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Climate change in the Himalayan region: susceptible impacts on environment and human settlements

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The Himalayan region, home to the world's highest mountain ranges, is an ecological and cultural hotspot crucial for the livelihood of nearly two billion people downstream. However, it faces significant vulnerabilities due to climate change, which threatens its fragile ecosystems and socio-economic frameworks. Notably, environmental risks include glacier retreat, biodiversity loss, and shifting water supplies, with adverse consequences for water availability and agricultural productivity. These climatic shifts exacerbate social and economic pressures, disrupting agro-based livelihoods, damaging infrastructure, and intensifying the frequency and severity of extreme weather events. This study highlights the urgent need for region-specific, sustainable development policies that integrate improved climate monitoring, ecosystem-based adaptation, and the synergy between indigenous knowledge and scientific advancements. A comprehensive framework is proposed to safeguard both ecological and socio-economic resilience in the face of ongoing climate change challenges in the Himalayas.

KEYWORDS

climate change, Himalayan region, socio-economic resilience, human settlement, adaptation and mitigation

1 Introduction

The Himalayan region is known as the "Third Pole" of the world, which rivals those of the polar regions, making it an essential environmental and ecological zone of global importance. This region is also called the "water tower of Asia," because it serves as the primary source of freshwater for approx. 1.65 billion people, feeding into ten major river systems like the Ganges, Brahmaputra, Indus and Mekong (Yao et al., 2012; Immerzeel et al., 2010). These systems are closely integrated with the livelihoods and agricultural, energy, and biodiversity systems throughout South and Southeast Asia, and this region's cryospheric, hydrological, and ecological systems. But this vital lifeline is facing unprecedented challenges due to climate change, a force that threatens its ecosystems, water resources and the human community that depends on them all (Sati, 2020). The Himalayas hold about 14% of the world's ice reserves, after the Arctic and Antarctic. Its glaciers, snowpacks, and rivers serve as critical reservoirs regulating water flow to

population centers downstream, including megacities. Himalayan glaciers store and release seasonal meltwater that feeds into river flow in its dry season, reduces the availability of water supply and helps mitigate against drought. This supports food security for millions through agricultural irrigation and hydropower generation. The region also has a hand in the monsoon, which acts as a climatic buffer by moderating seasonal rainfall patterns across Asia. The health of these natural systems is critical to regional stability, so the Himalayas are at the center of global concern over water security and climate resilience (Shrestha et al., 2015).

An extension of the arc of great mountains in the world (like right now, a multi-continental outfit), the Himalayan range spans over 2,400 Km across India, Nepal, Bhutan, China, and Pakistan and supports a diverse array of ecosystems, from alpine tundra to subtropical forests. Mountain altitudinal gradients harbor remarkable biodiversity, featuring endemic plant and animal communities, and provide critical habitats for flagship terrestrial species of global importance (e.g., snow leopard, red panda). The interconnected ecosystems provide crucial ecological services in carbon crediting, soil stabilization, and biodiversity conservation (Kumar and Murugesh Prabhu, 2012). Not until you pause to think a little, the area's socio-cultural diversity is truly remarkable. The Himalayas are home to over 50 million people of various ethnicities, customs, languages, and lifestyles. Traditional Indigenous systems offer resource management models, and solutions adapted to the harsh mountainous herding ecologies they have mastered. They provide ideas and information about how to live sustainably. Yet, given how climate alteration pressures exacerbate socio-economic demands, city activities must be balanced against the equilibrium and interlinkage of urban systems with the environment (Rana et al., 2021).

Despite growing recognition of the Himalayan region's importance, several critical research gaps remain. First, there is a need for more localized and high-resolution climate models to predict regional impacts more accurately, as current models often fail to capture the complexity of microclimates and diverse landscapes within the region. Second, data on glacier retreat and hydrological changes in the context of future climate scenarios remain limited, hindering precise assessments of water availability in the region. Moreover, research on the socio-economic implications of these environmental changes—particularly in relation to livelihoods, agriculture, and infrastructure—lacks a comprehensive, integrated approach that accounts for both short-term and long-term impacts. Additionally, while indigenous knowledge systems offer valuable insights into climate adaptation, their integration with modern scientific techniques remains underexplored. Finally, there is a critical need for robust monitoring systems to track both environmental changes and socio-economic outcomes in real-time, enabling timely and effective policy interventions. Addressing these gaps is essential to building a resilient, adaptive framework for the region. The primary objective of this study is to assess the vulnerability of the Himalayan region's ecosystems and socio-economic systems to climate change, with a particular focus on glacier dynamics, biodiversity, and water resource availability. This research aims to identify the key environmental and socio-economic risks posed by climate change, particularly those affecting water resources, agriculture, and infrastructure. Additionally, the study seeks to develop a comprehensive framework for region-specific, sustainable development policies that integrate climate resilience strategies, ecosystem-based adaptation, and the effective use of both indigenous knowledge and scientific innovations. This framework will help guide decision-making processes aimed at reducing the impacts of climate change and enhancing adaptive capacity in the Himalayas.

