Assessing Current Patterns and Impacts of Climate Change on Water Resources in Leh-Ladakh

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Abstract
Climate change and global warming have significantly impacted the water cycle and water resources in the Himalayan region. This study focused on the effects of climate change and human intervention on water resources in the Ladakh region over the past decades. Changes in snowfall and glacial patterns, rapid runoff, and erratic rainfall due to changes in the snow season and an increase in temperature have resulted in water scarcity in this area. Primary and secondary data on groundwater status, temperature changes, precipitation, glacial retreat, and increased water demand were collected and analyzed. Thus, this study aimed to evaluate the ecological, social, and economic impacts of climate change and identify the associated risks. A field survey was conducted using a questionnaire to collect primary data. The primary objective of this survey was to identify the available water resources, understand the issues leading to a decline in water sources, and assess groundwater overexploitation. It also aimed to capture community and stakeholder perceptions regarding water-related risks, evaluate the strategies and policies currently in place to address these challenges, and explore the approaches adopted to mitigate the impacts of climate change and rising temperatures in the region. This integrated approach provides a comprehensive understanding of water resource dynamics and vulnerabilities in the region.

Keywords: Climate Change, Water resources, Leh-Ladakh, Hydrology, Vulnerability Assessment, Anomaly Analysis

1. INTRODUCTION

The Himalayan region is one of the most severely affected by climate change, with its transformations marked by alarming unpredictability. The frequency of disasters in this region is approximately 44 times higher than that in the rest of India. Over the past decade, the gentle and persistent drizzles that once characterized the region have changed to intense cloudbursts and torrential downpours. The increased incidence of floods, thunderstorms, and landslides highlights an urgent warning and shows a stark glimpse of a precarious future, as emphasized in 2023 weather forecasts.

The Himalayas are witnessing an accelerated crisis, with glaciers losing mass at a rate 65 % faster in recent years. This rapid ice melt has led to the formation of new glacial lakes, which in turn are increasingly susceptible to overflows caused by cloudbursts, resulting in devastating floods. Unfortunately, the Himalayas have already lost over 40 % of their ice, further indicating a potential loss of up to 75 % within the next 75 years if current trends persist. Beyond glacial retreat, the vegetation line is also steadily shifting upward, rising by 11 to 54 meters per decade due to warming temperatures (Wadia Institute of Himalayan Geology, WIHG). Despite the presence of numerous perennial river systems, some Himalayan regions experience acute water shortages. It has been observed that glacial retreat alone does not significantly impact water availability. Instead, factors such as erratic rainfall patterns, depletion of groundwater reserves, the rapid expansion of urban settlements, and escalating water demands are driving the region towards water insecurity. This situation underscores the urgent need for adaptive water management strategies and climate-resilient development to safeguard the livelihoods and ecosystems dependent on this fragile mountain landscape.

The Himalayan region has the greatest number of glaciers (95,500) and largest ice volume (7.02±1.82×103 km^3) outside the polar regions (Immerzeel, W. W. et al., 2020). Most of the release of freshwater into springs and rivers, which is utilized as agricultural irrigation, municipal water supplies, hydropower, urban development, and industrialization, is dependent on the glacier ecosystem. More than 869 million people residing in the Indus, Suru, Nubra, Ganges, and Brahmaputra River basins depend on the water and climate variation provided by the region. (Biemans, H. et al., 2019). Glacier changes are impacting the region's hydrology, which varies significantly across locations in terms of frequency, intensity, and duration. These changes contribute to various hazards, including glacial lake outbursts, floods, flooding, runoff, and landslide-induced debris flows (Shean, D. E. et al., 2020). Glacial changes directly affect meltwater runoff and consequently the composition and seasonal variability of river flows descending from the mountains. The socio-economic and ecological impact of this glacier hydrology on the vulnerability of the downstream community varies spatially over different terrains. However, not only the downstream community but larger groups of communities depending on the ecological services provided by the Himalayan region are affected. This impact is more magnified due to rapid population growth, socio-economic development, and urbanization. In terms of increasing the number of this kind of climate change hazards, infrastructure, dams/hydropower projects, and tourism activities. Therefore, a thorough understanding of change in glacier hydrology, groundwater resources with climate changes and its impact is important to develop regional strategies and policies for adaptation to climate change sustainably (Rounce D.R et al., 2020).

Considering the direct and indirect impacts and apparent visible indicators of climate change in terms of glaciers retreating, floods, landslides, and biodiversity changes in the Himalayan region, numerous studies have been conducted (Bolch and others, 2012; Dobhal and others, 2013; Brun and others, 2017; Schmidt and Nüsser, 2017; Nüsser and Schmidt, 2021); however, very few studies have been conducted in the Ladakh region. Therefore, this study aims to provide a clear picture and understanding in this regard.

Ladakh is a high-altitude arid snow desert region that has the majority of glaciers and witnesses their mass losses and size reduction. The majority of glaciers in this area are confined to higher altitudes. Snowmelt water from these glaciers is a major factor that influences the economy of the region. As glaciers melt, water is the only water source available to fulfill all domestic, industrial, and agricultural demands of the area (Schmidt and Nüsser, 2020). With the increase in water demand and scarcity of water resources, the Ladakh region is highly vulnerable to climate change.

The water cycle governs various factors important for life to sustain, and in the region like a cold desert of Ladakh has become more valuable. Due to climate change, Ladakh is currently converted into an arid and semiarid cold desert. The region is experiencing water stress conditions, a decrease in soil moisture, and water holding capacity. The impact of climate change from the last decade is visible in terms of rainfall, cloudburst, decrease in glacier size and mass, rapid decrease in snowfall, temperature rise, and increased run-off in rivers and streams causing floods and landslides. According to the Wadia Institute study on Ladakh glaciers using satellite imaging and field survey, it was reported that the largest glacier of the Suru River valley in Ladakh has been retreating at a faster rate, and three glacial lakes have been formed and have the risk of outbursts of floods. In 1999, the Parachik glacier was retreating at a rate of 2 meters per annual, increased to 12 meters per annual in 2021 and now a higher retreat of 20 meters per annual is reported. So, if the glacier continues to retreat at such a high pace, it will worsen the water scarcity issues and also make the region more prone to disaster. It is indicated that these run-off or flash floods from glacial lakes outburst can be extended from 100 km to 400 km (Chevuturi et al, 2018). The increase in the incidents of ice avalanches, landslides, debris run-off, has caused potential damage to the water reserves of the area.

Khardung Pass, which was completely covered by a layer of thick snow approximately 4 meters thick in July until 1995, had no snow in 2017 (Azam et al., 2021). Current enduring climate change warnings combined with increasing population, urban development, and tourism have created a significant increase in water demand, leading to a shift towards overextraction of groundwater as an alternative source of water supply (Dolma et al., 2020). To cope with water scarcity, the construction of artificial glaciers as ice reservoirs is an appropriate adaptive strategy. These ice reservoirs have proven to be an important step in coping with changes in the cryosphere and have resulted in increased ice-melt water availability in water-stressed zones, thereby creating a positive impact on the socio-economics of the Ladakh region. This approach has been perceived by smallholders and the community to reduce water scarcity, reduce crop failure risks, and increase the possibility of growing cash crops. However, their effectiveness as a long-term climate change adaptation strategy remains uncertain. Strengthening these systems through enhanced planning and integration is essential to ensure their sustainability and resilience.

The Ladakh community, which faces acute water scarcity, faces escalating water disputes compounded by untreated sewage disposal, widespread use of dry toilets, and improperly constructed septic tanks. These practices, particularly in densely populated areas, directly pollute groundwater and exacerbate the region’s water quality crisis. Kumar et al., (2023) This continuous degradation of water resources adversely impacts water and food security, socio-economic well-being, and the achievement of sustainable development goals in the region. Despite these pressing challenges, Ladakh’s water resources have historically received limited attention from the scientific community. Critical gaps exist in understanding flow processes, resource reserves, and contaminant transfer mechanisms. Moreover, the impacts of climate change and anthropogenic pressures on these resources remain largely unexplored. The lack of comprehensive and systematic data further hampers efforts to monitor and assess changes in groundwater quality and quantity over time. Mehta et al., (2023)

Most existing studies rely on conventional approaches (CGWB, 2022) and are constrained by insufficient data and a lack of advanced research methodologies. Addressing these challenges necessitates detailed evaluations of both the quantitative and qualitative behaviors of the groundwater system in Ladakh. Thus, this study aims to critically assess the current state of water resources under the dual pressures of climate change and anthropogenic development in the Ladakh region. It seeks to propose actionable guidelines and innovative approaches for effective water resource management and sustainable development, paving the way for a resilient future.

1.1 STUDY AREA

Leh-Ladakh, situated in the trans-Himalayan region, forms the eastern part of the former Jammu and Kashmir (J&K) state in North India, with Leh as its main city. Geospatially, Leh is located at approximately 34.1526° N latitude and 77.5771° E longitude. The topography of the region is predominantly mountainous, with several high-altitude passes, and it is bordered by the Karakoram Range to the north and the Himalayas to the south. The region experiences a cold desert climate with sparse rainfall. Its hydrology is dominated by the Indus River system, which is fed by glaciers and snowmelt, crucial for agriculture and survival in this arid zone. Leh-Ladakh's environment is sensitive to climate change, with impacts visible in the form of glacier retreat and changes in snowfall patterns, which have direct consequences on water availability.

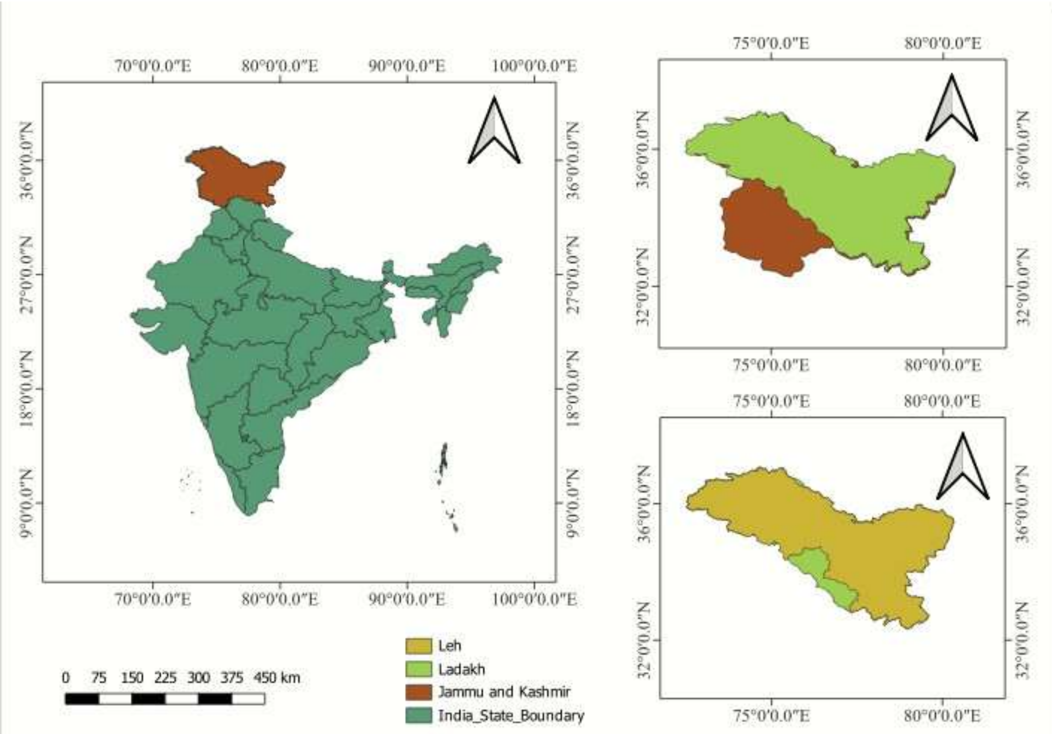


Figure 01: Study Area -Leh Ladakh

1.2 PHYSICAL ATTRIBUTES OF LEH

1.2.1 Temperature

The Himalayan ranges obstruct the entry of moisture-laden winds to reach Ladakh and block the rain clouds from the north; therefore, it is known as a rain shadow region. In this region, there is no monsoon season; only two major seasons, summer from May to October and winter from November to April, occur. The climate of Leh is a combination of Arctic and desert types. The main features of this semi-arid cold desert are the temperature fluctuations between −40 °C and -10 °C during winter and +35 °C to 10 °C between summer, with a mean annual temperature of 7.3 °C (Sharma et al. 2011; Chevuturi et al. 2018). To study the impact of temperature change, the Leh station dataset provided by the India Meteorological

Department (IMD) for daily maximum (Tmax, °C) and minimum temperature (Tmin, °C) for 20 consecutive years from 1999 to 2020 was considered.

