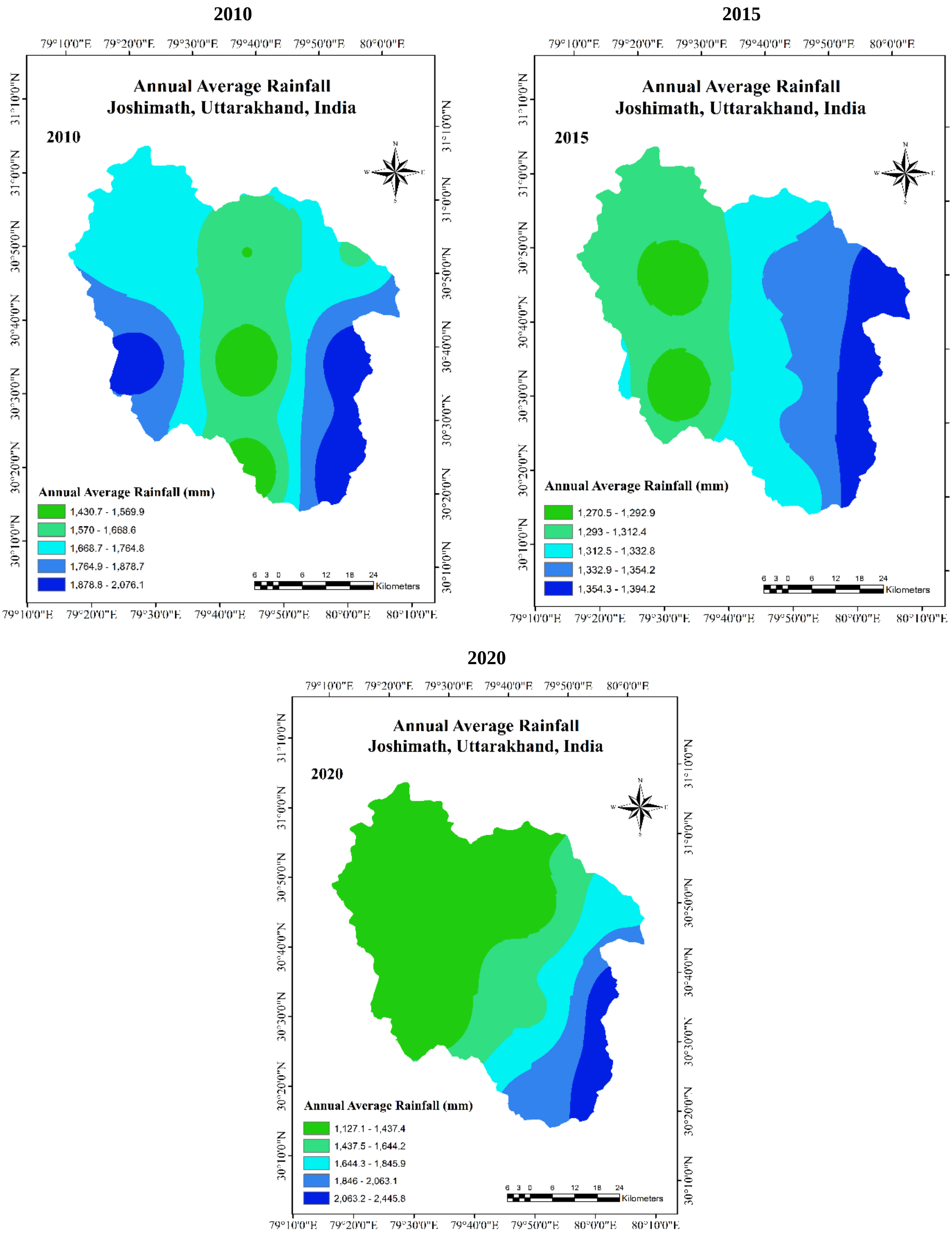


Figure 7. Annual average rainfall maps.

Land subsidence is the gradual sinking or settling of the Earth's surface, and it can occur due to various factors including heavy rainfall. When regions experience unusually high levels of precipitation, the water can infiltrate the soil and increase the weight on underlying geological layers. This excess weight can compress the sediments and rock layers beneath, leading to subsidence. Moreover, prolonged heavy rainfall can saturate the ground, making it more susceptible to subsidence.

In the context of the region experiencing increasing annual rainfall, there is a potential for land subsidence to become a more pressing issue. Subsidence can have far-reaching consequences, such as increased flooding risk, damage to infrastructure, and changes in groundwater levels. To mitigate these effects, it's essential for local authorities and stakeholders to monitor and manage the region's water resources effectively. Implementing sustainable land-use practices, maintaining drainage systems, and investing in infrastructure resilience are key steps to adapt to the changing climate and mitigate potential subsidence issues.

The region's annual average rainfall has shown a dynamic pattern over the years, with a temporary dip in the mid-2000s but an overall increasing trend towards heavier rainfall. These changes in precipitation patterns can have implications for the occurrence of land subsidence, a phenomenon that can lead to various environmental and infrastructure challenges. It is crucial for the region to adapt to these evolving climate conditions by implementing strategies to manage water resources effectively and promote sustainable land use practices to mitigate the potential consequences of increased rainfall.

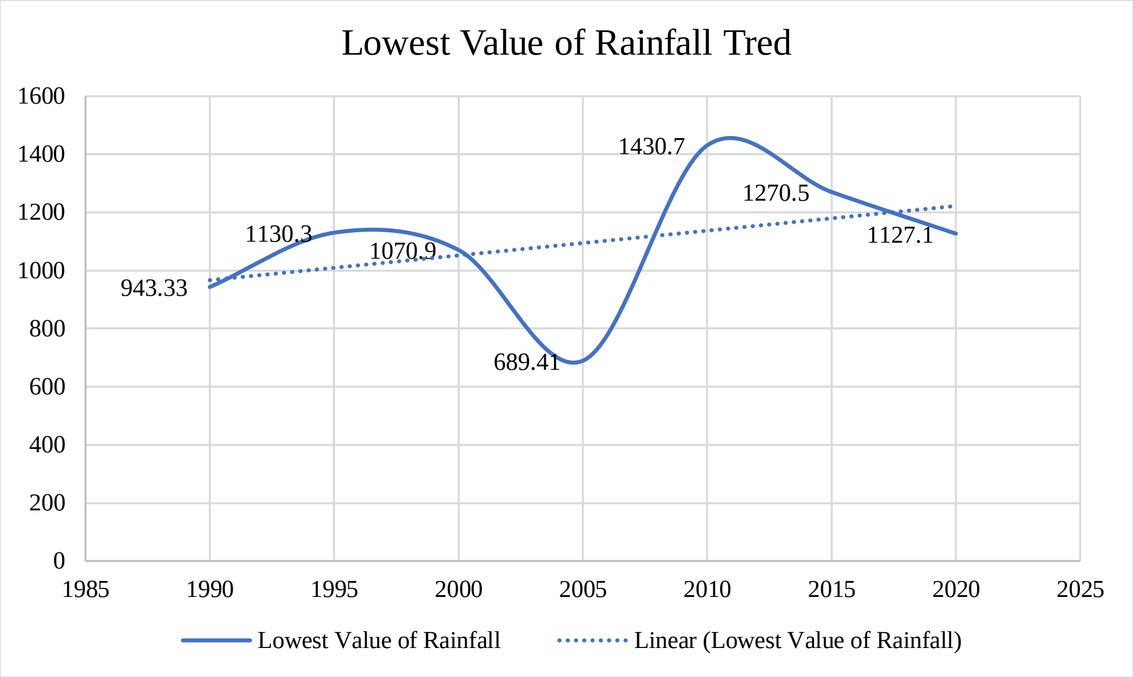


**Figure 8. Lowest rainfall trend along with Linear Trendline.**

### 4.2. Remote sensing indices

Remote sensing indices such as NDVI (Normalized Difference Vegetation Index), NDWI (Normalized Difference Water Index), and NDBI (Normalized Difference Built-Up Index) play a crucial role in the analysis of land subsidence in a particular area.

