Nature Environment and Pollution Technology
An International Quarterly Scientific Journal
p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454
Vol. 24 | No. S1 | pp. 175-185 | 2025
Original Research Paper
https://doi.org/10.46488/NEPT.2024.v24iS1.012
Open Access Journal

Assessing the Climate Change Impacts in the Jhelum Basin of North-Western Himalayas

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 27-07-2024
Revised: 29-08-2024
Accepted: 23-09-2024

Key Words:
Climate change
Water resources
LULC
LST
Natural hazards
Jhelum basin

ABSTRACT

Climate change, a critical global environmental crisis, profoundly impacts ecosystems, particularly in regions with delicate environmental balances. This study focuses on the Jhelum basin in the north-western Himalayas, examining the extensive effects of climate change on glaciers, snow cover, land use and land cover (LULC), land surface temperature (LST), water resources, and natural hazards. Rising temperatures have accelerated glacier melting and altered precipitation patterns, with significant implications for local water supplies and agriculture. The study analyses climate data from the Indian Meteorological Department (1990 to 2020), revealing increasing trends in both maximum and minimum temperatures, alongside variable precipitation trends across different locations. The retreat of glaciers and the expansion of glacial lakes have been observed, with lower-elevation glaciers showing the most significant reduction. LULC changes indicate a shift from agricultural land to settlements and horticulture, while LST has risen, particularly in urbanized areas, reflecting the impact of urbanization and climate change. Furthermore, the increased frequency of extreme weather events, such as floods and landslides, exacerbates the region's vulnerability, threatening infrastructure, biodiversity, and local communities. The findings highlight the necessity of comprehensive, integrated approaches to address climate change and ensure the resilience of the Jhelum basin. This research contributes valuable insights into the region's changing environmental dynamics, essential for informed decision-making and effective adaptation strategies in response to the ongoing climate crisis.

INTRODUCTION

Climate change is today's most serious environmental crisis, with far-reaching consequences for the planet's delicate ecosystems. The rate at which weather and climate patterns are changing emphasizes the importance of solving this global crisis. Studies have consistently demonstrated the far-reaching implications of climate change, encompassing a spectrum of phenomena including escalating global temperature extremes (Lindsey & Dahlman 2020, Bellard et al. 2012, Morak et al. 2013, Fischer et al. 2013), heightened frequency and severity of cyclones and floods (Holland & Bruyère 2014, Moon et al. 2019, Walsh et al. 2016, Kundzewicz et al. 2014), dwindling snow cover (Wang et al. 2014, Mir et al. 2015, 2017). In addition, there has been a noticeable increase in wildfires, desert expansion (Huang et al. 2020), and shifts in agricultural practices. Regions with development limits, as well as those with fragile ecosystems, such as coastal, mountainous, and island locations, are especially sensitive to these effects (IPCC 6th Assessment Report 2022). Temperature and precipitation appear to be the most important markers of climate change (Fischer et al. 2013). Changes in these parameters serve as important indicators of climatic behaviour (Easterling et al. 2000, Zhang et al. 2011, Rana et al. 2017). Studies on climate change in India have revealed a consistent upward trend in temperatures throughout the twentieth century (Srivastava et al. 2001, Dash et al. 2007, Kumar et al. 1994, Soora et al. 2013, Sahai 1998, De & Mukhopadhyay 1998, Singh & Sontakke 2002). Furthermore, rainfall patterns vary by location, with some places experiencing increasing trends and others experiencing decreases of varied degrees (Kripalani et al. 1997, 2003, Singh & Sontakke 2002, Kumar et al. 1992, Misra et al. 2018, Guhathakurta et al. 2011). Projections for India imply that these trends will continue, with temperatures rising and rainfall patterns changing by the end of the twenty-first century (Kumar et al. 2013, 2016).