1.2.2 Rainfall and Snowfall

Average daily rainfall ranged between 16.6 and 140 mm (IMD). The maximum daily rainfall was less than 140 mm. The rainfall was highest in July and August, ranging from 70-140 mm (Table 3 and Figure 4). The rainfall was low in other months (mean rainfall between 30–60 mm). Elevations above 5,500 m above sea level (m asl) received ~2,000 mm annual snowfall, and 3,500–5,500 m asl received snowfall of >600 mm (Lone et al. 2021). Leh received 90 mm snowfall, while Kargil received an average of 2,400 mm. The long-term mean annual rainfall at Leh station during 2023 was 140 mm (IMD 2024). Snowfall in the summer season was generally low. Winter precipitation (snow) was the main source of surface water. The quarterly average number of days with snowfall and days with >20 cm of snow was 30–50 days, respectively. Table 1 presents the mean annual rainfall in mm and the number of rainy days in Leh over five years.

Table 1: Mean annual rainfall in mm and the number of rainy days in Leh over five years

RAINFALL IN MM ANNUALLY AND THE NUMBER OF DAYS										
Month	**Number of days**	**2024**	**Number of days**	**2023**	**Number of days**	**2022**	**Number of days**	**2021**	**Number of days**	**2020**
Jan-March	45	39.6	32	10.78	30	16.9	23	28.3	17	14.83
April-June	53	63.83	30	76.71	28	37.46	28	36.43	22	33
July-Sep	37	99.84	48	140.2	20	68.4	23	70.11	24	59.99
Oct-Dec	20	18.54	40	18.58	25	15.53	18	16.06	17	15.5
SNOWFALL IN CM ANNUALLY AND THE NUMBER OF DAYS I										
Month	**Number of days**	**2024**	**Number of days**	**2023**	**Number of days**	**2022**	**Number of days**	**2021**	**Number of days**	**2020**
Jan-March	4	5.16	6	3.9	1	0.46	18	2.2	46	28.3

April-June	8	6.3	13	12.13	9	9.73	27	40.2	52	37.4
July-Sep	12	12.8	10	4.9	6	2.56	28	36.2	42	34.8
Oct-Dec	4	2.3	5	4.4	2	0.566	25	13.1	16	13.1

1.2.3 Wind and Evapotranspiration

The average annual number of sunny days was 325, the average monthly wind speed was between 4 and 7.2 km/h, and the average potential evapotranspiration from April to October was 514 mm. Studies have indicated that the annual actual evapotranspiration is approximately 84 mm. The relative humidity (RH) is generally low in the area and is highest between December and February (mean value of 55 %). During the summer months, the RH remained at approximately 40 % throughout the day. Owing to the high altitude, low humidity, and clear sky (low pollution levels), the intensity and duration of solar radiation are among the highest in the world, with a daily average solar energy of 7–8 kWatt-h/m^2.

Out of the total cold arid desert region of India, 87.4 % is in Leh (Wani et al. 2011), and this type of climate is due to the Western Disturbances (WD) from the Atlantic Ocean, Mediterranean, Black, and Caspian Seas, Summer Monsoons winds from the Bay of Bengal and the Arabian Sea, Tibetan anticyclone, and Inter-Tropical Conversion Zone fluctuation. Dimri et al. (2016)

1.2.4 Geomorphology

The region is characterized by a rocky, mountainous terrain with sparse or no vegetation, prone to weathering and erosion. Ladakh is the highest plateau land in India, at more than 3000 m, and also has both the Himalayan and Karakoram Mountain ranges with the upper Indus River valley zone. The mountains composed mainly of sedimentary rocks are actively disintegrating under the impact of harsh climatic and dry conditions. The altitude in this area ranges from 5,934 meters to 8,510 meters above mean sea level (AMSL), having variation in landscapes. The area is primarily drained by three significant rivers: Indus, Nubra, and Shyok. The Nubra River originates from the mighty Siachen Glacier, while the Shyok River has its source in the South and Central Rimo glaciers. The lower altitudes are defined by the Indus valleys and foothills, while the highest elevations belong to the towering peaks of the Karakoram Range. The region also features distinct southeast–northwest and northeast trending parallel mountain ranges, including the Ladakh and Karakoram Ranges. Sharma et al. (2018).

1.2.5 Drainage & Soil Type

The region lies within the Indus River basin, with the Indus, Nubra, and Shyok Rivers as its three primary water sources. The Indus River flows for approximately 422 km in Leh and originates from a perennial spring, Senge Khabab, in Tibet near Lake Mansarovar. This river enters India in the Leh region after crossing the southeastern boundary of the Kashmir region. Zaskar, Shyok, Gilgit, Hunza, Nubra, Shigar, Gasting, and Dras are the important tributaries that converge in the River Indus. The Nubra River, a perennial stream, originates from the Siachen Glacier and flows from northwest to southeast. Numerous streams, locally known as "Lungpa," feed into the Nubra River, descending from higher mountain peaks. The Nubra River flows for 80 km and then converges into the Indus River. The Shyok River, also a perennial river, originates from the South Rimo and Central Rimo Glaciers. Along its course, it intersects with smaller glaciers, including Chong, Thangman, and Tash Glaciers. Initially flowing northwest to southeast, the river shifts northwestward near Shyok village before converging with the Nubra River at Disket.

The Nubra block features a network of perennial and seasonal streams. The major streams flowing northward into the Shyok River include Starga Lungpa, Fastman Lungpa (originating from the Thursa Glacier), and Warshi Lungpa (fed by the Urdolep Glacier). Streams flowing southward into the Shyok River include Khalsr Dok, Tashi Lungpa, Sumdo Lungpa, Glachurap Lungpa, Taru Lungpa, Yaglung Lungpa, and Malasha Lungpa. Browm E. T et al., (2002). Cheema et al., (2019), Clift P.D et al (2008). The Ladakh region is covered with more than 1800 glaciers and covers 997 km^2. Fontes J. C., (1996), Lone, S.A (2017). Siachen glacier spreads to ~700 km^2, the Zanskar ranges, which include ~5,000 glaciers of ~3,187 km^2 area and an ice volume of ~816 km^3). The melt water contributes ~50 % to the river flow mainly in its upper catchments. Part of the glacier melt percolates through fractures and other lineaments into the aquifers. A very high percolation rate reduces stream flow, for example, by up to 90 % in Zanskar. Pangong Lake, Tsomoriri Lake, and hot springs of Panamic, Chumathang, and Puga are other important water bodies in the area. Archer, D. R et al., (2004). Ladakh glaciers have been impacted due to climate change, an increase in greenhouse gases, and temperature increase. About 12.5 % of the area covered by glaciers has been lost in the last two decades and about 90 glaciers of the Ladakh disappeared. And if the last 50 years are considered then almost 29 % of the Ladakh area of major glaciers has been decreased. Most of the glaciers near the highways are retreating at a faster rate. Mehta, M. et al., (2023) Rashid, (2019).

The soils of the district range from sandy to loamy in texture, characterized by low organic matter content and deficiencies in phosphorus and potash. These soils often contain boulders and gravels, making them shallow, weak, and friable. Owing to their sandy nature, they are highly susceptible to various forms of erosion. Soils formed on river terraces are particularly porous and coarse-grained. Soil fertility varies across different locations within the district, and the growing season is notably very short. Fort, M et al., (1989)

1.2.6 Geology

The rocks are igneous, metamorphic, and sedimentary. They have a Tertiary granitic batholith in Ladakh and Karakoram. Five magmatic cycles have been established: Shyok basic volcanics composed of basalt and andesite. Khardung acidic volcanics of non-marine lava flows, emplacement of granite on a regional scale, and porphyritic andesite eruption of the Saltoro hills. The area remained magmatically active from the Cretaceous to the post-Oligocene period. In this category, the structural hills cover a larger part of the study area (59.31 %), whereas denudational hills cover 16.75 % and the river bed occupied 0.87 % of the area. Lithologically, the maximum area is covered by granitoid rocks (74.48 %), and the remaining area is covered by recent sedimentary formations. The majority of the study area is covered by rocky terrain (80 %), mixed agricultural land (7.49 %), built-up land (6.85 %), and sandy area (5.01 %). The Upper Cretaceous to Eocene flysch sediments are exposed south of the Saltoro hills.

Table 2: Geologic Formation

FORMATION	AGE
Alluvial Lacustrine deposits, fluvio-glacial out wash material, Lamayuru deposits and Laminated Clays	Recent to Subrecent

Siwalik Clays/Teritiaries, liyan formation, Shegol formations (with Ophiolites)	Miocene to Pleistocene
Ninden/kalche formation	Eocene
Khalsi formation/shyok volcanics/Karakoram formation	Cretaceous
Qazilanker Conglomerate/zangla formation/Kiota limestones Jurassic	Jurassic
Murgo formation Triassic	Triassic
Panjal Traps\	Permian
Pengong Granitoids, Kuling formation, Phe volcanics/sasar Brangsa formation, Lipak formation	Permo Carboniferous
Muth Qurtzites/tacke/Kelung formation	Silurian Devonian
Thankung Schists/Phe formation, Pengong meta sedimentary group	Cambro Silurian
Karakoram Crystalline Complex/Lukung Schist, salkhalas, unclassified granites and gneisses	Pre-Cambrian

1.2.7 Water Resources and Hydrogeology

According to the geology of the area, the Ladakh region can be divided into two broad aquifer types: porous alluvial aquifers and fissured hard rock aquifers. The porous alluvial aquifers include unconsolidated recent and sub-recent alluvial lacustrine deposits, fluvio-glacial outwash material, Lamayuru deposits, moraines, and laminated clay deposits comprising sand, gravel, boulders, river cobbles in mechanically disintegrated loose sandy matrix, and pebbles (CGWB 2020). These types of aquifers are mostly available and promising. They can be both confined and unconfined and are highly permeable. Generally, unconfined aquifers are formed due to sloping land from the foothills to flat valleys and trapping the composed glacial outwash and snow and rain runoff. These porous aquifers occur in the Leh Plain in a 100 km^2 low-lying region between Phayang Nala in the west to Sabu Nala in the east and Nubra and Shyok Nala along the southern side of the Shyok River near Disket and Hunder. These aquifers play a vital role in terms of the availability and movement of groundwater on a sustainable basis. The depth of water in these aquifers ranges from very shallow to as deep as 45m bgl and is related to the river water level. These aquifers are mainly available for domestic and industrial purposes in Leh. Heisig, P.M et al., (2015), Henderson, A. L. et al., (2010).

Fissured hard-rock aquifers are formed by intragranular voids and fractures between rocks. The movement of water and storage is strictly restricted and not readily available in this region. The depth of the water level in these aquifers varies from 60 m bgl to 75 m bgl. These aquifers have various zones in terms of location and rock type. The granites and KPC batholiths of Shyok Suture Zone rocks are the major and potential aquifers in Leh, covering approximately 75 % of the Ladakh district. Zildat Ophiolitic Melange, Tangstse migmatites, Lamayuru formation, Kargil Molasse, and other aquifer types in the Shivalik and Kargil regions are also included. Furthermore, there are sedimentary aquifers, including the Indus and Zanskar zones, composed of conglomerate, sandstone, and shale. Marechal, J. C., (2018), Balamurugu et al., (2017). The recharge of both types of aquifers is controlled by the microclimate and catchment characteristics of the region. Schmidt, S., et al (2017), Muller. et al., (2020).

