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Impacts of Climate Change on the Himalayan Cryosphere: A Comprehensive Study of Snow Cover, Glacier Lakes, and Associated Geo-Hazards in Uttarakhand, India

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Abstract- The Himalayas are referred to as the "Third Pole" and contain the largest concentration of glaciers outside of the Arctic and Antarctic. The glaciers are, therefore, an important source of water for these river systems including the Indus, Ganga, and Brahmaputra that support nearly 15% of India's population. It has been observed during recent decades that the glaciers have retreated, and snow cover reduced significantly because of climate change, and this has resulted in the formation of lakes. In this study, the focus is on Uttarakhand in the Central Himalayas, assessing the relationship between climate change, snow cover, glacial lakes, and associated geo-hazards. There is a focus on key climate trends, snow cover dynamics, glacial lake expansion, and geo-hazards such as Glacier Lake Outburst Floods (GLOFs) using long-term satellite imagery, numerical models, and ground-based observations. The findings show that high-altitude areas are warming at 0.6 °C/decade, with declining rainfall trends, widespread reductions in the extent of snow cover, and deposition of potentially hazardous glacial lakes. Effective mitigation, long-term monitoring, and community-based approaches are necessary to minimize the risks to the environment and socio-economic sectors.

Index Terms- Climate change, Environmental changes, temperature effect, global warming

I. INTRODUCTION

The Himalayas, often called the "Water Tower of Asia," provide essential water resources to downstream regions through snow-fed rivers like the Indus, Ganga, and Brahmaputra (Immerzeel et al., 2010; Kour et al., 2016; Gurung et al., 2017). They hold more than half of the world's permanent snow and ice outside the Polar regions, with approximately 50,000 km² of glaciated areas (Jain et al., 2009).

These snow-fed rivers are vital for the livelihood of the rural population in the Indian Himalayas, where 80% of the population depends on them for agriculture and related activities (Government of India, 2010). However, rising temperatures and declining rainfall, particularly since the 1950s, have caused changes in snowfall patterns and snow accumulation, leading to variations in snow depth and melting (IPCC, 2013; Lutz et al., 2014; Shi and Wang, 2015; Smith and Bookhagen, 2018). This warming trend has affected water availability, hydropower generation, and ecosystems (Immerzeel and Bierkens, 2012; Azmat et al., 2017). Studies show both declines and increases in snow cover in different Himalayan regions (Negi et al., 2018; Li et al., 2019). Understanding these changes is critical for managing regional water resources, as more than 50% of the annual river discharge in the central Himalayas comes from snowmelt (Bookhagen and Burbank, 2010).

Research Objectives

- To map the spatial distribution and trends of monthly, seasonal, and annual snow-covered area (SCA), rainfall, and temperature using observed and satellite data products.
- To establish the relationship between snow cover, temperature, rainfall, and river discharge.
- To identify the spatio-temporal extent of glacial lakes and the potential for outburst floods.
- To explore the relationship between climate change and associated geo-hazards and suggest suitable measures for minimizing the possible impacts.

II. STUDY AREA

The study focuses on the Uttarakhand Himalayas, between 28°43′N and 31°27′N latitude and 77°34′E and 81°02′E longitude, for an approximate area of 51,383 square kilometers. The region comprises 13 districts, divided into two primary divisions: Garhwal and Kumaun. Elevations in this region range between 184 meters to 7,801 meters AMSL and have varying features such as ridges, valleys, glaciers, and snow-covered peaks.

The Uttarakhand Himalayas are generally cold climatic conditions, with temperature and rainfall variations very pronounced with elevation. This region supports major snow-fed rivers like Ganga and Bhilangana, which support water supply, irrigation, and hydropower generation for the downstream regions.

Climate conditions differ with altitude: high altitudes receive sub-zero temperatures and snowfall during the winter, while low areas receive temperatures exceeding 30°C. Rainfall mostly falls during the monsoon period; in winter, rain may fall in the form of snow in the mountains. Steep slopes, rugged topography, and climatic variability amplify vulnerability to environmental challenges and hazards.