Numerous studies have focused on the Himalayan region, which plays a critical role in shaping the hydrometeorological environment and is vulnerable to disasters such as floods and landslides (Shrestha et al. 2009, Xu et al. 2009, Dimri & Dash 2012, Vedwan & Rhoades 2001, Bhutiyani et al. 2010, Sabin 2020). Mountainous locations around the world, such as the Alps, Rockies, Andes, and the Himalayas, have been recognized as particularly vulnerable to climate change due to dramatic height changes over short distances, which result in accelerated warming trends (Shrestha et al. 2012, 2019, Negi et al. 2021). Observations show that the Himalayas are warming faster than the global average, with serious consequences for ecosystems and the socioeconomic well-being of the region's inhabitants, as well as those in the Indo-Gangetic and Brahmaputra plains, which rely directly or indirectly on Himalayan resources (Rautela & Karki 2015, Bhutiyani et al. 2007). Furthermore, the region has seen glaciers decrease and retreat at varied rates due to climate change (Immerzeel et al. 2010, Bolch et al. 2012, Schickhoff et al. 2016, Kääb et al. 2012). To effectively reduce and adapt to the effects of climate change, it is necessary to measure variations in key climatic variables, allowing for informed decision-making and strategic actions.

Climate change is causing a wide range of significant changes in Alpine regions like Kashmir Himalaya. Rising temperatures have sped up glacier melting and reduced snowpack, affecting hydrological regimes and jeopardizing freshwater supplies downstream. These changes heighten the risk of natural disasters such as floods and landslides, endangering infrastructure, populations, and ecosystems. Changes in precipitation patterns present issues for water resource management and agriculture, while the spread of exotic species and diseases threatens biodiversity and ecological stability. The Alpine tourism business, which relies on winter sports, is facing uncertainty as snow seasons shorten and landscapes change, affecting local economies and livelihoods. Urgent adaptation strategies and joint efforts are required to counteract these complex effects and ensure the resilience of Alpine habitats and communities in the face of ongoing climate change.

In the present study, we conducted a comprehensive evaluation of the existing scholarly literature to assess the effects of climate change in the Jhelum basin of the north-western Himalayas. Our study covers a variety of topics, including climate change in the basin and its effects on glaciers, lakes, snow cover, land use and land cover (LULC), land surface temperature (LST), water resources, and natural hazards in the region. By combining information from many sources, we hope to provide a comprehensive picture of the shifting environmental dynamics in the Jhelum basin caused by climatic shifts. Through our analysis, we hope to add to the information base required for effective decision-making and adaptation strategies in the face of climate change issues in the northern Himalayas.

STUDY AREA DESCRIPTION

The Jhelum basin, known as the valley of Kashmir, spans 15,948 square kilometers between 32° 20′-34° 50′ N and 73°

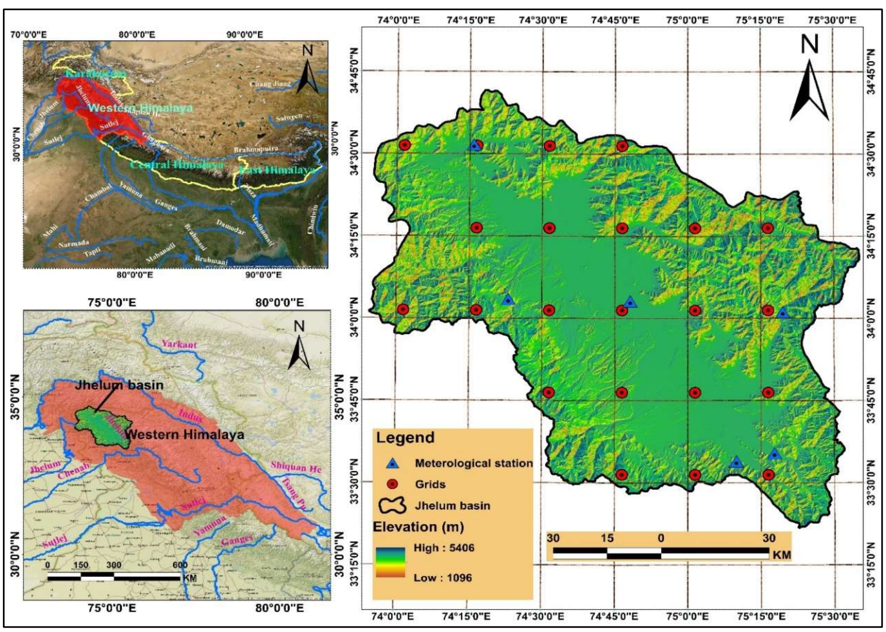

Fig. 1: Location map of the study area.