Most recharge occurs due to melted water from glaciers and fresh snow (44 % and 39 % respectively). Generally, 17 % recharge is from rainfall, mainly in the Valley-fill porous aquifers. According to the CGWB report (2009), the average recharge accounted for by annual precipitation is 21 mm per year. In hard rock aquifers, recharge occurs at 3000–3500 m. asl through the weathered and fractured Zone. Porous rocks, sandy and clay soil type, slope or lineament of plain of land, drainage density of regoliths, fractures and weathering of rocks are various promising factors on which the groundwater potential depends. Springs in the Leh valley occur at the contact points of geological formations and along fractures, faults, and thrust zones (CGWB, 2009). Approximately 86 documented springs in the region discharge between 0.0015 and 0.29 m^3/min during summer, with reduced discharge during winter (Balamurugan et al., 2016). The total groundwater discharge in the Leh district is estimated at 5.8 million cubic meters (MCM), accounting for 11.3 % of the annual recharge volume. The region's high hydraulic gradient often leads to the drying up of wells and springs in recharge zones, especially during the dry season. Bore well failures are also frequent, primarily due to the instability of loose regolith. Additionally, hot springs near Panamic and Chumathang discharge deep geothermal water at temperatures ranging from 73 °C to 85 °C, with flow rates of 0.009 to 0.02 m^3/s. Despite these unique hydrogeological features, no major or systematic study has been conducted to characterize the aquifer systems, estimate water resources, or understand groundwater behavior in the area. The 86 springs in the Leh Valley are located at various altitudes, ranging from 3,300 meters to 3,900 meters above sea level. The groundwater in the form of springs, bore wells, or spring wells with glacier-melt water is the major source of stream water supply in Leh city. In the last two decades, major glaciers fed streams and seasonal springs have almost dried in the summer season. The situation is more aggravated due to decrease in rainfall and snowfall with loss of glaciers in the region. Unpredicted rate of glacier retreating has created a change in flow pattern, change in availability of water and hence, the situation of flood and drought in the region. Additionally, with the rise in temperature, the rate of evaporation is increased which has further caused more than 15 % additional water losses in the region. (Dolma, K et al., (2020), Sharma, et al., (2021) Schmidt, et al., (2017))

The cumulative effect of decrease in precipitation, increase in temperature, and loss of glaciers has impacted the recharge efficiency of the aquifers, and this situation is further aggravated with excessive withdrawal of groundwater to meet the water demands. This has reduced, and this in return reduced the discharge in natural springs and streams and also led to drying of bore wells. Due to unavailability of water/ water deficit with increase in tourism, population, urbanization and increase in water demand an irreversible impact on agriculture and land use has been noticed. Yangchan, J et al., (2019)

Table 3: Type of Aquifers

Type of Aquifer	Nature of rock	Area (Km^2)	% of area	Groundwater potential	Source
Porous alluvial aquifers	Alluvial and piedmont rocks, recent and subrecent rocks	5557	12	Moderate yield (0.3-0.5 m3/min)	CGWB (2022)
Fissured hard rock aquifers	Igneous, metamorphic, and sedimentary rocks	39553	88	Low yield (0.1-0.15 m3/min)	CGWB (2022)

1.3 ANTHROPOGENIC ATTRIBUTES OF LEH

1.3.1 Leh Population and Tourists

The population graph presented indicates that the population of Leh has grown from 40484 in 1951 to

153000 in 2024, approximately 15000 per 10 years. There was a change of 8.3 % in the population compared to the population as per 1941-51. In the previous census of India in 2001, Leh District recorded an increase of 31.96 % in its population compared to 1991. It is now almost stable from 2001 to 2024.

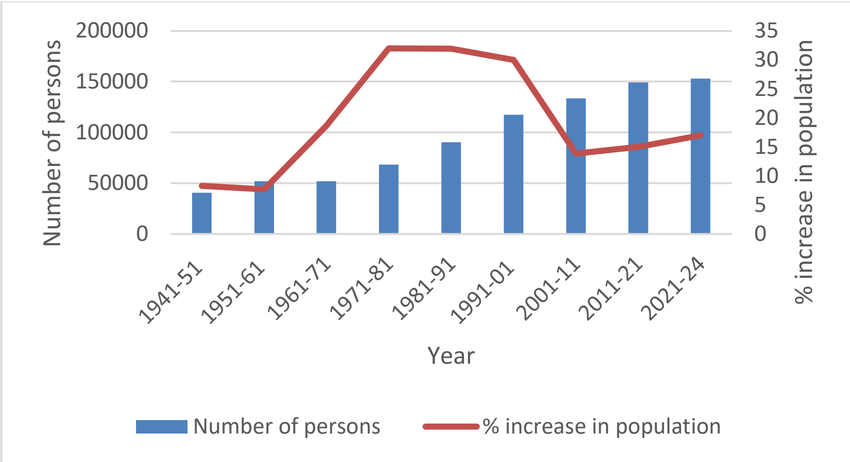


Figure 02: Leh Population

Tourism has gained wide recognition as an important industry in the district, given its potential for creating employment opportunities and generating income on a large scale in Leh. This industry has a direct bearing on the socio-economic scene of the district. The tourism industry provides employment to a large number of people engaged in related sectors such as transport, hotels, catering services, and cottage industries. Tourism promotes economic activity in remote regions. Tourism has grown exponentially from 2002 to 2024. The total number of Indian and foreign visitors each year increased from 8068 to 52500. That is, almost a 98.46 % increment was observed. These data indicate better connectivity through road and air.

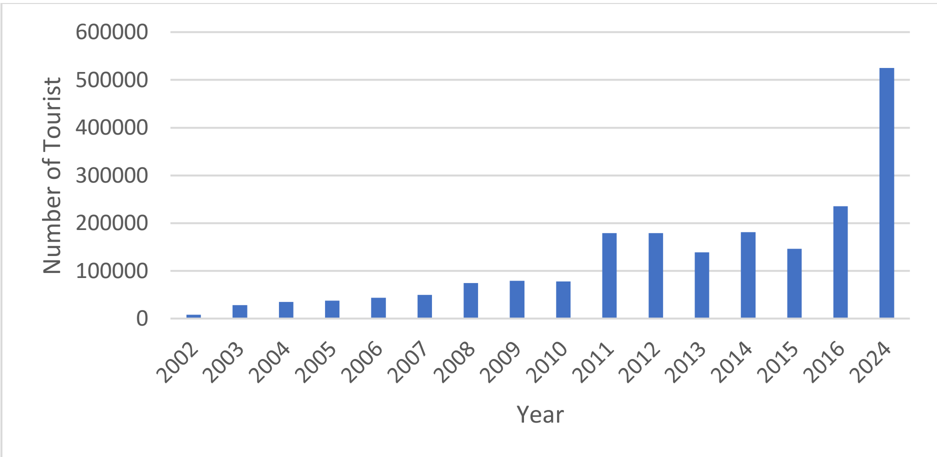


Figure 03: Tourists Visited Leh

Agriculture remains the primary source of livelihood in Leh, as is the case across the state. According to the records maintained by the Revenue Department, the district encompasses a reporting area of 45,167 hectares, of which 10,542 hectares are under cultivation. Efforts by relevant departments have significantly enhanced agricultural productivity, particularly for cash crops. Agricultural data include information on land use, cropping patterns, landholdings, fertilizer and pesticide usage, and the distribution and production of vegetable seedlings. In addition to agriculture, approximately 75 % of the families in the district are engaged in operating hotels or guesthouses, with access to 24-hour water supply. The district has also experienced a sharp increase in vehicular numbers, increasing fourfold from approximately 4,007 in 1994 to nearly 16,300 in 2007. Between 2011 and 2020, the concentration of atmospheric greenhouse gases (GHGs), including CO_2, NO_x, CH_4, along with black carbon and particulate matter, increased by approximately 39 % (Romshoo et al., 2022). Additionally, the district's semi-arid climate and the predominance of vegetation-free barren land have limited CO_2 sequestration, further exacerbating the warming trend (Zeb et al., 2020; Thakur et al., 2021).

1.3.2 Groundwater crisis and over usage

An extreme crisis of groundwater is noticed in 70 % of regions in India. According to CGWB (2023), the net annual groundwater availability in Hectare meter of Leh city has shown a huge variability in the last decades, as also indicated in Figure 7. The water level was found to be in the range of 4000–9000 ham (CGWB). In addition, with increased population, urbanization, and tourism, the ratio of annual groundwater extraction to the net annual groundwater availability, as represented by the stage of GW Dev %, increased to almost 35 %. Hence, groundwater withdrawal is increasing exponentially, but the recharge of groundwater is very slow. The results indicate that the increase in water demand and decrease in recharge rate are due to various factors in the Leh region.

The current number of bore wells and groundwater draft for irrigation, industrial, and tourism usage is ~115 and ~7 MCM/year, respectively. Hence, modelling and managing the impacts of groundwater extraction are imperative for resource sustainability. Groundwater extraction is high in Leh city. Almost 90 % of public, private, and government well water sources are supplied from groundwater and 10 % from snow melt. The water supply provided by the Public Health Engineering department is pumped from the shallow aquifer through pipelines to the town at a rate of 1.7 MCM/year. Water pumped through two different tube wells from Indus and PHE and 74 % of the community is dependent on this supply and the rest 18 % use hand pumps and 8 % use bore wells. Community preference for groundwater is due to its less availability, increased pollution, and reduced distance and time for collection of water.

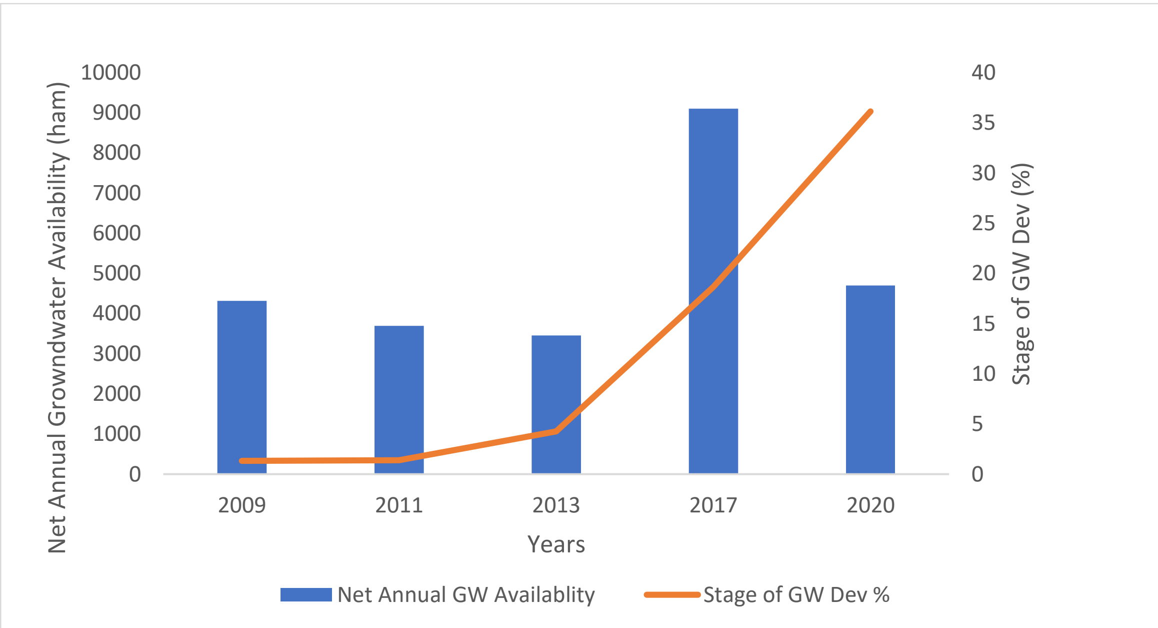


Figure 4: Net Annual Ground Availability and stage of GW Dev%

1.3.3 Water Demand

The average per capita water requirement in India ranges from 135 to 200 Liters per day; however, in Leh, due to increased tourism and the expansion of hotels, this demand has risen nearly fivefold. Population growth and urbanization have further exacerbated water demand, particularly during the summer season, when per capita water requirements are expected to rise further (Balamurugan et al., 2016; Müller et al., 2020). Over 95 % of the water supplied for domestic and industrial purposes in Leh comes from groundwater; however, there are no effective measures to regulate its over-extraction. According to the CGWB (2022), the net groundwater draft in Leh is currently 7 MCM and is projected to increase by 33 % by 2025.

A warming climate has also led to the expansion of agricultural land, driving higher irrigation and water demands. The government's push for increased food production to promote self-sustainability has contributed to a total sown area increase of approximately 21 km^2 over the past 15 years, at an annual rate of 1.7 km^2 (BORDA, 2019). Irrigation currently accounts for approximately 0.41 MCM, or 5.6 % of the total groundwater draft. The Leh Plain, particularly between Phyang Nala and Sabu Nala, where approximately 0.1 MCM is pumped annually, has been classified as a semi-critical zone based on the groundwater development (GWD) index (CGWB, 2009, 2011).

In addition, increasing hazards, such as flash floods, glacial lake outburst floods (GLOFs), landslides, and soil creep (Khan et al., 2021), are disrupting the ecosystem and adversely affecting groundwater recharge processes, further stressing the limited water resources in the region.

2. METHODOLOGY

This study focuses on the Leh–Ladakh region, which is characterized by its high-altitude terrain and arid climate, to assess its impact on limited water resources, including glacial melt, springs, and rivers. To understand the impact of limited resources in this region, an intensive analysis and study were conducted using both secondary and primary data.

Secondary data include historical and recent climate data with climate indices such as temperature and precipitation, hydrological data including river flows, glacial melt, spring discharge, and socioeconomic data, such as population growth, land use, and water consumption. This data set was collected and analysed with the help of various Methodology, to understand the current trend and variation pattern of temperature and precipitation observations which were extracted from IMD, The Anomaly Analysis and Innovative Trend Analysis (ITA) were performed. Temporal and spatial analysis was performed using the normalized difference water index (NDWI), normalized difference snow index (NDSI), and land use land cover (LULC) maps from 1999 to 2024.

