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Pardeep Singh *Editors*

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Environment and Development

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The Himalayas in the Anthropocene

Abhinav Yadav and Akanksha Singh

Abstract This chapter provides an overview of the Himalayas in the Anthropocene era, which is characterized by significant human impacts on the environment. The Himalayas, one of the world's most ecologically sensitive and biodiverse regions, are facing various environmental challenges, including climate change, deforestation, and land-use change. The chapter reviews the scientific literature on the effects of human activities on the Himalayan region, including the impacts on ecosystems, water resources, and biodiversity. The chapter also discusses the importance of the Himalayas as a global hotspot for biodiversity conservation and the challenges of protecting this unique and fragile ecosystem in the face of growing human demands. The chapter identifies five key themes that characterize the Anthropocene in the Himalayas: (1) climate change, (2) land-use change and forest degradation, (3) water resources and hydrology, (4) biodiversity conservation, and (5) human wellbeing. These themes reflect the interconnected and complex nature of the Himalayas' challenges and the need for integrated and holistic approaches to address them. The chapter also emphasizes the importance of interdisciplinary research and collaboration among scientists, policymakers, and local communities to develop effective strategies for mitigating the impacts of human activities on the Himalayan region. In conclusion, this chapter provides an overview of the challenges facing the Himalayas in the Anthropocene era and highlights the need for integrated approaches to address these challenges. The Himalayas are a critical region for biodiversity conservation and human wellbeing, and it is essential to develop strategies that balance human needs with environmental sustainability. The chapter underscores the importance of interdisciplinary research and collaboration in addressing the Himalayan region's complex and interconnected challenges.

Keywords Anthropocene · Himalayas · Biodiversity conservation · Climate change · Interdisciplinary research

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1 Introduction

The situation in the Himalayas, while not reaching a state of extreme crisis, is undeniably perilous. Although the timescale may have been exaggerated by the Intergovernmental Panel on Climate Change (IPCC), there is a genuine and urgent threat to the mountains due to global warming and various other pressures (Bhartiya & Choudhary, 2012; Yadav et al., 2004). This was painfully evident during the recent summer in Uttarakhand, an Indian Himalayan state, where an unprecedented catastrophe unfolded, leaving a lasting impact on human memory. Within a single day, cloudbursts, flash floods, landslides, and widespread destruction ravaged the region, resulting in a staggering loss of human lives. Estimates suggest that the number of casualties reached the thousands, and the economic damage ranged from US$500 million to around $2 billion. Another devastating event occurred in 2010 when a monsoon flood struck Pakistan, causing the loss of over 2000 lives, displacing millions, and incurring a financial burden of $40 billion (Gergel et al., 2002). However, despite the mounting evidence, policymakers in India and elsewhere are hesitant to acknowledge a glaring and dangerous truth: human activities have placed an overwhelming strain on the fragile Himalayan ecosystem, pushing it perilously close to its limits. Positive actions must be taken, including implementing restrictions on the number of tourists visiting during the monsoon season from June to September (Juyal et al., 2010). Many visitors are unaware of the risks they face, as demonstrated by the tragic loss of thousands of lives during the Uttarakhand disaster. Policymakers must proactively engage with scientists and experts to address the challenges confronting the Himalayas and its inhabitants, with the aim of achieving sustainable development (Saha et al., 2019).

While global warming often captures the headlines, numerous other factors contribute to the vulnerability of this delicate mountain region. The human population in the Himalayas is rapidly increasing, leading to accelerated changes in the landscape to accommodate the growing demands (Yan et al., 2020). Activities such as cattle grazing and rampant deforestation are taking a severe toll. If current trends continue, it is projected that one-third of the Indian Himalayan Forest cover could vanish by 2100. This alarming rate of deforestation will drive nearly one-quarter of endemic species to extinction and disrupt the natural water flow (Hofer, 1993). The altered Himalayan landscape resulting from human activities and warming temperatures also invites biological invasions and diminishes native biodiversity, causing lasting damage to the natural ecosystems (Laurance, 1999). Energy consumption is a fundamental need for the people of the Himalayas, primarily in the form of hydropower and dams. In the next decade or so, plans are underway to construct almost 400 new dams in the Indian and Tibetan Himalayas (Srivastava et al., 2013). However, this surge in dam-building comes at a great cost to the fragile ecosystem and the communities residing in submerged settlements. It is concerning that policymakers approving these schemes either lack comprehension of the scientific evidence or consciously choose to ignore it, especially considering the region's high seismic activity and delicate geology (Azam et al., 2018).

Unlike the Aravallis in India (around 4000 million years old) and the North American Appalachians (440–480 million years old), the Himalayas are relatively young, folded, and still in the process of rising. They exhibit greater tectonic activity compared to most other mountain ranges (Azam et al., 2018). Rising temperatures further exacerbate the challenges faced by the Himalayas. The melting of ice and snow leads to the formation of new glacial lakes and an increase in the volumes of existing ones. This, in turn, raises the threat of glacial lake outburst floods (Azam et al., 2018). Across the Himalayas, there are approximately 8800 glacial lakes spanning multiple nations, with over 200 of them categorized as dangerous. Recent scientific evidence suggests that floods originating in the Himalayas are predominantly caused by landslides that temporarily block mountain rivers (Srivastava et al., 2013). The Himalayas are experiencing a faster warming rate than other mountain ranges. Additionally, the increased use of reinforced concrete in building construction, replacing traditional wood and stone masonry, is likely to contribute to a heat-island effect, intensifying regional warming (Ives, 2012).

Moving forward, several critical steps must be taken in the Himalayas. It is clear that the social and economic development of the Himalayan population cannot be undermined. Positive indicators such as increased literacy levels, improved school enrolment, and reduced infant mortality demonstrate progress (Aryal et al., 2014; Kargel et al., 2011). However, these very same people will bear the brunt of the region's escalating ecological degradation and environmental instability. Regulations intended to protect them, such as those related to mining and floodplain development, are poorly enforced or rarely implemented (Dimri & Allen, 2020). In fact, some in India attribute the current economic downturn to environmental regulations. While implementing an environmental tax on tourists to limit numbers and raise funds may be unpopular, it is an idea that warrants thorough discussion (Aryal et al., 2014). Most urgently, Himalayan countries need to establish an international network to monitor risks associated with glacial lakes and providearly warnings of potential hazards (Kargel et al., 2011). Similar to the tsunami warning systems installed around the Indian Ocean in the past decade, scientists and engineers must advocate more forcefully against rampant construction on riverbanks or floodplains that are consistently affected by monsoon floods (Godard et al., 2014). If the people of the Himalayas were more informed about the geological vulnerability and ecological fragility of their mountain home, they would likely exert more tremendous pressure for compliance with laws and regulations aimed at protecting it (Banerjee & Shankar, 2013; Satyal et al., 2017). India and other affected countries should incorporate basic Himalayan geology and ecology knowledge into their school curricula. By educating students about their environment, they will develop a stronger connection to the land and a heightened awareness of its delicate balance (Penny et al., 2022).

2 The Himalaya and Climate Change

Climate change poses significant challenges to the Himalayas, making it one of the most vulnerable regions on Earth. The effects of global warming are amplified in this mountain range, impacting various aspects of the ecosystem and human livelihoods (Aryal et al., 2014; Ramachandran et al., 2023). The Himalayas are home to a vast expanse of glaciers, often referred to as the "Third Pole" due to the substantial ice cover. However, rising temperatures have accelerated the rate of glacial melt, leading to the formation of glacial lakes (Kumar et al., 2015). These lakes can pose a serious threat as they are prone to glacial lake outburst floods (GLOFs). When a glacial lake bursts, it releases massive water, endangering downstream communities, infrastructure, and ecosystems. The frequency and intensity of GLOFs have increased in recent years, causing significant loss of life and property (Li et al., 2016). Furthermore, glacial melt alters the timing and volume of river flows originating from the Himalayas. Rivers like the Ganges, Brahmaputra, and Indus are lifelines for millions of people in South Asia, providing water for drinking, irrigation, and hydropower generation. However, with changing precipitation patterns and accelerated glacial melt, the flow of these rivers becomes unpredictable (Kumar et al., 2015). Water scarcity becomes a pressing issue during the dry season, affecting agriculture and causing conflicts over water resources.

Conversely, during the monsoon season, the increased volume of water leads to a higher risk of devastating floods. Agriculture is the primary livelihood for a significant portion of the population in the Himalayan region (Bisht et al., 2016). Changes in water availability and timing of river flows directly impact agricultural practices and food security. As glacial melt alters the hydrological cycle, the availability of water for irrigation becomes uncertain (Wilcock et al., 2008). Unpredictable weather patterns, such as erratic rainfall and changing temperatures, make it challenging for farmers to plan their cropping cycles and adapt to changing conditions (Bhatt et al., 2015). In some cases, traditional crop varieties and agricultural practices are no longer viable, leading to reduced yields and economic hardship for farming communities. The Himalayan region is renowned for its unique and diverse ecosystems, ranging from alpine meadows to dense forests (Yu et al., 2017). Climate change significantly threatens these ecosystems and the flora and fauna they support(. Shifts in temperature and precipitation patterns can disrupt the delicate balance of these ecosystems, causing changes in species distribution, phenology (the timing of biological events), and ecological interactions (Anderson et al., 2022). Many species are adapted to specific temperature ranges and habitats, and as these conditions change, their survival is jeopardized. The loss of biodiversity in the Himalayas has far-reaching consequences for ecosystem functioning, pollination, seed dispersal, and overall ecosystem resilience (Verma et al., 2013).

Human communities in the Himalayas heavily rely on ecosystem services provided by the region's natural resources. Forests act as water catchments, regulating the flow of water and preventing soil erosion. They also provide fuelwood, timber, and non-timber forest products that are essential for local livelihoods (Hodges, 2006).

However, climate change, coupled with unsustainable land-use practices, has led to widespread deforestation and forest degradation. Logging, expansion of agriculture, and infrastructure development have fragmented forest habitats, reducing their ability to provide critical ecosystem services (Bhatt et al., 2015; Öztürk et al., 2015). This loss of forest cover has cascading effects on water availability, soil erosion, and the stability of slopes, increasing the risk of landslides and other natural disasters.

In addition to the environmental consequences, the impacts of climate change in the Himalayas have severe social and economic implications. The region is characterized by remote and marginalized communities with limited access to resources and infrastructure (Kumar et al., 2015). Climate change exacerbates existing vulnerabilities, making these communities more susceptible to food insecurity, water scarcity, and natural disasters. Displacement and migration become prevalent as people seek better livelihood opportunities in other areas (Dahal et al., 2021). Indigenous cultures and traditional knowledge systems are also at risk of being lost as communities are forced to adapt to changing conditions (Roth, 2007). To address the challenges posed by climate change in the Himalayas, both mitigation and adaptation strategies are necessary. Mitigation involves reducing greenhouse gas emissions on a global scale to limit the extent of climate change (Chaturvedi et al., 2011). This requires transitioning to cleaner and renewable sources of energy, promoting energy efficiency, and adopting sustainable land-use practices. It also involves international cooperation to address the common but differentiated responsibilities of nations in combating climate change (Rawat et al., 2012). Adaptation strategies are crucial for building resilience and enhancing the capacity of communities to cope with the impacts of climate change. This includes improving early warning systems for floods and landslides, implementing climate-smart agricultural practices, promoting sustainable water resource management, and strengthening disaster preparedness and response mechanisms (Ingty, 2017; Karki et al., 2021).

Furthermore, preserving and restoring natural ecosystems, such as forests and wetlands, can enhance their resilience and ability to provide essential ecosystem services. Effective adaptation and mitigation measures require collaboration among governments, scientists, policymakers, and local communities (Shaheen et al., 2013). Indigenous knowledge and traditional practices should be integrated into climate change policies and strategies, as they often hold valuable insights into managing the impacts of climate change. Education and awareness campaigns can foster a sense of responsibility and promote sustainable practices among local communities (Kumar et al., 2015). The Himalayas are at a critical juncture with their rich cultural and ecological heritage. Taking concerted action to address climate change in this region is essential for its wellbeing and millions of people who depend on its resources (Chitale et al., 2014). By prioritizing sustainable development, resilient ecosystems, and the wellbeing of local communities, it is possible to navigate the challenges of climate change and secure a sustainable future for the Himalayas and its inhabitants.

2.1 Land Use

Land-use change and forest degradation in the Himalayas have become major environmental concerns due to human activities, including population growth, agricultural expansion, infrastructure development, and unsustainable logging practices (Singh et al., 2008). These activities have led to significant transformations in the landscape, with far-reaching ecological and socio-economic consequences. The Himalayan region is characterized by diverse forest ecosystems, ranging from temperate broadleaf forests to alpine meadows (Sharma et al., 2000). These forests provide numerous ecosystem services, including carbon sequestration, water regulation, soil conservation, and habitat for a wide array of plant and animal species. However, the growing demand for land and resources has put immense pressure on these forests, resulting in deforestation and forest degradation (Chowdhuri et al., 2021; Srinivasan & Wilcove, 2021).

2.2 Population Growth

In the Himalayan region has led to the expansion of settlements and agricultural activities. As communities seek to meet their subsistence needs, forests are cleared for agriculture, often through slash-and-burn practices (Gull et al., 2022). These practices involve removing a patch of forest, burning the vegetation, and cultivating crops for a few years until the soil fertility declines, leading to the abandonment of the land and the clearing of new areas (Rak et al., 2016; Rawat et al., 2012). This cycle of shifting cultivation contributes to widespread deforestation and habitat destruction.

2.3 Agricultural Expansion

Also involves the conversion of forests into permanent croplands. Large-scale commercial agriculture, including cash crops and plantations, further accelerates deforestation (Bhatt et al., 2015). In some cases, forested areas are converted into pasturelands for livestock grazing, contributing to ecosystem degradation through overgrazing and soil compaction.

2.4 Infrastructure Development

Is another driver of land-use change in the Himalayas. The construction of roads, highways, dams, and hydropower projects requires the clearing of large areas of forests (Molden et al., 2014; Sarkar, 2023). These infrastructure projects fragment habitats, disrupt wildlife corridors, and alter the natural flow of water, affecting downstream ecosystems. Expanding urban areas and tourism infrastructure also contributes to the loss of forest cover, as land is cleared for buildings, resorts, and associated amenities (Kumar et al., 2021).

2.5 Unsustainable Logging Practices

Have further exacerbated forest degradation in the Himalayas. Timber extraction for commercial purposes, without proper regulations and monitoring, has led to overharvesting and illegal logging (Huang et al., 2021). This has depleted valuable timber resources andisrupted forest ecosystems, affecting biodiversity, carbon storage, and soil stability (Jha et al., 2022).

3 The Consequences of Land-Use Change and Forest Degradation in the Himalayas

The consequences of land-use change and forest degradation in the Himalayas are far-reaching. Deforestation disrupts the water cycle, as forests play a crucial role in regulating water flow, acting as natural reservoirs, and controlling soil erosion (Hoekman et al., 2020). Forests help retain water during the monsoon season, releasing it gradually throughout the year, ensuring a steady flow in rivers and streams. Reduced forest cover increases water runoff, leading to soil erosion, sedimentation in rivers, andncreased risk of floods and landslides during heavy rainfall events (Mukhopadhyay, 2012; Tsatsaros et al., 2013).

3.1 The Loss of Forest Cover

Also has implications for carbon sequestration and climate change. Forests act as carbon sinks, absorbing and storing atmospheric carbon dioxide through photosynthesis (Bhatta & Vetaas, 2016). Deforestation releases this stored carbon back into the atmosphere, contributing to greenhouse gas emissions and exacerbating climate change (Alamgir et al., 2014). The Himalayan region’s forests are estimated to store significant amounts of carbon, and their conservation is crucial for mitigating global climate change.

Furthermore, forest degradation and habitat loss have adverse impacts on biodiversity in the Himalayas (Table 1). These forests are home to numerous endemic and endangered species, including charismatic mammals like the snow leopard, Bengal tiger, and red panda (Chitale et al., 2014). Deforestation fragments habitats and isolates populations, reducing genetic diversity and making species more vulnerable to extinction. The loss of forest cover also disrupts food chains, impacting the availability of food and shelter for wildlife. The degradation of forests in the Himalayas also has profound socio-economic implications Chakraborty et al., 2016). Forests are a vital source of livelihood for local communities, providing fuelwood, timber, non-timber forest products, and ecosystem services. Many rural households depend on forests for their energy needs, using firewood for cooking and heating (Ramirez-Villegas & Challinor, 2012). Deforestation reduces the availability of these resources, leading to increased fuelwood scarcity and the need to travel greater distances to collect firewood. This places a burden on women and children, who are primarily responsible for collecting fuelwood, and contributes to environmental degradation as people resort to unsustainable practices to meet their energy needs (Singh & Kumar, 2022).

Moreover, forest ecosystems play a significant role in supporting traditional cultures and indigenous knowledge systems in the Himalayas. Forests are intricately linked to the spiritual and cultural beliefs of local communities, forming the basis of their identities and rituals (Chitale et al., 2014). Forests also provide medicinal plants, food, and materials for traditional crafts, which are important for local economies and cultural heritage. Forest degradation threatens the preservation of these traditional practices and knowledge systems, leading to cultural erosion and loss of identity (Tripathi et al., 2022). Addressing land-use change and forest degradation in the Himalayas requires a comprehensive and multi-faceted approach. Effective strategies should include:

3.2 Strengthening Land-Use Planning and Regulations

Governments and local authorities need to develop and enforce land-use plans that prioritize sustainable practices, discourage deforestation, and promote responsible agriculture and infrastructure development.