2 Climate change impacts on the Himalayan environment

The Himalayan region, crucial for its ecological and hydrological function, is highly sensitive to climate change, with significant impacts on the environment and human communities. Scientists and policymakers recognize the region as one of the world's most vulnerable ecosystems, undergoing unprecedented changes in its cryosphere, hydrology, biodiversity and ecosystems that will ripple through water resources, agriculture and livelihoods. The details of climatic indicators have been discussed in below sub-sections.

2.1 Glacier retreat and cryosphere changes

Himalayan glaciers are retreating at an alarming rate due to global warming and impacting millions across Afghanistan, India, Nepal and Pakistan by threatening water supplies to major rivers, namely, the Ganges, Indus and Brahmaputra. The Gangotri Glacier has retreated over 1,500 m since 1935. With accelerated melting initially boosts runoff but leads to extreme water scarcity for millions far upstream once critical thresholds are crossed (Kumar and Murugesh Prabhu, 2012). Glacier retreat also expands glacial lakes, which heightens the risk of GLOFs. These floods can decimate infrastructure, communities, and ecosystems. For example, the 1985 Dig Tsho GLOF devastated Nepal's villages, hydropower plants, and farmlands. Similar events, along with the growing risk from expanding high-altitude lakes such as Tsho Rolpa in Nepal, necessitate immediate plans for risk mitigation, including solid early warning systems and glacial lake monitoring.

2.2 Hydrological alterations

Changes in precipitation patterns due to climate change represent a major shift in the hydrology throughout the Himalayan region. Increasing temperatures have resulted in less snowfall and altered seasonal runoff dynamics, fundamentally changing river flows. The Melting of snow and glaciers has brought on the river peaks (flow) at an earlier time of year, with rivers such as the Indus facing changed seasonal streams. This change interrupts the flow of water needed for agriculture, drinking and utility-scale hydropower generation in downstream areas, especially during dry summer when water demand is at its peak. Climate change increases the variability of the South Asian monsoon, a key driver of Himalayan hydrology. Erratic monsoons — with heightened spates of rainfall and extended dry periods — exacerbate the potential for flooding and drought. For example, the 2013 floods in Uttarakhand were attributed to

FIGURE 1
Direct and direct impact on Mountain Ecosystem services.

extreme rainfall due to changing monsoon dynamics, which caused severe infrastructural and human losses. The nexus of monsoon variability and glacial melt also has downstream impacts on sediment transport, groundwater recharge, and ecosystem health, exacerbating the water crisis in the region (Lepcha et al., 2021).

2.3 Biodiversity and ecosystem changes

The Himalayan region, renowned for its unique biodiversity and endemic species, faces significant threats from climate change, leading to habitat loss, species extinction, and shifts in ecosystem composition. Increased temperatures and changes in vegetation zones are causing habitat fragmentation, particularly in alpine ecosystems, which adversely affect species like the endangered snow leopard and red panda, reducing prey availability and pushing them toward extinction. Phenological changes, such as altered flowering times in *Rhododendron arboreum* and disrupted migration patterns in birds, are also impacting ecological interactions and food webs. For instance, the mismatch in the timing of plant flowering and herbivore grazing patterns destabilizes ecosystems. Furthermore, vital ecosystem services provided by the Himalayas, including water purification, soil stabilization, and carbon sequestration, are increasingly threatened by climate change and unsustainable land use (Figure 1). The degradation of forests and alpine meadows undermines their role in climate regulation and human livelihoods, while also negatively affecting the regional economy, particularly in agriculture, tourism, and disaster resilience. This underscores the need for integrated conservation efforts that prioritize both biodiversity preservation and human health (Yadav et al., 2021).

3 Impacts on human settlements and migration

The Himalayan region is sensitive to climate change and anthropogenic influences because of its fragile ecosystem and active geological processes. Such impacts degrade the environment and have broader consequences for human settlements, livelihoods, economic vulnerability, forced migration and human health and infrastructure.