55′-75° 35′ E. Surrounded by the Great Himalayan and Pir Panjal ranges, the valley has a moderate climate with cold, moist winters and mild summers. It receives an average annual precipitation of 710 mm, predominantly from winter western disturbances and, to a lesser extent, the Indian Summer Monsoon (Fig. 1). Climate change poses significant threats to this region, particularly impacting its hydrology. Rising temperatures are likely to alter precipitation patterns, reducing snowfall and increasing rainfall in winter, which affects the timing and volume of river discharge. Accelerated glacial and snow melt will lead to higher spring flows and potential summer water shortages. These changes could result in more frequent and severe flooding, exacerbated erosion, and unpredictable water availability, challenging water resource management and the valley's ecological balance.

DATASETS AND METHODOLOGY

This study uses a comprehensive methodological framework that includes satellite data, climatic data, and a thorough literature analysis to analyze the effects of climate change on land use and land cover (LULC), land surface temperature (LST), water resources, and natural hazards in the Jhelum basin.

Data Collection

Satellite imagery from Landsat, MODIS, and Sentinel-2 was used to analyze variations in LULC and LST from 1990 to 2020. The images were processed and analyzed using remote sensing techniques to extract useful information.

Climate Data

Historical climate data, including temperature and precipitation records, were gathered from several meteorological stations in the Jhelum Basin. The dataset covers the years 1990 to 2020, offering a long-term view of regional climate patterns.

Literature Review

To contextualize and corroborate our findings, we undertook a thorough review of the current literature on climate change effects in the Jhelum basin. This review contributed to the identification of essential metrics and methodology employed in earlier studies.

Data Analysis

LULC Change Analysis.

Preprocessing: Satellite imagery was preprocessed to correct for atmospheric conditions, geometric distortions, and sensor errors.

Classification: Supervised classification approaches, such as maximum likelihood classification, were used to divide the images into distinct LULC classes.

Change Detection: Post-classification comparison methods were used to detect changes in LULC during the study period. The findings were confirmed with ground truth data and high-resolution images.

LST Change Analysis: Land surface temperatures were retrieved from thermal infrared bands from satellite images. Temporal changes in LST were examined using statistical approaches to find significant trends and spatial patterns. Urban and rural areas were compared to determine the impact of urbanization on LST.

Climate Data Analysis: Temperature and Precipitation Trends: Time series analysis of gathered climatic data was employed to identify trends in maximum and minimum temperatures, as well as precipitation patterns. Statistical approaches such as the Mann-Kendall trend test and Sen's slope estimator were used to determine the significance and rate of change.

Correlation Analysis: The relationships between climate variables and observed environmental changes (e.g., glacier retreat, and glacial lake expansion) were investigated to determine the underlying causes of these changes.

Synthesis and Integration

The findings from satellite data analysis, climate data analysis, and literature review were integrated to provide a holistic understanding of climate change impacts in the Jhelum basin. This integrated approach ensures that the results are robust and comprehensive, highlighting the interconnected nature of environmental changes in the region.

RESULTS

Climate Change in Jhelum Basin

There are many studies such as those by Kumar et al. (2010), Bhat (2010), Shafiq et al. (2018), Ahsan et al. (2021), in the Jhelum basin which reflect the changing state of temperature and precipitation variables. Due to unprecedented greenhouse gas emissions especially 1980s onwards world over, the temperature rates increased, which have also been observed in the Jhelum basin as well (Jaswal et al. 2010, Ahsan et al. 2022). This section focuses on changing precipitation and temperature during the 1990 to 2020 period. For at least 30 years climate data is required to study climate change and find effective trends (Livezey et al. 2007). Hence, 31 years data period (1990 to 2020) was selected for this study.

The average annual precipitation ranges between 74 cm (Srinagar) to 145 cm (Gulmarg) in the Jhelum basin. The average annual T*max* ranges from 20.53°C (Kupwara) to 11.93°C (Gulmarg); while the average annual T*min* ranges from 7.66°C (Srinagar) to 2.71°C (Gulmarg) in the Jhelum basin (Fig. 2). This study reveals that the precipitation is changing in the Jhelum basin, with half of the stations showing annual linear change rate ranging between -0.66 mm per year in Srinagar to -27.5 mm per year in Gulmarg; while another half of the stations show increasing linear trend varying from 1.71 mm per year in Pahalgam to 9.62 mm per year in Kupwara. Both the maximum (T*max*) and minimum (T*min*) temperatures are increasing across all the stations in the Jhelum basin except for a minute decrease in Gulmarg station. The T*max* linear change rate ranges between -0.0007°C/year in Gulmarg to 0.04°C/year in Kukernag. The T min linear change rate varies from -0.028°C/year in Gulmarg to 0.028 in Pahalgam (Fig. 3). These change rates are in line with recent studies in the basin such as Ahmad et al. 2022, Mir et al. 2023. It is important to note that the linear trend rates depend on the length and quality of the time series. Hence, these trend rates may vary depending on the time of consideration.