A field survey was conducted to collect primary data using stakeholder interviews with local communities and policymakers to gather insights on water usage and related challenges with traditional practices. This integrated approach provided a comprehensive understanding of water resource dynamics and vulnerability in the region.

2.1 THE ANOMALY ANALYSIS

An Anomaly represents a deviation of a particular climate Indices like temperature and rainfall From a Baseline average with the help of Observation Data that has been collected for the region. Anomalies usually refer to the extremities observed from the collected data, which are unusual compared to the average recorded.

Anomaly = Observation Data – Baseline Average

The anomaly analysis was performed using temperature data that were recorded for both maximum, minimum observations, and rainfall in mm, both with monthly records (1999–2024), collected from IMD and analyzed using MS Excel with descriptive statistical visualizations. Positive anomalies indicate higher than average values, whereas negative anomalies indicate lower than average values, which serve as crucial tools for understanding the changing trends and climate change impacts on the region.

2.2 THE INNOVATIVE TREND ANALYSIS (ITA)

Innovative Trend Analysis (ITA) is a graphical method that recognizes trends without making any assumptions about the data or linearity. ITA plots data against itself, which allows visualization of trends in different parts of the data, unlike traditional methods. It evaluates using a graphical method that evaluates the first and second halves of the dataset to identify nonlinear or concealed patterns that a traditional test may overlook. It is used to depict nuanced climate behavior such as intensified warming or cooling and rainfall extremes, which helps in understanding various climate extremities that occur throughout the time series of a particular region.

ITA is performed using MS EXCEL for sorting and arranging the IMD data of Maximum and Minimum Temperature and Rainfall in mm, Monthly (1999- 2024) and then performing the analysis using R Studio with the help of “trendchange” Package, which provides the plot graphs showing Monotonic or Non-monotonic trends with Trend slope and indicator, Slope Standard Deviation, Correlation Coefficient and confidence intervals.

2.3 GEOSPATIAL ANALYSIS

2.3.1 Normalized Difference Water Index (NDWI)

The Normalized Difference Water Index (NDWI) is a spectral index designed to enhance and detect the presence of surface water bodies and surface moisture conditions using multispectral remote sensing data. The NDWI is calculated using the green and near infrared (NIR) bands, which extract high reflectance of water in the green band and strong absorption in the NIR band.

NDWI = (Green − NIR) / (Green + NIR)

NDWI values theoretically ranges from -1 to +1, where the positive values indicate the presence or surface of water and high moisture content, values close to zero represent mixed of moist soil and some of the water bodies and negative values indicate towards dry soil, bare land, Vegetation or Built-up areas. NDWI analysis was performed on dataset from LANDSAT 5, 7, 8/9 from USGS Earth Explorer using QGIS. NDWI is commonly applied in order to understand the environmental change is used for water resource monitoring.

2.3.2 Normalized Difference Snow Index (NDSI)

The normalized difference snow index (NDSI) is a spectral index used to identify snow-covered areas by leveraging the reflectance properties of snow in the visible and shortwave infrared (SWIR) regions of the electromagnetic spectrum. Snow shows high reflectance in the green band and strong absorption in the SWIR band.

NDSI = (Green − SWIR) / (Green + SWIR)

The value ranges from -1 to +1, where higher positive values indicate a strong snow presence, moderate values suggest mixed snow and non-snow surfaces, and negative values indicate snow-free areas such as vegetation, bare land, water bodies, built-up areas, and terrain shadows. This spectral index is broadly used in cryospheric studies, climate change analysis, and snow cover monitoring.

3. RESULTS AND DISCUSSION

3.1 ANOMALY ANALYSIS OF TEMPERATURE AND RAINFALL

The anomaly analysis for Leh from 1999 to 2024 reveals variability in both temperature and precipitation by showing deviations from the baseline average; this analysis allows us to identify extreme years and shifts in trends that are otherwise obscured in absolute climatological values.

3.1.1 Temperature Anomaly Patterns

The anomaly analysis for temperature was performed on both maximum and minimum temperature observations, with baseline averages recorded every month. The data ranged from 1999 to 2024, and the analysis was performed with a five-year temporal gap to understand the trends and patterns of temperature over 25 years.

The temperature anomaly series shows a clear consistency of positive anomalies, indicating a warming phase in Leh. Initially, the anomaly analysis exhibited a mix of negative and neutral anomalies, but later, with increasing time, the record showed consistent above-average temperatures, which suggests that there is a warming trend in Leh. There is an inter annual variability, occasional negative or weekly positive anomalies interrupt the warming trend. However, these cooler phases are neither prolonged nor sufficient to offset the cumulative warming signals that are being reflective through the anomalies. The increasing warming trend not only indicates a rising wind temperature for both maximum and minimum observations but also points towards the intensification of thermal extremes.

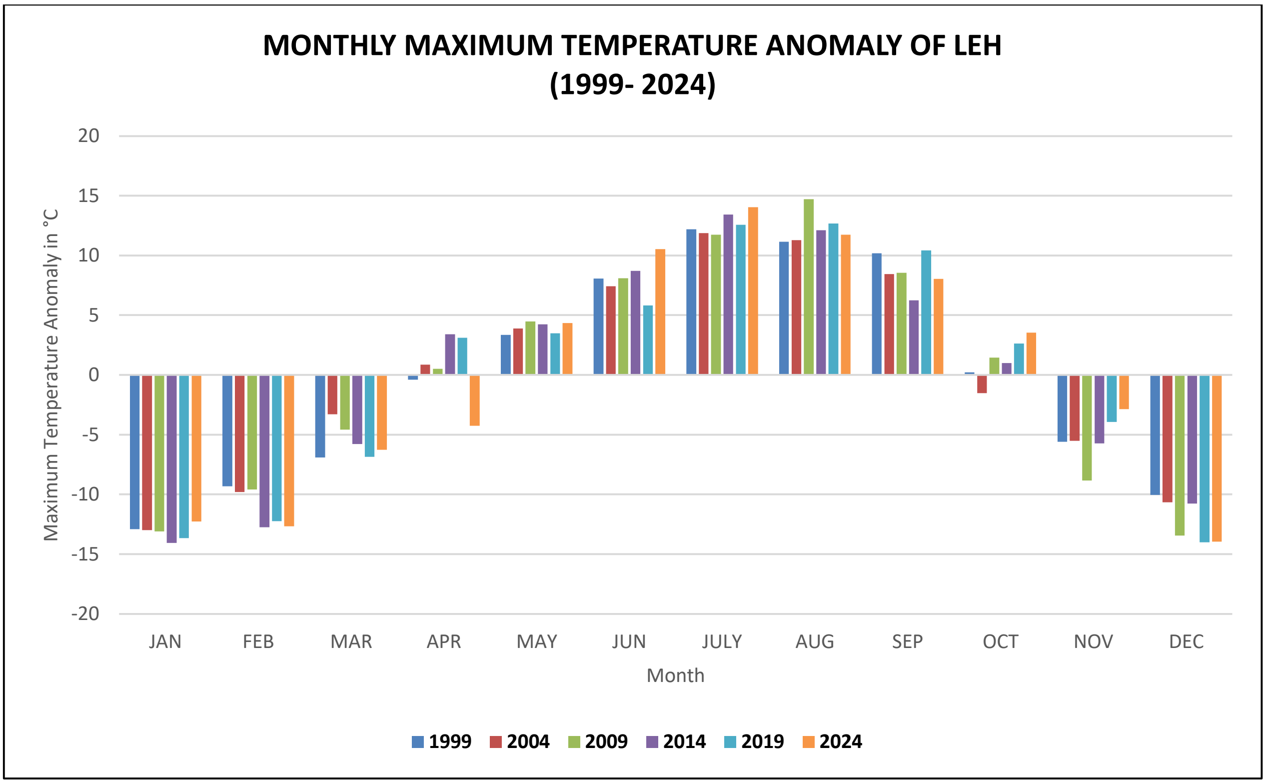


Figure 5: Monthly Maximum Temperature Anomaly of Leh

Table 04: Monthly Maximum Temperature Anomaly of Leh

Monthly Maximum Temperature Anomaly of Leh (1999-2024)												
YEAR	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JULY**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
1999	-12.90	-9.32	-6.90	-0.39	3.36	8.06	12.18	11.16	10.19	0.21	-5.59	-10.05
2004	-12.99	-9.79	-3.30	0.86	3.88	7.43	11.87	11.28	8.44	-1.52	-5.52	-10.66
2009	-13.11	-9.58	-4.59	0.52	4.49	8.09	11.73	14.71	8.55	1.46	-8.83	-13.46
2014	-14.06	-12.76	-5.78	3.39	4.23	8.71	13.44	12.10	6.24	0.98	-5.73	-10.77
2019	-13.65	-12.25	-6.85	3.12	3.47	5.81	12.58	12.67	10.43	2.62	-3.93	-14.00
2024	-12.26	-12.66	-6.26	-4.26	4.34	10.54	14.04	11.74	8.04	3.54	-2.86	-13.96

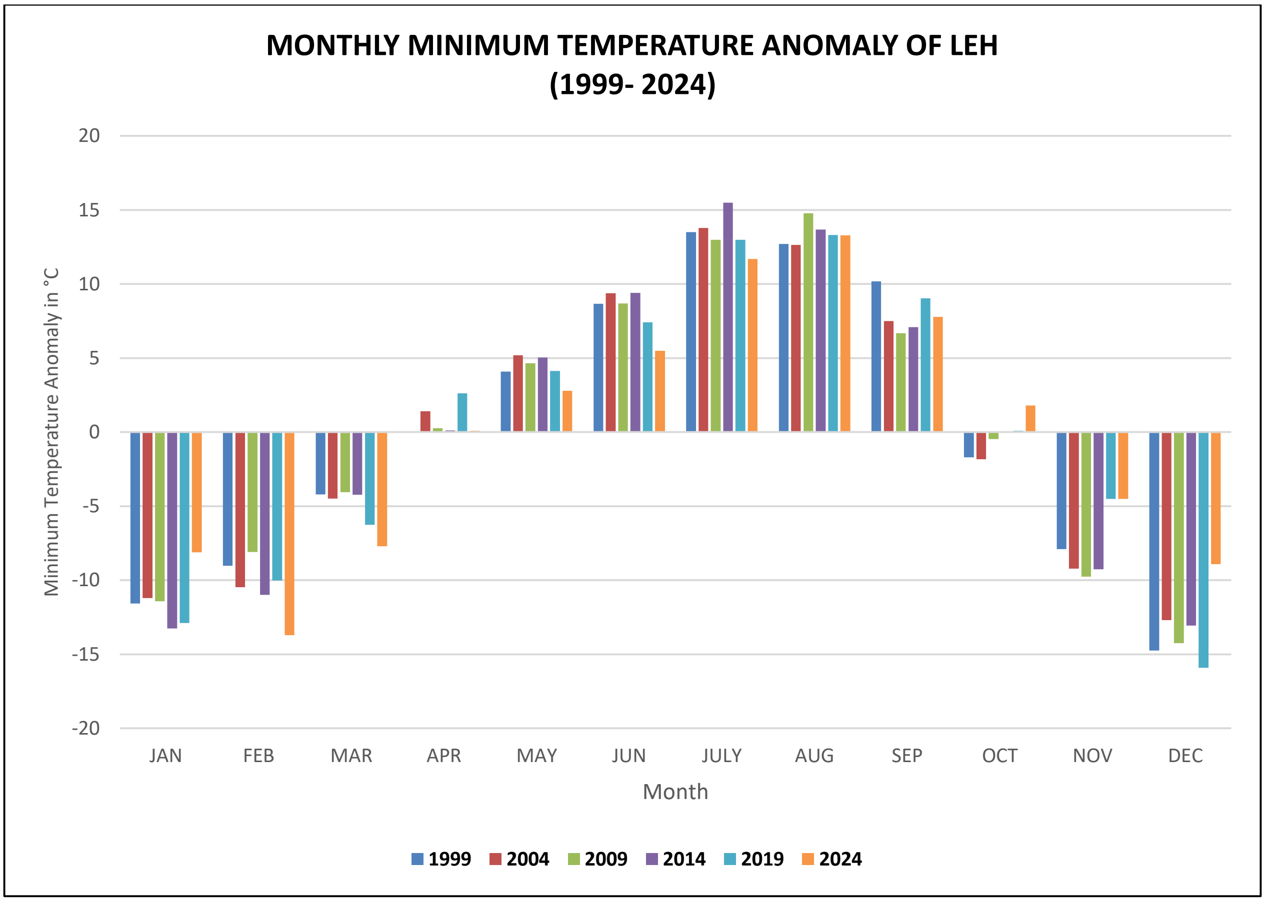


Figure 6: Monthly Minimum Temperature Anomaly of Leh

Table 5: Monthly Minimum Temperature Anomaly of Leh

MONTHLY MINIMUM TEMPERATURE ANOMALY OF LEH (1999- 2024)												
YEAR	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JULY**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
1999	-11.58	-9.04	-4.21	0.03	4.10	8.67	13.50	12.70	10.17	-1.70	-7.90	-14.74
2004	-11.21	-10.48	-4.49	1.41	5.19	9.38	13.78	12.64	7.51	-1.83	-9.22	-12.69
2009	-11.41	-8.09	-4.05	0.26	4.64	8.69	12.98	14.79	6.68	-0.47	-9.76	-14.26
2014	-13.25	-10.98	-4.23	0.12	5.04	9.41	15.49	13.69	7.09	-0.05	-9.27	-13.07
2019	-12.90	-10.02	-6.26	2.62	4.13	7.42	12.99	13.32	9.03	0.08	-4.51	-15.91
2024	-8.11	-13.71	-7.71	0.09	2.79	5.49	11.69	13.29	7.79	1.79	-4.51	-8.91

3.1.2 Rainfall Anomaly Patterns

Anomaly analysis for rainfall was performed on observations with baseline averages recorded monthly. The data ranged from 1999 to 2024, and the analysis was performed with a five-year temporal gap to understand the trends and patterns of rainfall for 25 years.