NDVI measures the health and density of vegetation, making it a valuable tool in monitoring land subsidence. As land sinks, vegetation stress increases, leading to changes in NDVI values. A decrease in NDVI can indicate areas where subsidence has affected plant health.

NDWI focuses on the presence of water bodies and their changes over time. Land subsidence often leads to alterations in water distribution, such as increased ponding or flooding. NDWI helps in identifying these shifts, which are indicative of subsidence-related issues.

NDBI, on the other hand, highlights the extent of built-up areas. As land subsides, infrastructure can be damaged or compromised. A rise in NDBI values might indicate an increase in the built environment due to subsidence-related construction or infrastructure repairs.

The combination of these indices provides a comprehensive understanding of land subsidence, offering insights into its causes and impacts. This information is invaluable for urban planning, disaster mitigation, and environmental conservation efforts in the affected area, allowing for timely intervention to mitigate subsidence-related risks.

#### 4.2.1. Normalized difference vegetation index (NDVI)

The analysis of NDVI (Normalized Difference Vegetation Index) using LANDSAT imagery obtained from USGS for the years 2000, 2010, 2015, and 2020 in this region has provided valuable insights into land cover changes over time. The NDVI values, however, have been significantly affected by the presence of large ice deposits in the region. Additionally, there have been notable changes in other land cover classes including water bodies, built-up areas, and vegetation.

The presence of substantial ice deposits in the region, accounting for nearly 50% of the entire area, which can ideally be seen in the Figure 8, can have a profound impact on land subsidence. Land subsidence, often associated with the excessive withdrawal of groundwater or the compaction of unconsolidated sedimentary layers, is exacerbated by the presence of ice. As the ice melts due to rising temperatures, it can lead to a phenomenon known as "glacial isostatic adjustment" (GIA). GIA occurs when the Earth's crust rebounds as the weight of ice is removed. In areas with heavy ice deposits, the removal of ice can result in a gradual uplifting of the land. This uplift, caused by the melting of ice, may offset the effects of land subsidence to some extent. However, it is crucial to consider the interplay of various factors, including GIA, when assessing the overall impact on land subsidence. The gradual rebounding of the crust can alleviate subsidence in some areas but exacerbate it in others, depending on the complex geological and hydrological conditions.

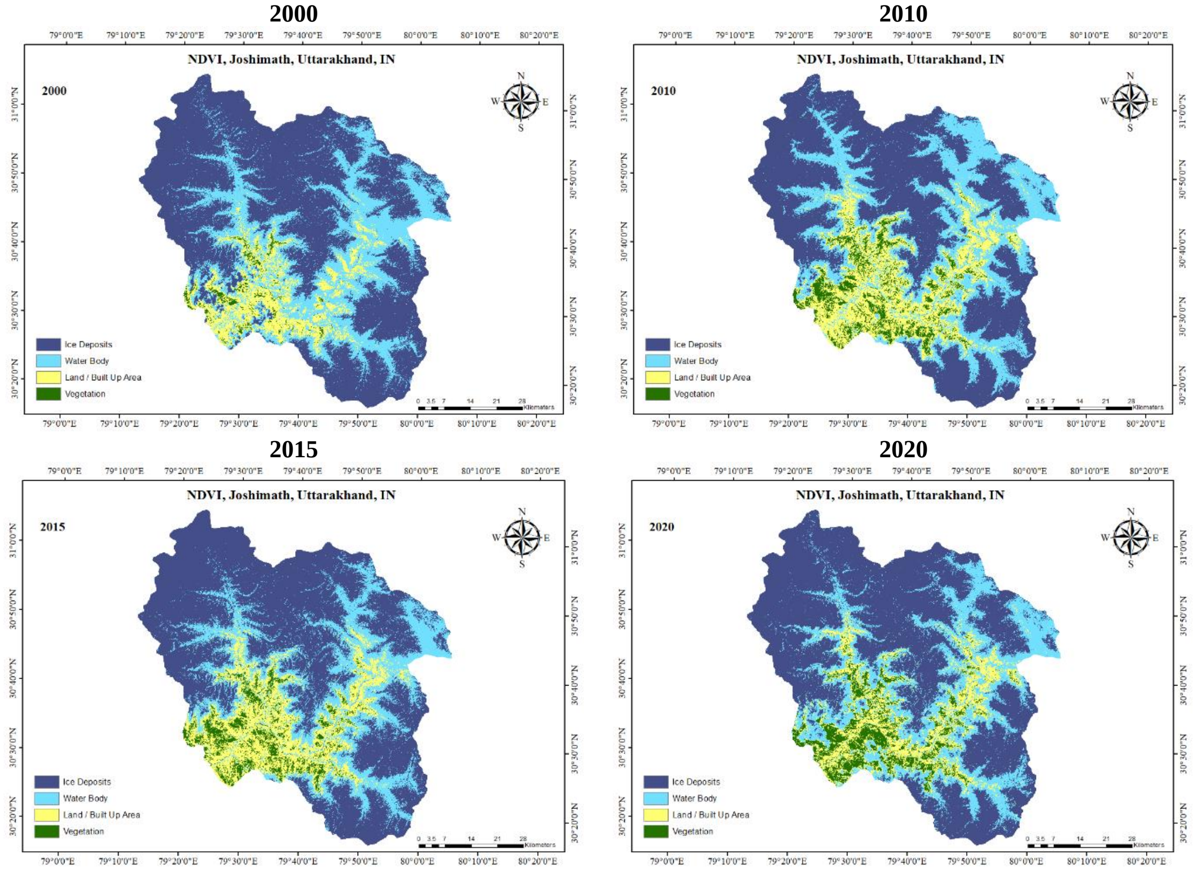


**Figure 9. NDVI map.**

The data provided for the years 2000, 2010, 2015, and 2020 reflect changes in land cover classes within the region. The percentage of water bodies has seen slight fluctuations over the observed years, with values of 29.76, 29.83, 25.63, and 26.92. This variation suggests changes in the water table level or natural seasonal variations. A decrease in water body percentage from 2010 to 2015 and a subsequent increase may be indicative of altered hydrological patterns or human activities affecting water bodies.

Built-up areas have seen notable changes, with values of 10, 16.42, 15.04, and 11.74. This data indicates urbanization and infrastructure development trends in the region. The increase in built-up areas from 2000 to 2010 is likely a result of population growth and urban expansion. However, the subsequent decrease from 2010 to

2015 and a slight rise by 2020 may be due to factors like economic fluctuations, land-use planning or environmental considerations.

Vegetation, as represented by NDVI, has shown positive changes over the years, with values of 1.21, 5.62, 4.66, and 6.63. This indicates an increase in vegetation density and health. The growth in vegetation could be linked to efforts in afforestation, reforestation or natural ecological restoration initiatives in the region, possibly aimed at mitigating the effects of land subsidence and enhancing environmental sustainability. The percentage area distribution can be visualized in Figure 9.