Fig. 2: Precipitation time series of different stations of Jhelum basin.

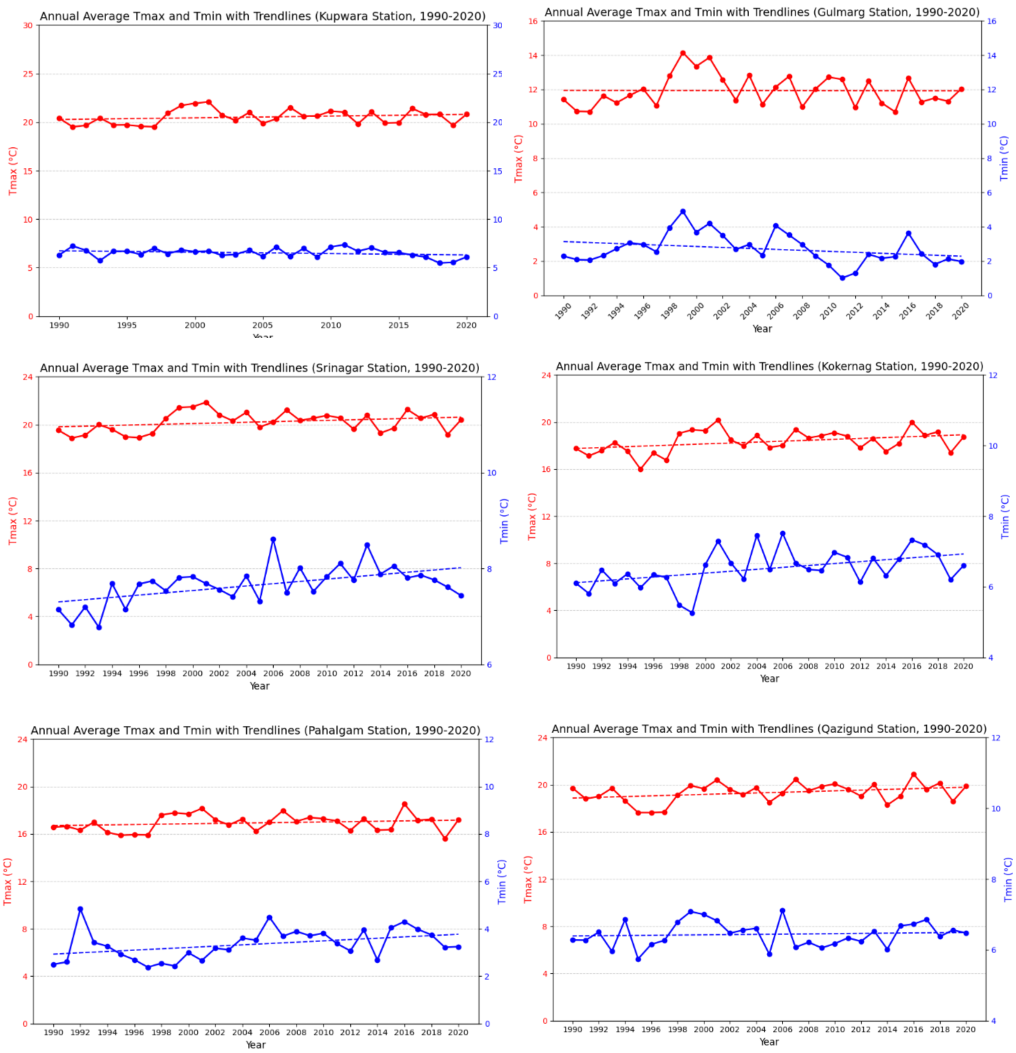

Fig. 3: T*max* and T*min* time series of different stations of Jhelum basin.