3.1 Livelihoods and economic vulnerabilities

Himalayan communities rely heavily on climate-sensitive sectors such as agriculture, forestry and tourism for their livelihoods, but these are increasingly threatened by climate change. Shifting precipitation patterns, glacial retreat, and erratic monsoon seasons reduce agricultural productivity, and worsen food insecurity, and force migration, disrupting community structures (Vargas-Burgos et al., 2023). Forestry faces threats from altered vegetation cycles, biodiversity loss, and more frequent forest fires impacting timber and non-timber forest products (NTFPs) like medicinal herbs, which are crucial for income generation and subsistence for many communities. Tourism, a key economic driver, declines due to reduced snow cover and climate-induced disasters like GLOFs and landslides. These challenges exacerbate economic inequity, hitting the hardest of those most disadvantaged, including women and indigenous peoples, who directly depend on natural resources for food and livelihoods (Malik and Ford, 2024).

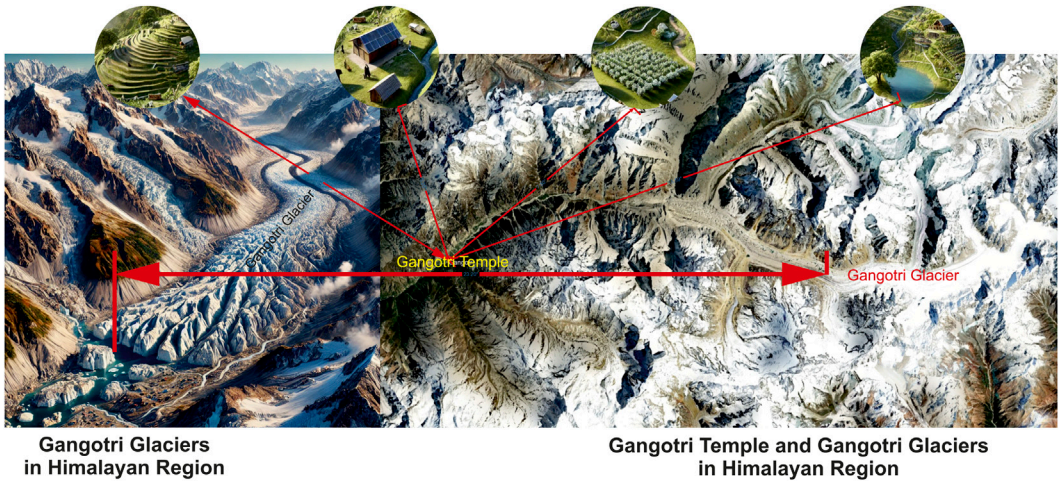

FIGURE 2
Impact of climate change on mountain social-ecological systems, including ecosystem services and products, livelihoods of mountain people address direct and indirect impacts in Indian Himalayan Region near Gangotri Glacier.

3.2 Displacement and migration

The rise in natural disasters in the Himalayan zone, such as landslides, floods and earthquakes, has led to the displacement of communities. Deforestation and unsustainable construction destabilize slopes and, with erratic rainfall, plunge them into devastating landslides that engulf entire communities. Likewise, river floods also displace thousands, making them homeless and vulnerable to secondary disasters such as epidemics and economic collapse. Increasingly, the movements have been driven by climate: entire communities have left for urban settlements looking for safety and livelihoods. This has flooded cosmopolitan centers with unregulated urbanization processes, shanty town expansion and scant access to basic needs such as potable drinking water, sanitation and medical services. Xenophobia, racism, and various forms of cultural alienation and isolation are also psychosocial risks carried by migrant groups due to socio-cultural struggles like loss of identity and social cohesion. Moreover, the migration of working-age populations can make rural settlements susceptible to labor shortages, hampering agricultural productivity and local economic development (Bhusal et al., 2021).

3.3 Infrastructure and health risks

The Himalayan region's socio-economic development is highly impacted by climate-related hazards that damage critical infrastructure, such as roads, frequently destructed by landslides and floods, and hydropower plants increasing vulnerability through dam failures and downstream flooding. These challenges result in significant economic costs and hinder disaster recovery efforts. Additionally, climate change exacerbates health risks, including the spread of vector-borne diseases such as malaria and dengue to higher altitudes, increased respiratory illnesses due to declining air quality, and unaddressed mental health issues stemming from climate-induced displacement and livelihood disruptions. The uncertainty and violence around climate-induced displacement and livelihood disruptions make mental health issues—anxiety, depression, trauma—soaring. However, high burdens of disease already exist and the fragile healthcare infrastructure further struggles to address these emerging health challenges, placing vulnerable populations at greater risk (Alam et al., 2022).