The presence of heavy ice deposits in the region can influence land subsidence through glacial isostatic adjustment, causing the land to gradually uplift as the ice melts. The observed data for water bodies, built-up areas, and vegetation reflect dynamic changes in land cover and land use, likely driven by factors such as urbanization, climate change, and conservation efforts. Understanding the interactions between these factors and their implications for land subsidence is essential for sustainable land management and environmental planning in the region.

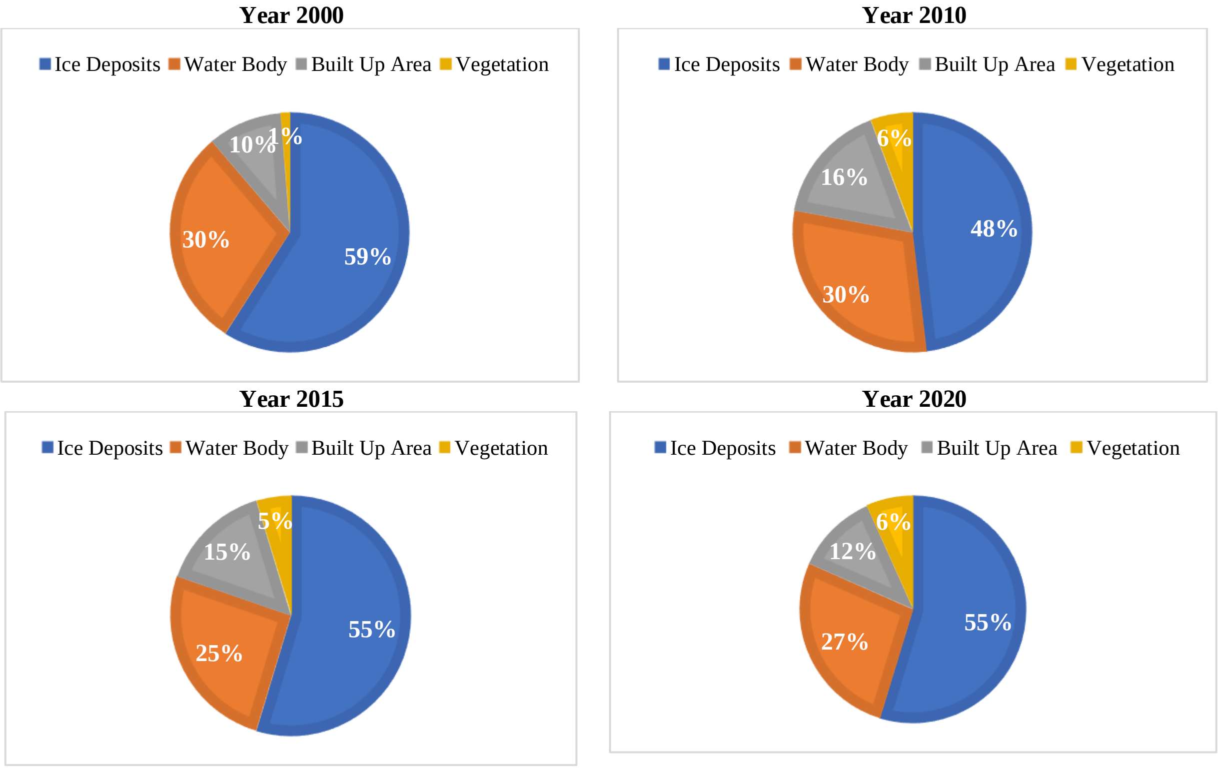


**Figure 10. NDVI area distribution over the year.**

### 4.2.2. Normalized difference water index (NDWI)

In the analysis of Normalized Difference Water Index (NDWI) using Landsat imagery for the years 2000, 2010, 2015, and 2020, significant variations in NDWI values were observed and the same were mapped (Figure 10). NDWI is a commonly used remote sensing index to detect changes in water content in the landscape. In our case, we found that higher NDWI values cover varying percentages of the area over the years. This suggests changes in water availability and distribution, which can have important implications for land subsidence and environmental dynamics.

Land subsidence is the gradual sinking or settling of the Earth's surface, and it is often associated with the depletion of groundwater resources. The changes in NDWI values observed in our analysis could be indicative of alterations in the distribution of water resources. When NDWI values decrease over time, as seen from 2000 to 2010, it might suggest a reduction in available water. This can lead to increased groundwater extraction, which in turn can contribute to land subsidence. Conversely, when NDWI values increase, as observed from 2010 to 2015, it may indicate replenishment of water resources, potentially mitigating land subsidence. However, other factors such as land use changes and climate variations can also influence these trends.

The variations in NDWI values from 2000 to 2020 have significant environmental implications. A decrease in NDWI, as seen from 2000 to 2010, might signify a heightened risk of land subsidence due to over-extraction of groundwater, which can lead to ground compaction and sinking. Conversely, an increase in NDWI, as observed from 2010 to 2015, is a positive sign for the environment, suggesting improved water availability. This can benefit ecosystems, support agriculture, and reduce the risks of subsidence. However, maintaining a stable water balance is crucial to prevent long-term environmental damage.