Climate Change Impacts in the North-Western Himalayas

Climate change is a global phenomenon that impacts the Earth and its systems in various ways. Primarily caused by human-induced factors such as the use of fossil fuels and deforestation, climate change has resulted in a significant shift in the global climate system. This transformative process is evident in the visible rise in global average surface temperatures, as well as an increase in extreme weather events like heatwaves, storms, floods, and wildfires (IPCC 2023, Abbass et al. 2022). The implications of this climate shift can be observed in polar regions, where melting ice caps and glaciers contribute to rising sea levels, posing a threat to coastal regions and island nations through erosion and increased vulnerability to storm surges (IPCC 2023). Climate change also exacerbates ocean acidification, which affects marine life, while weather changes disrupt habitats, impacting biodiversity (Tang 2020). Agriculture faces challenges as climate change puts stress on ecosystems, and water scarcity worsens, affecting both drinking water quality and quantity, as well as industrial needs (Du Plessis & du Plessis 2019, Cai et al. 2015). Climate change exacerbates social and political imbalances and leads to displacement (Thomas et al. 2015). Addressing this issue requires global cooperation to reduce emissions and ensure a sustainable future.

The Jhelum basin, located in the North-western Himalayan region, is experiencing significant climate impacts that have far-reaching consequences for its ecology, people, and economy. Rising temperatures in this region have caused glaciers to retreat and altered precipitation patterns. Climate change has also affected land use and land cover (LULC), land surface temperature (LST), and stream flow while intensifying the occurrence of extreme weather events such as cloudbursts and flash floods. These changes have profound implications for water supplies, agriculture, biodiversity, and the overall well-being of the local community.

Impact on glaciers and glacial lakes: The Jhelum basin is home to approximately 307 glaciers and 393 glacial lakes, covering an area of 102.1 km^2 and 22.13 km^2, respectively. These glaciers are melting and losing mass at an alarming rate. The overall glacier area has decreased by 20%, from 85.25 km^2 to 68.17 km^2, with an annual reduction rate of 0.56 km^2. Glaciers located at lower elevations, between 3800 and 4200 meters above sea level, have experienced a 35% decrease in area, with an annual decline rate of 0.22 km^2. The number of glacial lakes has increased by 71, covering an additional area of 3.29 km^2 (Fig. 4). The recession of glaciers and expansion of glacial lakes in the region have been extensively studied and documented by Mir et al. (2018), Romshoo et al. (2020), Ahmed et al. (2021), Dar et al. (2021), Sen et al. (2023), Majeed et al. (2023) and Ahmad et al. (2021). This rapid loss of glacier mass and the growth of glacial lakes can be attributed to rising temperatures and decreasing precipitation in the region, consistent with previous research conducted by Shafiq et al. (2021), Dad et al. (2021), Bashir et al. (2023), Romshoo et al. (2020), Mir et al. (2021), Ahsan et al. (2021), Gujree et al. (2022) and Bhat et al. (2023).

Impact on LULC and LST: Over the last two decades, the study area has witnessed a considerable change in land use and land cover (LULC), with notable changes observed in various classes. The widespread expansion of new settlements has resulted in a decrease in agricultural areas, while bare terrain, exposed rock, and horticulture have increased significantly. The conversion of agricultural land into residential buildings is visible, as seen by the increase in built-up areas. Agricultural land is widely being converted into horticulture due to climate change, economic returns, and population growth (Fig. 5). The same phenomena have also been reported in various parts of the Kashmir valley (Rasool et al. 2021, Ahmed et al. 2021, Fayaz et al. 2021). Furthermore, surface temperature has risen in the Jhelum basin from 2000 to 2020. According to the study, there was a 2-degree Celsius increase in temperature over this period, with urbanized areas, particularly around Srinagar, witnessing a noticeable spike in land surface temperature (Fig. 5). The extension of built-up regions, as well as the replacement of water bodies and vegetation with urban infrastructure, all contribute to the rise in temperature, demonstrating the impact of urbanization on local climate conditions.

Climate change in the Kashmir valley is apparent not only in LULC changes but also in land surface temperature (LST) patterns. The analysis of LST maps from 2000 to 2020 shows a steady rise in surface temperature, with a large