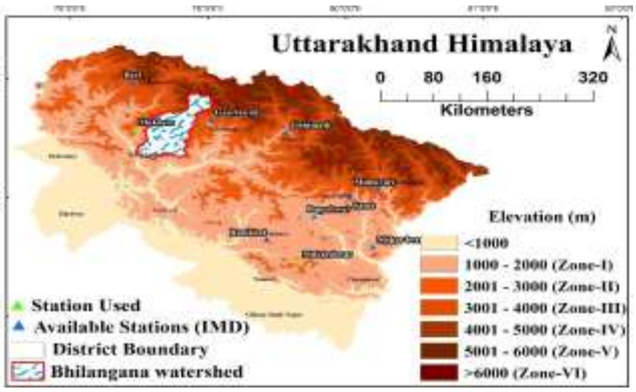

Figure 1: Location map of the Uttarakhand Himalaya

Administrative Division
Administratively, Uttarakhand Himalaya has 13 districts and two major divisions (Kumaun and Garhwal). On 9th November 2000, Uttarakhand became a spate state with 53,699km2 area, which previously amalgamated with Uttar Pradesh. Kumaun division includes six districts (Almora, Bageshwar, Champawat, Nainital, Pithoragarh and Udham singh nagar), where Garhwal division comprises seven districts (Dehradun, Haridwar, Tehri Garhwal, Uttarkashi, Chamoli, Pauri Garhwal and Rudraprayag) (Figure 2.2). Out of 13 districts, 10 are located in high hill regions and the remaining 3 are in the lowland regions. Geographically, the region can largely be alienated into three zones, those are as follows

- **Upper Hills: -** Chamoli, Rudraprayag, Uttarkashi, Bageshwar and Pithoragarh
- **Middle Hills: -** Almora, Tehri Garhwal, Pauri Garhwal, Nainital and Champawat,
- **Foothills: -** Dehradun, Haridwar and Udham singh nagar

Most of the upper hill regions are usually covered by dense snow during the winter season, while middle and foothill regions are relatively warmer. The upper reaches of rainfall up to the middle hills region and when it comes towards higher hills, transforms into snowfall.

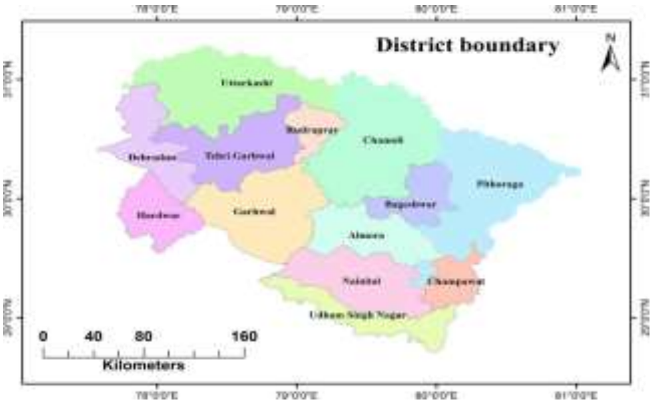

Figure 2. Administrative map of the Uttarakhand Himalaya

III. METHODOLOGY

Various tools and techniques were employed to analyze climate dynamics, snow cover changes, glacier lake formation, and geo-hazards. The research methodology will be bifurcated into the following sub-components:

Climate Trend Analysis
The Mann-Kendall Test is a Statistical trend detection tool for long-term temperature average data. The tool's efficiency lies in its detection of statistically significant trends without assuming a normal data distribution.

Sen's Slope Estimator
This was applied to measure the amount and direction of temperature trends and rainfalls over time.

The data was then classified into four seasonal seasons: pre-monsoon March-May, monsoon June-September, post-monsoon October-November, and winter December-February

Snow Cover Mapping
Using the NDSI derived from MODIS, delineate the extent of the snow cover. In order to effectively separate snow from other types of land covers, NDSI thresholds had to be calibrated.

Temporal Analysis

The temporal analysis of snow cover changes is conducted at a seasonal, annual, and elevation zones level to capture the climate variability impacts.

Glacier Lake Analysis

The NDWI and NDPI were applied to extract the glacier lakes in the image data. The application of NDWI and NDPI distinguished water bodies from surrounding terrain in the image data, based on which extraction was carried out using the data of Landsat.

Area, depth, and volume of lakes were computed to assess expansion over time.

Hydrological Modeling

The HEC-RAS model was implemented for the simulation of possible outburst flood scenarios emanating from dangerous glacier lakes. For different percentages of the drainage, peak-discharge rates were calculated to assess the potential downstream flood hazards.

Geo-Hazards Assessment

Landslide Susceptibility

Landslides-prone areas were determined using a combination of topographic- (elevation and slope), climatic- (rainfall patterns), and geological data through spatial modeling techniques, including frequency ratio and GIS-based overlay analysis.

Mapping High-Risk Zones of Erosion

The zones of high risk of erosion were mapped through analysis of riverbank stability, sedimentation rates, and hydrological data.

Data Integration and Validation

Remote sensing data were processed and analyzed through the use of GIS platforms such as ArcGIS and Google Earth Engine.

Ground observations such as GPS surveys were used for validation of the satellite-derived data to ensure accuracy in spatial and temporal analyses.

Cross-validation of trend and relationship findings was done employing both descriptive as well as inferential statistical analysis between climatic, hydrological and glaciological variables.