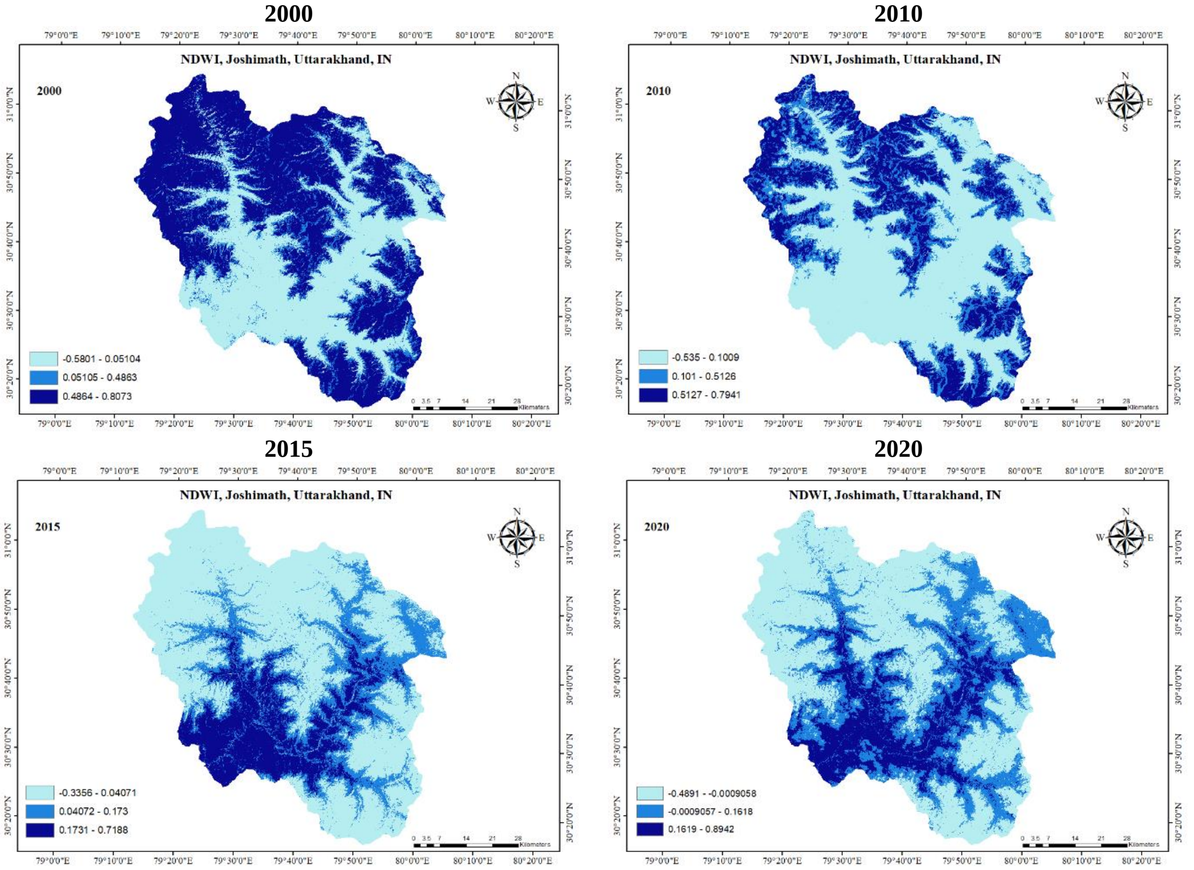


**Figure 11. NDWI map.**

The findings from our NDWI analysis highlight the importance of responsible water resource management. To mitigate the potential effects of land subsidence, it is essential to implement sustainable water management practices. This may include the regulation of groundwater extraction, the promotion of water conservation, and the monitoring of land use changes that can impact water availability. Moreover, considering the effects of climate change on water resources is vital in long-term planning. Sustainable and informed policies are crucial to maintaining a healthy balance between water availability and land stability.

The NDWI is a remote sensing index that measures the presence of water in a given area. It is particularly useful in monitoring changes in water bodies and can provide valuable insights into hydrological trends. In our analysis, NDWI values were assessed using Landsat imagery for four different years: 2000, 2010, 2015, and 2020. The key finding from our analysis is that higher NDWI values covered 50% of the area in 2000, 25% in 2010, 63% in 2015, and 53% in 2020. These percentages indicate significant fluctuations in water content over time and can be visualized through the graph in Figure 12.

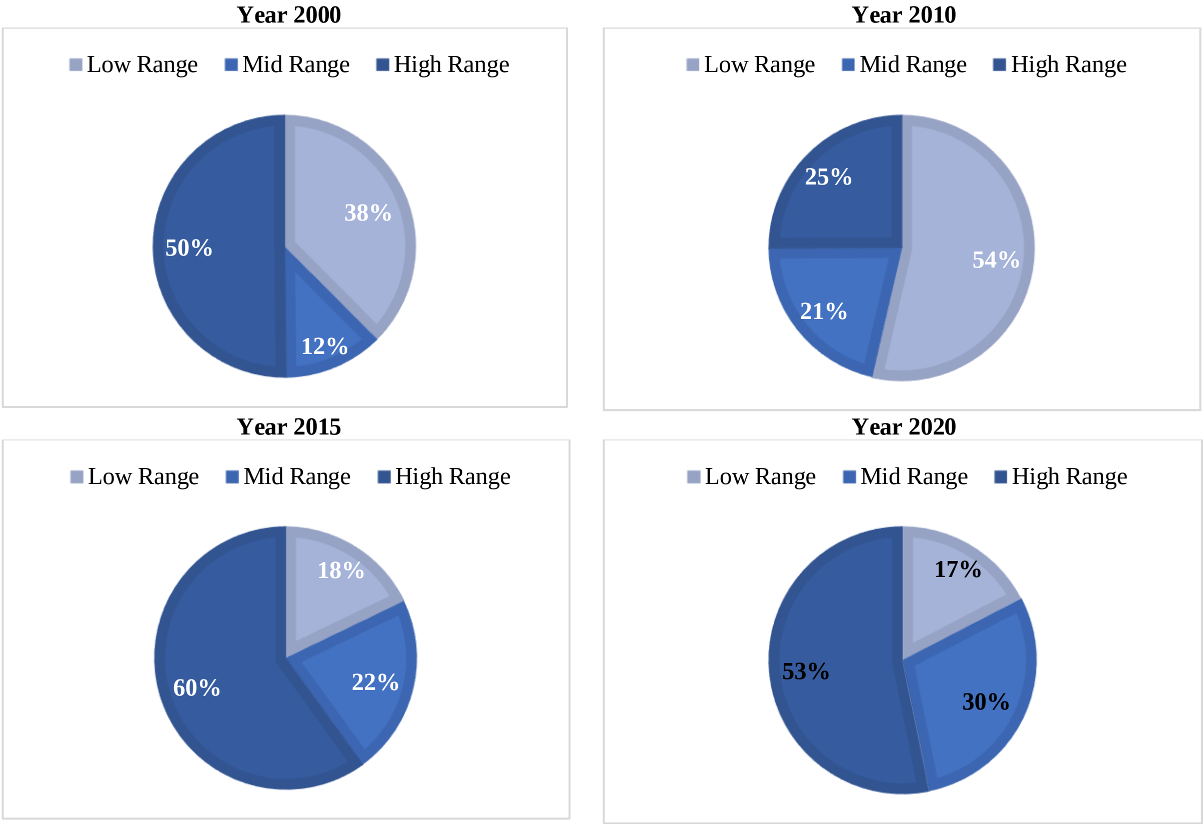


**Figure 12 NDWI Area Distribution over the year**

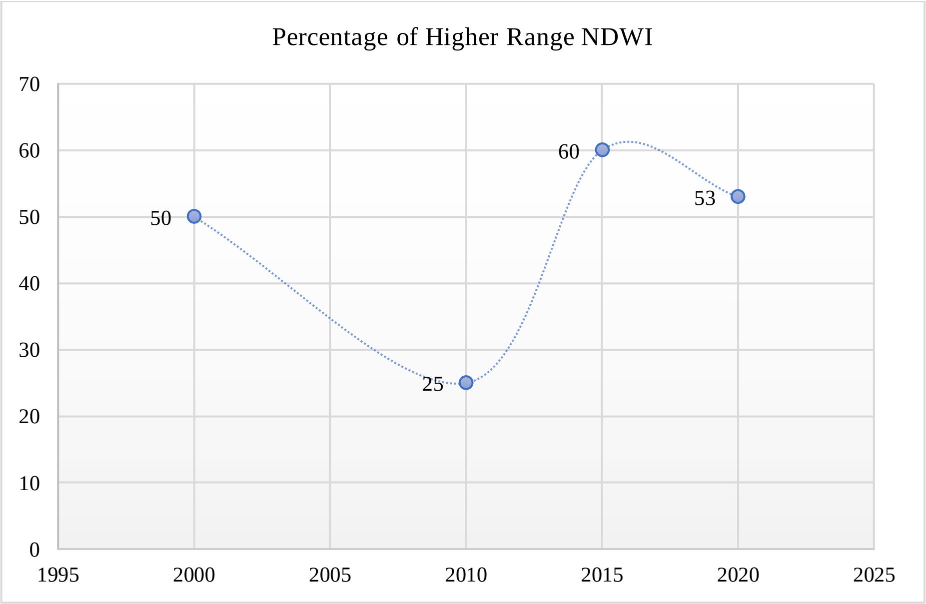


**Figure 13. Variation in percentage change in higher value of NDWI.**

### 4.2.3. Normalized difference built-up index (NDBI)

The analysis of the Normalized Difference Built-up Index (NDBI) using Landsat imagery from the United States Geological Survey (USGS) for the years 2000, 2010, 2015, and 2020, as shown in Figure 13, reveals significant variations in the NDBI values, indicating changes in the urban built-up areas. NDBI is a commonly used index to quantify the concentration of urban infrastructure and impervious surfaces within a given region. Higher NDBI values correspond to a greater concentration of urban development within the area under study.