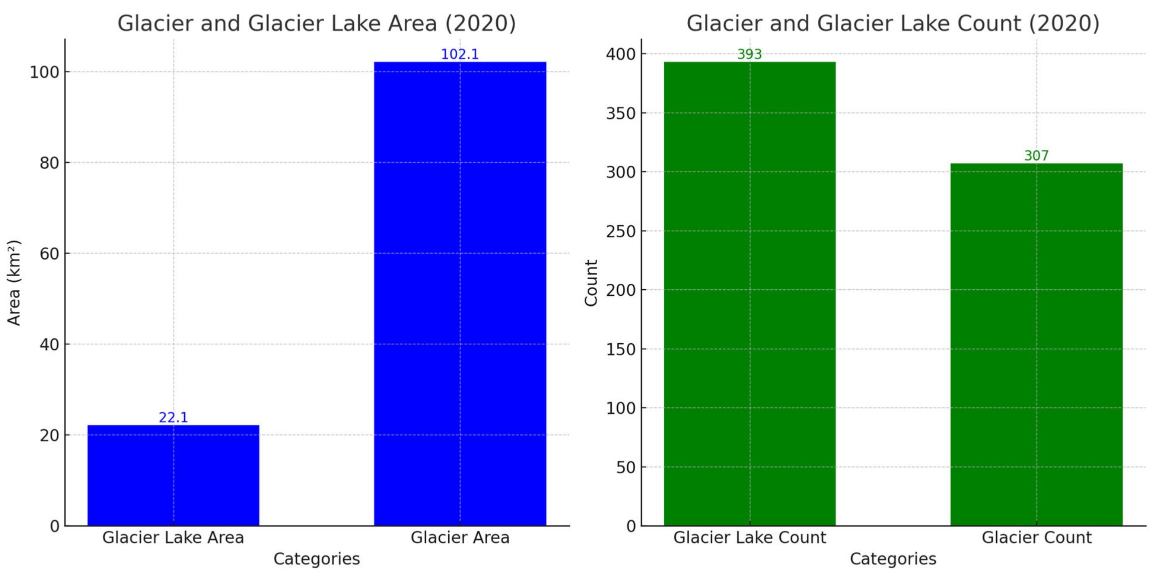

Fig. 4: Glacier and Glacial Lake area and count in the Jhelum basin.

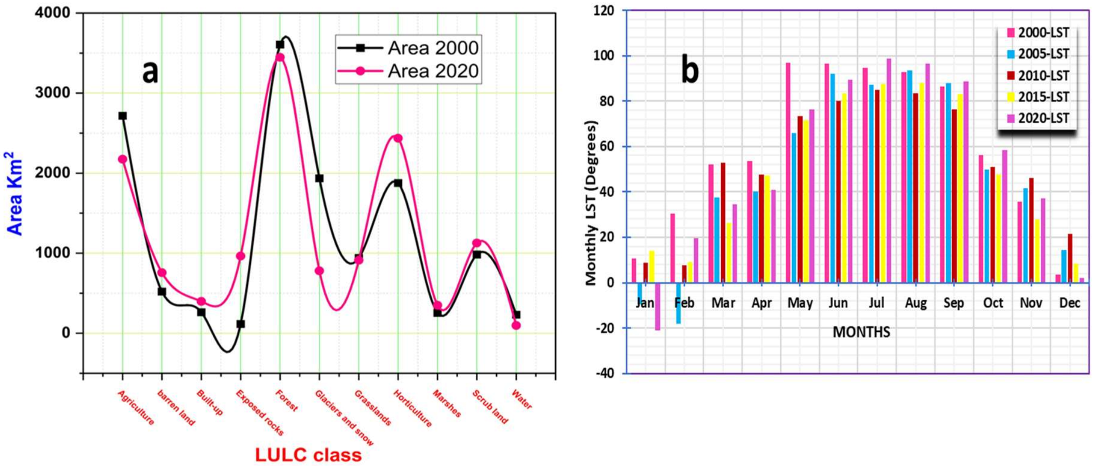

Fig. 5: LULC and LST changes in the Jhelum basin from 2000 to 2020.

increase in places experiencing extreme heat exceeding 22 degrees Celsius. Due to greater radiation release, urbanized areas, such as Srinagar, have higher LST values. The seasonal temperature differences, with summers being warmer, correspond to the valley's northern hemisphere position. The monthly and annual LST trends show a complex relationship with fluctuating temperatures, with more fluctuation in recent years (2010, 2015, and 2020). This suggests a dynamic reaction to climate change, which could be influenced by factors such as increasing urbanization, changes in land cover, and global climatic patterns. Overall, the combined study of LULC and LST highlights the varied influence of climate change on the environmental dynamics of the Jhelum basin.