3.3 Promoting Sustainable Agricultural Practices

Encouraging agroforestry, organic farming, and the use of efficient irrigation techniques can reduce the need for forest clearing and minimize the environmental impact of agriculture (Layek et al., 2022).

3.4 Implementing Responsible Logging Practices

Enforcing regulations and promoting sustainable logging practices, such as selective logging and reforestation, can ensure the conservation of forest resources while meeting the demand for timber.

3.5 Supporting Community-Based Forest Management

Empowering local communities to manage and benefit from forest resources through participatory approaches can incentivize sustainable practices and enhance local livelihoods (Alamgir et al., 2014).

3.6 Investing in Reforestation and Restoration Efforts

Large-scale reforestation initiatives, including afforestation and reclamation of degraded areas, can help restore forest cover, enhance ecosystem services, and provide economic opportunities for local communities.

3.7 Enhancing Monitoring and Law Enforcement

Strengthening monitoring systems, using technologies like satellite imagery and remote sensing, can help detect and prevent illegal logging and encroachments in forested areas (Hu et al., 2017). Stringent law enforcement and penalties for forest offenses are crucial for deterring illegal activities.

3.8 Promoting Awareness and Education

Raising awareness among local communities, policymakers, and the public about the importance of forests, their role in sustaining ecosystems, and the benefits of sustainable land-use practices can foster a culture of conservation and responsible resource management.

3.9 Encouraging International Cooperation

Collaborative efforts among Himalayan countries and international organizations can facilitate knowledge sharing, capacity building, and financial support for conservation and sustainable land-use initiatives.

By adopting a holistic and collaborative approach, it is possible to mitigate land-use change and forest degradation in the Himalayas, safeguard ecosystem services, protect biodiversity, support local livelihoods, and ensure the sustainable development of this ecologically significant region.

Table provides a concise overview, within each aspect

Table 1 Summarizing the key points regarding land-use change and forest degradation in the Himalayas

Aspect	Impact
Population growth	- Increased demand for land resources
	- Expansion of settlements and agricultural activities
Agricultural expansion	- Deforestation for shifting cultivation
	- Conversion of forests to permanent croplands
	- Overgrazing and soil compaction due to livestock
Infrastructure development	- Clearing of large forest areas for construction
	- Habitat fragmentation and disruption of wildlife corridors
	- Alteration of natural water flow and hydrology
Unsustainable logging	- Overharvesting and illegal logging
	- Depletion of valuable timber resources
	- Disruption of forest ecosystems and biodiversity
Consequences	- Disruption of the water cycle and increased soil erosion
	- Reduction of carbon sinks and increased greenhouse gas emissions
	- Loss of habitat for numerous plant and animal species
	- Increased risk of floods, landslides, and natural disasters
	- Fuelwood scarcity and environmental degradation
	- Threat to traditional cultures and indigenous knowledge systems
Strategies	- Strengthen land-use planning and regulations
	- Promote sustainable agricultural practices
	- Implement responsible logging practices
	- Support community-based forest management
	- Invest in reforestation and restoration efforts
	- Enhance monitoring and law enforcement
	- Promote awareness and education
	- Encourage international cooperation

4 Water Resources in the Himalayas

Water resources and hydrology in the Himalayas are of utmost importance due to the region's role as the source of major rivers providing water for millions downstream. Often referred to as the "Water Towers of Asia," the Himalayas play a crucial role in the region's hydrological cycle and water availability (Kattel et al., 2023). However, climate change and glacial melt pose significant challenges to water resources, altering river flows, seasonal patterns, and ultimately affecting water management, agriculture, hydropower generation, and downstream communities (Srivastava et al., 2013). The Himalayas are home to an extensive network of glaciers, snowfields, and high-altitude lakes, collectively known as the cryosphere. These glaciers act as natural reservoirs, storing vast amounts of freshwater in the form of ice (Das & Sharma, 2019). As temperatures rise due to climate change, the Himalayan glaciers are experiencing accelerated melt, resulting in increased water runoff. The melting of glaciers contributes to the formation of glacial lakes and alters the timing and volume of river flows downstream (Xu et al., 2009). One of the immediate consequences of glacial melt is the formation of glacial lakes. As glaciers retreat, meltwater accumulates in depressions, leading to the creation of new lakes. These glacial lakes can be unstable and pose a significant risk of glacial lake outburst floods (GLOFs) (Chalise et al., 2006). When the dam-like moraine holding the water in the glacial lake fails, a sudden release of water occurs, resulting in devastating floods downstream. The frequency and intensity of GLOFs have increased in recent years, causing loss of life, destruction of infrastructure, and displacement of communities (Chowdhury et al., 2021). Furthermore, glacial melt affects the timing and volume of river flows originating from the Himalayas. Rivers such as the Ganges, Brahmaputra, Indus, and Yangtze depend on the seasonal melting of glaciers and snowfields for their water supply. However, as glaciers recede, the seasonal patterns of river flows are altered (Khanal et al., 2015). During the dry season, reduced glacial melt leads to decreased water availability, posing challenges for agriculture, hydropower generation, and overall water security. This has significant implications for downstream communities that rely on these rivers for irrigation, drinking water, and industrial use (Goswami & Goyal, 2021).

Changes in precipitation patterns also contribute to shifts in the hydrological regime of the Himalayan region. Climate change affects the timing, intensity, and spatial distribution of rainfall (Ahmed et al., 2021). Some areas may experience more frequent and intense rainfall events, leading to increased surface runoff and the risk of flooding. On the other hand, prolonged dry spells and reduced rainfall in other regions exacerbate water scarcity and drought conditions (Bhattarai & Conway, 2021). These changes in precipitation patterns make water resource management and planning more challenging, requiring adaptive measures to ensure sustainable water supply for both human and ecological needs. In addition to climate change impacts, increasing water demand poses additional challenges for water resource management in the Himalayas (Mukherji et al., 2015). Population growth, urbanization, and economic development contribute to rising water demand for various sectors, including agriculture, industry, and domestic use (Table 2). Meeting this increasing demand places additional stress on already limited water resources in the region (Ahmad et al., 2015). The competition for water resources among different sectors necessitates effective water management strategies to ensure equitable distribution, environmental sustainability, and efficient utilization of water resources.

4.1 Agriculture

Is a primary consumer of water in the Himalayan region, with irrigation being a vital component of agricultural practices. Farmers depend on adequate water supplies for crop production and sustenance of their livelihoods (Wilcock et al., 2008). Changes in river flows and water availability directly impact agricultural productivity and food security. Shifts in precipitation patterns and reduced glacial meltan disrupt traditional cropping cycles, affecting the timing and quantity of water needed for irrigation (Malhotra et al., 2022). The variability and uncertainty in water availability challenge farmers' ability to plan and adapt their agricultural practices to changing conditions.

4.2 Hydropower Generation

Is another critical sector that relies on water resources in the Himalayas. The region has immense hydropower potential due to its steep topography and numerous rivers (Bhattarai & Conway, 2021). Hydroelectric power provides a renewable energy source and contributes to the region's energy security. However, changes in river flows, including reduced glacial melt, can impact the efficiency and reliability of hydropower generation. Lower river flows during the dry season can lead to reduced power output, affecting energy production and stability of the power grid (Casale et al., 2020).

4.3 Downstream Communities

In the Himalayas heavily depend on the rivers originating from the region. These rivers support livelihoods, provide water for domestic and industrial use, and sustain ecosystems in downstream areas. Changes in river flows, water quality, and timing of water availability can have far-reaching impacts on these communities (Bocchiola et al., 2020). Reduced water availability during dry periods can lead to water scarcity, affecting agriculture, sanitation, and overall quality of life. Changes in river flows can also impact the ecology and biodiversity of downstream ecosystems, disrupting the natural balance and potentially threatening aquatic species.

To address the challenges related to water resources and hydrology in the Himalayas, a multi-faceted approach is necessary. This includes:

4.4 Integrated Water Resource Management

Implementing comprehensive and integrated water resource management strategies that consider the needs of various sectors, ecological requirements, and the impacts of climate change (Asher & Bhandari, 2021). This involves sustainable water allocation, water-use efficiency, and demand management practices.

4.4.1 Climate Change Adaptation

Developing and implementing adaptation measures to cope with the impacts of climate change on water resources. This includes promoting water-saving agricultural techniques, enhancing water storage and conservation infrastructure, and improving early warning systems for floods and droughts.

4.4.2 Sustainable Agriculture Practices

Encouraging the adoption of climate-smart agricultural practices that optimize water use, such as drip irrigation, precision farming, and water-efficient crops (Sotomayor-Ramirez et al., 2004). Promoting agroforestry and soil conservation techniques can also contribute to better water management and soil health.

4.4.3 Hydropower Planning and Management

Conducting comprehensive assessments of hydropower projects, considering the potential impacts of climate change on river flows, and ensuring sustainable and environmentally responsible development (Bocchiola et al., 2020). Evaluating the feasibility of alternative renewable energy sources can also diversify the energy mix and reduce reliance on hydropower.

4.4.4 Community Engagement and Participation

Involving local communities and stakeholders in water resource management decisions, ensuring their participation and knowledge are incorporated into planning processes. Empowering communities to participate in water governance and enhancing their capacity to manage and conserve water resources (Asher & Bhandari, 2021).

4.4.5 Transboundary Cooperation

Strengthening transboundary cooperation among Himalayan countries to address shared water challenges, promote equitable water-sharing arrangements, and develop joint strategies for sustainable water resource management.

Research and monitoring: Conducting scientific research to enhance understanding of hydrological processes, monitor changes in water availability, and assess the impacts of climate change on water resources (Tanwar, 2007). This information can inform evidence-based decision-making and adaptive management strategies.

4.4.6 Education and Awareness

Promoting water literacy and raising awareness among communities, policymakers, and stakeholders about the importance of water resources, the impacts of climate change, and the need for sustainable water management practices.

By implementing these strategies, the Himalayan region can work towards ensuring equitable water distribution, resilience to climate change impacts, sustainable agriculture, and the preservation of downstream ecosystems and communities. Effective water resource management is crucial for the region's socio-economic development, ecological integrity, and overall wellbeing (Table 2).

5 Biodiversity in the Himalayas

Biodiversity conservation is of paramount importance in the Himalayas, given the region's exceptional biodiversity and its role as a global hotspot for endemic and endangered species (Campbell, 2018). However, human activities, coupled with the impacts of climate change, pose significant threats to the unique flora and fauna of the Himalayan ecosystem. Habitat fragmentation, poaching, invasive species, and climate change-induced shifts in species distribution and ecological interactions are some of the major challenges faced in conserving biodiversity in the region (Dahal et al., 2021).

The Himalayas are home to an incredible array of plant and animal species, many of which are found nowhere else in the world. The region's diverse habitats, including temperate forests, alpine meadows, and high-altitude ecosystems, support a wide range of life forms (Bhagwat, 2012). From charismatic large mammals like the snow leopard, Bengal tiger, and red panda to countless species of plants, birds, reptiles, and amphibians, the Himalayas teem with biological richness.

However, human activities have significantly impacted the biodiversity of the Himalayas. Habitat fragmentation resulting from infrastructure development, agriculture, and urbanization has led to the loss and fragmentation of natural habitats (Bhattacharjee et al., 2017). Large-scale construction projects, such as roads, dams, and urban settlements, disrupt wildlife corridors and isolate populations, making it

Table 2 Provides a concise overview, and additional factors and nuances may be considered within each aspect

Aspect	Impact
Climate change and glacial melt	- Altered river flows and seasonal patterns
	- Increased risk of glacial lake outburst floods (GLOFs)
	- Reduced water availability during the dry season
	- Changes in precipitation patterns and water distribution
Water resource management	- Challenges in water allocation and equitable distribution
	- Increased demand for water resources for agriculture, industry, and domestic use
	- Need for integrated and sustainable water management strategies
Agricultural impacts	- Disruption of traditional cropping cycles
	- Reduced water availability for irrigation
	- Implications for agricultural productivity and food security
Hydropower generation	- Altered river flows affecting power generation
	- Reduced power output during dry seasons
	- Need for comprehensive planning and assessment of hydropower projects
Downstream communities	- Impacts on water availability and quality
	- Water scarcity and its effects on livelihoods
	- Ecological implications for downstream ecosystems
Strategies	- Integrated water resource management
	- Climate change adaptation for water resources
	- Adoption of sustainable agricultural practices
	- Responsible hydropower planning and management
	- Community engagement and participation
	- Transboundary cooperation
	- Research, monitoring, and data collection
	- Education and awareness

difficult for species to move between fragmented habitats. This fragmentation reduces genetic diversity, restricts gene flow, and increases the vulnerability of species to environmental changes and genetic disorders (Gupta et al., 2020).

Poaching and illegal wildlife trade pose another serious threat to the biodiversity of the Himalayas. Several species in the region, including the snow leopard, Himalayan musk deer, and various bird species, are targeted for their valuable body parts, skins, or feathers, driven by illegal international markets (Newbold et al., 2014). Poaching not only directly impacts the targeted species but also disrupts ecological balances and threatens the overall ecosystem health.

Invasive species also pose a significant challenge to biodiversity conservation in the Himalayas. Non-native species introduced intentionally or unintentionally can outcompete native species, disrupt ecological interactions, and alter ecosystem dynamics (Boral & Moktan, 2022). Invasive species often have no natural predators or controls in their new environment, allowing them to rapidly spread and outcompete native species for resources. This can lead to the displacement or even extinction of native species, leading to a loss of biodiversity and ecological integrity.

Climate change further exacerbates the pressures on biodiversity in the Himalayas. The region is experiencing temperature increases at a faster rate compared to global averages, affecting the distribution, phenology (timing of biological events), and behaviour of many species (Dahal, 2020). As temperatures rise, suitable habitats for certain species may shift to higher altitudes, potentially leading to range contractions or local extinctions. Alpine species that are adapted to specific temperature and moisture conditions may face challenges as their preferred habitats shrink or disappear (Salick et al., 2009).

Changes in precipitation patterns also impact the availability of water resources, affecting the survival and reproductive success of many species. Changes in the timing and amount of rainfall can disrupt the phenology of plants and the availability of food sources for herbivores and pollinators (Bhutiyani et al., 2010). These changes can have cascading effects on the entire food chain and ecological interactions, impacting the survival and reproduction of dependent species.

Biodiversity conservation efforts in the Himalayas require a multi-faceted approach. Effective strategies should encompass the following.

5.1 Protected Areas and Habitat Restoration

Establishing and effectively managing protected areas and nature reserves are vital for preserving the biodiversity of the Himalayas. These areas provide safe havens for endangered species, help maintain ecological processes, and support research and monitoring efforts (S. Banerjee et al., 2022). Additionally, restoring degraded habitats through reforestation, habitat connectivity initiatives, and ecosystem restoration projects can enhance biodiversity conservation.

5.2 Anti-Poaching and Wildlife Crime Control

Strengthening anti-poaching measures, increasing patrols, and improving law enforcement to combat wildlife crime are critical for protecting vulnerable species (Bauer, 2016). Collaborative efforts between law enforcement agencies, local communities, and conservation organizations can help curb poaching and illegal wildlife trade.

5.3 Invasive Species Management

Implementing effective measures to prevent the introduction and spread of invasive species is crucial. This includes strict quarantine measures, early detection and rapid response systems, and public awareness campaigns to prevent the release of non-native species into natural habitats (Lamsal et al., 2018).

5.4 Climate Change Adaptation

Integrating climate change considerations into biodiversity conservation strategies is essential. This involves assessing the vulnerability of species and ecosystems to climate change, identifying, and protecting climate refugia, and promoting landscape-level conservation planning those accounts for future climate scenarios (Devkota et al., 2019).

5.5 Community Engagement and Sustainable Livelihoods

Engaging local communities in conservation efforts is vital for long-term success. Empowering local communities by involving them in decision-making processes, providing alternative livelihood options, and raising awareness about the importance of biodiversity and sustainable resource use can foster support and stewardship of the Himalayan ecosystems (Thompson, 2010).

5.6 Research and Monitoring

Conducting scientific research to understand the ecological dynamics, species distributions, and responses to environmental changes in the Himalayas is critical for informed decision-making (Gondhalekar et al., 2015). Monitoring programs that track population trends, phenological shifts, and habitat changes provide valuable insights for conservation planning and adaptive management.

5.7 International Cooperation

Collaborative efforts between Himalayan countries, international organizations, and research institutions are essential for knowledge sharing, capacity building, and collaborative research and conservation initiatives (Gondhalekar et al., 2015). Transboundary cooperation is particularly crucial for protecting migratory species and managing shared ecosystems.

5.8 Education and Public Awareness

Promoting environmental education and raising public awareness about the value of biodiversity and the importance of its conservation are key elements in fostering a culture of conservation (Gupta, 2008). Engaging local schools, community centres, and media outlets can help in still a sense of responsibility and encourage public support for biodiversity conservation.

By implementing these strategies and fostering a comprehensive and collaborative approach, biodiversity conservation in the Himalayas can be enhanced (Table 3). Protecting the unique flora and fauna of the region not only preserves its ecological integrity but also ensures the sustainability of ecosystem services, supports local livelihoods, and maintains the cultural heritage associated with he diverse biodiversity of the Himalayas (Barrett & Bosak, 2018).