Surveys of Perception and Community

120 respondents across villages were interacted with on their perceptions relating to climate change, GLOF risks and landslide hazards to bring in an integrated

IV. CONCLUSION AND DISCUSSION

1. Climate Trends

Temperature:

The absolute warming trend is 0.6°C/decade, with more significant warming at higher elevations due to elevation-dependent climate sensitivity. This has further enhanced glacier retreat and increased the rates of snowmelt in the region.

From the seasonal analysis, it can be noted that most of the warming is occurring during the pre-monsoon and post-monsoon seasons, which points toward a shift in the thermal dynamics impacting the changes in snowmelt and river discharge patterns.

Figure 3: Temperature trends in the Uttarakhand Himalayas showing a warming trend of up to 0.7°C per decade at high elevations.

Rainfall

A trend of -12.2 mm/decade in annual rainfall was found in the Bhilangana basin. On the other hand, the frequency of extreme rainfall events has increased, which indicates an increase in variability in climatic conditions.

Spatial trends indicate significant decreases in rainfall at lower elevations, while higher elevations had occasional increases during certain seasons.

Figure 2: Rainfall trends in the Uttarakhand Himalayas, highlighting a declining trend over the decades, with occasional variability.

2. Snow Cover Dynamics

Elevation-based Analysis

There is a significant decline in SCA at increased elevations (>3,600 m) with an average rate of -75 km²/decade. It is mainly attributed to an increase in temperature and reduced snowfall.

At lower elevations (<2,000 m), the SCA increased to the rate of 6 km²/decade possibly due to increased precipitation and temporary snowmelt accumulation over the colder months.

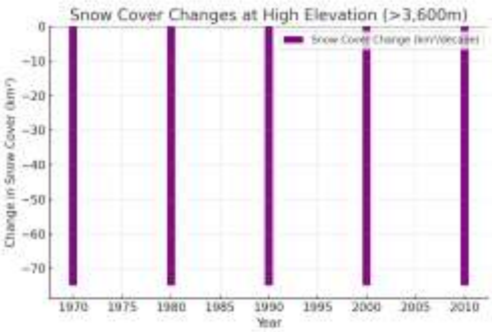

Figure 3: Changes in snow-covered area (SCA) at elevations above 3,600m, showing a consistent decline of approximately 75 km² per decade.

Time Series Analysis

In the Bhilangana basin, SCA has reduced by 110 km² over two decades, with changes that have taken place rapidly through climate anomalies.

3. Glacier Lakes and GLOFs

Lake Formation

There are 14 glacier lakes recorded in the Bhilangana basin in this study, which have a high growth rate of their average area, volume, and depth in the last decade.

Rising temperatures have enhanced the glacier retreat and fragmentation process that accelerates new lake formation

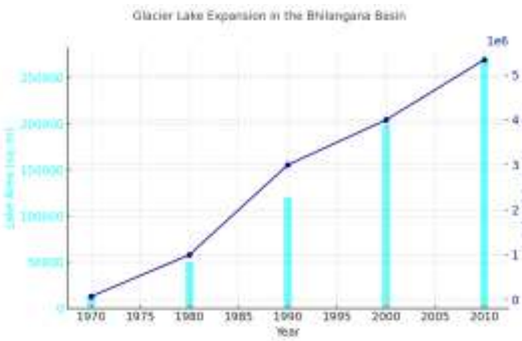

Figure 4: Glacier lake expansion in the Bhilangana basin, illustrating an increase in lake area and volume over recent decades.

Flood Risks

Hydrological modeling with HEC-RAS showed peak discharge rates between 13.18 m³/s and 230.39 m³/s, which demonstrates the destructive nature of GLOFs.

Analysis identified one lake as highly hazardous, which is a threat to the downstream population and infrastructure.

4. Geo-Hazards

Landslides

Landslide-prone areas were delineated, and it was found that 122.5 km² is highly prone and 182.1 km² is moderately prone. These areas are concentrated in steep slopes and areas affected by deforestation and infrastructure projects.

Anthropogenic activities, such as road construction and hydropower projects, have enhanced landslide hazards in the region.

Riverbank Erosion

Riverbank erosion is most serious in the middle course of Bhilangana River, where agricultural land is eroded, and sedimentation is a major problem downstream.

A greater sediment load has increased the chances of flooding with heavy rainfall.

Mitigation Strategies for Climate-Induced Hazards in the Himalayas

Monitoring Systems

Implementation of Satellite-Based Systems: Utilize advanced satellite-based remote sensing technologies, such as Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat, for real-time monitoring of glacial lakes, snow cover, and glacier retreat. These systems provide high-resolution spatial and temporal data essential for tracking changes in the cryosphere and detecting early warning signs of potential hazards.

Ground-Based Observations

Complement satellite data with field surveys and GPS-based measurements to ensure accuracy and validate remotely sensed data. Deploy automated weather stations to continuously monitor critical parameters like temperature, precipitation, and snow depth in remote areas.