Impact on water resources: The North-Western Himalayas region, crucial for water supply due to its vast glaciers and monsoon-fed rivers, is experiencing significant impacts from climate change, particularly on its water resources. Rising temperatures are causing accelerated glacial melting, leading to the formation of glacial lakes and an increased risk of outburst floods (Prakash & Nagarajan 2018). It has experienced a 21% reduction in glacier area due to climate change, impacting the main water source and increasing the risk of glacial lake outburst floods (GLOFs), threatening the socioeconomic stability of the region (Lone & Jeelani 2024). This poses an immediate danger to downstream communities and threatens long-term water scarcity as glaciers shrink. Changing precipitation patterns contribute to reduced rainfall and alter stream discharge patterns, affecting agriculture, drinking water availability, and the region's hydrological stability (Sharma & Choudhury 2021, Panwar 2020). These changes disrupt biodiversity and local livelihoods and have far-reaching consequences for major rivers that support millions in the Indian subcontinent (Negi et al. 2022, Anjum et al. 2023). Adaptive water management practices and comprehensive strategies are necessary to address these impacts. Changes in precipitation patterns impact water resource management and groundwater reserves and result in flash floods and soil erosion (Mir et al. 2021). The quality of water resources is at risk due to increased sedimentation, higher turbidity levels, and the leaching of pollutants. These issues can cause water contamination problems and jeopardize human and aquatic ecosystem health (Lone et al. 2021). Changes in water availability affect alpine ecosystems, leading to habitat loss, shifts in species composition, and impacts on biodiversity (Roy & Rathore 2019).

As the North-Western Himalayan water sources feed major rivers that support millions in Asia, the impacts of these changes in stream discharge extend far beyond the Himalayan region. This underlines the critical need for adaptive water management practices and comprehensive strategies to address climate change impacts on stream discharge in the North-Western Himalayas. Proactive measures, such as improved water storage capacity, the construction of smaller-scale reservoirs, and enhanced water-use efficiency in agriculture, are crucial for mitigating the impacts of climate change on water resources in the North-Western Himalayas.

Impact on natural hazards: Climate change is a global, intricate, and evolving challenge that significantly influences natural hazards, particularly hydro-meteorological and climatic hazards. This rapid ongoing transformation in climate, as evidenced by changes in temperature, precipitation, and atmospheric conditions, is mainly attributed to anthropogenic factors (Hansen & Stone 2016). Consequently, it leads to a cascade of effects on various natural hazards, especially within mountain ecosystems and neighboring landscapes. The influence is characterized by an increasing intensity and frequency of extreme weather and climatic events, encompassing cloudbursts, floods, droughts, melting glaciers, glacial lake outburst floods, snow avalanches, heatwaves, and cold waves (Srivastava & Srivastava 2020, Ramya et al. 2023). The forecasts indicate a constant upward trajectory, underscoring persistent problems and challenges confronted by communities inhabiting highly exposed mountainous and vulnerable regions (Kohler & Maselli 2009, Masson-Delmotte et al. 2021). The role of climate change in exacerbating risks related to natural hazards is particularly evident in areas where existing disaster risk management mechanisms are ill-equipped to manage new, emerging, or cascading risks. The poorest and most vulnerable people, living in the less developed regions of the world, are at the greatest risk (Wani et al. 2022). The Vale of Kashmir in the north-western part of the Indian Himalayan Region is one such example. This multi-hazard-prone region has a long history of hydro-meteorological and climatic disasters, including cloudbursts, floods, snow storms, droughts, and cold waves (Wani et al. 2022). Heavy precipitation, particularly from July to September, has resulted in unprecedented floods in the past (Ballesteros-Cánovas et al. 2020), great magnitude, defying the existing prediction mechanisms and human logic, as seen in September 2014. Climate change has led to an increase in the incidence of rainfall-induced landslides (Shah et al. 2023). Episodes of hailstorms and erratic snowfall, especially during harvest time, have become serious concerns for fruit growers who suffer heavy losses annually (Rashid et al. 2020, Bhat et al. 2023). Erratic snowfall and windstorm events have consistently challenged walnut production in the region (Mir & Kottaiveeran 2018). Farmers, heavily reliant on rainfall for crop production, are compelled to shift from one crop type to another, such as rice to maize, due to altered rainfall patterns and temperature fluctuations. The pastoralist community has suffered material and human losses due to increased occurrences of lightning, thunderstorms, and cloudbursts. While there is limited research available to ascertain the influence of climate change on natural hazards at the local level, the consequences are visible to the affected communities, examined, and documented to a certain level. The local experts unanimously agree with the global community's perspective that there is a need to address climate change in alignment with disaster risk reduction strategies and not in isolation. This holistic approach will help mitigate the impacts of disasters on human life, natural ecosystems, and biodiversity and minimize human contributions to climate change.