6 Human Wellbeing in the Himalayas

Human wellbeing in the Himalayas is intricately linked to the region's natural resources and ecosystems. The lives and livelihoods of millions of people residing in the Himalayas depend on the availability of water, fertile land, forests, and other ecosystem services (Miehe et al., 2009). However, the region is facing numerous challenges that directly impact human wellbeing, including climate change, changes in water availability, disruptions in agriculture, increased frequency of natural disasters, and the loss of ecosystem services (Nibanupudi, 2012).

6.1 Climate Change is One of the Key Drivers Affecting Human Wellbeing in the Himalayas

The region is experiencing significant shifts in temperature and precipitation patterns, leading to changes in weather conditions and climate extremes (Chakraborty & Sherpa, 2021). Rising temperatures have far-reaching consequences for agriculture, water availability, and human health (Pant et al., 2017). Changes in rainfall patterns, including increased variability and intensity, pose challenges for agricultural practices, making it difficult for farmers to plan their planting and harvesting schedules (Rani, 2023).

Table 3 Different aspect of anthropogenic activities in Himalayas and their impacts

Aspect	Impact
Habitat fragmentation	- Loss and fragmentation of natural habitats
	- Disruption of wildlife corridors and genetic diversity
	- Impacts on species' ability to move between habitats
Poaching and wildlife trade	- Threat to endangered species through illegal hunting and trade
	- Ecological imbalances and disruption of food chains
Invasive species	- Displacement of native species and disruption of ecological interactions
	- Alteration of ecosystem dynamics and biodiversity loss
Climate change	- Altered species distribution and phenology due to temperature changes
	- Shifting habitats and potential range contractions
	- Changes in precipitation patterns affecting species and ecosystem dynamics
Strategies	- Establishing and managing protected areas and nature reserves
	- Restoring degraded habitats through reforestation and restoration
	- Strengthening anti-poaching measures and wildlife crime control
	- Implementing invasive species management and prevention measures
	- Integrating climate change considerations into conservation strategies
	- Engaging local communities and promoting sustainable livelihoods
	- Conducting research and monitoring to inform conservation efforts
	- Fostering international cooperation and collaboration
	- Promoting education and public awareness of biodiversity conservation

6.2 Agriculture is a Primary Source of Livelihood for Many Communities in the Himalayas

Disruptions in agriculture due to climate change, including altered rainfall patterns and increased frequency of extreme weather events like droughts and floods, can lead to crop failures, food shortages, and decreased income for farmers (Bhatt et al., 2015). The changing climatic conditions also affect water availability for irrigation, further exacerbating the challenges farmers face.

6.3 Water Scarcity is a Pressing Concern in the Himalayas

Particularly during dry periods when glacial melt and snowmelt decline. Water availability for domestic use, agriculture, and industry is directly impacted by changes in river flows and reduced snow and glacier reserves (Batool et al., 2019). Inadequate access to clean water and sanitation facilities poses risks to public health, leading to waterborne diseases and hygiene-related issues. Water scarcity also affects hydropower generation, which plays a crucial role in meeting the region's energy needs (Pramanik & Bhaduri, 2016).

The Himalayas are prone to natural disasters, including landslides, flash floods, and avalanches, which have been exacerbated by climate change. These events pose a significant threat to human lives, infrastructure, and the environment (Ahmad et al., 2018). Increased frequency and intensity of natural disasters disrupt communities, displace populations, and destroy homes and livelihoods. The economic and social impacts of such disasters are significant, exacerbating poverty and undermining development efforts in the region (Chhogyel et al., 2020).

6.4 The Loss of Ecosystem Services

In the Himalayas further impacts human wellbeing. Ecosystem services, such as pollination, nutrient cycling, water regulation, and provision of non-timber forest products, are essential for sustaining human livelihoods and cultural practices (Singh et al., 2019). Deforestation, habitat degradation, and the loss of biodiversity reduce the availability of these services, affecting food security, traditional practices, and the overall quality of life for Himalayan communities (Singh et al., 2010).

Food security is a major concern in the Himalayas, as changes in climate and water availability directly impact agricultural productivity. The disruption of agricultural practices, loss of crops due to extreme weather events, and the decline in water availability for irrigation all contribute to food insecurity (Chhogyel et al., 2020). Vulnerable communities, such as small-scale farmers and marginalized groups, are particularly affected, as they heavily rely on agriculture for subsistence and income generation.

The impacts of these challenges on human wellbeing extend beyond the material aspects of life. The cultural heritage of Himalayan communities, which is deeply intertwined with their natural surroundings, is at risk (Bhatt et al., 2015). Traditional knowledge, customs, and spiritual practices rooted in the relationship with nature face challenges due to environmental changes (Shrestha et al., 2022). The loss of cultural heritage not only erodes the identity of communities but also affects social cohesion and the wellbeing of individuals.

To address these challenges and promote human wellbeing in the Himalayas, several strategies can be employed:

6.5 Climate Change Adaptation

Implementing adaptation measures to cope with the impacts of climate change is crucial. This involves promoting climate-resilient agricultural practices, enhancing water management techniques, and developing early warning systems for natural disasters (Jethi et al., 2016). Building climate resilience in infrastructure, such as resilient housing and infrastructure design, can also minimize the impacts of extreme weather events.

6.6 Sustainable Water Resource Management

Ensuring equitable access to clean water for domestic use, agriculture, and industry through sustainable water resource management practices is essential (Mishra et al., 2017). This includes water conservation, watershed management, and promoting efficient irrigation techniques. Developing and maintaining water storage and distribution systems can help mitigate the impacts of water scarcity (Tsatsaros et al., 2013).

6.7 Diversification of Livelihoods

Supporting the diversification of livelihoods beyond agriculture can enhance resilience and reduce dependency on climate-sensitive sectors (Campbell, 2018). Promoting alternative income-generating activities such as ecotourism, sustainable forestry, and non-timber forest products can provide additional sources of income and alleviate pressure on natural resources.

6.8 Disaster Risk Reduction

Strengthening disaster risk reduction measures through community-based initiatives, early warning systems, and infrastructure resilience can mitigate the impacts of natural disasters (Pradhan & Leimgruber, 2022). This includes land-use planning, building codes, and community training programs to enhance preparedness and response capacities.

6.9 Conservation and Restoration of Ecosystems

Implementing conservation measures to protect and restore ecosystems is crucial for maintaining ecosystem services. This involves promoting sustainable forest management, reforestation, habitat restoration, and the conservation of biodiversity (Kumar et al., 2019). Engaging local communities in conservation efforts fosters stewardship and ensures the sustainability of ecosystem services.

6.10 Education and Awareness

Promoting education and raising awareness about climate change, water conservation, disaster preparedness, and sustainable practices are essential components of enhancing human wellbeing. Empowering communities with knowledge and information enables them to make informed decisions and adapt to changing circumstances.

6.11 Social Safety Nets

Establishing social safety nets and support systems for vulnerable communities can provide a safety net during times of crisis. This includes targeted interventions, social assistance programs, and access to healthcare and education.

6.12 Strengthening Governance and Policy

Enforcing and implementing policies that promote sustainable development, environmental protection, and social inclusion are crucial for enhancing human wellbeing in the Himalayas (Rana et al., 2022). Strengthening governance systems, promoting transparency, and engaging stakeholders in decision-making processes ensure the effective implementation of sustainable practices (see Table 4).

By adopting these strategies, the wellbeing of Himalayan communities can be enhanced, fostering resilience, sustainable development, and the preservation of cultural heritage. Balancing human needs with the conservation of natural resources is essential to ensure the long-term wellbeing of both people and the environment in the Himalayas.

Table 4 Shows the impact and strategies with different aspects

Aspect	Impact	Strategies
Climate change	- Shifts in temperature and precipitation patterns	- Implement climate-resilient agricultural practices
	- Altered weather conditions and climate extremes	- Enhance water management techniques
	- Challenges for agricultural planning and practices	- Develop early warning systems for natural disasters
	- Increased vulnerability to extreme weather events	- Build resilient infrastructure, such as resilient housing and infrastructure design
Water availability	- Reduced water availability for domestic, agricultural, and industrial use	- Promote sustainable water resource management practices
	- Water scarcity and inadequate access to clean water	- Emphasize water conservation and watershed management
	- Impacts on hydropower generation	- Implement efficient irrigation techniques
	- Ensuring equitable water distribution	- Develop and maintain water storage and distribution systems
Agriculture	- Disruptions in agricultural practices	- Promote livelihood diversification beyond agriculture
	- Crop failures and food shortages	- Support alternative income-generating activities such as ecotourism and sustainable forestry
	- Challenges in water availability for irrigation	- Alleviate pressure on natural resources
	- Increased vulnerability of small-scale farmers and marginalized groups	
Natural disasters	- Increased frequency and intensity of natural disasters	- Strengthen disaster risk reduction measures
	- Disruption of communities and livelihoods	- Implement community-based initiatives
	- Destruction of homes and infrastructure	- Develop early warning systems
	- Economic and social impacts	- Enhance infrastructure resilience
Loss of ecosystem services	- Reduction in availability of ecosystem services	- Implement conservation measures for ecosystems

(continued)

Table 4 (continued)

Aspect	Impact	Strategies
	- Impacts on food security and traditional practices	- Promote sustainable forest management
	- Decreased biodiversity and cultural heritage	- Restore habitats and promote habitat restoration
	- Reduced availability of non-timber forest products	- Conserve biodiversity
Education and awareness	- Lack of knowledge and information	- Promote education on climate change, water conservation, and disaster preparedness
	- Limited awareness of sustainable practices	- Raise public awareness on sustainable practices
	- Inadequate adaptation and decision-making capacities	
Social safety nets	- Vulnerability of communities during crises	- Establish social safety nets and support systems for vulnerable communities
	- Lack of access to healthcare and education	- Provide targeted interventions and social assistance programs
		- Ensure access to healthcare and education
Strengthening governance and policy	- Weak implementation of sustainable practices	- Enforce policies that promote sustainable development and environmental protection
	- Limited engagement in decision-making processes	- Strengthen governance systems
	- Lack of transparency in decision-making	- Promote transparency
		- Engage stakeholders in decision-making processes

7 Conclusion

The Himalayas face multiple interconnected challenges, including climate change, land-use change, water resources, biodiversity conservation, and human well-being. Rising temperatures contribute to glacial melt, altering river flows and impacting water availability, agriculture, and ecosystems. Human activities such as deforestation disrupt the water cycle, exacerbate ecological imbalances, and diminish habitats. Changes in precipitation patterns and water demand pose challenges for water resource management. Biodiversity conservation is crucial due to the region's unique flora and fauna, threatened by habitat fragmentation, poaching, invasive species, and climate change. Disruptions in agriculture, water scarcity, natural disasters, and loss of ecosystem services impact human wellbeing, including food security, livelihoods, health, and cultural heritage. Addressing these challenges requires climate change adaptation, sustainable land-use practices, integrated water resource management, biodiversity conservation, and community engagement. By preserving natural resources, safeguarding biodiversity, and promoting sustainable development, the Himalayas can achieve long-term sustainability and resilience, striking a balance between human needs and environmental preservation.

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Sustainability in the Indian Himalayan Region: Understandings the Ecosystem Services, Climate Change Impacts, Land Use Shifts and Their Threats

Sabir Hussain, Sheenu Sharma, Ram Chand Bhatti, and Anand Narain Singh

Abstract Climate change in the Indian Himalayan region (IHR) is facing significant challenges in providing multiple ecosystem services. The IHR, renowned for its rich biodiversity and critical water resources, is experiencing rapid shifts in temperature and precipitation patterns. Several studies have observed a significant decreasing trend in temperature and precipitation over both space and time scales, resulting in reduced snow cover, accelerated glacial melting, altered hydrological regimes, and changes in species distribution and behaviours. The impacts of climate change on ecosystem services are diverse and far-reaching. Water resources, a vital ecosystem service, are affected through streamflow changes, reduced water availability, and altered water quality. Diminished snow cover and altered precipitation patterns impact subsistence agriculture, compromising food security and livelihoods of local communities. Biodiversity, another critical ecosystem service, is threatened as species face challenges adapting to changing climatic conditions. The consequences of these impacts are significant for human well-being in the IHR. Reduced water availability affects domestic, agricultural, and industrial water supply, leading to potential conflicts and socio-economic disruptions. Changes in agricultural productivity and livelihoods can increase vulnerability and food insecurity among local communities. Disturbances in forest ecosystems and biodiversity can have cascading effects on ecosystem stability, cultural heritage, and ecotourism activities. Effective adaptation strategies such as sustainable water resource management, climate-smart agriculture, conservation and restoration of ecosystems, community-based adaptation, and integrated landscape management are required to address these challenges. Furthermore, research and monitoring efforts should be strengthened to improve understanding of climate change impacts and inform evidence-based decision-making. This chapter shows how Indian Himalayan ecosystems, which are

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important for the provision of ecosystem services, can maintain sustainability despite a variety of stressors including climate change and changes in land use.

Keyword Indian Himalayan region · Climate change · Ecosystem services · Livelihood · Sustainability

1 Introduction

The Indian Himalayan Region (IHR) is geographically located between 23.23°–34.08° N and 73.17°–95.51°E and includes eleven states and two union territories from the eastern to the western Himalayan region. The IHR extends from Jammu and Kashmir in the region of the west to Arunachal Pradesh in the North-Eastern part of India. The Himalayan region has been a significant source of freshwater for India and many other Asian countries. The region is often referred to as the Water Tower of India, which provides critical resources for livelihood to millions of people within and outside the region (Immerzeel et al., 2010; Tewari et al., 2017; Xu et al., 2009). It provides refugia to millions of plants and animal species, a well-known biodiversity hotspot, and offers multiple vital ecosystem services (Negi et al., 2019). The region is also home to one-tenth of the world's known higher-altitude plant and animal species, where elevations vary from 300 m to more than 6000 m, and habitat to half of India's native plant species (Padma, 2014). Nearly 40% of the IHR geographical area is covered by forest, which constitutes one-third of India's forest cover (Negi et al., 2019). The region is a repository of geological, agricultural, and harvested wild assets, besides being a centre of cultural, social, and religious identity for many people (Birch et al., 2014; Saxena et al., 2002). The mountains of IHR contain the headwaters of ten major river systems, including the Amu Darya, Brahmaputra, Ganges, Indus, Irrawaddy, Mekong, Salween, Tarim, Yangtze, and Yellow, providing services to 1.3 billion people downstream (Eriksson et al., 2009). Most people in the river basins depend directly on these water resources for food production, hydropower, industry, and domestic supply (Mirza et al., 2001).

However, the Himalayas are also one of the world's most degradation-prone and fragile mountain ranges. They possess ecosystems vulnerable to geological changes, human exploitations, and climate changes, which have multifaceted impacts on human well-being (Dyurgerov & Meier, 2005; Liu & Chen, 2000). Despite significant uncertainty surrounding climate change-induced impacts, research at the global level demonstrates a marked influence on species extinction rates, distribution patterns, vegetation phenology, ecosystem structure, ecosystem functioning, and ecosystem services (Jewitt et al., 2015; Ma et al., 2021; Pacifici et al., 2015). In plant ecology, the relationship between biogeographic species patterns and climate was observed years before when research was initiated on climate change (Reu et al., 2011) and it was found that climate acted as a primary factor in regulating the spatial distribution patterns of many tree species (Woodward & Williams, 1987). Most forest tree species were found to be sensitive to climate change (Hansen & Phillips, 2015) and adapted to various climatic settings, referred to as a climatic niche (Pearson & Dawson, 2003; Peterson, 2011). Mountain systems worldwide are susceptible to climatic variability and change as glaciers, snow, and permafrost all interact and respond to the climate in distinct ways (Messerli & Ives, 1997). In addition to this, the IHR has a high dependency of local inhabitants on forest resources (Negi et al., 2018; Phondani et al., 2016; Rawal et al., 2012) any adverse impacts such as uncontrolled forest fire (Sharma & Pant, 2017), shifting cultivation, agriculture expansion and land use changes might cause unparalleled forest degradation, biodiversity loss, loss of ecosystem functioning and services in the region (Reddy et al., 2013, 2015; Chakrabarty et al., 2017). The loss of ecosystem structure and function caused by any factor would directly impact human well-being. It was observed that the physical and biological environment in the Hindu Kush Himalaya (HKH) region shows a catastrophic increase in social and economic vulnerability of its inhabitants, which consequently threatens the physical and mental well-being of the people living in this region (Wester et al., 2019). This would be the reflection of the services degradation consequences as people get essential ecosystem goods such as food, fodder, timber, and medicine and a wide range of basic services such as fresh air, water, climate regulation, carbon sequestration recreational, spiritual well-being, arts and inspiration (Yatoo et al., 2020). Forest ecosystem changes deteriorate the ecosystem's overall functioning and become a significant global carbon sink and a source of sustenance for large populations both upstream and downstream (Rasul, 2014). Moreover, developing countries like India are experiencing an abrupt increase in urbanisation thereby converting forest land into built-up (Batar et al., 2017) making it more complex to sustain a sustainable developmental agenda (Shen et al., 2016). The Himalayan region is a vast and geographically diverse area spanning several countries in South Asia, including India, Nepal, Bhutan, Tibet (China), and parts of Pakistan and Afghanistan (Fig. 1). It is renowned for being home to the majestic Himalayan Mountain range, which stretches over 2400 kms across the region (Tullis, 1934).