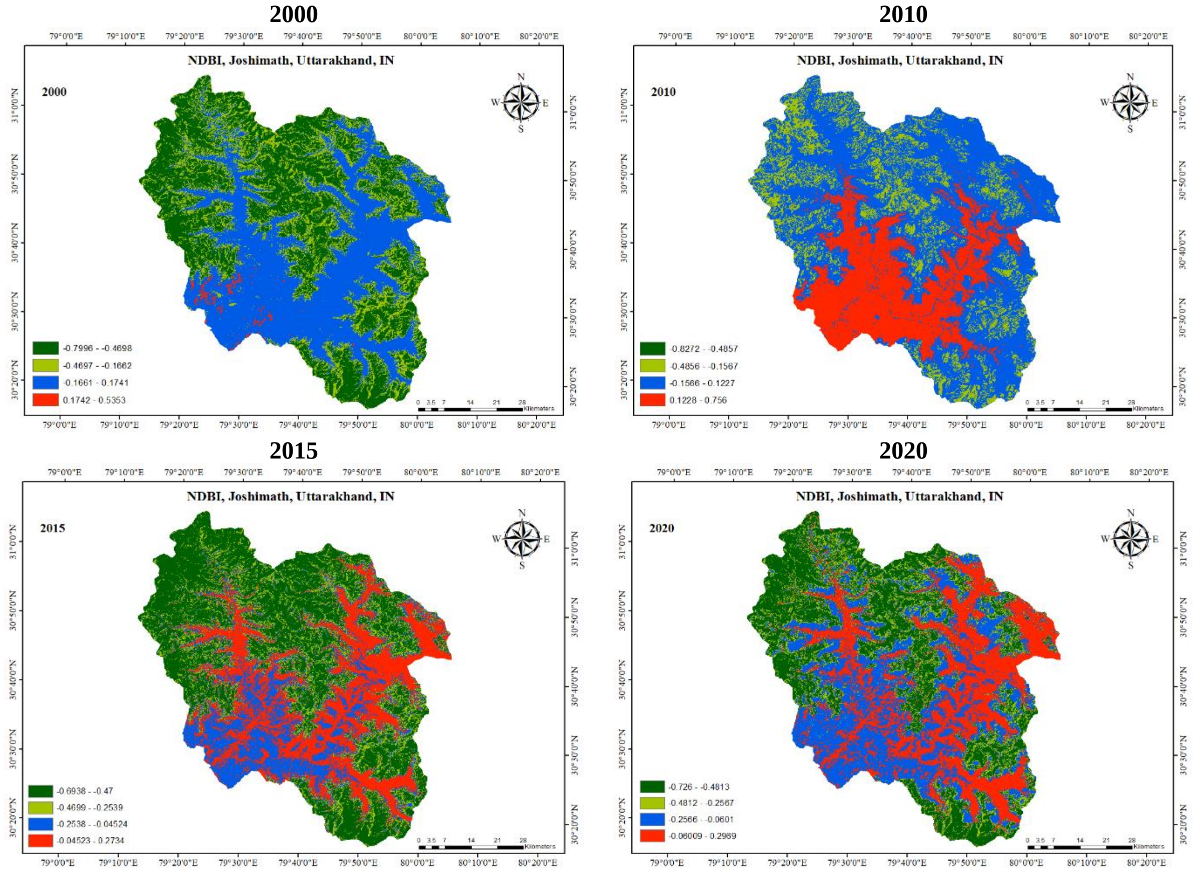


**Figure 14. NDBI map.**

The data, as also shown in Figure 14, explains that the higher NDBI values cover grew steadily as 1%, 17%, 26%, and 28% of the total area in the years 2000, 2010, 2015, and 2020, respectively. These changes over time not only provide insights into the expansion of urban built-up areas but also offer valuable information about the rate of change and its potential implications, including land subsidence.

The variations in NDBI values over the years suggest dynamic patterns of urbanization and land use changes. The increase in NDBI, indicating a higher concentration of urban development, is a clear sign of urban expansion. This expansion could be due to factors such as population growth, economic development, and infrastructure projects. As urban areas expand, natural landscapes are often transformed into impervious surfaces like roads, buildings, and parking lots. This has several implications, one of which is land subsidence.

Land subsidence, or the sinking of land, can be a consequence of rapid urbanization and increased impervious surface coverage. When large areas are covered by impermeable surfaces, rainwater cannot be absorbed into the ground. Instead, it runs off, leading to a decline in groundwater levels. Over time, the excessive extraction of groundwater for urban use exacerbates this problem. As groundwater is depleted, the soil compacts, causing the land to sink. This phenomenon is particularly pronounced in urban areas where the demand for water is high and the rate of urbanization is rapid.

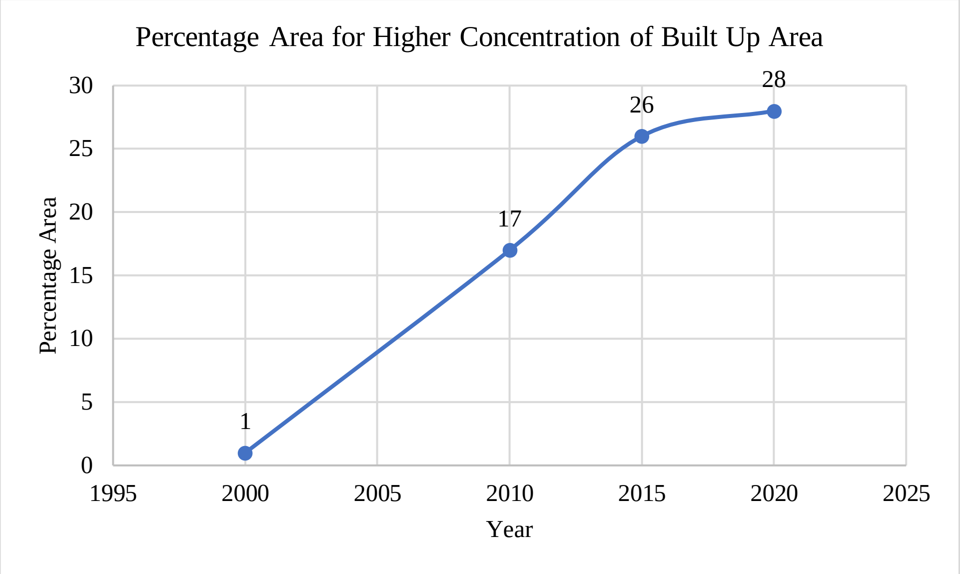


**Figure 15. Variation in percentage area of higher NDBI value (higher built-up area).**

The analysis of NDBI values from Landsat imagery over the years 2000, 2010, 2015, and 2020 indicates significant urban expansion and changes in land use which includes heavy new infrastructure projects like NTPC Power Plant and expanding Army base in the township. The higher NDBI values reflect a greater concentration of urban development within the study area. These changes have the potential to contribute to land subsidence, a phenomenon driven by the conversion of natural landscapes into impervious surfaces and the unsustainable extraction of groundwater. Understanding these changes is crucial for urban planners, policymakers, and environmental experts to address the challenges of urbanization and its environmental consequences, including land subsidence, which can have far-reaching impacts on infrastructure and the environment.