4 Adaptation strategies and policy recommendations

Adaptation infrastructure in the Himalayan region must recognize that the interlinked crises of climate change, biodiversity loss and socio-economic vulnerability must come together (Figure 2).

Understanding people's intentions to adapt to climate change is critical for designing effective interventions, as these intentions are shaped by risk perception, access to resources, and socio-cultural dynamics (Arunrat et al., 2017). Adaptation measures such as adopting climate-resilient agricultural practices, improving water management, and enhancing community-based disaster preparedness can strengthen resilience and reduce vulnerability. A core strategy is ecosystem-based adaptation (EbA), which harnesses the resilience of natural systems to insulate against climate impacts and support biodiversity. Transboundary conservation initiatives can help protect critical habitats and migratory corridors by strengthening protected area networks. Restoration with native species, land-use techniques, and soil conservation can reduce floods and erosion and be useful for carbon sequestration. Incorporating traditional ecological knowledge with scientific approaches ensures solutions that are culturally sensitive to the local populations, who remain an integral steward of the region.

Regarding policy recommendations, the involvement of the local community in decision-making must take precedence, reinforced by capacity-building initiatives and, potentially, sustainable livelihood

avenues like agroforestry and ecotourism. Governments should establish strict constraints on uncontrolled urbanization, the overdevelopment of hydropower and resource overhunting. Even though the Himalayan ecosystem is transnational, collaboration between countries is necessary for sharing climate data and disaster management. In addition, robust climate financing mechanisms must be used to incentivize sustainable practices and deploy early warning systems to mitigate risk from glacial lake outbursts of floods and landslides. Such an inclination towards integrating these strategies to ensure the health and survival of the fragile Himalayan ecosystem would boost resilience, biodiversity, and livelihoods for millions of people (Kattel, 2022).

4.1 Community-based adaptation

Community-based adaptation emphasizes participatory approaches that integrate Nature-Based Solutions (NbS) to enhance resilience against climate change (Sultan et al., 2022). NbS, such as wetland restoration, afforestation, and sustainable agricultural practices, not only address local vulnerabilities but also ensure ecological sustainability while empowering communities to adapt effectively. Traditional irrigation systems like the *kuhl* in Himachal Pradesh and *zabo* in Nagaland are proven examples of sustainable water use that enhances resilience towards changing precipitation patterns. Likewise, the agroforestry techniques of Bhutanese farmers, who intersperse food crops with soil-stabilizing tree species, improve food security and mitigate the risk of landslides. This NbS approach enhances soil health, carbon sequestration, and biodiversity, while also providing multiple livelihood benefits. Many success stories illustrate the efficacy of community-based adaptation. In Ladakh, for instance, engineer Chewang Norphel created artificial glaciers that preserve winter snowmelt to supply summer drinking water and agricultural requirements. Grassroots women's groups in Nepal have also adopted rotational grazing systems, and there is evidence that this reduces overgrazing and improves the grassland ecosystem. This is only a small sample of how empowering local communities and preserving traditional practices can lead to innovative, low-cost, sustainable solutions to climate resilience (Adhikari et al., 2018).

4.2 Technological innovations

New technologies are enhancing community-based adaptation in the Himalayas. Remote sensing (RS) and Geographic Information Systems (GIS) allow scientists to monitor near real-time monitoring of climatic variables for early warning systems help to facilitate risk assessments for landslides, glacial lake outburst floods (GLOFs), and other climate-induced disasters (ICIMOD's satellite-based GLOF prediction systems. Climate-resilient agriculture practices are more and more vital for protecting livelihoods. Drought-resistant crops, precision irrigation techniques and crop diversification have all provided some success against erratic rainfall patterns. Renewable energy initiatives, such as micro-hydropower and solar energy farms, provide clean energy to remote settlements and contribute to decarbonizing the economy, as seen in Bhutan and Indian Himalayan villages (Kaku, 2019).