2 The Indian Himalayan Region

The Indian Himalayan Region (IHR) encompasses a vast area stretching across eleven states and two union territories, spanning from the eastern to the western Himalayas (Fig. 2). It is endowed with a unique and diverse ecological setting, characterised by its high altitudes, steep slopes, and varied climatic conditions, resulting in a rich biodiversity and a wide range of habitats (Rai & Singh, 2021; Singh, 2006). The classification of the Indian Himalayan Region takes into consideration diverse factors like geography, climate variations, vegetation types, and altitude levels (Ahirwal et al., 2021). Physiographically, the IHR is divided into Trans-Himalaya, Great Himalaya, Sub-Himalaya/Shivalik, and Middle/Lesser-Himalaya (Chakrabarti, 2016) (Fig. 3). The Trans-Himalayan region encompasses the Zaskar, the Ladakh, the Kailash, and the Karakoram ranges. It stretches for about 1000 km in the east–west direction and has an average elevation of more than 3000 m asl. The region has an extremely

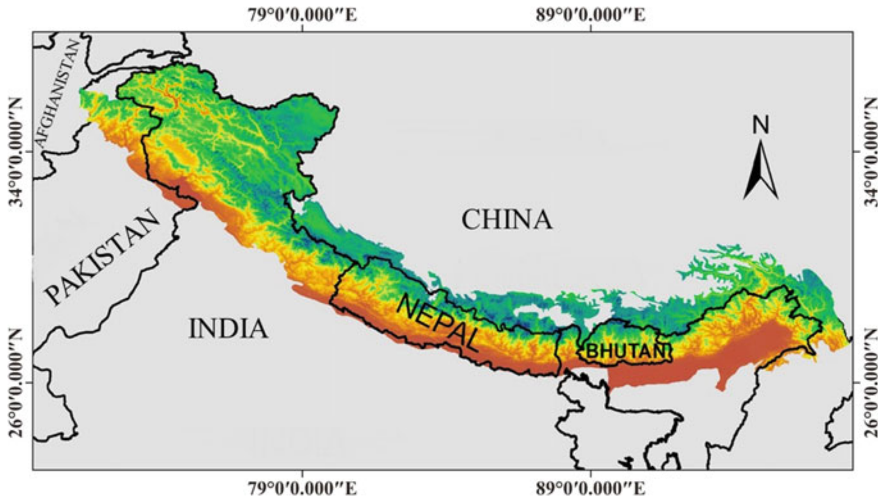

Fig. 1 Spatial distribution of Himalayas across different nations. (*Source* Shruthi et al. 2022)

cold and arid climate with sparse vegetation, rocky terrain, and extensive plateaus (Dvorský et al., 2011). Only a few species of trees grow at some inhabitation places; the region has the minimum forest cover in the Himalayan zone. Most of the vegetation in this zone is herbaceous and shrubby (Kala & Mathur, 2002). The variability in landscape type, vegetation diversity, distribution patterns, and life forms corresponds to the elevational changes (Dolezal et al., 2016). The greater Himalayas have an average elevation of 6000 m asl and include some of the highest peaks in India, such as Kanchenjunga, Dhaulagiri, and Nanga Parbat (Fort, 2011; Jahan, 2022). The vegetation includes coniferous forests, alpine meadows, and shrubs. The climate is cold, with heavy snowfall in winter (Das et al., 2020).

The Sub-Himalayan/Shivalik occupies the foothill region of the Himalayas, consisting of low hills and valleys with elevations ranging from 300 to 1500 m asl. Shivalik region serves as a transitional zone between the plains and the higher Himalayas (Yadav et al., 2015). The vegetation includes tropical, subtropical, and deciduous forests (Joshi et al., 1991; Khan et al., 2011). Shivalik range is the most unstable due to unconsolidated land mass, uneven landscape, torrential rains, and unscientific management practices (Yadav et al., 2005). The vegetation in the Shivalik region varies with the altitude and climatic conditions (Kumar & Hole, 2021). In the lower slopes, the region is covered with tropical and subtropical deciduous forests consisting of trees like sal, teak, oak, and bamboo. As the altitude increases, the woods transition into temperate forests with species like pine, deodar, rhododendron, and various broadleaf trees (Haq et al., 2022; Tripathi et al., 2022). On the other hand, the Middle/Lesser Himalayas occupy the region between the Shivalik in the south and the Greater Himalayas in the north. The elevation of the region ranges from 3500 to 4500 m. The Middle Himalayas also exhibit a wide range of vegetation types due to variations in altitude and climatic conditions (Joshi et al., 2022).

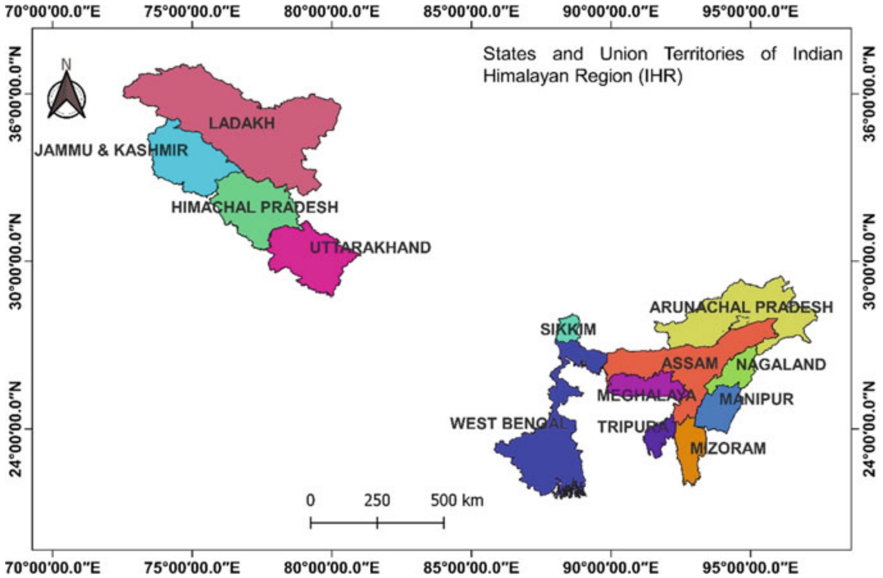

Fig. 2 Various states and union territories of the Indian Himalayan Region

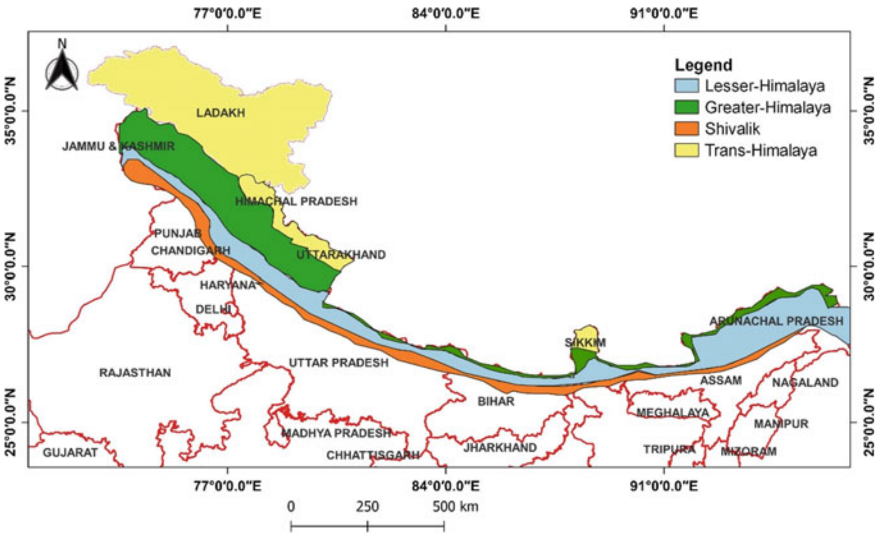

Fig. 3 Physiographical regions of the Indian Himalayan Region. (*Source* Author)

The Indian Himalayan region has a diverse ecosystem due to high altitude, varied topography, and distinct climatic conditions. It supports diverse vegetation communities, including oak, coniferous, and mixed forests (Jina et al., 2008). The subtropical forests cover the lower slopes, whereas, as the altitude increases, the temperate forests dominated by conifers such as pine, cedar, fir, and spruce are observed. Subalpine and alpine forests appear at even higher altitudes, comprising dwarf shrubs, junipers, and birch trees (Mir et al., 2019). However, the whole region is under threat due to several natural factors. The foothills of lower Shivaliks represent the most fragile ecosystem of the Himalayan Mountain range because of its peculiar geological formations (Vashisht et al., 2020). Ecosystems in the Himalayas have reported a remarkable fluctuation since 1960 (Panigrahy et al., 2015). Environmental degradation has been reported to change the forest structure and functions (Gottfried et al., 2012). Moreover, the IHR is highly vulnerable to natural and anthropogenic perturbations and has a higher probability of changes in the ecological structure and functioning of the forest ecosystem (Ravindranath et al., 2005). In such situations, it is imperative to consider both the documentation of ecosystem structural changes and, more crucially, their primary causes. The forest cover change is mainly driven by anthropogenic disturbances (Pandit et al., 2007).

Similarly, land use change is considered one of the leading drivers of global biodiversity loss (De Chazal & Rounsevell, 2009). Expanding forest alteration, degradation, and conversion to other land uses and climate change pose threats to the Himalayan forests and their biodiversity (Pandit et al., 2007). Several other factors have affected the ecosystem of the Indian Himalayan region and its diverse life forms. Any ecosystem deterioration would influence the sustenance and survival of living beings. This could ultimately lead to a catastrophic change in the region.

3 IHR, Ecosystem Services, and Human Welfare

The most noteworthy role of the ecosystem is the provision of multiple ecosystem functions and services that are combinedly termed ecosystem multifunctionality (Manning et al., 2018). The ecosystem function is the set of ecosystem functions vital for the existence of the ecosystem itself, living diversity, ecosystem structure, and human well-being. In contrast, ecosystem services are the benefits that are more concerned with human well-being. Various researcher across the globe has defined and interpreted the meaning of ecosystem services in many ways. Daily et al. (1997) defines ecosystem services as the conditions and processes through which natural ecosystems and their living diversity sustain and fulfil human needs. The benefits human populations derive, directly or indirectly, from ecosystem functions are the ecosystem services (Costanza et al., 1997). Likewise, the Millennium Ecosystem Assessment (MEA, 2005) defines ecosystem services as the benefits people obtain from the ecosystem. In all cases, the stresses of ecosystem services are ecosystems value for the welfare of human beings. Each ecosystem in every corner of the biosphere can provide ecosystem functions and services. However, there may be differences in the capacity to generate and supply multiple ecosystem services. The Indian Himalayan Region is one such region that provides enormous ecosystem services to the entire region and sustains a vast population of human beings (Nüsser et al., 2019). These ESs are generated as a consequence of interaction and exchange between biotic and abiotic components of an ecosystem (De Groot et al., 2002) and the relationship between ecosystem services and human well-being has been given in Fig. 4. The ESs delivered by the ecosystem are the direct material benefits (fuel wood, fodder, wild edibles, minor forest products), indirect benefits (purification of air and water, mitigation of floods and droughts, detoxification and decomposition of wastes, carbon sequestration) and direct non-material benefits (recreation, aesthetics, spiritual and arts and inspirational values) (Costanza et al., 1997; De Groot et al., 2010; MEA, 2005). The forests of IRH provide a wide range of ecosystem goods such as timber, fodder, firewood, non-timber forest products, and services such as carbon sequestration, water regulation, and nutrient cycle to the local inhabitants (Badola et al., 2015; Joshi & Joshi, 2019; Negi & Maikhuri, 2017; Rawal et al., 2013; Semwal et al., 2007). The Himalayan forests also help to capture essential atmospheric moisture, regulate river flow and reduce erosion and sedimentation downstream (Bruijnzeel & Bremmer, 1989).

Singh (2007) reported a value of \$1150/ha/year for the ES of the regional Himalayan forests. A Spiti Valley study on ecosystem services provisioning found an overwhelming value of US\$ 3622 $\pm$ 149 HH^{-1} yr^{-1}, 3.8 times higher than the average annual household income (Murali et al., 2017). Based on a questionnaire survey in Chamoli and Champawat of Uttarakhand, Joshi et al. (2011) estimated the total value of the ecosystem goods collected from the oak forests as per the local selling price was 27,053.08 USD per village per year, whereas the total value of the ecosystem goods collected from the pine forests was 19,870.52 USD per village per year. In the most populated zone (1500–2000 m) of the central Himalayas, pine and oak forests appear in different densities, providing the local population with several life-supporting ecosystem services (Singh & Singh, 1992; Semwal et al., 2007; Negi

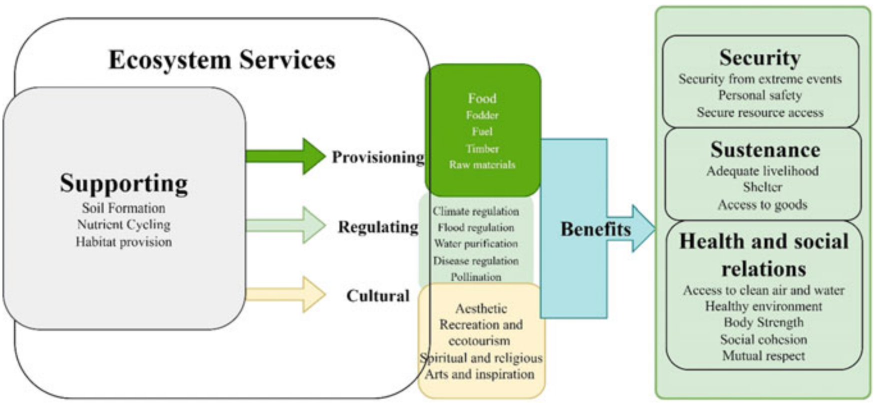

Fig. 4 An overview of ecosystem service's significance for human well-being. (*Source* MEA 2005)

et al., 2012). Indigenous tribes in the Himalayan area have traditionally gathered, used, and preserved medicinal plants as essential to their medical systems and livelihoods (Samant et al., 2011). The ecosystem services are the outcomes of the stability of ecosystem structure and functioning (Balvanera et al., 2006). The Himalayan freshwater ecosystems provide critical supporting services for terrestrial ecosystems, fishery dynamics, pollution management, and many other provisioning and cultural services, such as tourism and water supply (Kattel, 2022). The biodiversity and biomass of the forests of the Dachigam National Park of the Kashmir Himalaya suggest that pine forests are the most valuable forest type with abundant aboveground, below-ground, and total biomass. At the same time, scrub is the lowest-value forest type in the region (Haq et al., 2021). Global mountain regions provide a pleasant landscape, offering many cultural ecosystem services to their residents and tourists (Schirpke et al., 2016). Rural communities' well-being and economic stability are closely tied to the state and quality of natural resources (Tewari & Campbell, 1995).

However, a significant loss of ecosystem services in the Himalayas has been caused by reduced habitats and biodiversity. To obtain ecosystem services, humans have altered forest ecosystems to various degrees (Kremen, 2005) through the use of disturbances such as fire, cutting, and grazing and maintained them in these modified states (Ford et al., 2012; Schmerbeck et al., 2015; Triviño et al., 2015). The forests of the Himalayas have shown a great degree of variation ever since the emergence of the mountains 60–70 million years ago, but changes in the past few decades have been highly drastic, primarily driven by human activities (Bisht et al., 2022; Khera et al., 2001). These include trans-human grazing, conversion of forests to agricultural land, lopping in oak forests, timber extraction, surface burning, and litter removal (Rao & Pant, 2001; Singh, 2002). Not only in India but the Himalayan region has faced the same problem in other parts of Himalaya in the world (Peh et al., 2016; Shrestha et al., 2022). The changing climate strains mountain people, many of whom are poor and exposed to additional survival threats and potential inequities (Gentle & Maraseni, 2012).

4 Climate Change in the Himalayas and Its Impact on Ecosystem Services

Climate change is one of Earth's significant challenges, posing a threat to the environment and economic, social, and human survival. Climate change has emerged as a global environmental issue, forcing the world to engage in global climate submissions (Han & Ahn, 2020). Mountains are early indicators of climate change (Singh et al., 2010) and the impacts of change are more prominent in the mountain ecosystems. Given the consequences of climate change on the planet's life-sustaining system, it is identified as the most significant global health threat of the twenty-first century (Watts et al., 2018). It has been reported that the HKH regions have experienced a significantly higher warming rate than the global average rate of Earth warming over the past 100 years (Du et al., 2004). Globally, there are very few regions where climate change is more evident and rapid than in the Himalayan region (Gottfried et al., 2012; Shrestha et al., 2012). Numerous studies have observed increased temperature in the IHR (Sontakke et al., 2009; Bhutiyani et al., 2010). Analyses of temperature trends in the Himalayan region display that temperature increase is more significant at higher altitudes, whereas lower temperature increase is relatively common in the lowlands (Shrestha et al., 1999). A study conducted in the western Indian Himalayas by Dimri and Dash (2012) observed that the temperature in the region has increased by 1.1–2.5 °C. A similar result was observed by Diodato et al. (2012) where the average maximum temperature was increased by 0.5 °C from 1971 to 2005 compared to the average maximum temperature during the period 1901–1960. Such trends were seen in many other Himalayan regions of India (Bhutiyani et al., 2007; Singh et al., 2008). Similar findings were reported from the Himalayan region of other countries. The temperature in the Tibetan Plateau was observed to increase at a rate of 0.16 °C per decade between 1955 and 1996 (Liu & Chen, 2000). Sharma et al. (2000) found an increasing temperature trend across the Koshi river basin in eastern Nepal. So, the consequences of climate change are notable in various regions of the Himalayan. Climate change has not only impacted the temperature trend but also altered the precipitation trends in the region (Shekhar et al., 2010). Likewise, Bhutiyani et al. (2010) found a downward trend of precipitation in monsoon and average annual rainfall in the north-western Indian Himalayas from 1866 to 2006. Sontakke et al. (2010) reported a similar outcome in the western Indian Himalayas between 1960 and 2006. Although a study on the water availability in the Karnali River Basin of Nepal Himalaya from 1981 to 2016 described that the historical river discharge data analysis does not show any significant trend, there is some inter-annual variability (Dahal et al., 2020).