Precipitation anomalies display strong and inconsistent behavior. Both negative and positive anomalies occurred frequently, with no clear long-term increasing or decreasing trend. This shows the inherently random nature of precipitation in this cold-aired region, where annual totals are highly sensitive to a small number of extreme events. There is a rising influence of episodic high-intensity events rather than gradual changes in the average rainfall. The extended negative anomaly points to drought-like conditions, exhibiting scarcity in the region, which is already constrained by limited hydrological resources.

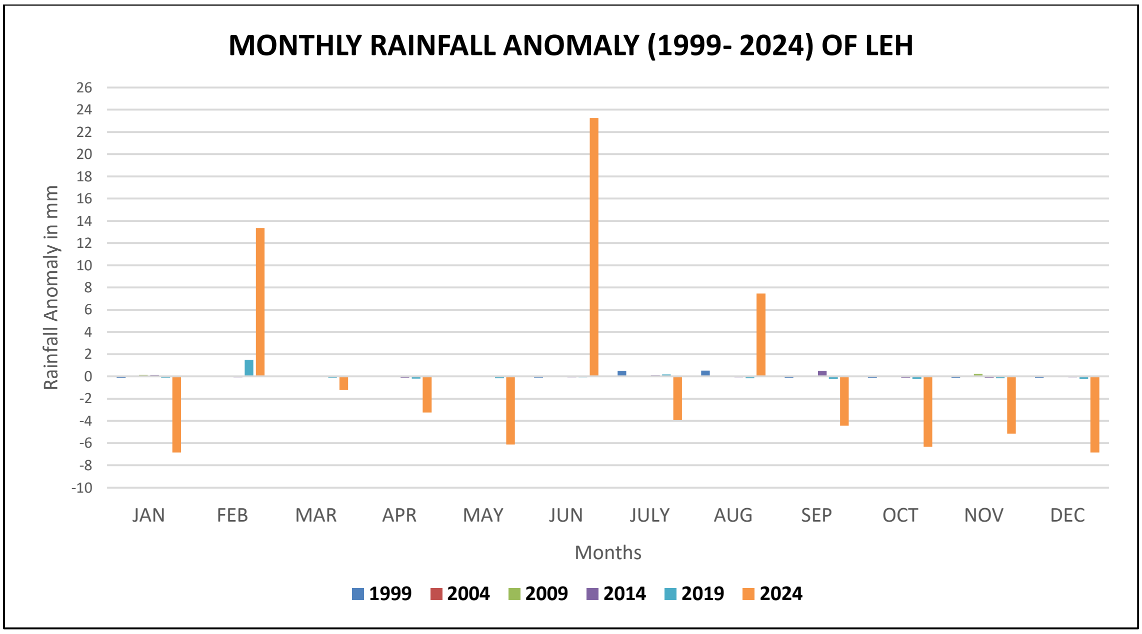


Figure 7: Monthly Rainfall Anomaly of Leh

Table 6: Monthly Rainfall Anomaly of Leh

MONTHLY RAINFALL ANOMALY OF LEH (1999- 2024)												
YEAR	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JULY**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
1999	-0.15	-0.05	-0.05	-0.05	-0.05	-0.12	0.49	0.53	-0.13	-0.15	-0.15	-0.15
2004	0.00	-0.02	-0.01	0.01	-0.02	0.07	-0.02	0.02	-0.02	0.05	-0.02	-0.02
2009	0.16	-0.06	-0.04	-0.06	-0.06	-0.04	-0.06	-0.02	0.02	-0.06	0.23	-0.03
2014	0.12	-0.07	0.00	-0.10	-0.06	-0.09	0.08	-0.08	0.49	-0.10	-0.10	-0.08
2019	-0.11	1.50	-0.10	-0.21	-0.17	-0.08	0.16	-0.17	-0.22	-0.22	-0.17	-0.22
2024	-6.83	13.37	-1.23	-3.23	-6.13	23.27	-3.93	7.47	-4.43	-6.33	-5.13	-6.83

3.1.3 Temperature - Rainfall Anomaly Analysis

The anomaly pattern of both temperature and rainfall, when analyzed together, indicated a warm stress regime combined with hydrological uncertainty. Warmer temperatures enhance evapotranspiration and accelerate snow and ice melt. Erratic rainfall fails to provide consistent replenishment and balance out the deficiencies. The combination of these anomalies increases the vulnerability of Leh systems. The increasing frequency of positive temperature anomalies and negative rainfall anomalies is concerning, as it signals a shift towards drier and hotter conditions in Leh.

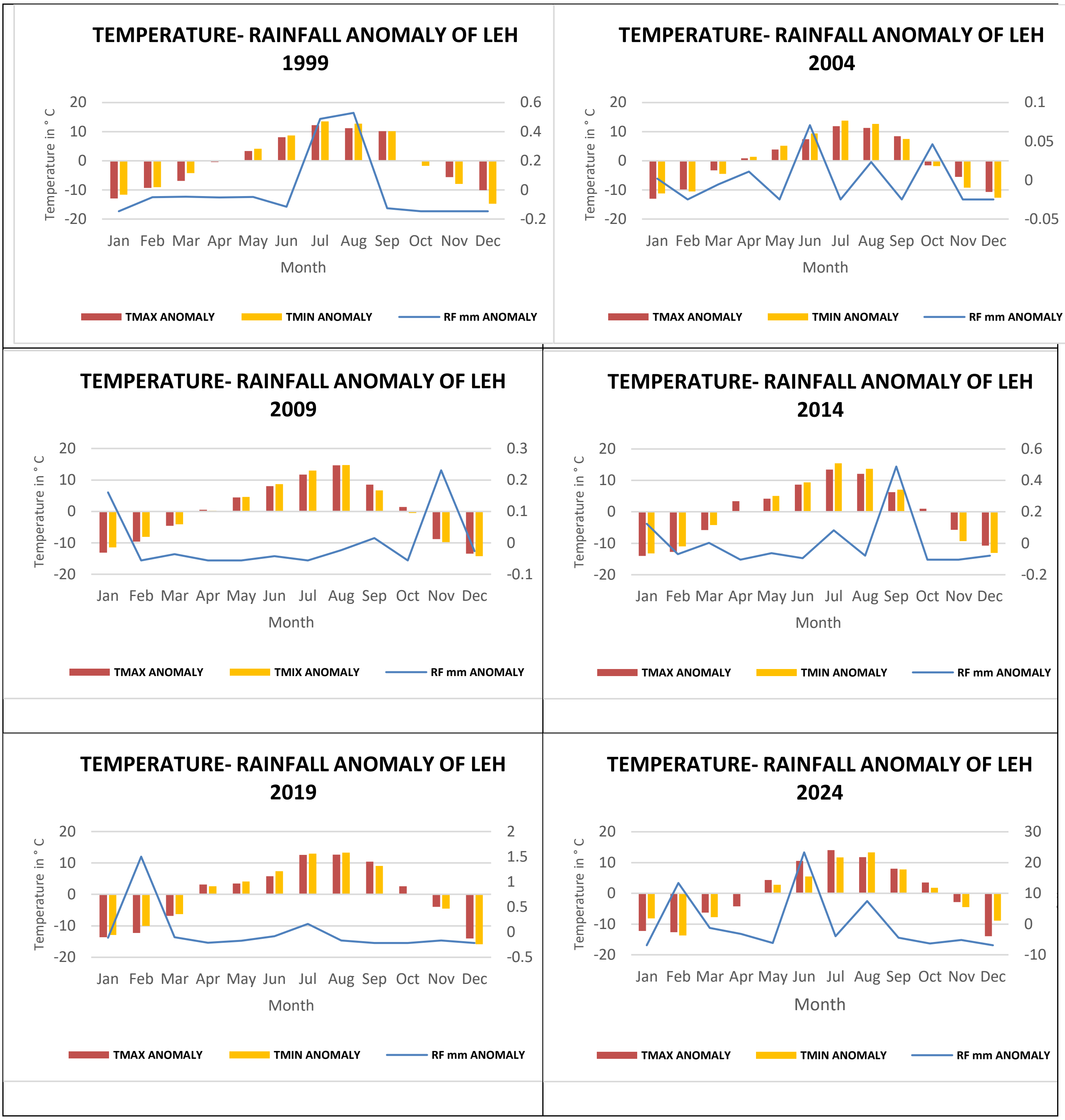


Figure 7 Temperature –Rainfall Anomaly of Leh from 1999-2024

3.2 THE INNOVATIVE TREND ANALYSIS OF TEMPERATURE AND RAINFALL

The Innovative Trend Analysis (ITA) Studies temporal changes by dividing the time series into two equal halves and plotting them against each other. Points over the 1:1 line show no trend. Points above the line show an increasing trend, and points below the line show a decreasing trend. The analysis was performed on maximum and minimum temperature and rainfall data from 1999 to 2024 with a five-year temporal gap from IMD. This helps identify monotonic trends with observations on consistent increase or decrease in patterns, non-monotonic behaviors, and clustering of point plots, as well as the direction and magnitude of the trend with trend slope and trend indicator.

3.2.1 Temperature Trends

Maximum Temperature Trend: The analysis of the maximum temperature for the period 1999–2024 shows a predominantly monotonic increasing trend that reflects a sustained rise in daytime warming conditions. The maximum temperature consistently plots above the 1:1 line in the ITA, confirming a persistent warming trend throughout the analysis of 25 years. In the early years, there was a relatively stable monotonic behavior with a moderate positive slope, followed by a clear intensification of the warming trend. There was the presence of initial non-monotonic clustering in 2019 and 2024, which suggests short-term variability but hardly interrupts the overall increasing pattern. The slope standard deviation increased towards the later years. In the trend analysis, decades enhanced the variability and potential heat extremes with a consistently high correlation coefficient, confirming that the increasing trend remained statistically robust. Overall, the analysis revealed a transition from gradual warming to a more pronounced and variable increase in maximum temperature, indicating intensifying heat stress conditions.

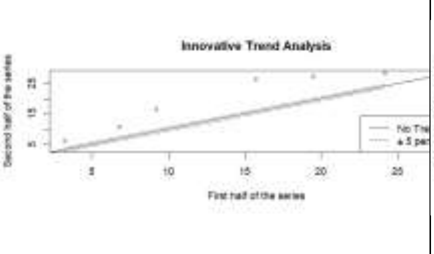
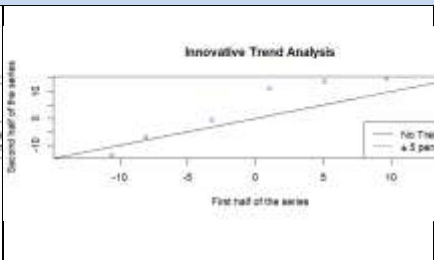
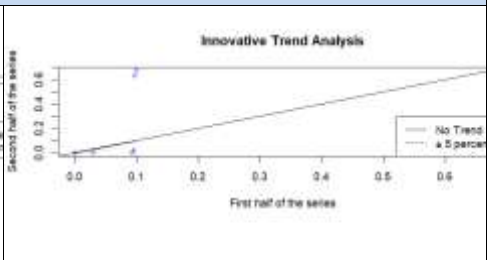
Minimum Temperature Trends: The analysis of minimum temperature shows a stronger and more consistent monotonic increasing trend throughout the study, which indicates persistent warming. Which indicates towards a persistent warming. It shows a clear dominance of an increasing pattern above the trend line for most of your and few minor non-monotonic behaviors in the initial series. From 1999 onwards, the minimum temperature trend displays a high correlation coefficient and relatively low slope standard deviation, suggesting that the observation of warming is a systematic rather than random trend. The increasing magnitude of the trend slope over time reflects significant acceleration in minimum temperature rise.