DISCUSSION

This study thoroughly examines the effects of climate change in the Jhelum basin, with an emphasis on evolving climatic patterns and their substantial implications for the environment, hydrology, and human activities. This study analyses 31 years of climate data from 1990 to 2020 to identify important temperature and precipitation trends, offering light on the basin's major climatic shifts. The findings of this study show a general increase in both maximum and minimum temperatures over the Jhelum basin, except for a slight decrease at Gulmarg. This trend is consistent with global patterns of rising temperatures due to increased greenhouse gas emissions. The heterogeneity in precipitation trends, with some stations experiencing drops and others experiencing increases, highlights the complexities of climate change, which is influenced by a variety of factors such as altitude, elevation, and localized weather patterns. This diversity emphasizes the significance of doing localized studies to fully assess climate change implications, as global models may not adequately capture regional specificities.

One of the most significant issues raised in this study is the effect of climate change on the hydrology of the Jhelum basin. Rising temperatures are causing glaciers and snowpacks to melt more quickly, altering stream flow patterns. According to the research, there is an increased chance of floods in the spring and early summer, followed by potential water shortages in late summer and autumn. This seasonal variation in water availability presents considerable issues to water resource management, agriculture, and local people who rely largely on continuous water supply. The formation of new glacial lakes and the growth of existing ones raises the possibility of glacial lake outburst floods (GLOFs), which can inflict massive devastation downstream. The retreat of glaciers, combined with the expansion of glacial lakes, represents not only a loss of essential water reserves but also increased disaster risks that necessitate immediate attention and mitigating measures.

This study also investigates changes in land use and cover (LULC) in the Jhelum basin. The conversion of agricultural land to residential and horticultural areas indicates socioeconomic changes caused by population expansion and shifting economic incentives. Climate change, on the other hand, influences these changes by making some types of land use more viable or required when temperatures rise and precipitation patterns shift. The growth in built-up areas, as well as the resulting rise in land surface temperatures (LST), indicate the effects of urbanization and the urban heat island effect, which exacerbates local climate change.

Extreme weather events, such as cloudbursts and flash floods, have become more frequent and intense, highlighting the region's increasing climate volatility. These incidents not only disrupt daily life but also result in huge economic losses and endanger human safety. This study emphasizes the need for better prediction systems and disaster preparedness to lessen the negative effects of such disasters.

The conclusions of this study have far-reaching consequences for the North-Western Himalayas and other similar places. Climate change's cascading effects on hydrology, land use, and extreme weather events need a comprehensive approach to climate adaptation and mitigation. Adaptive water management methods, such as increasing water storage capacity and improving water-use efficiency, are critical for dealing with fluctuating water supplies. Furthermore, including climate change considerations in land use planning and catastrophe risk reduction measures is critical for establishing resilient communities.

CONCLUSION

In conclusion, studies in the Jhelum basin indicate significant changes in temperature and precipitation patterns over the past decades. Rising greenhouse gas emissions since the 1980s have contributed to global and regional temperature increases. From 1990 to 2020, precipitation trends in the Jhelum basin show variability, with some stations experiencing decreases and others increasing. Temperature trends reveal a general increase in both maximum and minimum temperatures, except for a slight decrease at Gulmarg. These findings are consistent with recent research and underscore the importance of long-term, high-quality climate data for accurate trend analysis. The Jhelum basin in the North-western Himalayas is significantly impacted by climate change, which has caused rising temperatures, retreating glaciers, and altered precipitation patterns. These changes have affected land use, land surface temperatures, and stream flow while increasing extreme weather events like cloudbursts and flash floods. The region's glaciers are rapidly melting, leading to more glacial lakes and heightened risks of outburst floods, threatening water resources, agriculture, and local communities. Additionally, shifts in land use and rising land surface temperatures highlight the impact of urbanization and climate change on the local environment. These findings underscore the urgent need for adaptive water management practices and comprehensive strategies to mitigate the adverse effects of climate change on the Jhelum basin and beyond.

ACKNOWLEDGEMENT

The authors are very much thankful to the United States Geological Survey for providing free satellite data used in this study.

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