Climate change globally over the last decades has been connected with the variability in the hydrological elements such as evaporation rate, soil moisture, water runoff, and water infiltrations (Roa-Gracia et al., 2011). The indications of climate change are very explicit in the IHR in various forms, such as changes in the distribution and structure of ecosystems, melting of snow and glaciers, stream flow change, extreme weather events, and many more (Rashid et al., 2015; Singh et al., 1997; Tewari et al., 2017). Plant species such as *Betula utilis* (Himalayan birch) have been reported to shift toward the Eastern Himalayas with declining trends toward the west (Hamid et al., 2019). Another study from the Indian Himalayan Region observed that the Eastern Indian Himalayan Region was at higher risk when compared to the Western Indian Himalayan Region due to high climatic exposure and frequent hazards (Sekhri et al., 2020). The region's temperature increase might have impacted the traditional rainfall trends, and water-based natural disasters are more likely in the eastern Himalayas under high climatic dynamics (Sharma et al., 2009). Changes in species richness and beta diversity have vigorously responded to climatic warming (Bhattacharjee et al., 2017), where the treeline ecotone species is susceptible to losses.

Climate change has significantly impacted the ecosystem services of the Indian Himalayan Region (IHR). According to a recent study conducted in the eastern

Himalayas, climate change has been found to have direct repercussions on ecosystem services, livelihoods, and human well-being (Tse-ring et al., 2010). The research highlights the tangible impacts of climate change on the region, emphasising its influence on vital aspects of the environment, local economies, and the overall welfare of communities. The Indian Himalayas are the source of several major river systems, including the Ganges, Brahmaputra, and Indus (Singh, 2002). Climate change has led to melting glaciers, altering the hydrological regime in the region. The reduced snow and ice cover affect water availability, leading to changes in streamflow, decreased water quality, and increased vulnerability to droughts and floods (Romshoo et al., 2022). This impacts water availability for domestic, agricultural, and industrial purposes (Pritchard et al., 2020; Bhatta et al., 2020). A study conducted in the eastern Himalayas has found that climate change directly affects ecosystem services, livelihoods, and human well-being (Tse-ring et al., 2010).

The research highlights the tangible impacts of climate change on the region, emphasising its influence on vital aspects of the environment, local economies, and the overall welfare of communities. Climate change-induced snow cover reductions and precipitation patterns have adverse effects on subsistence agriculture in high-elevation villages in India and Nepal (Smadja et al., 2015). These changes directly impact the agricultural practices of these communities, posing significant challenges to their livelihoods and food security (Ogra & Badola, 2015; Smadja et al., 2015). Rising temperatures and altered precipitation patterns affect crop growth, flowering, and ripening, impacting yields (Craufurd & Wheeler, 2009). Forests in the IHR provide various ecosystem services, including timber, non-timber forest products, carbon sequestration, and habitat for wildlife. Climate change impacts forests through increased temperatures, changing precipitation patterns, and altered disturbance regimes such as wildfires and insect outbreaks. These factors contribute to forest degradation, reduced productivity, and increased vulnerability to pests and diseases (Negi et al., 2012). Climate change has caused shifts in temperature and precipitation patterns, altering the distribution and behaviour of species. Many alpine and subalpine species are moving to higher elevations, leading to changes in ecosystem composition and disrupting ecological interactions (Joshi et al., 2012). These alterations in the ecosystem have had an impact on the biophysical structure and functioning of the ecosystem, leading to a decline in the benefits it provides and ultimately impacting human well-being (Fig. 5). Moreover, changing climatic conditions affect breeding patterns, migration routes, and habitat suitability, which can eventually lead to population declines and extinctions.

Similarly, the IHR attracts many tourists and offers recreational opportunities such as trekking, mountaineering, and wildlife viewing. Climate change can impact tourism and recreation by altering landscapes, reducing snow cover for winter sports, and affecting the availability of wildlife for ecotourism. Temperature and precipitation patterns can also impact the timing and quality of tourism activities (Nyaupane & Chhetri, 2009).

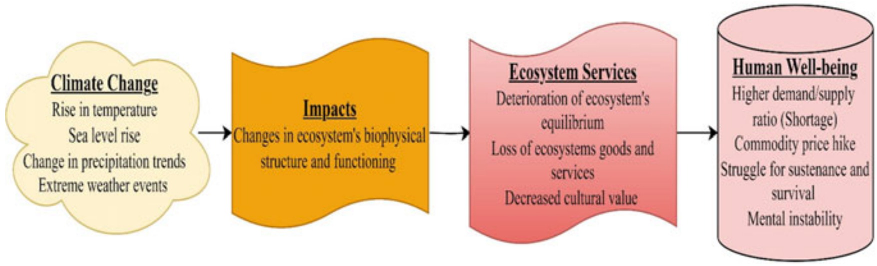

Fig. 5 Climate change impacts on ecosystem services and human well-being

5 Change in Land Use and Land Cover of the Indian Himalayan Region

Land use refers to using land for various purposes. In contrast, land cover specifies the natural and artificial cover on the land surface (natural vegetation, agriculture, bare land, water bodies, and build-up). Land use land cover (LULC) has become a major crucial area in the scientific world. Understanding the LULC dynamics has been an impactful tool to assess the change in ecosystem structure and its land use with climate change. LUCC significantly affects climate change, biogeochemical cycles, ecosystem services, and biodiversity (Clerici et al., 2019; Mondal & Zhang, 2018; Shi & Chen, 2018). Land use and land cover are two different terms; however, these concepts are used interchangeably (Barnsley et al., 2000). The land use change is mainly regulated by the ecological condition, slope and aspect, socio-economic factors, and rise in human population (urban sprawl). Population growth, industrialisation, and urbanisation have rapidly changed the LULC (Samal & Gedam, 2015). Several studies in the Himalayan region of India have witnessed changes in the LULC in various areas. A survey by Rasool et al. (2021) in Kashmir Himalaya finds that primary land use has changed, with cropland agriculture losing the most (−5%). In contrast, economically fruitful horticulture gained the most (+ 4.29%) during the study period in Kashmir. However, fortunately, they found that the change in forest cover in the study area was observed to be 0.22% and 0.27% for the periods 1976–1998 and 1998–2014, respectively. Saha et al. (2022) observed a decrease in vegetation, agricultural land, and fallow land from 23 to 20%, 35 to 28%, and 23 to 19%, whereas there found an increase in plantation and built-up areas from 14% to 24% and 2%-8%, respectively during the study period in Sub-Himalayan North Bengal. Similarly, in the Lidder Valley of Kashmir Himalaya, degraded forest and settlement have increased by 20 and 52.8 km^2, respectively from 1980 to 2013 (Rashid et al., 2017).

Land use land cover analysis of the area surrounding the Tehri reservoir of Garhwal Himalaya found that the forest cover decreased by 54.71 km^2, which is −5.7% of the geographical area, followed by agricultural land by 6.06 km^2 (−0.4%) and scrubland and grass cover by 4.23 km^2 (−0.28%) during the year 2000–2010 (Parihar et al., 2022). Nevertheless, compensatory afforestation has increased forest cover by 5.65% in the same period (Parihar et al., 2022). A decreasing trend in agricultural land, forest cover, snow, and glaciers was observed in north Kashmir, while horticulture, built-up/urban area increased from 1992 to 2018 (Fayaz et al., 2020). A drastic change in LULC has been reported from Kohima and Dimapur of Nagaland state, where built-up areas have increased significantly in both the districts at the rate of 322.6 ha/year and 301.9 ha/year, respectively, during 1998–2018, and these changes have resulted in agricultural and forest cover declination. Numerous other reports and findings from different regions of IHR discuss the changing scenario of LULC in the areas (Mishra, 2022; Sur & Singh, 2020; Thakur et al., 2022). The LULC changes in any region would alter an ecosystem's structural and functional characteristics, resulting in the ecosystem's disturbance and causing biological diversity loss (Abdela, 2021; Kumi et al., 2021). Therefore, to further reduce LULC change and ecosystem degradation, understanding the causes and effects of LULC change is crucial. Many factors impact an area's land use and cause significant environmental disturbances. The construction of large-scale infrastructure growth and dam construction has historically been a primary cause of forest degradation in the entire Himalayan region (Ellwanger et al., 2020; Foggin et al., 2021).

Further, exploitation of natural resources, mainly harvesting fuel wood, timber, fodder, medicine, climate change, and changes in traditional land use practices have recently led to serious forest loss and degradation of the ecosystem's primary structure. Anthropogenic activities were reported to be the leading causes of the loss of forest cover and forest fragmentation, but natural factors also contributed (Rasool et al., 2021). In Kashmir Himalaya, the LULC changes were driven by various forces ranging from natural, demographic, and economic, resulting in pressures on land and various environmental complications (Rasool et al., 2021). In some places, the change in LULC could result from increased agricultural and settlement areas at the expense of open forests and grazing/wastelands (Thakur et al., 2022). These changes in vegetation cover have altered the hydrological cycle, affecting the soil infiltration, surface runoff, aquifer recharge, evapotranspiration, and soil available water (Sterling et al., 2013).

6 Major Threats to Ecosystem Health and Sustainability

Since the 1972 Stockholm Conference on the Human Environment, ecologists have devoted considerable attention to studying how natural ecosystems react to the diverse threats caused by human activities. In this context, health is defined as the absence of signs of ecological dysfunction based on indicators and using human judgement rather than objective standards. This is the foundation of ecosystem health: ecological research has successfully incorporated physiological methodologies (Lu et al., 2015). What defines "health" reflects our viewpoint on ecosystem evaluation and the metrics we employ to measure them. According to Schaeffer et al. (1988), ecosystem health is the absence of disease. In this case, the disease was defined as the ecosystem's failure to function within acceptable boundaries, which resulted in an insufficient homeostatic repair mechanism. According to Rapport (1989) ecosystem health may be viewed from three angles: vital signs and system integrity, capacity to withstand stress, and threats caused by environmental stress that are impacted by social and cultural values. Ecosystem health is closely connected to sustainability, which is understood to be a comprehensive, multi-scale, dynamic assessment of system resilience, organisation, and vigour (Costanza et al., 1992). According to Mageau (1998), a sustainable ecosystem can preserve its structure and function in the face of external stress.

Human-induced climate change has been causing widespread alterations in species distribution patterns throughout the mountain ecosystems (Telwala et al., 2013). Biodiversity is the most vital natural asset, providing livelihood options through ecosystem services (Costanza et al., 1997). However, due to overexploitation and habitat degradation, biodiversity is decreasing alarmingly (Samant et al. 2011). Significant threats to ecosystems and biodiversity are habitat loss, habitat fragmentation, over-exploitation, pollution, invasion of alien species, global climate change, and disruption of community structure (Novacek & Cleland, 2001). 10% of the world's vascular plants are thought to be in danger, according to the International Union for Conservation of Nature and Natural Resources (IUCN). In most nations worldwide, biological invasion has become one of the primary sources of economic and environmental harm (Bellard et al., 2016). Because of increased commerce, tourism, climate change, and anthropogenic disturbances, plant invasions in mountainous areas are anticipated to grow. These invasions can affect the balance of local floral and faunal species, having long-lasting detrimental effects (Pauchard et al., 2009).

Ecosystem services that benefit the human population in terms of social and economic value depend on the environment's health. Provisioning, regulating, supporting, and cultural services are the four primary ecosystem services (Costanza et al., 1997; MEA, 2005). In many nations, ecosystem services have been integrated into environmental management. For instance, in China, the Natural Forest Conservation Programme (NFCP) and the Grain to Green Programme (GTGP), two national programs that pay for ecosystem services, have improved ecosystem conditions and had favourable social and economic benefits (Liu et al., 2008). The idea of sustainability, which is meant to satisfy the present and future societal demand for ecosystem services, is strongly tied to ecosystem health. The ability to provide ecosystem services continually for future generations has been emphasised as a crucial problem within environmental justice. The state and potential of an ecosystem to maintain its organisational structure, its vigour of function, and its resilience under stress, as well as to continue providing excellent ecosystem services for current and future generations in perpetuity, are the basis for our definition of ecosystem health, which we base on this discussion.

Researchers and scientists have noted several significant concerns about the sustainability and health of ecosystems. These threats can significantly affect ecosystem health, biodiversity, and the supply of ecosystem services.

(i) **Habitat Loss and Fragmentation**: The most significant challenges to ecosystems worldwide are habitat loss and fragmentation. They are the outcome of deforestation, urbanisation, and converting wilderness areas for agricultural use. The decline and extinction of species, the disturbance of ecological processes, and the decreased resilience of ecosystems are all consequences of habitat loss and fragmentation (Foley et al., 2005).

(ii) **Climate Change**: Multiple ecological functions are impacted by climate change. Temperature and precipitation variations can affect agricultural productivity and food distribution services. Rising sea levels may endanger coastal infrastructure and communities, which may impact cultural services like tourism. Changes in rainfall patterns can impair water supply, affecting hydrological regulation and provisioning services (MEA, 2005).

(iii) **Pollution**: The health of ecosystems is seriously threatened by pollution, which includes soil, water, and air contamination. Heavy metals, herbicides, and industrial chemicals are just a few examples of the pollutants that can build up in ecosystems, killing species, upsetting food webs, and affecting how well ecosystems work. Eutrophication, which results in algae blooms and oxygen reduction in water bodies, is another effect of pollution (Carpenter, 1998). Ecosystem services can suffer from pollution. For instance, water quality can be harmed by industrial waste and agricultural runoff, which has an impact on services like clean drinking water and fisheries. Air pollution can harm human health, and ecosystems' aesthetic and cultural values can be diminished (De Groot et al., 2002).

(iv) **Overexploitation and Unsustainable Resource Use**: Overusing ecosystem resources can reduce the availability of goods and services. For instance, unsustainable fishing methods can cause fish stocks to dwindle, threatening food security and way of life. Water availability may decrease due to excessive water extraction, which may affect provisioning and regulating services like irrigation and hydrological regulation (MEA, 2005).

(v) **Species invasion**: Species invasion can impair ecosystem functions. They may outcompete local species, which could impair pollination functions and alter plant communities. Pest invasions can harm crops, which affects food provisioning services. They can also change ecological processes like decomposition and nutrient cycling (Chapin et al., 2000).

Similarly, the uncontrolled and rapid growth of Indian cities and socio-economic development exert immense pressure on both natural and semi-natural ecosystems (Das & Das, 2019). Therefore, it is imperative to implement effective strategies and measures for land use planning to ensure the sustainability of ecosystems and their associated ecosystem services in rapidly urbanising regions (Haase et al., 2014; Wolff et al., 2015). Threats to biodiversity, such as habitat loss, pollution, and climate change, can disrupt ecosystems and decrease species diversity. This, in turn, impairs ecosystem function, including processes like nutrient cycling, pollination, and natural pest control. As ecosystem function is compromised, the provision of crucial ecosystem services, such as food production, water purification, and climate regulation, is also diminished.

Consequently, the loss of these services directly impacts human well-being by reducing access to clean water, nutritious food, and a stable climate, among other benefits. Therefore, the conservation and sustainable management of biodiversity are vital to maintaining healthy ecosystems, which underpin the ecosystem services necessary for human well-being and quality of life. However, proper restoration activities aimed at mitigating ecosystems' loss and ecological degradation might facilitate their recovery, ultimately supporting human well-being (Fig. 6).

7 Conclusion and Recommendations

Understanding the impact of climate change on human well-being in the Indian Himalayan Region is crucial, considering its influence on ecosystem services. The ecosystems in the region are essential for economic growth and human well-being as they provide various invaluable public goods and services. These include freshwater, food, life-saving medicinal resources, energy, biodiversity, and traditional knowledge associated with the region. However, the region is also highly vulnerable to natural hazards, and there is growing concern about climate change's current and potential impacts. These impacts may manifest as abnormal floods, droughts, and landslides. Numerous studies have documented a notable decline in temperature and precipitation across various spatial and temporal scales. These alterations have resulted in adverse effects such as the depletion of biodiversity, disturbances in the functioning of ecosystems, and a reduction in the availability of ecosystem services. To mitigate the consequences and promote resilience, the following steps are recommended:

(i) Prioritise the conservation and restoration of key ecosystems such as forests, wetlands, and alpine meadows in the IHR. This includes measures like afforestation, reforestation, and preserving biodiversity-rich areas to enhance ecosystem resilience and maintain vital services.

(ii) Implement sustainable water resource management practices to ensure equitable access to water for both human needs and ecosystem requirements. This includes promoting water conservation, efficient irrigation techniques, and watershed management to mitigate the impacts of reduced snow and glacier melt.

(iii) Promote climate-smart agricultural practices that are adapted to the changing climate in the IHR. This includes promoting climate-resilient crop varieties, efficient water use, agroforestry, and soil conservation measures to enhance agricultural productivity while minimising environmental degradation.