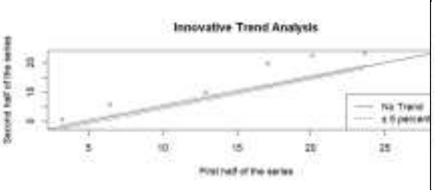
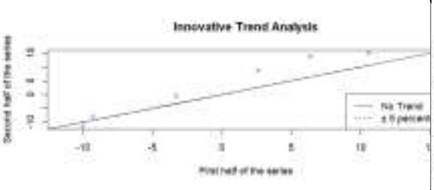
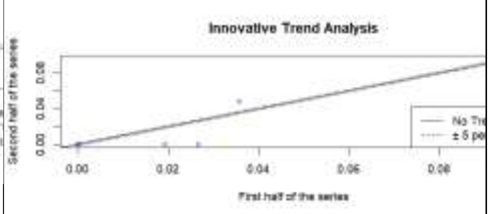
3.2.2 Rainfall Trends

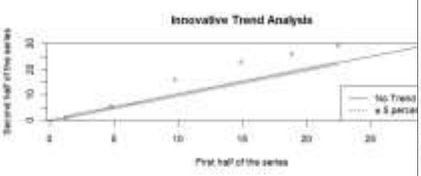
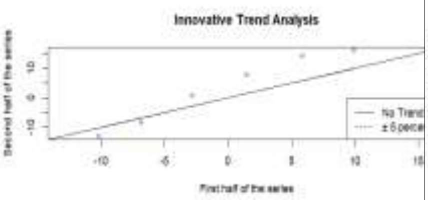
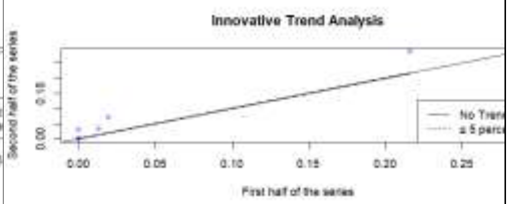
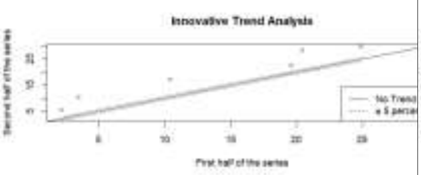
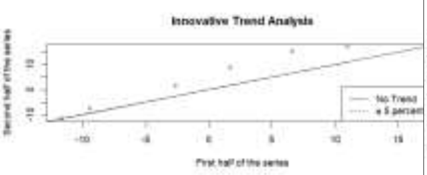
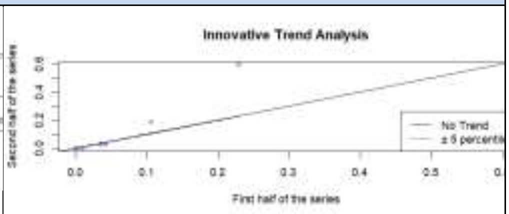
In contrast to temperature, rainfall demonstrated a predominantly non-monotonic trend over the 25-year period of 25 years. We showed high variability and dispersed clustering in the scatter plots of ITA. In the early years, there was a weak increase on both sides of the 1:1 line, which pointed towards the absence of a stable long-term trend. This variability persisted, reflecting irregular rainfall behavior and fluctuating seasonal contributions. However, there was a notable shift in the later years, particularly from 2019 onwards, where the trend began to exhibit a clearer decreasing tendency. By 2024, rainfall displayed a distinct monotonic decreasing trend supported by a strong negative slope and reduced dispersion, suggesting a transition from variability-dominated behavior to a sustained drying condition. The analysis pointed towards growing precipitation uncertainty in the earlier decades, followed by an emerging drying regime in the recent period.

Table 6: Innovative Trend Analysis of Temperature and Rainfall

INNOVATIVE TREND ANALYSIS (ITA) OF TEMPERATURE AND RAINFALL (1999- 2024)							
year	**Climate indices**	**Parameters**					
		Trend Slope	**Trend Indicator**	**Slope Standard Deviation**	**Correlation Coefficient**	**Upper CI (95%)**	**Lower CI (95%)**
1999	TMAX	1.0053	4.5946	0.1263	0.9572	0.2475	-0.2475
	TMIN	0.668	-39.3643	0.1328	0.9603	0.2603	-0.2603
	Rainfall	0.0253	21.8448	0.0112	0.5304	0.022	-0.022
2004	TMAX	0.7719	3.3345	0.0893	0.9772	0.1751	-0.1751
	TMIN	0.5662	-68.2979	0.0752	0.9869	0.1475	-0.1475
	Rainfall	-0.0016	-3.2934	0.0007	0.8923	0.00142	-0.00142
2009	TMAX	0.7871	3.9297	0.075	0.9874	0.147	-0.147
	TMIN	0.5533	-76.4882	0.0792	0.9857	0.1553	-0.1553
	Rainfall	0.0047	6.8182	0.0008	0.9864	0.00147	-0.00147
2014	TMAX	0.9031	4.0092	0.1004	0.9764	0.1968	-0.1968
	TMIN	0.7714	-62.3161	0.0632	0.9918	0.1238	-0.1238
	Rainfall	0.0113	9.6363	0.0014	0.9853	0.00278	-0.00278
2019	TMAX	1.1309	5.9494	0.1463	0.9531	0.2868	-0.2868
	TMIN	0.8337	-46.3598	0.1257	0.9654	0.2463	-0.2463
	Rainfall	-0.0456	-7.7353	0.0028	0.9927	0.00551	-0.00551
2024	TMAX	1.1417	4.2723	0.237	0.8801	0.4645	-0.4645
	TMIN	1.175	-9.0192	0.0903	0.9766	0.1769	-0.1769
	Rainfall	-1.0667	-6.3158	0.2227	0.8845	0.4365	-0.4365

INNOVATIVE TREND ANALYSIS OF LEH (1999)		
		
Maximum Temperature (Monthly) Monotonic Increasing trend in temperature	**Minimum Temperature (Monthly)** Monotonic increasing trend with low non-monotonic pattern in beginning.	**Rainfall in mm (Monthly)** Non-Monotonic trend with low upward clusters showing weak increasing trend

INNOVATIVE TREND ANALYSIS OF LEH (1999)		
INNOVATIVE TREND ANALYSIS OF LEH (2004)		
		
Maximum Temperature (Monthly) Monotonic Increasing trend patterns in temperature	**Minimum Temperature (Monthly)** Monotonic increasing trend followed in temperature (min).	**Rainfall in mm (Monthly)** Non-Monotonic trend pattern shows a medium decrease in the trend.

INNOVATIVE TREND ANALYSIS OF LEH (2009)		
		
Maximum Temperature (Monthly) Monotonic Increase in the trend pattern	**Minimum Temperature (Monthly)** Begins with non-monotonic and follows a monotonic pattern then with an increasing trend flow.	**Rainfall in mm (Monthly)** Non monotonic trend with low increasing trend
INNOVATIVE TREND ANALYSIS OF LEH (2014)		
		
Maximum Temperature (Monthly) Monotonic increasing trend	**Minimum Temperature (Monthly)** Monotonic increasing trend	**Rainfall in mm (Monthly)** Non monotonic trend with low increasing trend flow.

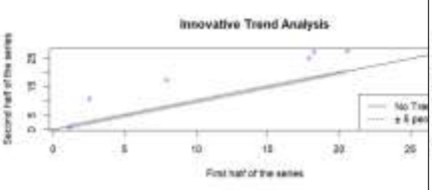
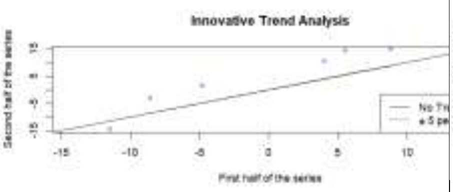
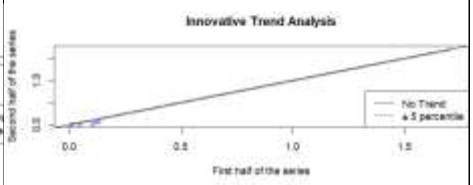
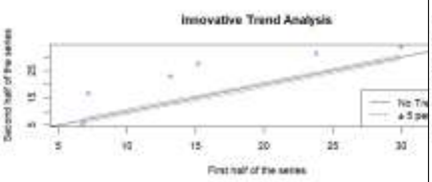
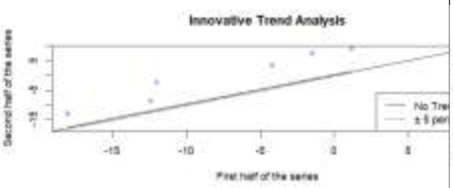
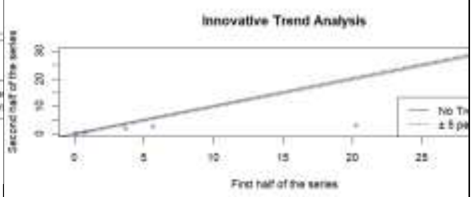
INNOVATIVE TREND ANALYSIS OF LEH (2019)		
		
Maximum Temperature (Monthly) Begins with non-monotonic trend and then monotonic trend with increasing pattern.	**Minimum Temperature (Monthly)** Non monotonic trend with high increasing trend	**Rainfall in mm (Monthly)** Non-Monotonic trend with weak or low decreasing trend
INNOVATIVE TREND ANALYSIS OF LEH (2024)		
		
Maximum Temperature (Monthly) Begins with non-monotonic but continuous in monotonic increasing trend.	**Minimum Temperature (Monthly)** Monotonic increasing trend	**Rainfall in mm (Monthly)** Monotonic Decreasing trend

Figure 8: Innovative Trend Analysis of Temperature and Rainfall (1999-2024)

3.3 GEOSPATIAL ANALYSIS

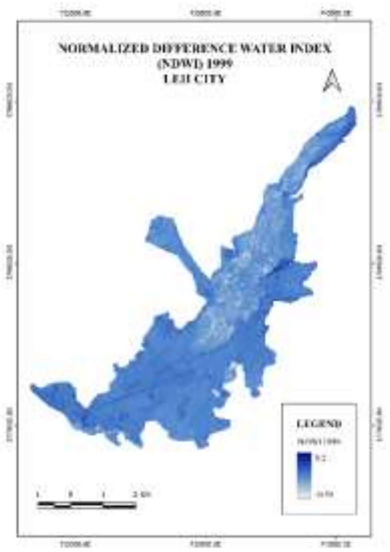
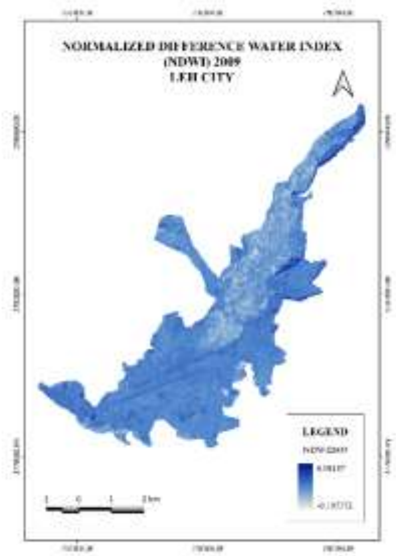
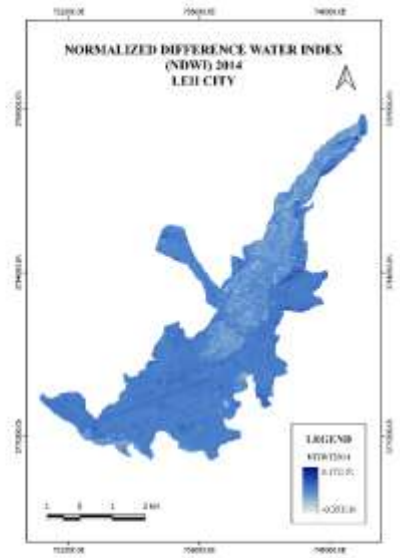
3.3.1 Normalized Difference Water Index (1999- 2024)

The analysis of NDWI from 1999 to 2024 indicates a continuous dominance of low to negative NDWI values, which reflect limited surface water availability and low soil moisture conditions in Leh city. In 1999, the NDWI values ranged from 0.2 to -0.54, which suggested the presence of localized moist surfaces or small water bodies in the extensive dry and bare land areas. By 2009, the range narrowed to 0.08 to -0.19, indicating a notable reduction in surface moisture and an expansion of dry surfaces. Although 2014 showed a slight recovery in the isolated areas, with values reaching up to 0.17 and negative values to -0.35, highlighting the continued prevalence of dry soil and limited water retention. The declining trend became more evident in 2019 and 2024, where the NDWI values were mostly negative and reached as low as -0.54, signifying intensified surface trainers and increased exposure of bare land. The analysis shows a temporal pattern that reveals a gradual but consistent decline in surface water and soil moisture over the 25 years. This suggests increasing aridity, reduced hydrological resilience, and limited contribution of surface water resources in Leh city.