Early Warning Systems

Community-Driven Warning Mechanisms

Establish community-based early warning systems (EWS) equipped with sirens, alarms, and mobile alerts to warn residents of imminent hazards such as GLOFs and landslides. Train local residents in operating these systems and interpreting hazard signals.

Integration with Remote Sensing Data
Use remotely sensed data to model flood inundation scenarios and generate risk maps. These maps can serve as a basis for issuing timely warnings to vulnerable communities.

Emergency Communication Networks
Develop robust communication networks to disseminate warnings quickly to remote areas. These networks should include mobile apps, SMS alerts, and radio communications.

Afforestation and Ecosystem Restoration
Large-Scale Afforestation Campaigns: Promote reforestation in landslide-prone areas using native tree species like deodar and oak, which enhance soil stability and reduce surface runoff. Reforestation not only mitigates landslide risks but also restores ecological balance.

Restoration of Degraded Land: Undertake ecosystem restoration projects in degraded forest areas and abandoned agricultural lands, focusing on increasing vegetative cover to prevent soil erosion and stabilize slopes.

Community Participation: Encourage local communities to participate in afforestation drives by providing incentives such as employment opportunities and resources for sustainable agroforestry practices.

Climate-Resilient Infrastructure
Design and Construction Standards: Incorporate climate-resilient designs in infrastructure projects, such as roads, bridges, and hydropower plants, to withstand extreme weather events. Use high-quality materials and engineering techniques suited for mountainous terrains.

Avoidance of High-Risk Zones: Implement stringent land-use regulations to restrict construction in high-risk areas identified through hazard zonation maps. Encourage development in relatively safer zones with lower landslide and flood risks.

Retrofitting Existing Infrastructure: Strengthen existing infrastructure by retrofitting buildings, bridges, and roads to improve resilience against earthquakes, landslides, and flash floods.

Disaster Preparedness and Risk Reduction
Capacity Building
Conduct regular training and drills for local communities to prepare them for geo-hazards. Focus on evacuation procedures, first aid, and the use of early warning systems.

Emergency Management Teams
Deploy well-equipped rapid response teams like the National Disaster Response Force (NDRF) and State Disaster Response Force (SDRF) to ensure swift action during emergencies.

Resource Prepositioning
Strategically stockpile essential supplies, such as food, water, and medical kits, in remote areas to facilitate disaster response.

Policy and Governance
Enforcement of Environmental Regulations: Strengthen policies to regulate deforestation, illegal construction, and unplanned tourism in ecologically fragile zones.

Integrated Hazard Management Plans
Develop integrated disaster management plans at the regional and district levels that address multiple hazards, including GLOFs, landslides, and floods. These plans should involve stakeholders from government agencies, NGOs, and local communities.

Transboundary Cooperation
Collaborate with neighboring countries like Nepal and China for cross-border data sharing and coordinated hazard management efforts in the Himalayan region.

Advanced Hazard Zonation and Mapping
GIS-Based Hazard Zoning: Use Geographic Information System (GIS) tools to create detailed hazard maps highlighting areas prone to landslides, floods, and GLOFs. These maps should be updated regularly based on the latest remote sensing data and field surveys.

Multi-Criteria Risk Assessment Models
Incorporate multi-criteria decision-making techniques to assess risks associated with multiple hazards, considering factors like slope, aspect, precipitation, and land use.

Public Accessibility
Ensure hazard maps and zonation data are publicly accessible to improve awareness and decision-making at the local level.

Sustainable Land Use Practices
Controlled Grazing
Regulate livestock grazing in vulnerable areas to prevent overgrazing and maintain vegetative cover.

Terracing and Check Dams
Promote terracing and the construction of check dams to reduce soil erosion and manage water flow during heavy rains.

Traditional Knowledge Integration
Incorporate traditional land management practices of local communities, which are often well-suited to the regional environment and climate.

V. CONCLUSION

The significant impacts of climate change in the Himalayan cryosphere have been underscored through this study, especially concerning the Uttarakhand region. Glacier retreat was increased by an increasing rate of temperature at 0.6°C per decade along with the decreasing amount of rainfall; also, at higher elevations, it reduced snow cover and has been responsible for forming hazardous glacial lakes. In this process, risk associated with GLOFs, landslides, and riverbank erosion enhances threat to the ecosystem, infrastructure, and livelihoods.

Real-time monitoring systems, early warning mechanisms, climate-resilient infrastructure, and community-based approaches are the effective mitigation strategies to be taken to address these challenges. Sustainable land-use practices, afforestation, and policy reforms are critical to reduce vulnerabilities and build long-term resilience.

A multidisciplinary approach to integrate modern technology, traditional knowledge, and transboundary cooperation can help mitigate risks caused by climate change and promote the safety of the Himalayan environment and communities.

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