(iv) Strengthen community-based adaptation strategies by engaging local communities in decision-making processes and providing them with the necessary knowledge and resources to cope with climate change impacts. This can include

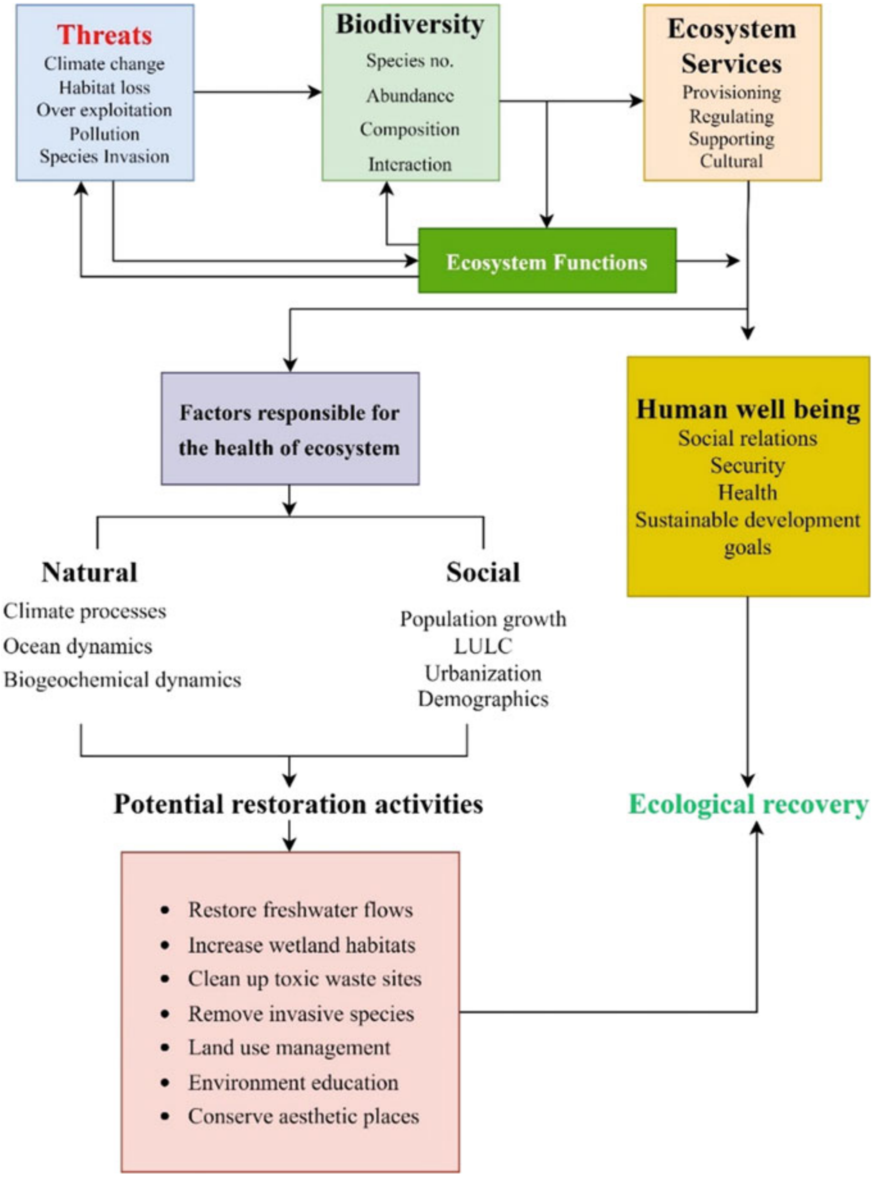

Fig. 6 A theoretical framework for ecological recovery using threats, biodiversity, and ecosystem services as critical parameters

capacity building, early warning systems, and livelihood diversification to reduce vulnerability and enhance adaptive capacity.

(v) Adopt an integrated landscape management approach that considers the interconnectedness of ecosystems, land use, and human activities. This approach ensures sustainable development while maintaining ecosystem services, minimising conflicts, and promoting biodiversity conservation.

(vi) Support research and monitoring initiatives to improve understanding of climate change impacts on ecosystem services in the IHR. This includes long-term monitoring of key indicators, assessing vulnerability and adaptation options, and promoting interdisciplinary research collaborations. These recommendations aim to promote sustainable development, enhance ecosystem resilience, and minimise the adverse impacts of climate change on the ecosystem services of the Indian Himalayan Region.

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Himalayan Dam Projects in India and Their Implications: A Deep Dive into the Dhauliganga Hydropower Initiative

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Abstract Indian Himalayan region represents a confluence of remarkable biodiversity that is challenged with developing sustainable hydropower infrastructure. The present study examines different dam projects across the Indian Himalaya, specifically focusing on the Dhauliganga Hydropower Initiatives. Our study first elucidates the threatened flora and endangered fauna that characterize this unique ecosystem, thus spanning the ecological wealth of the region. We then outline the current landscape of river basins housing major dams, encompassing regions including Jammu and Kashmir, Himachal Pradesh, Uttarakhand, and Northeastern India. Crucially, the impacts of these infrastructural projects present a two-fold challenge: environmentally, they disrupt local ecosystems, while socioeconomically, they induce displacement, affecting local communities. Our in-depth examination of the Dhauliganga Basin illustrates the intricate balance between harnessing energy and preserving

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ecology. Drawing from the diverse hydroelectric projects, forest types, and ecological vulnerabilities within the basin, we emphasize the need for a balanced approach. In conclusion, we advocate for holistic development strategies that prioritize sustainable energy harnessing and conservation. This research seeks to contribute insights that shape the course of future hydropower projects toward greater environmental and social sustainability.

1 Introduction

Extending across India, Bhutan, China, Nepal, and Pakistan, the Himalayan region is often recognized as the 'third pole,' encapsulating geological and cultural significance that stretches back approximately 40–50 million years (Harrison et al., 1992). This vast expanse originates from the subduction of the Indian plate beneath the Eurasian plate, not only highlighting the impressive power of nature but also giving rise to some of the world's most vital rivers, including the Indus, Ganges, and Tsangpo–Brahmaputra (Yin, 2006). The Himalaya provide a habitat for approximately 53 million people and profoundly influence the livelihoods of nearly 600 million individuals residing within its expansive drainage basin.

The Himalayas hold significant cultural value and potential for renewable energy generation through hydropower (Lewis, 1994). This potential can facilitate the worldwide shift towards cleaner energy, mitigate carbon emissions, strengthen energy security, and boost local economies. However, pursuing this potential also brings environmental and social concerns. The region's delicate ecosystem risks degradation and biodiversity loss from construction, while local communities face displacement. Altered river flows can disrupt downstream ecosystems, and exclusive dependence on hydroelectricity might limit energy source diversification. India has committed to enhancing its reliance on renewable energy to 40% by 2030, with hydroelectricity being a cornerstone of this strategy (TERI, 2021). However, climate change challenges, like glacier retreat and flood risks, complicate sustainable hydropower endeavors in the region.

Hydroelectric projects exhibit variability in terms of their design and environmental ramifications. Run-of-River (RoR) projects direct river water through turbines and back downstream without large reservoirs. This design generally causes minimal upstream disruption and lessens the risk of large-scale habitat fragmentation. However, they can still modify flow regimes and potentially impact aquatic life downstream (Fryirs, 2013). Reservoir Projects use dams to store water for controlled release, ensuring consistent electricity output. While ensuring energy stability, these reservoirs can lead to large-scale flooding, displacing local communities and wildlife and changing aquatic ecosystems (Zarfl et al., 2015). Pumped Storage Projects utilize two reservoirs at different elevations: during low demand, water is pumped upward using excess power, and during high demand, it is released downward through turbines to generate electricity. While they offer flexible energy storage and grid stabilization, they might lead to water loss due to evaporation, local temperature changes that affect aquatic life, and potential disruptions in both upstream and downstream ecosystems.

The significance of these dams is undeniable; from a global count of 5000 large dams in 1950, this number ballooned to 58,000 by September 2021 (Zarfl et al., 2015). The Himalayan river basins, especially the Ganga, Indus, and Brahmaputra, have become focal points for dam construction due to their immense hydropower potential (Hussain et al., 2019). However, with development comes challenges. The ecological implications of these dam constructions, especially within the unique ecosystem of the Himalaya, are concerning. With a diverse range of endemic and threatened flora and fauna, there is an increasing risk to the balance of these pristine ecosystems (Pandit et al., 2014). Despite India housing a significant portion of the world's population, there is a gap in understanding the cumulative ecological impacts of its aggressive dam-building endeavours.

Nestled amidst the captivating Himalayan landscape, the Dhauliganga River Basin uniquely positions itself as an integral sub-basin of the Alaknanda River Basin. It is emerging from glacial reserves and harmonizes with neighboring river basins by exhibiting shared high-altitude ecosystems. Yet, its distinct contribution to the Ganga Basin sets it markedly apart. In the Jammu and Kashmir region, it provides a gentle contrast to the expansive realms of the Indus, Chenab, and Ravi Basins, emphasizing its nuanced yet pivotal role in the larger Ganga watershed. Within Himachal Pradesh, the Dhauliganga weaves a different story from the heavily hydropower-centric narratives of the Sutlej and Beas Basins, focusing instead on its integral contribution to the Ganga's lifeblood. As it meanders through Arunachal Pradesh, it draws parallels with the glacial origins of the Brahmaputra and Lohit Basins, yet its impact remains uniquely localized. In Uttarakhand, the basin seamlessly integrates with the Alaknanda and Bhagirathi Basins, further emphasizing its crucial role in the Ganga River's formation. Amid the tapestry of India's myriad river basins, the Dhauliganga Basin etches its significance by threading together diverse ecosystems, potential for power generation, and deep-rooted cultural vistas.

The Dauliganga river boasts a steep gradient and substantial flow rates, making it a prime candidate for harnessing hydroelectric power. Numerous glacial lakes are forming in this region due to the temperature rise. Some of them may burst, i.e., Glacier Lake Outburst Flood (GLOF) may occur, causing loss of lives, properties, and infrastructures in downstream areas. In fact, several hydroelectric projects have also been proposed in this region. Comprehensive research can direct sustainable energy production, mitigating potential ecological disturbances. In light of the above, this study sets forth the following objectives: (i) Provide a thorough analysis of dam constructions in the Indian Himalayan ecosystem, examining their distribution, potential, and the ecological and socioeconomic consequences they entail; and (ii) Delve into the Dhauliganga basin of Uttarakhand, exploring both the challenges and opportunities linked to its hydroelectric development, while proposing strategies to balance energy goals with the preservation of its distinct ecological assets.

2 Indian Himalayan Region: An Insight into the Bounteous yet Endangered Biological Wealth

Spanning an expansive and ecologically varied area of approximately 530,000 km^2 and stretching across 2500 km, we encounter the Indian Himalayan Region (IHR). Despite encompassing just 13% of India's geographical landscape, the Indian Himalayan region (IHR) shelters nearly 50% of the country's documented biodiversity, a substantial portion of which is endemic to the IHR. Despite its relatively compact dimensions, the IHR boasts remarkable diversity in its physiography, geography, climate, and altitude, enriched by its abundantly diverse biota (IUCN Red List). Hence, the IHR offers a habitat for a multitude of biosphere reserves, national parks, and wildlife sanctuaries, providing a haven for exceptional and vulnerable species such as the snow leopard, red panda, and black-necked crane. The locality includes diverse ecosystems, spanning alpine meadows, temperate forests, and subtropical forests (Kumar & Pandit, 2018). The cultural diversity of the IHR is equally vibrant, interwoven with myriad indigenous communities, each contributing their unique languages, traditions, and festivals (Vedwan & Rhoades, 2001).

2.1 Threatened Flora of the Indian Himalayan Region

The breathtaking expanse of the Indian Himalayan region, often dubbed the "abode of snow", not only forms an imposing natural barrier but also serves as a melting pot of ecological diversity. Within this magnificent region, we find a plethora of unique plant species, each playing a pivotal role in its intricate ecosystem. Yet, a growing concern is the increasing number of these species that are now on the brink. Table 2 offers a comprehensive glimpse into the threatened flora across various states and territories in this region. The categorization—spanning from critically endangered (highlighted in red), endangered (deep yellow), vulnerable (light yellow), near-threatened (green), to rare (black)—is a stark reminder of the fragility of our natural heritage (Hilton-Taylor & Brackett, 2000) (Table 1).

In the picturesque valleys and lofty peaks of Jammu and Kashmir, we encounter species like the medicinal *Aconitum heterophyllum*, the beautiful *Lilium polyphyllum*, and the aromatic *Nardostachys jatamansi*, among others like *Aconitum violaceum*, *Angelica glayca*, *Gentiana kurroo*, *Lilium polyphyllum*, *Nardostachys jatamansi*, *Saussurea costus*, and *Ulmus wallichiana* (Table 1).

Himachal Pradesh, known for its verdant meadows and snow-capped mountains, houses gems like the vibrant Acer caesium, the rare *Erysimum thomsonii*, and the coveted *Saussurea costus*, a plant that holds both economic and medicinal significance. In Himachal Pradesh, the threatened flora list includes *Acer caesium*, *Allium stracheyi*, *Saussurea bracteata*, *Campanula wattiana*, *Silene kunawarensis*, *Carex munroi*, *Hedysarum microcaly*, *Eremurus himalaicus* among others.

Table 1 Details of threatened floral taxa of the Indian Himalayan region (CR-critically endangered, EN-VU-vulnerable, NT-near-threatened, and R-rare species)

Jammu and Kashmir	Himachal Pradesh	Uttarakhand	Sikkim, West Bengal, and Arunachal Pradesh
• Aconitum heterophyllum$_{NT}$	• Acer caesium$_{VU}$	• Acer caesium$_{VU}$	• Acer hookeri$_{NT}$
• Aconitum violaceum$_{VU}$	• Allium stracheyi$_{VU}$	• Acer oblongum$_{NT}$	• Pimpinella tongloensis$_{NT}$
• Angelica glayca$_{NT}$	• Saussurea bracteata$_{R}$	• Allium stracheyi$_{NT}$	• Pimpinella wallichii$_{NT}$
• Gentiana kurroo$_{CR}$	• Saussurea costus$_{NT}$	• Trachycarpus takii$_{R}$	• Calamus inermis$_{NT}$
• Lilium polyphyllum$_{CR}$	• Erysimum thomsonii$_{R}$	• Catamixis baccharoides$_{VU}$	• Phoenix rupicola$_{R}$
• Nardostachys jatamansi$_{CR}$	• Campanula wattiana$_{R}$	• Lactuca filicina$_{NT}$	• Ceropegia hookeri$_{NT}$
• Saussurea costus$_{CR}$	• Silene kunawarensis$_{R}$	• Saussurea costus$_{NT}$	• Lactuca cooperi$_{NT}$
• Ulmus wallichiana$_{VU}$	• Carex munroi$_{R}$	• Berberis lambertii$_{VU}$	• Begonia rubella$_{R}$
	• Hedysarum microcaly$_{NT}$	• Cyananthus integra$_{R}$	• Codonopsis affinis$_{R}$
	• Eremurus himalaicus$_{R}$	• Arenaria curvifolia$_{NT}$	• Dennstaedtia elwesii$_{R}$
		• Arenaria ferruginea$_{NT}$	• Juncus sikkimensis$_{R}$
		• Hedysarum microcalyx$_{VU}$	• Lagerstroemia minuticarpa$_{R}$
		• Aphyllorchis gollani$_{NT}$	• Coelogyne treutleri$_{R}$
		• Aphyllorchis parviflora$_{R}$	• Cymbidium eburneum$_{VU}$
		• Archineottia microglottis$_{R}$	• Cymbidium hookerianum$_{VU}$
		• Calanthe alphina$_{R}$	• Cymbidium whiteae$_{NT}$
		• Calanthe mannii$_{R}$	• Paphiopedilum fairrieanm$_{NT}$
		• Didiciea cunninghami$_{NT}$	• Cotoneaster simonsii$_{R}$
		• Diplomeris hirsuta$_{VU}$	• Cissus spectabilis$_{NT}$
		• Flickingeria hesperis$_{NT}$	• Acer osmastonii$_{NT}$

(continued)

Table 1 (continued)

Jammu and Kashmir	Himachal Pradesh	Uttarakhand	Sikkim, West Bengal, and Arunachal Pradesh
		• Cypripedium $elegans_{R}$	• Aneilema $glanduliferum_{VU}$
		• Christella $kaumaunica_{VU}$	• Cymbidium $eburneum_{VU}$

The rugged terrains of Uttarakhand, a land interspersed with sacred shrines, is home to species such as the towering *Trachycarpus takii*, the herbaceous *Allium stracheyi*, and the vibrant-hued *Berberis lambertii*. The other species of Uttarakhand include *Acer caesium*, *Acer oblongum*, *Catamixis baccharoides*, *Lactuca filicina*, *Saussurea costus,* etc..

Diving further east, the territories of Sikkim, West Bengal, and Arunachal Pradesh—regions drenched in monsoons and rich tribal cultures—harbor diverse species. Here, we find the resilient *Acer hookeri*, the delicate *Pimpinella wallichii*, and the rare *Phoenix rupicola* (Table 1). The threatened flora of the region also encompasses *Pimpinell atongloensis*, *Calamus inermis*, *Ceropegia hookeri*, *Lactuca cooperi*, *Begonia rubella*, and *Codonopsis affinis*. It is paramount to prioritize conservation efforts to protect these species, especially those categorized as critically endangered and endangered, to maintain the ecological balance and rich biodiversity of the Indian Himalayan region.