3.3.2 Normalized Difference Snow Index (1999- 2024)

The NDSI analysis over the 25-year period of 25 years revealed a highly variable and non-monotonic pattern of snow cover distribution, which also indicated strong spatial heterogeneity. In 1999, the NDSI value ranged from 0.66 to -0.53, which indicates the presence of substantial snow cover alongside snow-free surfaces, such as exposed land, vegetation, built-up areas, and shadowed regions. The deduction in maximum NDSI value in 2009 ranging from 0.47 to -0.31 suggested a decrease in either snow extent or snow purity with mixing of snow and non-snow surfaces. In 2014, there was a renewed variability in NDSI values, reaching up to 0.56, while still encompassing large snow-free areas, reflecting a fragmented snow cover condition. Similarly, in 2019, there was a relatively strong snow presence but maintained heterogeneity across the landscape. In 2024, the wide range of NDSI values ranging from 0.57 to -0.69 highlighted the pronounced contrast between persistent snow-covered zones and extensive snow-free areas, particularly in built-up and exposed terrain. NDSI did not demonstrate a clear long-term increase or decrease trend; instead, it reflected inter annual variability, which may be driven by climatic fluctuations, seasonal accumulation, or melting dynamics, indicating that while snow cover remains present in parts of the region, its special continuity and consistency have weakened over time.

NORMALIZED DIFFERENCE WATER INDEX (NDWI) 1999- 2024

1999	2009	2014
		
Data Source: LANDSAT 5 TM C2	Data Source: LANDSAT 5 TM C2	Data Source: LANDSAT 8/9 OLI/ C2
Values: (0.2) – (-0.54)	Values: (0.080 – (-0.19)	Values: (0.17) – (-0.35)
The region has some water sources and moist soil with portions of dry surfaces and bare soil too	The region has low content of water and less soil moisture and has dry surfaces with bare soil	The region has low presence of water bodies and low soil moisture content with composition including dry soil and bare land.

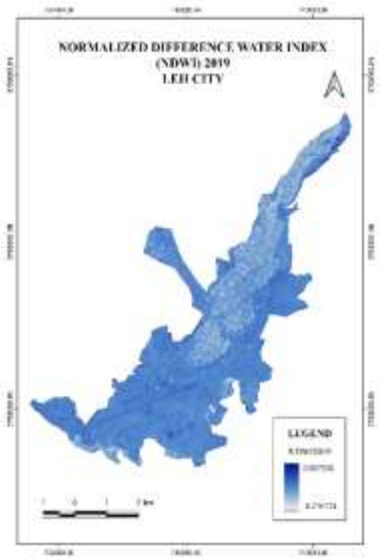
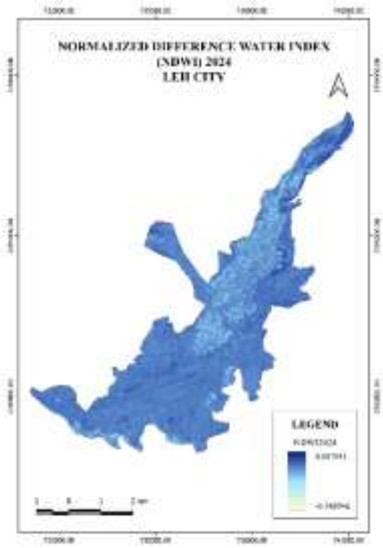
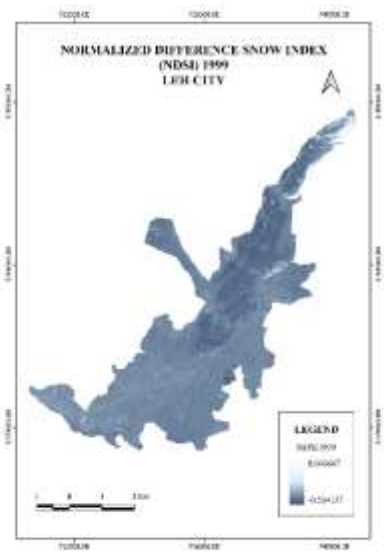
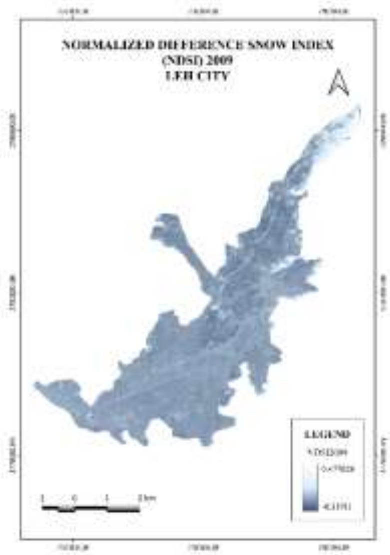
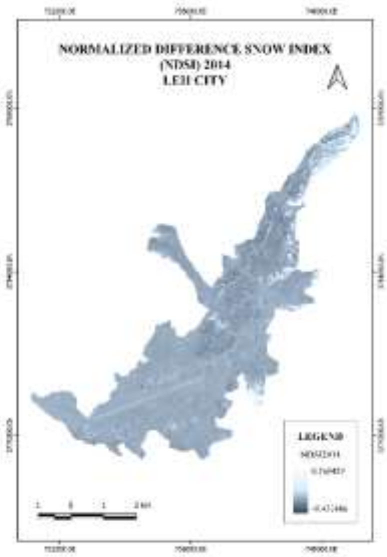
2019	2024
	
Data Source: LANDSAT 8/9 OLI/ C2	Data Source: LANDSAT 8/9 OLI/ C2
Values: (0.09) – (-0.23)	Values: (0.08) – (0.54)
The region has low water content on surface and soil and consist of bare and dry soil.	The region has low water content on surface and soil and consist of bare and dry soil.

Figure 9: Normalized Difference Water Index (NDWI) 1999- 2024

The Temporal analysis ranging from 1999 – 2024 shows a gradual decline in surface water and soil moisture content leading to more dryer and bare soil with less water proportions in the region.

NORMALIZED DIFFERENCE SNOW INDEX (NDSI) 1999- 2024

1999	2009	2014
		

Data Source: LANDSAT 5 TM C2	Data Source: LANDSAT 5 TM C2	Data Source: LANDSAT 8/9 OLI/ C2
Values: (0.66) – (-0.53)	Values: (0.47) – (-0.31)	Values: (0.56) – (-0.43)
The region ranges from areas with strong snow presence with mixed surfaces to snow free land with snow free land and area with vegetation, built up and shadows.	The region consists of some areas with snow mixed with other surfaces, more likely heterogenous snow and snow free areas	The region ranges significantly from strong snow cover areas, high confidence of snow to areas with negligible snow cover.

Figure 10: Normalized Difference Snow Index (NDSI) 1999- 2014

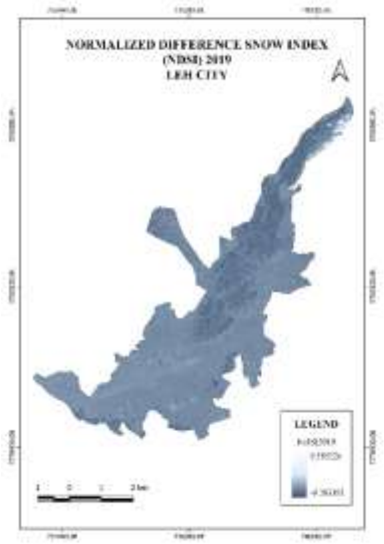
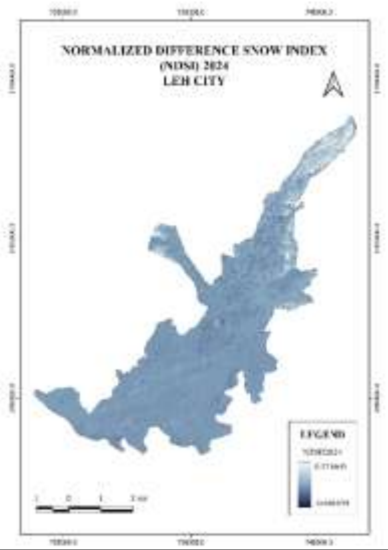
2019	2024
	
Data Source: LANDSAT 8/9 OLI/ C2	Data Source: LANDSAT 8/9 OLI/ C2
Values: (0.58) – (-0.28)	Values: (0.57) – (-0.69)
The region shows strong snow cover presence which is heterogenous in nature and mixed with other surfaces with portions of no snow cover.	The region ranges from areas with strong snow presence with mixed surfaces to snow free land with snow free land and area with vegetation, built up and shadows.

Figure 10: Normalized Difference Snow Index (NDSI) 1999- 2024)

The Temporal analysis ranging from 1999 – 2024 shows a variation in pattern, the pattern is inconsistent with increase and decrease of snow cover but mainly some parts of region maintain the snow cover than built up that remains snow free.

3.4 FIELD SURVEY ANALYSIS

In view of the available time and resources to perform the survey, the survey adopted the following method for collecting data and information.

1) Interview surveys of government officials
2) Questionnaire hearing surveys

The survey was conducted in Leh city. Government officials, urban residents, and rural residents were selected as representatives to answer the survey questions. The field survey method conducted was a questionnaire survey, which aimed to identify problems and causes regarding water sources and usage patterns, perceptions of community on water-related risks, vulnerability, available adaptation strategy & policy, and other infrastructure recommendations to tackle the climate change impact in the Ladakh region.