4.3 Policy frameworks and governance

Addressing the complex challenges in the Himalayan region requires comprehensive policy frameworks and effective governance mechanisms. The environmental impacts are transboundary in nature and the ecosystem is collective; therefore, it is essential to reinforce regional cooperation among Himalayan countries. Some initiatives, such as the Hindu Kush Himalayan Monitoring and Assessment Program (HIMAP), act as platforms for collaborative research and data-sharing between countries, creating collective approaches to adaptation. Integrating climate risks in national and local development plans Includes climate-proofing infrastructure projects, endorsing ecosystem-based adaptation, and integrating vulnerability assessments into land-use planning. Such initiatives are seen in actions, such as India's own National Mission for Sustaining the Himalayan Ecosystem (NMSHE), which focuses on scientific research and policy measures based on the region's requirements. International support is also crucial for making adaptation efforts possible. United Nations initiatives, notably the Green Climate Fund (GCF) and the Adaptation Fund support vulnerable communities with financial and technical assistance. Such resources can be redirected to strengthen capacity-building, promote technological innovations, and replicate successful community-based practices. But, these funds must be distributed equitably and used transparently to maximize the impact of the investment (Kotru et al., 2020).

5 Future research directions

The Himalayan region is home to complex geophysical and ecological systems that are becoming increasingly susceptible to cascading climate impacts on social and health systems, and thus, urgent and interdisciplinary research acts are required. One key direction is encouraging interdisciplinary approaches combining glaciology, hydrology, ecology, and socio-economic sciences to fully grasp interactions and feedback shaping environmental and societal vulnerabilities. These approaches are crucial for disentangling the complex impacts of glacier retreats, changes in hydrological regimes, and biodiversity shifts on human settlements and ecosystems. Participatory transition pathways (or collaborative frameworks that integrate climate science, local knowledge systems, and socio-economic analyses) reveal actionable insights that help communities construct adaptive capacity to their complex threat environments (Kumar et al., 2023).

Improving data availability is critical for advancing predictive modelling and evidence-based policymaking in the Himalayas. The substantial data gaps in areas such as glaciology, hydrology, and biodiversity hinder vulnerability and resilience assessments of the region. Investments in observational networks, including automated weather stations, satellite remote sensing, and field-based monitoring, are essential to create high spatial and temporal resolution datasets. Long term studies on glacier mass balance, hydrological flows, and biodiversity are needed, alongside cross-border data-sharing platforms to ensure inclusivity (Xenarios et al., 2019). Incorporating socio-economic indicators like migration, diversification of livelihoods, and poverty dynamics into climate resilience frameworks will guide context-specific, culturally

appropriate adaptation strategies. The groundwork for future research must be laid in the form of interdisciplinary approaches, better data systems and ongoing socio-economic assessments, enabling an integrated response to the region's emerging environmental challenges (Matta et al., 2022).

Climate change poses significant socio-economic challenges in the Himalayan region, particularly for communities that depend on agriculture, forestry, and tourism. Marginalized groups face more vulnerability due to limited adaptive capacity, poverty, and inadequate infrastructure. Addressing these environmental and socio-economic challenges requires coordinated local, national, and global efforts. Key strategies include strengthening early warning systems, supporting community-led adaptation initiatives, and funding region-specific climate research to enhance understanding of local climate dynamics (Jha et al., 2021). International cooperative frameworks are vital for transboundary resource management and disaster risk reduction. Sustainable development must balance environmental preservation with socio-economic upliftment through measures like sustainable infrastructure development, renewable energy adoption, and the enforcement of stringent environmental policies to mitigate the adverse impacts of climate change and ensure resilience without compromising natural resources or livelihoods (Matta G., 2020).

6 Conclusion

The Himalayan region, with its fragile ecological systems and reliance on seasonal climate patterns, is highly vulnerable to the cascading impacts of climate change, including melting glaciers, altered precipitation, and increased extreme weather events. These environmental stresses threaten freshwater availability, biodiversity, and increase the risk of natural disasters like landslides and floods. Adapting to climate change in the Himalayan region requires a combination of ecosystem-based approaches, such as afforestation and watershed management, alongside community-driven initiatives like sustainable agriculture and disaster preparedness programs. These measures can enhance resilience, safeguard critical ecosystem services, and ensure the sustainable livelihoods of vulnerable mountain communities.

To address these challenges, local communities must be empowered through education, capacity building, and access to green technologies, enabling them to contribute to sustainable, region-specific solutions. Moving forward, a collaborative, scientifically informed, and equity-centered approach is essential to developing policies that balance ecological preservation with the wellbeing of local populations. Such an approach will help safeguard the Himalayas, creating a climate-resilient model that can inform sustainable development globally. Researchers and policymakers must work together to ensure the long-term viability of both the region and its interconnected ecosystems.

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