The threatened flora discussed above calls for intensified conservation efforts. It is imperative to harness both community involvement and scientific interventions to protect these species, especially the critically endangered and endangered ones. By doing so, we not only preserve the rich biodiversity of the Indian Himalayan region but also ensure the continued health of an ecosystem that countless communities and wildlife depend upon.

2.2 *Endangered Fauna in the Indian Himalayan Region*

The Indian Himalayan region, characterized by its immense biodiversity and various ecosystems, has long been recognized as a crucial habitat for various fauna species. However, the escalating threats, primarily due to human-induced activities, have rendered several species vulnerable to extinction. Table 3 provides a comprehensive view of this endangered fauna across different regions of the Indian Himalayan region.

Jammu and Kashmir is marked by species such as the Kashmir grey langur, Himalayan musk deer, and the Hangul, indicating this region's importance in faunal biodiversity. The other endangered species of the region include Sambar, Snow leopard, Urial, Kashmir musk deer, and Common leopard.

Table 2 Details of endangered faunal taxa in the Indian Himalayan region (CR-critically endangered, VU-vulnerable, NT-near-threatened and R-rare species)

Jammu andKashmir	Himachal Pradesh	Uttarakhand	Sikkim, West Bengal, and Arunachal Pradesh
• Kashmir grey langur$_{NT}$	• Tibetan wolf$_{NT}$	• Peter's tube-nosed bat$_{CR}$	• Tibetian Wolf$_{NT}$
• Himalayan musk deer$_{NT}$	• Himalayan serow$_{VU}$	• Fishing cat$_{VU}$	• Red Fox$_{R}$
• Kashmir musk deer$_{NT}$	• Bearded vulture$_{R}$	• Tiger$_{NT}$	• Tibetian fox$_{R}$
• Hangul$_{CR}$	• White-rumped vulture$_{CR}$	• Snow leopard$_{NT}$	• Red panda$_{NT}$
• Sambar$_{VU}$	• Slender-billed vulture$_{CR}$	• Sloth bear$_{VU}$	• Fishing Cat$_{VU}$
• Wild yak$_{VU}$	• Himalayan tahr$_{NT}$	• Indian elephant$_{NT}$	• Clouded Leopard$_{VU}$
• Urial$_{VU}$	• Himalayan musk deer$_{NT}$	• Pygmy hog$_{CR}$	• Leopard$_{VU}$
• Common leopard$_{VU}$	• Koklass pheasant$_{NT}$	• Swamp deer$_{VU}$	• Tiger $_{NT}$
• Snow leopard$_{VU}$	• Snow leopard$_{VU}$	• Himalayan tahr$_{VU}$	• Snow Leopard$_{VU}$
	• Red-headed vulture$_{CR}$	• Serow$_{VU}$	• Tibetian Wild Ass$_{NT}$
		• Himalayan monal$_{R}$	• Pygmy$_{CR}$
		• Bharal$_{R}$	• Musk Deer$_{NT}$
		• Himalayan Quail$_{CR}$	• Tibetian Gazelle$_{R}$
		• Oriental White-rumped Vulture$_{CR}$	• Serow$_{VU}$
		• Slender-billed Vulture$_{CR}$	• Himalayan Tahr$_{NT}$
		• King Vulture$_{CR}$	• Bharal$_{R}$
		• Baer's Pochard$_{CR}$	• Great Tibetian sheep$_{R}$
		• Egyptian Vulture$_{NT}$	• Crestless Porcupine$_{R}$
		• Black-bellied Tern$_{NT}$	• Asian elephant$_{NT}$
		• Cheer Pheasant$_{VU}$	• Barking deer$_{R}$
		• Long-tailed Duck$_{VU}$	• Bengal florican$_{CR}$
		• Saras Crane$_{VU}$	• Black-necked crane$_{R}$
			• Great one-horned rhino$_{VU}$

Table 3 Overview of the large dams (10–15 m in height with a storage capacity of over 60 million cubic meters) situated throughout the Indian Himalayan region

Dam	River	District	Power output (MW)	Year
Jammu and Kashmir				
Bagliharda	Chenab	Ramban	900	2009
Dulhasti	Kishenganga	Bandipore	390	2006
Nimo Bazgo	Indus	Leh	45	2014
Salal	Chenab	Resai	690	1986
Sewa—III	Sewa	Kathua	120	2010
Uri-II	Jhelam	Baramula	240	1997
Himachal Pradesh				
Baira Siul	Bairat, Bhaleed, Ravi	Chamba	180	1981
Bhakra	Satluj	Bilaspur	1325	1963
Chameera I	Ravi	Chamba	540	1994
Chameera II	Ravi	Chamba	300	2003
Chameera III	Ravi	Chamba	231	2012
Karchami Wangtoo	Ravi	Kinnur	1091	2011
Kol	Satluj	Balaspur	800	2014
Largi	Beas	Mandi	126	2006
Malani	Ravi	Kullu	86	2001
Nathpa Jhakri	Satluj	Kinnur	1500	2001
Pandoh	Beas	Mandi	990	1977
Parbati-III	Sainj	Kullu	520	2014
Pong	Beas	Kangra	396	1974
Uttrakhand				
Dhauliganga	Dhauliganga	Pithoragarh	280	2005
Koteshwar	Bhagirathi	Tehri Garhwal	400	2011
Ramganga	Ramganga	Gaghwal	190	1974
Ichari	Tons	Dehradun	360	1972
Maneri	Bhagirathi	Uttarakashi	90	1984
Tehri	Bhagirathi	Tehri Garhwal	1000	2005
Sikkim, West Bengal and Arunachal Pradesh				
Rangit III	Rangit	WEST	60	2000
Teesta-V	Teesta	NORTH	170	2007
Teesta-IV	Teesta	Darjeeling	160	2016
Ranganadi	Ranganadi	Papum Pare	405	2001

Apart from being the habitat of the Tibetan wolf, Bearded vulture, and White-rumped vulture, Himachal Pradesh also houses rare avian diversity such as the Koklass pheasant, Himalayan quail, and Himalayan monal indigenous to this region. The presence of such diverse species emphasizes the ecological significance of Himachal Pradesh.

Encompassing both terrestrial and avian species, Uttarakhand, among the former, Peter's tube-nosed bat, the Fishing cat, and the majestic Tiger are the most iconic. The Snow leopard and the Indian elephant are other notable mentions. Avian species like the Serow, Pygmy, and the Himalayan tahr also call this region home. The presence of varied species in the region demonstrates its habitat diversity.

Sikkim, West Bengal, and Arunachal Pradesh are collectively marked by a high density of endangered fauna. The Tibetan wolf, Red fox, and the Clouded leopard are some of the prominent mammals. The region also provides habitat to the Red panda, Fishing cat, and the rare Tibetan Gazelle. The area is further famous for its bird species, including the Bengal florican and the Black-necked crane. Such diversity indicates the richness and significance of the biodiversity in this region.

Since the Indian Himalayan region is a reservoir of biodiversity, it is imperative to underscore the gravity of the situation wherein a substantial number of species find themselves on the brink, designated as endangered or vulnerable. Each species, irrespective of its conservation status—be it critically endangered, endangered, or merely near-threatened—holds a pivotal place in upholding the ecological equilibrium of its habitat. Hence, our endeavors ought to converge on the conservation of their natural habitats, staunching the relentless tide of poaching and enlightening local communities about the indispensability of these species to our shared ecological future.

3 Major Dams in the Indian Himalayan Ecosystem

While hydroelectric plants represent a sustainable transition in the energy landscape, the criteria for designating a dam as "major" or "large" varies. The International Commission on Large Dams (ICOLD) defines a large dam as one exceeding 15 m in height from its foundation or between 5 and 15 m with a reservoir volume above 3 million cubic meters. Conversely, India's Central Water Commission (CWC) terms a "major dam" as one over 15 m from its foundation or 10–15 m with a storage capacity of over 60 million cubic meters (www.icold-cigb.org). The following section overviews major dams built in the Indian Himalayan region.

3.1 Hydropower Infrastructure and Development in Jammu and Kashmir

Jammu and Kashmir holds a significant hydropower potential, estimated at 20,000 MW (Nisar & Monroy, 2012). The Baglihar Hydroelectric Power Plant is located on the Chenab River in the Ramban area (Table 1). This run-of-the-river power station was initially proposed in 1992 and approved in 1996, with construction commencing in 1999. The plant boasts a capacity of 900 MW (JKPDC, 2017). Another prominent installation is the DulHasti hydroelectric power station, with a capacity of 390 MW, situated in Kishtwar. Developed by NHPC, this run-of-the-river facility on the Chenab River operates within a rugged Himalayan landscape, quite distant from major cities in the Jammu Division. Comprising a 70-m gravity dam, the water from the dam flows through a 9.5-km headrace tunnel before reaching the power plant and eventually being released back into the Chenab. Constructed between 1985 and 2007, the energy it produces benefits several states, including Jammu and Kashmir, Punjab, Haryana, Uttar Pradesh, Uttarakhand, Rajasthan, Delhi, and the Union Territory of Chandigarh (NHPC, 2016).

In the Union Territory of Ladakh, the Nimoo Bazgo Power Project is a noteworthy installation on the Indus River. Situated 75 km from Leh in the village of Alchi, its foundation was laid in 2001, and approved in 2005, with construction starting in 2006. With a power capacity of 45 MW, all of its units are now operational. Notably, this project was inaugurated in 2014 (PIB, 2019).

Another significant project is the Salal Hydroelectric Power Station on the Chenab River in the Reasi District (Table 1). Recognized as the maiden hydropower project in Kashmir developed by India under the Indus Water Treaty stipulations (Dar, 2011), its construction followed a 1978 agreement with Pakistan. With a power capacity of 690 MW, 1.5% of its electricity production supplies Jammu and Kashmir, while the rest is distributed through the Northern Grid to various other states.

The Sewa-II hydroelectric power plant, with an output capacity of 120 MW, stands in the Mashka region of Kathua district on the Sewa River, a Ravi River tributary. Developed by NHPC Limited, this plant boasts a gravity-style concrete dam (Encardio-Rite, 2023).

Lastly, the Uri-II hydroelectric plant in the Baramulla District serves as the second run-of-the-river power project on the Jhelum River. Positioned in the Uri area and established downstream of the already operational 480 MW Uri-I power plant (commissioned in 1997), this state-owned facility by NHPC houses four 60 MW generation units. The Uri-II power plant aims to generate 1123.76 million units of electricity annually, distributing power across a diverse range of states: Jammu and Kashmir, Haryana, Himachal Pradesh, Uttarakhand, Uttar Pradesh, Delhi, Punjab, Rajasthan, and Chandigarh, all managed by NHPC. This extensive electricity distribution showcases the project's regional impact and contribution to power supply reliability.

3.2 Hydropower Projects in Himachal Pradesh: An Overview

Himachal Pradesh boasts a formidable hydro potential, estimated at 27,436 MW (Est & Tonnes, 2018). One major project harnessing this potential is the Baira Siul Power Station (Table 1). This station taps into the combined inflow of the Baira, Siul, and Bhaledh tributaries of the Ravi River, with a total installed capacity of 180 MW (3 × 60 MW). It is expected to produce 779.28 MUs of energy annually with 90% reliability and 95% installed capacity availability. The project, headquartered at Surangani, was initiated by the Central Government in 1970–1971, and by 1981 all three units were operational.

The iconic Bhakra Dam near Bilaspur is a concrete gravity dam on the Satluj River. This 226-m-high dam forms the Gobind Sagar reservoir and has a power capacity of 1325 MW. The Chamera Dam spans the River Ravi, assisting the local hydroelectric project in the Chamba district. With its reservoir, Chamera Lake, the dam powers multiple stages: Chamera-I (540 MW), Chamera-II (300 MW), and Chamera-III (231 MW). The first phase was completed in 1994, while the third stage produced electricity in 2012.

In the Kinnaur region, the Sutlej River is home to the Karcham Wangtoo Hydroelectric Plant, boasting a 1091 MW capacity (Table 1). It is a run-of-the-river project, i.e., a hydroelectric power generation method with little to no water storage. Instead of relying on a reservoir's stored water, a run-of-the-river system relies on the natural flow and elevation drop of a river or stream to generate electricity. It is strategically placed between the 300 MW Baspa II Hydroelectric Plant and the 1500 MW Nathpa Jhakri Dam on Satluj. Similarly, the Larji Hydroelectric Power Project in the Mandi District leverages the Beas River with a design capacity of 126 MW.

Further, the Pandoh Dam, an embankment dam on the Beas River, plays a pivotal role in hydroelectricity production. As a run-of-the-river power design, it diverts the Beas River through a vast network of tunnels to the Dehar Power House with an impressive 990 MW capacity.

Near Barmana, the Kol Dam Hydropower Station is an embankment dam on the Sutlej River. With an 800-MW power plant, its construction started in 2000 and concluded in 2015. The Parbati-III Power Station also utilizes multiple rivers and nallahs to generate 520 MW of electricity.

Lastly, the Pong Dam, or Beas Dam, is an earth-fill embankment structure on the Beas River. Constructed in 1974, it was India's tallest at that time. Apart from irrigation, the dam supports a 396 MW power plant. The resultant lake, Maharana Pratap Sagar, also doubles as a renowned bird sanctuary.

3.3 Comprehensive Overview of Uttarakhand's Dam Infrastructure

Uttarakhand boasts a hydropower potential of over 20,000 MW, of which only 3900 MW has been harnessed (Mongabay). This utilization represents approximately one-third of the state's total installed capacity.

Located near Dharchula and the borders with Tibet and Nepal, the Dhauliganga Dam stands on the Dhauliganga River as a concrete-faced rock and earth-fill embankment dam (Table 1). It is a run-of-the-river dam with minimal pondage (NHPC, 2016). This dam was constructed through a collaboration between Bauer Maschinen, Daewoo Engineering and Construction, and Kajima Construction Corporation, Ltd. Additionally, the HCC, Hindustan Construction Company, and Samsung Corporation [E&C] Group joined forces to erect HRT & PH. The dam generates a total of 280 MW of hydropower (4 × 70 MW).

Situated 13 km north of Dakpathar, the Ichari Dam is a concrete gravity structure on the Tons River. Completed in 1972, it was primarily established for hydroelectric generation. This dam diverts water from the Tons River, supplying the Khodri Power Station (120 MW) and subsequently the Chibro Power Station (240 MW).

Twenty-two kilometers downstream of the Tehri Dam in the Tehri District lies the Koteshwar Dam on the Bhagirathi River (Table 1). Integrated into the Tehri Hydropower Complex, this gravity dam manages the Tehri Dam's irrigation tailrace and forms the lower reservoir for the Tehri Pumped Storage Power Station. A 400 MW run-of-the-river power station is also part of this infrastructure (THDC, 2011). The project received approval in 2000, and its journey towards sustainable energy production began with the commissioning of its first generator on March 27, 2011, followed by another on March 30, 2011.

Nestled within the Pauri Garhwal district, the Ramganga Dam, recognized by the name Kalagarh Dam, stands tall as an embankment dam constructed on the Ramganga River. Located three kilometers upstream of Kalagarh and within the boundaries of the Jim Corbett National Park, this dam has a power capacity of 190 MW. Last but not least, the Tehri Dam is the pinnacle of dam structures in India and holds the title of the 12th tallest globally at 260.5 m (Table 1). This multipurpose rock and earth-fill embankment dam is positioned on the Bhagirathi River in the Tehri Garhwal district. Acting as the primary dam for the Tehri hydropower complex and THDC India Ltd, it was completed in its first phase in 2006. The Tehri Dam supports a reservoir that caters to agriculture and urban water supplies, generating 1000 MW of hydroelectricity. Presently, 1000 MW variable-speed pumped-storage systems are under construction for the dam, with the inaugural two units anticipated to be functional by 2023 (THDC, 2011). An initial assessment of the Tehri Dam Project was done in 1961 during Jawaharlal Nehru's tenure, with its design, incorporating a 600 MW power plant, finalized by 1972. Construction began in 1978 after feasibility evaluations but faced delays due to financial, environmental, and societal concerns. Technical and financial aid came from the USSR in 1986, but political turbulence later truncated this support. The project's reins were then taken over by India, initially overseen by the Uttar Pradesh Irrigation Department. Yet, in 1988, the Tehri Hydro Development Corporation was formed to spearhead the project, financed 75% by the federal government and 25% from auxiliary channels.

3.4 Hydropower Initiatives in Northeastern India: A Synopsis

The Rangit Dam is the cornerstone of the Rangit Hydroelectric Power Project Stage III, strategically situated on the Rangit River, a prominent tributary of the Teesta River, in the South Sikkim district of Sikkim (Jain et al., 2007). Completed in 1999, this run-of-the-river hydroelectric facility commenced operations in 2000 (NHPC, 2016).

Another notable project, Teesta-V, with a capacity of 510 MW in northern Sikkim, stands out as a globally acclaimed exemplar of hydropower sustainability (NHPC). This initiative, commissioned in 2008, was devised as part of a cascade of hydropower ventures along the Teesta River (Table 1). Its purpose was not only to cater to the Energy and Power Department of Sikkim but also to power various state-owned distribution enterprises in the eastern region of India.