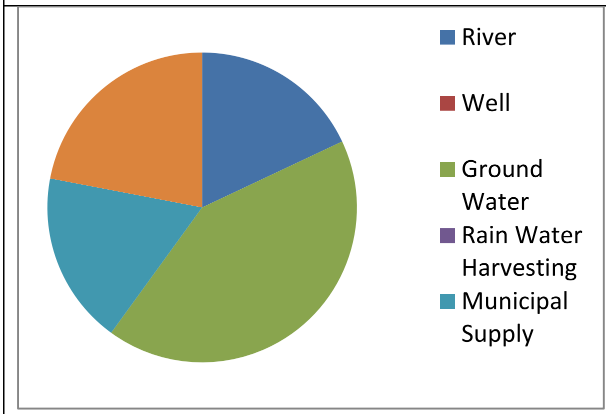
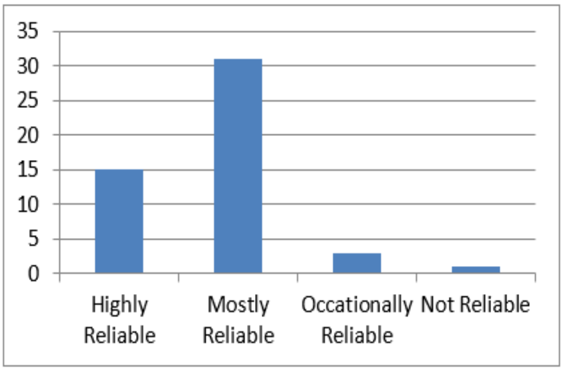
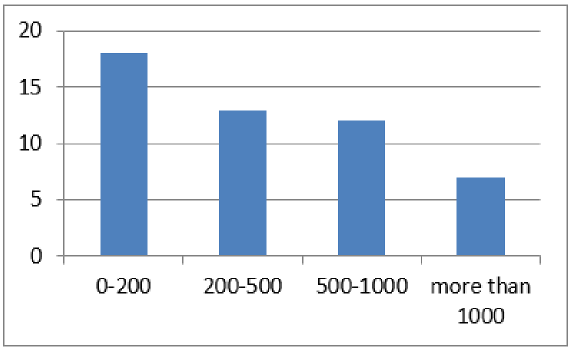
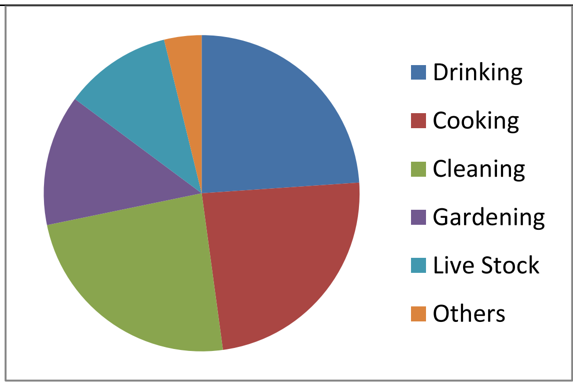
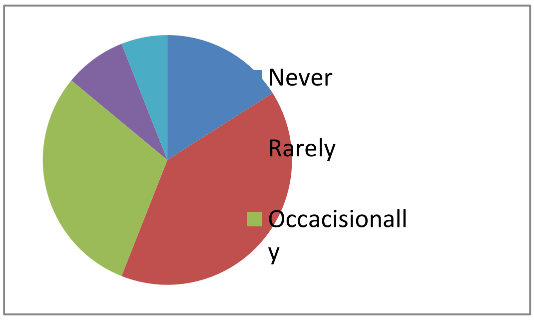
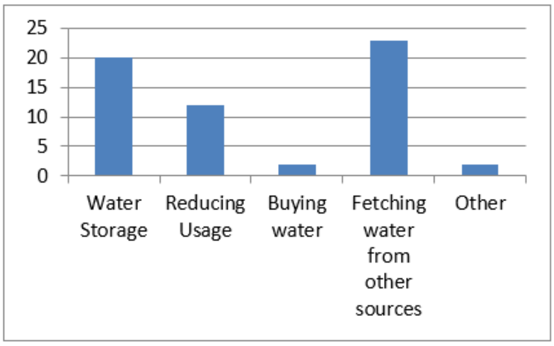
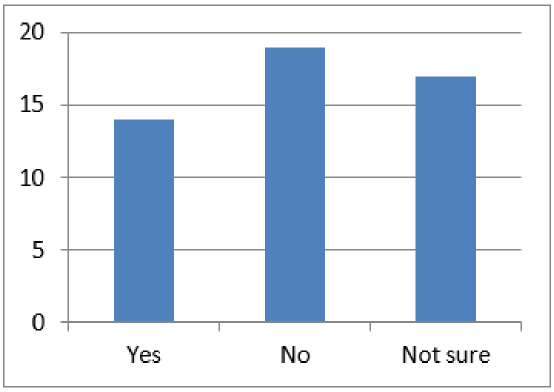
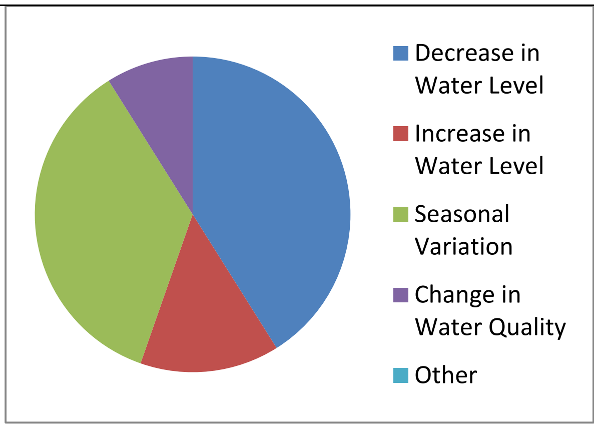
<table>
<tr><td>What is the primary source of water for your household?</td><td>How reliable is your primary water source throughout the year?</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>How many Liters of water does your household consume daily on average?</td><td>For what purposes do you use water in your household?</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>How often do you experience a water shortage?</td><td>What measures do you take during water shortage?</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Have you noticed any changes in water availability over the past 5-10 years?</td><td>If yes, what change have you noticed?</td></tr>
</table>

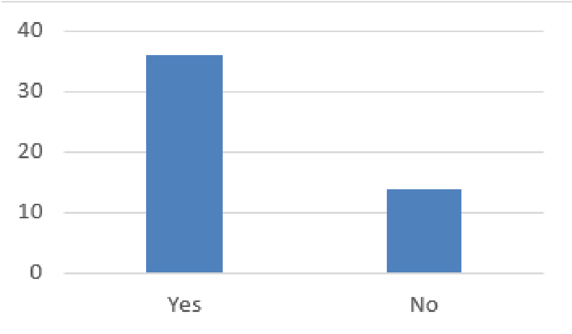
Figure 11: Survey Results

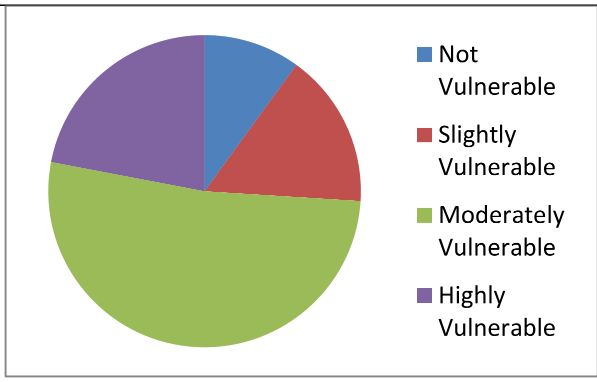




Have you experienced any water-related disaster (e.g. floods, drought) in the past 5 years?

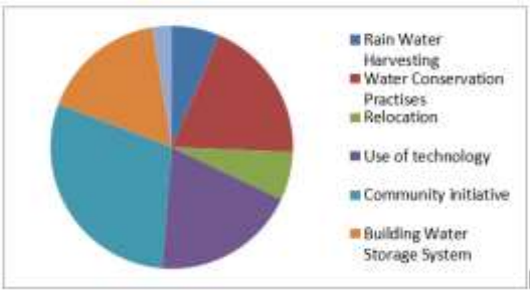
How vulnerable do you feel to water-related risks in your area?

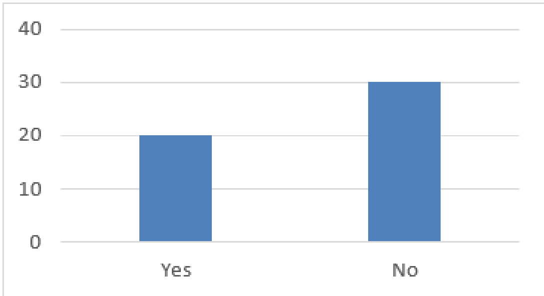




What adaptation strategies do you view to cope with water-related risks?

Are there any government or community programs that assist you in managing water-related risks?

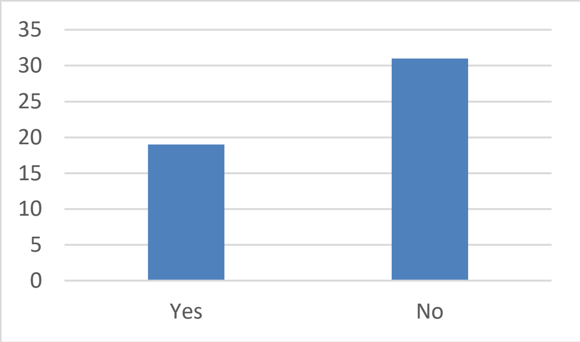
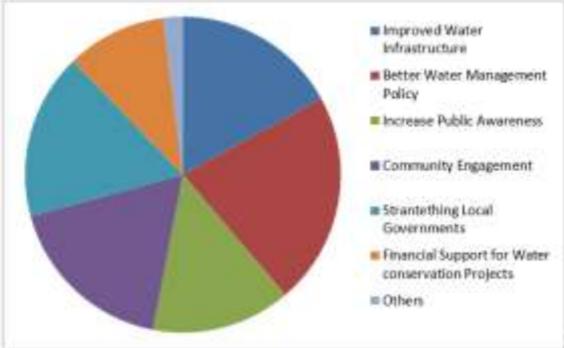
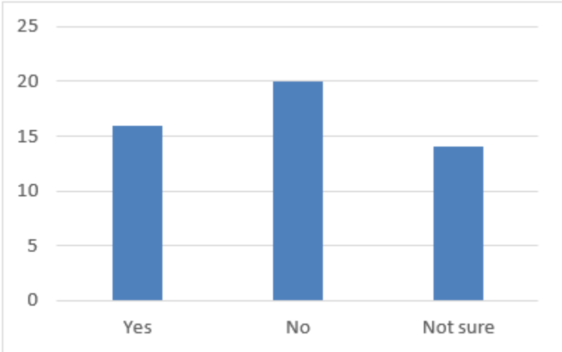




Do you participate in any community or governmental water management programs?

What measures do you think should be taken to improve water reliance in your area?

The survey reveals significant reliance on groundwater and general satisfaction with the reliability of current water sources. However, water shortages are a common issue, indicating areas for improvement. Awareness and perception of water-related risks vary, with most feeling vulnerable and having experienced recent water-related disasters. Adaptation strategies are in place, but there is a clear need for better policy support, community engagement, and infrastructure improvements. Engagement in governmental programs is relatively low, pointing towards an opportunity for increased participation and

	
Do you think current policies and infrastructures are adequate to handle water related risks?	

external support. The findings suggest a need for comprehensive measures to address water security and resilience effectively.

The major challenge for the analysis and quantification of climate change, urbanization, land use change, reduced precipitation, and increased temperature on water resources is the lack of primary and secondary data on these factors. There is no previous inventory of the number of springs, discharge rates, number of wells, retreating glaciers, and loss of snow-covered areas. Hence, the exploitation of water resources is difficult to predict. Therefore, to assess the current scenario of the impact of climate change on water resources, this study is based on the last 5–10 years of secondary data. The data indicate that the rise in water demand in Leh has created pressure on existing water resources.

4. CONCLUSION AND RECOMMENDATIONS

The above data indicate that Leh receives very little rainfall, and towns depend entirely on groundwater, springs, traditional reservoirs, ponds, and khuls that store or carry snowmelt from glaciers. Generally, traditional reservoirs, ponds, and khuls exist in every village and are in very derelict condition. Continuous effort is put by the community for maintenance of these traditional structures and improving their efficiency. Most glaciers at lower altitudes are melting at a faster rate and are lost, and glaciers at higher altitudes take longer to melt. Therefore, most springs and streams have a lower discharge, thus creating a water crisis. It is noticed that standard deviation of 4-6.6 degrees Celsius in maximum daytime temperature in the last five years and similarly 3-4 °C in minimum nighttime temperature. The commercial sector has decreased viability of water supply, hotels are closed as pumping wells had gone dried. Lot of community-based adaptation and mitigation has been done but still more efforts are required. Some recommendations based on the study are mentioned below:

4.1 Recommendations

Owing to the dominance of loose unconsolidated sandy soil in the upper reaches and low rainfall of this area, common watershed management structures, such as gabions, check dams, farm bunding, farm ponds, and digging of trenches on slopes, are not feasible. Plan of possible water conservation (both ground and surface) for fulfilling both drinking and irrigation demand of this valley are

Among the nine springs surveyed in this region, seven exhibit a substantial discharge, which is adequate relative to the demand for drinking water. The excess discharge from these high-output springs is stored in a tank via a pipeline, and this stored water is utilized for irrigation during the summer months. It is recommended to renovate the side walls of all existing pond structures for storage purposes, ensuring that the foundations of these structures remain undisturbed, as excavation and digging can lead to leakage issues. Due to the prevalence of loose sandy soil in this area, water may migrate to other regions within the valley. The watershed is flanked by two perennial streams that maintain a significant discharge throughout the year. The upper reaches of this valley are dominated by glaciers, resulting in the transport of glacial deposits by these streams, which are subsequently deposited along the drainage beds and around the confluence of the streams. This transported material, along with water, covers a substantial portion of the valley, contributing to land cover. Effective management of the area along the drainage bed and adjacent to agricultural zones is crucial for soil moisture and groundwater conservation. It is advisable to divert some stream discharge through a canal or pipeline into the barren land surrounding the drainage line in the upper reaches of the Changla Valley to create an artificial glacier above the Zingrul spring, and below and around the Shangnum spring in the Varila Valley. During winter, the stored water forms an artificial glacier due to freezing, and in summer, these smaller ice bodies melt earlier than glaciers at higher altitudes due to their lower elevation. The Leh agriculture department is advocating for solar greenhouse projects that utilize solar energy for food production. These greenhouses capture sunlight, maintaining an internal temperature conducive to growing both seasonal and off-season vegetables. These initiatives positively impact community livelihoods and the environment by reducing greenhouse gas emissions, as they replace vegetable imports previously transported by trucks. The study highlights the lack of adequate and accurate secondary data as a significant factor in assessing the current impact of climate change and formulating policies and strategies to address it. Ideally, a monitoring system should be implemented, incorporating both ground-based and satellite-based methods to provide accurate and real-time data. The future availability of water resources cannot be assessed without such monitoring systems. The Ladakh region is visibly affected by climate change. Climate change modeling can serve as a valuable tool for predicting and understanding the near future, aiding in the development of adaptable strategies and policies. Hotels and tourism stakeholders, in collaboration with the government, should promote awareness campaigns and strive to convey messages about water and environmental conservation to tourists and guests visiting Leh.

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