### 4.3. Geology

The analysis of the geology in the studied area using the Bhukosh database of the Geological Survey of India (GSI) is of paramount importance in understanding the factors contributing to land subsidence in the region, particularly in the Central Crystalline region, where this phenomenon has occurred. The classification of the studied area into eight distinct geological classes, which can be visualized well in Figure 15, provides a foundational framework for comprehending the geological composition and its implications for land subsidence. The largest area being covered by the Central Crystalline geological class is a crucial starting point as it is directly associated with the subsidence issue. Central Crystalline regions typically consist of hard, crystalline rocks, which, while generally stable, can still be susceptible to land subsidence under certain conditions.

The presence of Badrinath Granite/tourmaline granite as the second-largest geological class also holds significance, as the composition of these rocks can play a role in subsidence. Granite is known for its relatively low porosity, and its weathering over time can lead to the formation of fractures and faults, which might contribute to land subsidence. Additionally, the presence of tourmaline granite is interesting, as tourmaline is a mineral known for its water-absorbing properties, and the alteration of these rocks can lead to changes in volume, further contributing to subsidence.

The most intriguing aspect is the mention of unmapped areas due to the unavailability of data in the GSI database. These unmapped regions could hold critical clues to understanding the underlying causes of land subsidence. The absence of data in these areas might suggest that the geological conditions there are relatively unknown, and this lack of information could potentially be linked to the subsidence problem. These areas might have unique geological characteristics or anomalies that are contributing to the subsidence but have not been adequately studied or documented.

In the context of land subsidence occurring in the Central Crystalline region, it's crucial to consider various factors that could trigger subsidence. For instance, the crystalline rocks in this area may be subject to stress and strain due to natural geological processes or human activities like mining, construction, or groundwater extraction, and we have identified this in the analysis of NDWI and NDBI indices indicating huge groundwater extraction and expansion of human activity related infrastructures. The presence of faults, fractures or zones of weakness within the Central Crystalline rocks could make them susceptible to subsidence, especially if they are subjected to excess stress or if their hydrological properties are altered. The unmapped areas could potentially hold information about localized geological anomalies that are contributing to land subsidence.

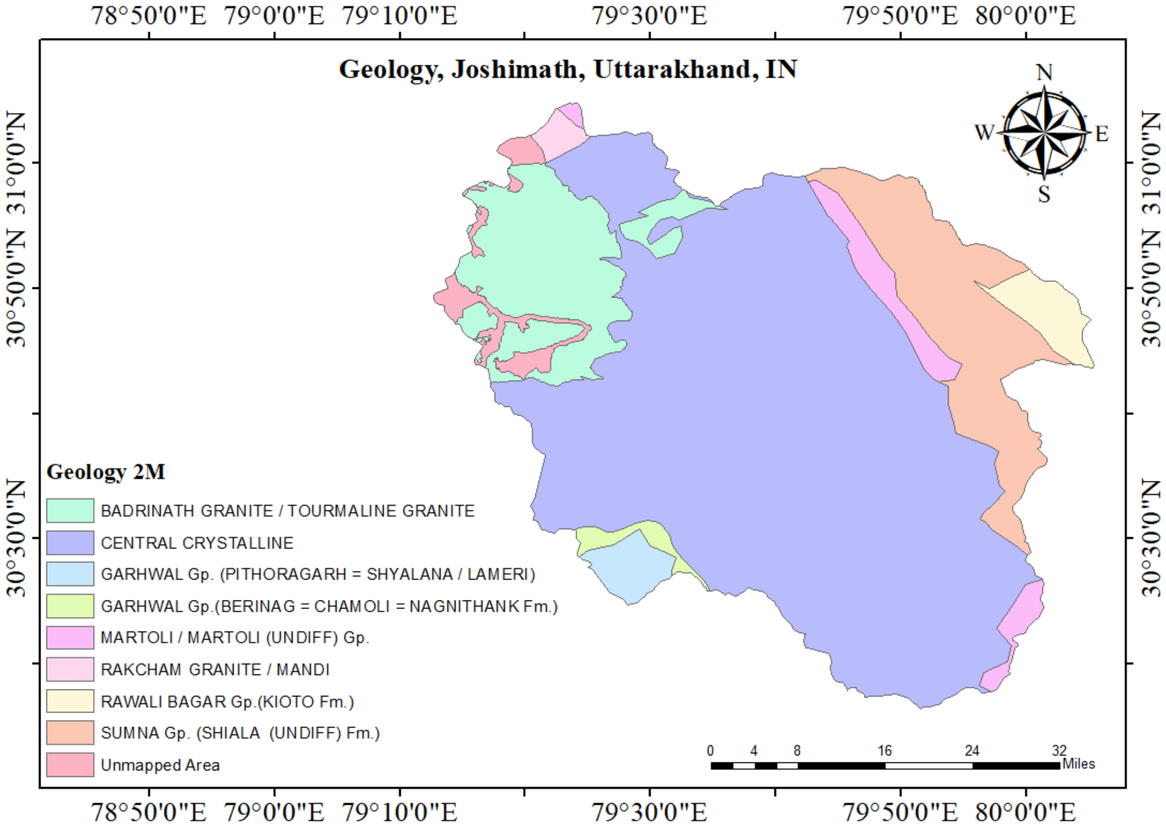


**Figure 16. Geology map.**

The Bhukosh database of the GSI is instrumental in identifying and understanding the geological composition of the study area, which is essential for investigating the causes of land subsidence, particularly in the Central Crystalline region. The prevalence of specific rock types such as granite and tourmaline granite along with the presence of unmapped areas, all offer valuable insights into the potential triggers for subsidence.

## 4.4. Geomorphology

The incorporation of Geomorphological analysis into GIS Bhukosh Database is a crucial step in understanding and assessing the geological and environmental characteristics of a region, which, in turn, has significant implications for land subsidence. Geomorphology is the study of the Earth's surface features and their origin, evolution, and classification. By analysing the geomorphology of a particular area, we gain valuable insights into the geological processes shaping the landscape. The study suggests that the region is mostly formed of "highly dissected hills and valleys," as seen in Figure 16. This finding suggests a complex and rugged terrain with various geological and tectonic activities that can influence land subsidence.

The presence of a significant amount of snow cover in the region, as found during NDVI analysis too, is also crucial. Snow accumulation and melting can contribute to changes in the region's water table and overall hydrogeological conditions, which can, in turn, affect land subsidence. Furthermore, the identification of valley glaciers and anthropogenic terrains in the area with visible piedmont slopes is significant. Valley glaciers are associated with glacial isostatic adjustment, a phenomenon where the Earth's crust responds to the melting of glaciers, potentially leading to land subsidence. The presence of anthropogenic terrains implies human activities such as mining, excavation, or construction, which can directly impact land subsidence through excessive groundwater extraction, soil compaction, and other factors. Therefore, the combined findings of geomorphology, snow cover, and specific terrain features are crucial in understanding the potential risks of land subsidence in the region.

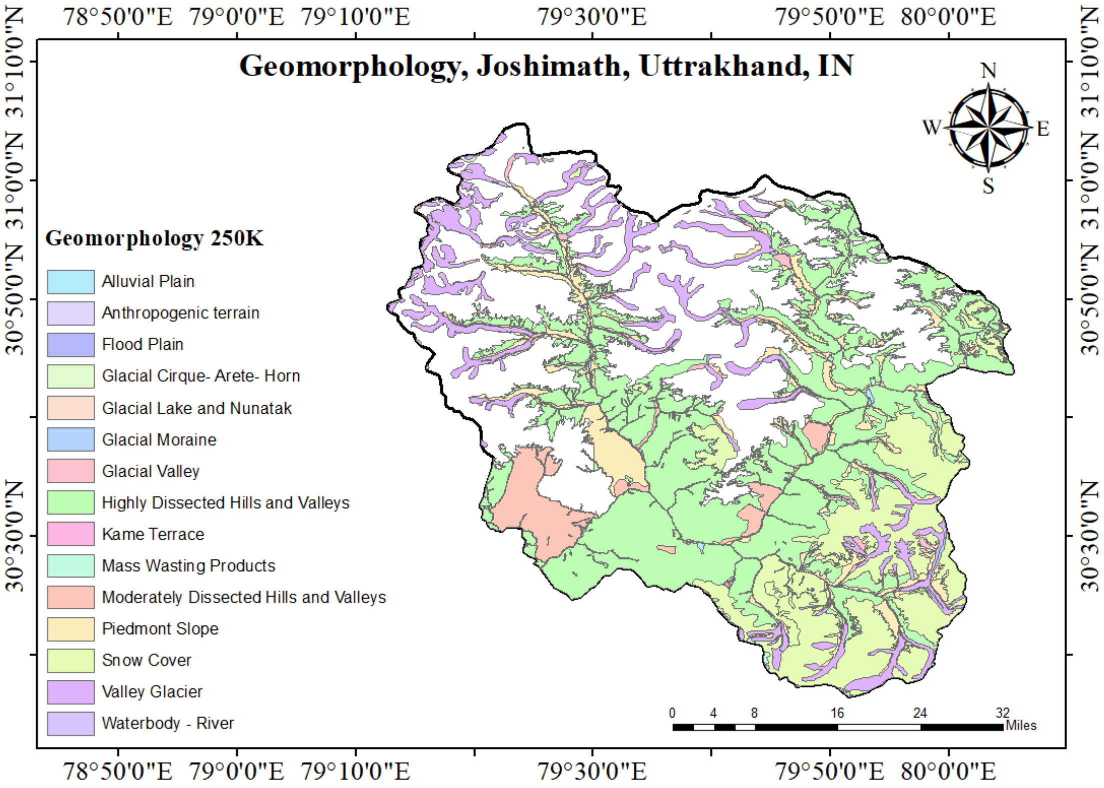


Figure 17. Geomorphology map.

The integration of geomorphological data into GIS Bhukosh database provides a comprehensive understanding of the region's geological and environmental characteristics. The identified "highly dissected hills and valleys," coupled with the presence of snow cover, valley glaciers, and anthropogenic terrains, all play pivotal roles in shaping the landscape and influencing land subsidence. Geomorphology aids in recognizing the geological processes at work, while the presence of snow cover and specific terrain types highlights the potential factors contributing to land subsidence. This knowledge is invaluable for land management, urban planning, and disaster mitigation efforts in the region, helping to mitigate the risks associated with land subsidence and ensuring the sustainable development of the area.

## 4.5. Lithology

The lithological data from the Geological Survey of India (GSI Bhukosh) plays a crucial role in understanding and predicting the possibility of land subsidence in the region, while also shedding light on the area's geomorphology. The dominance of Gneiss, comprising Calc Silicate can be seen in Figure 17, and gravel in the region is significant for land subsidence considerations. Gneiss is a metamorphic rock with distinct foliated layers, making it prone to differential compaction and subsidence. The presence of gravel indicates the potential for underground voids, which can lead to land subsidence when the voids collapse or settle.

Furthermore, the presence of Basal Conglomerate with Massive Quartzite and Amphibolite suggests that certain areas may have more resistant bedrock, which can affect the local subsidence patterns. These areas may experience less subsidence compared to regions dominated by softer lithologies. The occurrence of limestone, Schist Marble, and Grey Sand is also essential to consider. Limestone, for example, is soluble in water, and the presence of extensive limestone deposits can lead to karst terrain, characterized by sinkholes and subsidence features as the limestone dissolves over time. Schist marble and grey sand can also influence local subsidence patterns based on their compaction and erosion characteristics.

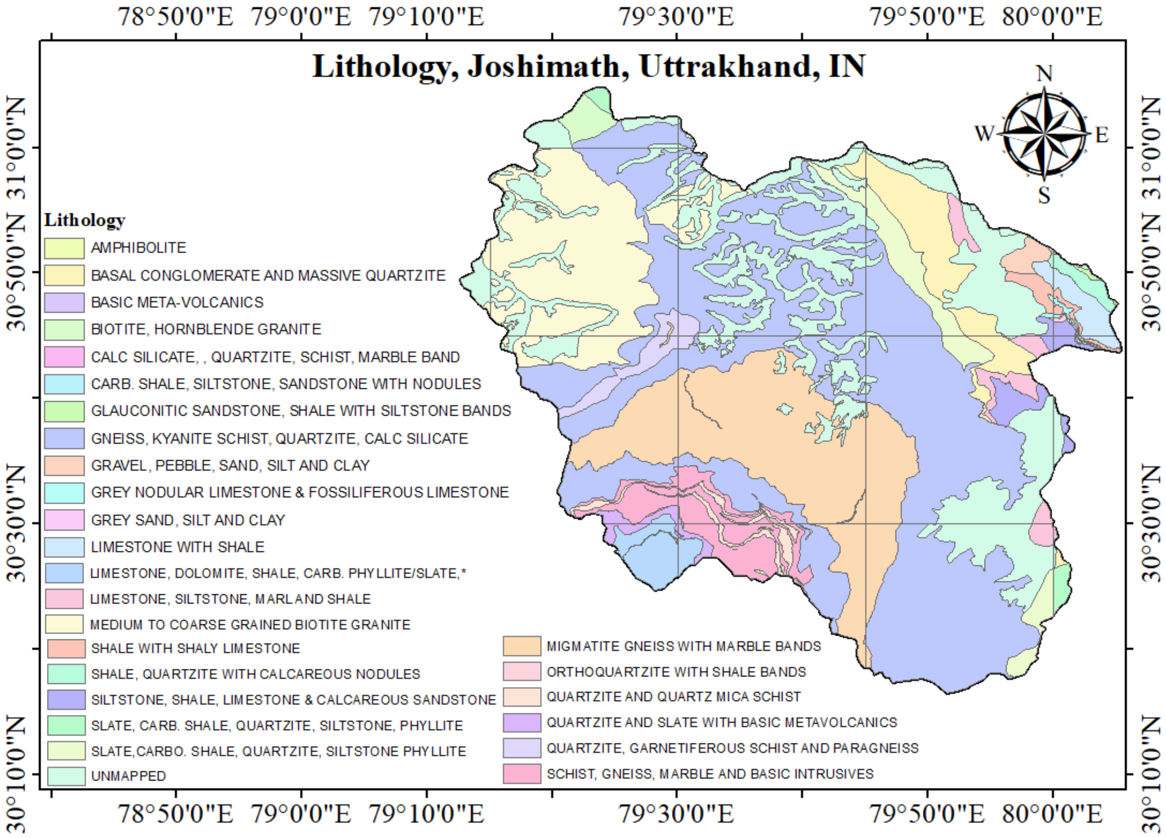


**Figure 18. Lithology map.**

In terms of geomorphology, the lithological data helps us understand the underlying geological structures and the landscape evolution of the region. Gneiss and Amphibolite, for instance, are associated with complex folding and faulting processes, which may have shaped the terrain. The presence of different lithologies can also explain variations in the topography, as softer rocks erode more quickly than harder ones, resulting in variations in landforms such as hills and valleys. The limestone and schist marble deposits can give rise to unique landforms like sinkholes and caves, adding to the geomorphological diversity of the region.

The lithological data from GSI Bhukosh has provided critical insights into the possibility of land subsidence and the geomorphological characteristics of the region. Understanding the distribution of different rock types and their properties is vital for land use planning, infrastructure development, and the assessment of potential subsidence risks. This information is indispensable for the sustainable development and environmental management of the region, taking into account both its geological and geomorphological features. NTPC power plant; Google Earth imagery is showed in figure 18.

Figure 19. NTPC power plant; Google Earth imagery.

## 6. Conclusions

The comprehensive analysis of land subsidence in Joshimath has been meticulously conducted by integrating multiple data sources and information. This research work draws upon various datasets and features to provide a holistic understanding of the subsidence phenomenon in the region. To begin with, the annual rainfall data from IMD Pune is a crucial element in this analysis, as it helps identify potential correlations between precipitation patterns and land subsidence events, shedding light on the role of water infiltration in subsurface weakening.

Furthermore, satellite imagery and remote sensing indices have been employed to track ground deformation over time, enabling the observation of surface changes and the identification of subsidence-prone areas. These technologies are instrumental in providing a temporal and spatial perspective on land subsidence.

In addition to meteorological and satellite data, geological, geomorphological, and lithological information from the GSI Bhukosh website is integrated into the analysis. This data assists in understanding the underlying geological factors contributing to land subsidence, such as the presence of vulnerable rock types and the influence of tectonic activity in the region.

By combining these diverse datasets and features, the analysis offers a multi-dimensional view of land subsidence in Joshimath, allowing for a more comprehensive and insightful assessment of this critical environmental issue. This holistic approach facilitates a deeper understanding of the driving forces behind land subsidence and informs future mitigation and management strategies in the region.

In conclusion from our comprehensive analysis, we have identified the following observations as potential reasons for land subsidence in the region,

The analysis of Normalized Difference Vegetation Index (NDVI) has revealed a concerning issue in the region: a significant accumulation of ice. This ice deposition poses a serious threat of land subsidence. As temperatures rise and ice melts, the excess water from the thawing ice could infiltrate the soil, reducing its stability and leading to land subsidence. This phenomenon is particularly worrying, as land subsidence can result in widespread damage to infrastructure, including roads, buildings, and agricultural fields, and can also disrupt local ecosystems. Therefore, addressing the causes and implications of this ice deposition is crucial to mitigate potential environmental and socioeconomic consequences in the region.

The analysis of Normalized Difference Water Index (NDWI) changes over time offers crucial insights into the dynamic fluctuations in water content within a given region. These variations in NDWI hold significant implications for the risk of land subsidence and the overall environmental well-being of the area. An increasing NDWI might indicate excessive water accumulation, potentially leading to land subsidence and ecosystem disruption, while a decreasing trend could signify water scarcity, impacting both human activities and natural habitats.

The annual average rainfall analysis explains that the persistent high rainfall, exceeding the annual average by approximately 900 mm, since 1990, poses a significant threat of land subsidence in the area. Excessive and sustained precipitation can lead to several compounding factors that exacerbate subsidence including soil saturation, increased groundwater levels, and reduced soil stability. The weight of the waterlogged soil compresses the underlying sediments, causing them to compact and settle. In regions with vulnerable geology, such as loose sediments or clays, this phenomenon can result in land subsidence, which, in turn, poses risks to infrastructure, property, and the environment. The situation necessitates careful monitoring, land use planning, and mitigation strategies to safeguard the affected area from the potentially devastating consequences of this heightened rainfall pattern.

The analysed time has resulted in a significant increase in human activity in the region, as illustrated in Figure 2, which highlights the significant expansion of an army helipad in the town. Figure 18 also highlights a key development: the establishment of the NTPC Thermal Power Plant. However, this expansion has had an unsustainable impact on biodiversity, contributing to the loss of natural resources. Such unrestrained human activity has become a trigger for natural hazards, as evidenced by the rising issue of land subsidence. Urgent attention and sustainable methods are required to offset these negative environmental impacts and protect the region's fragile ecological equilibrium.

The predominant geological feature in the area is characterized by central crystalline formations, which often consist of hard, impermeable rocks. This geological composition is a crucial factor when assessing the potential for land subsidence, particularly in the context of groundwater extraction as elucidated in the Normalized Difference Water Index (NDWI) analysis. The impermeable nature of central crystalline rocks limits the natural recharge of groundwater and reduces the water table's capacity to replenish itself, making the region more vulnerable to subsidence. As groundwater is extracted, these rocks are unable to adequately support the land above, leading to a gradual sinking of the ground surface. This phenomenon, known as land subsidence, can have detrimental effects on infrastructure, ecosystems, and water resources, highlighting the importance of managing groundwater resources in these geological settings to mitigate such risks.

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# تحلیل فرونشست زمین در شهرستان جوشیمات با استفاده از GIS و سنجش از دور

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## چکیده:

در این مطالعه گسترده، تحلیل کاملی از فرونشست زمین در منطقه جوشیمات با استفاده از ابزار سنجش از دور (RS) و سیستم اطلاعات جغرافیایی (غیر نظامی) انجام شده است. این اکتشاف شامل پارامترهای محوری رنگارنگی از جمله بارندگی سالانه، زمین شناسی، ژئومورفولوژی و سنگ شناسی است که با ادغام شاخص‌های مختلف گرد شده است. جوشیمات، شهری جذاب که در جغرافیای ناهموار ایالت اوتاراکند هند واقع شده است، به دلیل ویژگی‌های منحصر به فرد جغرافیایی و آسیب پذیری آن در برابر آسیب پذیری‌های محیطی متمایز است. این ردیابی با پشتوانه نرم افزار ArcMap، یک ابزار فنی غیرنظامیان، در حین استفاده از داده‌های به دست آمده از سازمان تحقیقات فضایی هند (ISRO) و مرکز ملی دید از راه دور (NRSC) انجام می‌شود. این رویکرد جامع با هدف ارائه درک غیرقابل ارزیابی به فرآیندهای پویا مرتبط با فرونشست زمین در منطقه، ارائه داده‌های حیاتی برای استراتژی‌های کاهش بلایا و عملیات زمین پایدار در منطقه است. قابل ذکر است که این منطقه در اواخر دسامبر ۲۰۲۲ با یک مورد قابل توجه فرونشست زمین مواجه شد که بر دقت و کاربردی بودن این مطالعه تاکید می‌شود. این رویداد نه تنها بر ضرورت درک فرونشست زمین در جوشیمات تأکید می‌کند، بلکه بر ضرورت نظارت مداوم و تعریق کاهش نیز تأکید می‌کند. ادغام این منابع داده‌های مختلف و راه‌های منطقی نویدبخش افزایش درک پویایی فرونشست زمین و آگاه کردن تصمیم گیرندگان در پیگیری شیوه‌های کاربری انعطاف پذیر و پایدار از زمین در جوشیمات و سایر مناطق آسیب پذیر است.

**کلمات کلیدی:** فرونشست زمین، سنجش از دور، GIS، ArcMap، ژئومورفولوژی.