Further downstream, the Teesta Low Dam—IV Hydropower Plant, another run-of-the-river hydroelectric station, graces the Teesta River in the Kalimpong district of West Bengal (NHPC, 2016). Venturing into Arunachal Pradesh, the Ranganadi Dam stands tall on the Ranganadi River, also known as the Panyor River. This concrete gravity diversion dam supports a run-of-the-river scheme. Integral to Stage I of the Ranganadi Hydroelectric Project, the dam lays the groundwork for the 405-megawatt Dikrong Power House. Moreover, as part of the project's envisioned Stage II, the dam is set to bolster an additional power plant of 180 megawatts, doubling as a water reservoir for Stage I.

The sections above furnish an extensive synopsis of the hydroelectric infrastructure traversing the Indian Himalayas, accentuating the vast potential and dedicated endeavors orchestrated by the nation to exploit this renewable energy reservoir (Table 1). From the captivating panoramas of Jammu and Kashmir to the undulating terrains of Himachal Pradesh and Uttarakhand, and ultimately to the diverse biomes of Northeast India, each locality has harnessed its hydroelectric potential, cultivating practices that endorse sustainable energy approaches. The mentioned projects not only assume a pivotal role in fulfilling the energy requisites of the vicinity but also underscore India's unwavering commitment to a greener and more sustainable energy destiny. As India advances in its journey towards an eco-conscious future, these hydroelectric ventures, distinguished by intricate schematics and substantial capacities, pave the way for more ingenious and sustainable energy resolutions within the nation.

4 Impacts of Dams on the Indian Himalayan Ecosystem and Mitigation Strategies

In the Indian Himalayan region, the dams' construction affects human communities and the environment in various direct and indirect ways. This section delves into the environmental and socioeconomic consequences of dam construction.

4.1 Environmental Impacts of Dam Construction in the Himalayan Region

4.1.1 General Environmental Impacts and Economic Considerations

Dams exert multiple direct and indirect pressures on the environment, manifesting as air and water pollution, deforestation, and impacts on various flora and fauna. While hydropower expansion boosts the region's economic progress, it simultaneously induces environmental degradation and sparks conflicts regarding land and water resource reallocation (Schmutz & Moog, 2018). The conversion of mountain rivers into hydroelectric project cascade disrupts the native ecosystems. Rivers are often redirected into tunnels, causing significant riverbeds to dry up. Consequently, habitats of species relying on flowing water for migration or distribution face potential devastation (Bhatt & Pandit, 2016). Like the migratory species Mahseer (Tor tor) in Himachal Pradesh, a native carp of the Indian Himalayas has also experienced disrupted migration patterns. These large dams transform habitats from flowing rivers to stagnant waters, hinder crucial migratory patterns, alter natural river flows, and lead to siltation, changing water temperatures, and habitat loss. Rivers and wetlands, vital for groundwater recharge, suffer when disrupted, affecting groundwater dynamics (Dudgeon, 2000). Additionally, these dams introduce predatory species, increase disease prevalence, and negatively impact riverine biodiversity.

4.1.2 Local Impacts: Kinnaur's Springs

The Kinnaur region in Himachal Pradesh, India, is endowed with mountainous landscapes where local springs hold immense significance. Beyond being primary sources of freshwater for nearby communities, these springs also contribute to upholding the ecological equilibrium of the region. These springs formed naturally from underground aquifers and water table replenishment processes, play a vital role in the everyday lives of the locals by meeting domestic needs and facilitating agricultural practices. Dam constructions have been linked to the drying up of these local springs (Erlewein, 2013) by altering natural underground water flows and disrupting the geology through excavation. These changes not only endanger the local environment but also affect cultural connections to water sources, posing considerable agricultural and economic challenges for the community. This underscores the multifaceted consequences of large-scale infrastructure development in fragile ecological regions.

4.1.3 Deforestation and Its Consequences: The Kol Dam

The construction of the Kol Dam brought about significant environmental changes, particularly due to deforestation linked to its development. Removing trees for the dam project had cascading effects on the ecosystem. Trees are pivotal in holding the soil together with their root systems (Erlewein, 2013). When these trees were removed for the dam's construction, the soil became more susceptible to erosion, especially during heavy rains or water run-offs.

Soil erosion, in turn, has multiple negative impacts. Firstly, it leads to land quality degradation, affecting local agriculture and reducing the land's capacity to support vegetation. As the top layer of nutrient-rich soil washes away, it can reduce soil fertility. Secondly, the eroded soil ends up in rivers and waterways, leading to siltation. This accumulation of silt in water bodies can affect aquatic life and reduce the dam's lifespan as the reservoir gets filled with sediments.

The consequences of deforestation reverberate across the wildlife habitats of Kinnaur, prompting the migration of various species and culminating in a decline in biodiversity. Furthermore, deforestation disrupts the local microclimate, leading to fluctuations in temperature and humidity. The absence of the tree canopy, which traditionally moderates the regional climate, intensifies these alterations. The aggregate impact of these environmental changes holds the potential to significantly influence local communities, affecting their livelihoods, which include farming and fishing, along with their daily lives characterized by shifts in water quality, availability, and the regional climate.

4.1.4 Flood Plains, Hydro-Meteorological Disasters, and Specific Project Impacts

The encroachment on flood plains in the Sutluj basins for dam construction has brought about environmental and socioeconomic challenges. Flood plains, by nature, act as buffer zones during high rainfall or snowmelt, accommodating excess water and preventing sudden inundations downstream. When these plains are encroached upon or altered due to large constructions like dams, it restricts the natural flow of water. This, in turn, heightens the risk of hydro-meteorological disasters. Flash floods, for instance, become more probable as the water that would usually be absorbed or slowed by flood plains now moves downstream with greater speed and volume.

Glacial Lake Outburst Floods (GLOFs) are another significant concern. These occur when the dams or natural barriers holding back glacial lakes fail, causing large volumes of water to be suddenly released. Dam constructions in such sensitive regions can either directly or indirectly contribute to conditions that increase the likelihood of GLOFs.

Delving into specific projects reveals apparent environmental aftermaths. A case in point is the Chamera hydropower project, which left a significant ecological imprint, impacting 982.50 hectares of forested land (Bhattacharyya, 2007). Forests encompass intricate ecosystems hosting a variety of plant and animal species. The loss of such an extensive forested area can disrupt local wildlife habitats, trigger soil erosion, alter microclimates, and even have implications for local livelihoods, especially if communities depend on forest resources. Additionally, the biodiversity of aquatic ecosystems has suffered. The Tehri Dam region has experienced a decline in its fish diversity. Dams can obstruct fish migration routes, reducing fish populations in specific areas. This disrupts ecological balance and affects local communities relying on fishing for their sustenance and income.

Throughout the years, especially in 2009, 2010, 2012, and 2013, Uttarakhand experienced devastating floods that many environmentalists and experts partly link to dam construction and presence. The rationale for this correlation is intricate. Large dams have the potential to alter the natural flow and sediment transport of rivers, causing sediment buildup upstream and erosion downstream. When faced with intense rainfall events, which are frequent in the monsoon-prone Uttarakhand region, the controlled or forced water discharge from dam reservoirs can worsen flooding downstream.

4.1.5 Environmental Toll of Tihri and Koteshwar Dams

The construction of the Tehri and Koteshwar dams necessitated the conversion of a significant 4193.813 hectares of forested land. However, this is not just any ordinary forest terrain; it constitutes a portion of the Himalaya—a region acknowledged worldwide for its unparalleled biodiversity. Within these forests dwell a plethora of species, many of which are exclusive to this region (endemic) and others facing threats (Kumar et al., 2018). The alteration or removal of such vast expanses of forest does not merely entail the loss of trees; it signifies a disturbance in the ecological tapestry, where each living organism, regardless of size, has a role. The disappearance of these habitats could result in a decline of species, some of which might be teetering on the edge of extinction or possess critical roles within the ecosystem.

Moreover, the Himalayas are not just about biodiversity. They play an essential role in climate regulation, act as water towers providing freshwater to millions downstream, and are central to numerous cultural and spiritual narratives. When dams alter the Himalayan landscape, they don't just change a piece of land; they influence a living, breathing ecosystem with regional and global significance.

4.1.6 EIA Process and Calls for Revaluation

The evident outcomes witnessed and experienced by the inhabitants of the region, have sparked debates and conversations concerning the Environmental Impact Assessment (EIA) process. EIA is a globally employed tool to forecast the environmental effects of a proposed project before its execution. The flooding events in Uttarakhand prompted queries about the adequacy and thoroughness of the EIA procedures that preceded the construction of these dams. Were all potential impacts taken into consideration? Were the assessments comprehensive and founded on rigorous scientific methodologies? These questions accentuate the need for a more comprehensive and accountable assessment mechanism, ensuring the thorough examination of environmental, socioeconomic, and cultural dimensions before initiating extensive infrastructural projects.

In summary, while dams can offer potential advantages, such as hydroelectric power generation and water storage for irrigation, evaluating and mitigating their environmental impacts is essential to ensure the sustainability of development.

4.2 Socioeconomic Impacts and Induced Displacement Due to Dam Construction

4.2.1 Global Perspective and Key Issues

The repercussions of dam construction ripple through societies, primarily manifesting as forced displacement and necessitating resettlement. A prevailing global concern, induced displacement often emerges as collateral damage from extensive natural resource exploitation. Multifaceted conflicts arise from land and water resource reallocation due to large dam construction (Rana et al., 2007). Central issues include the displacement of local communities with inadequate rehabilitation, loss of livelihoods, environmental degradation, and altered water flows affecting downstream communities. Additionally, the submergence of culturally significant areas exacerbates the sense of loss among affected groups. While dams bring potential economic benefits, these often bypass displaced communities, exacerbating economic disparities and raising broader concerns about rights, identity, and equitable development.

4.2.2 Sikkim's Opposition to Dam Projects

Contrastingly, in Sikkim, India, the indigenous Bhutia communities of Lachungpas and Lachenpas have successfully opposed all proposed hydropower projects in their areas, Lachung and Lachen (Dukpa, et al., 2019). Since 2003, over 168 major dams have been proposed in India's Eastern Himalayas. The push for hydropower by the Central and State Governments has caused significant conflicts in the northeast region. Many contentious projects, such as the Teesta Stage IV, Teesta Stage VI, Panam in Sikkim, Subansari Lower HEP in Assam, Tipaimukh Dam in Tripura, and the Dibang Multipurpose Project in Arunachal Pradesh, have faced delays, cancellations, or are awaiting clearance. This northeast region, rich in tribal diversity, has communities protected by Article 371 of the Indian Constitution. Still, large dam developments, seen as "development" tools, often go against the desires of these tribal groups. Such conflicts occasionally turn violent, with some anti-dam protesters losing their lives. Despite this, the Lachungpas and Lachenpas successfully halted five projects within a few years, maintaining their anti-dam stance. Yet, neighboring Dzongu, home to the Lepchas, is often highlighted in media as the central anti-dam movement in North Sikkim.

4.2.3 Impact on Nomadic Communities: Himachal Pradesh and Jammu and Kashmir

In Himachal Pradesh and Jammu and Kashmir, indigenous nomadic communities like the Gaddis and Gujjars, traditionally reliant on pastoralism and seasonal migrations, face significant disruptions due to dam constructions. These dams lead to losing vital grazing lands, forced relocations, limited access to essential natural resources, and cultural and economic challenges. Moreover, altered local ecosystems and the influx of external populations during construction put their traditional way of life and economic stability at grave risk (Sharma & Rana, 2014).

4.2.4 Gendered Impacts in Jammu and Kashmir

In Jammu and Kashmir, dam constructions have significantly impacted the women of Kathua and Pul Toda. Kathua's women, deeply involved in village economies and agriculture, faced challenges with the loss of fertile lands and diminished roles in livestock management, eroding their self-sustenance. Conversely, Pul Toda's businesswomen, who had carved a niche in local trade, grappled with the dual challenges of losing their financial independence and intensified societal constraints post-dam construction (Nisar & Monroy, 2012). This shift not only impacted their economic roles but also altered their socio-cultural dynamics and bargaining power within the community.

4.2.5 Socio-Cultural Shifts: The Kol Dam Example

The construction of the Kol Dam led to notable socio-cultural shifts within affected communities, transitioning them from traditional joint family systems to nuclear family setups. This structural change, rooted in the strains of displacement and the challenges of adapting to new environments, was intensified by their primary agricultural background. With the loss of fertile farmland and a lack of alternative skills outside agriculture, these communities, as highlighted by Thakur and Thakur, faced heightened economic vulnerabilities in their new settings, grappling with both the erosion of their cultural identity and economic stability.

4.2.6 Legacy of the Bhakra Dam

The Bhakra Dam in Bilaspur district, Himachal Pradesh, symbolizes both the triumphs and challenges of post-independence developmental initiatives in India. While its construction in the 1950s showcased India's aspirations for progress by providing irrigation and generating hydroelectric power, it also led to large-scale displacements. Mishra's 2019 study emphasizes that the resettlement plans were inadequately planned, leaving many inhabitants grappling with issues like loss of fertile land, cultural alienation, economic hardships, and fractured community bonds. The dam's legacy, thus, underscores the importance of comprehensive and empathetic resettlement strategies in developmental projects.

4.2.7 Socioeconomic and Cultural Impacts of Tihri and Koteshwar Dams

Further fueling concerns is the example of the Tehri Dam, one of the highest dams in the world. The backwater flows from this dam's reservoir, particularly near Chiniyalisaur in Uttarakhand, have had detrimental effects on the surrounding areas (Rana et al., 2007). Agricultural fields, the lifeblood of many local communities, have been adversely affected. This is crucial, as agriculture is not just about livelihood in this region; it's deeply intertwined with culture, tradition, and local socioeconomic systems. When fields get inundated or rendered less productive due to changes in the water table or silt deposition, it affects crop yields and the very fabric of the community that relies on them.

In 1979, the construction of the Tehri Dam in Uttarakhand prompted the massive displacement of thousands, submerging the old Tehri town and several villages. Despite the passage of time, rehabilitation efforts remain inadequate and marred by the absence of a holistic resettlement plan. Many relocated inhabitants, previously reliant on farming and fishing, grapple with unsuitable lands and economic uncertainties in new areas. Beyond the tangible challenges, the dam's construction has inflicted profound emotional distress. Severing connections to ancestral lands has left many yearning for their lost homes. At the same time, the dispersal of close-knit communities has led to a palpable sense of alienation and identity loss. The Tehri Dam saga underscores the vital importance of balancing developmental aims with the comprehensive well-being of the affected communities.

The construction of dams, particularly in ecologically fragile areas like the Himalayas, has adverse ecological and socio-cultural consequences. The Koteshwar

Dam serves as a poignant case in point. The dam's construction affected the inhabitants of Payal village deeply. While designed for larger development goals like power generation and water storage, such infrastructure projects often overlook or underestimate their impact on smaller communities. For the villagers of Payal, the dam not only altered their immediate environment but potentially their entire way of life, as relocation, altered livelihoods, and socio-cultural shifts became inevitable.

Dams in India symbolize the balance between development and community well-being. While they promise progress, they also cause socioeconomic and cultural disruptions. The varied reactions, from resistance in Sikkim to adaptations at Kol Dam, highlight diverse experiences. However, the need for sensitive resettlement remains clear. Development should respect and protect community rights and emotions.

4.3 Mitigating the Impacts of Large Hydroelectric Projects on Development Activities

Hydroelectric projects often wield significant influence over developmental pursuits. As elaborated above, their establishment brings about substantial social and environmental consequences. These encompass widespread displacement of families, erosion of traditional livelihoods, disruption of social bonds, and degradation of environmental conditions (Rana et al., 2007). Communities forced to relocate frequently confront reduced access to essential amenities like water, electricity, and sanitation. Once teeming with diverse flora and fauna, the local ecosystem experiences drastic changes, leading to habitat loss and contamination of water resources. Furthermore, empirical data indicates that displaced women encounter hurdles in accessing fundamental rights, including food, health, and shelter. Additionally, marginalized groups are often marginalized further during compensation processes. In this context, we present a set of recommendations aimed at alleviating these consequences.

4.3.1 Environmental Impact Analysis (EIA)

Environmental Impact Analysis (EIA) has emerged as a fundamental mechanism for assessing the consequences of hydroelectric projects, revealing their advantages and disadvantages. A comprehensive EIA not only delineates the range of impacts but also proposes feasible solutions that can garner the endorsement of all stakeholders—ranging from project developers and financers to local communities and government bodies. Thus, it's imperative to undertake a robust EIA to discern the full spectrum of a project's ramifications rather than blanket endorsements or rejections of developmental endeavours.

A robust EIA should provide a holistic analysis, capturing not only environmental consequences but also socioeconomic and cultural impacts. Incorporating a cumulative impact assessment can shed light on the combined effects of multiple projects on river ecology and local microclimates. Local communities can voice their concerns by fostering a participatory approach, leading to better project design or more effective rehabilitation measures. Given the region's biodiversity and vulnerability to climate change, EIAs must assess potential losses in flora and fauna, changing precipitation patterns, and glacial melt rates. Simultaneously, they should factor in seismic risks, downstream effects, and economic displacements, focusing on the broader well-being of the Himalayan ecosystem and its inhabitants. Emphasizing enforcement, transparency, and adaptive management in the EIA can ensure that dam construction in the Himalayas is both sustainable and accountable.

4.3.2 Stakeholder Consultation

Stakeholder consultation is pivotal in mitigating the environmental and socioeconomic impacts of large dams in the Indian Himalayas. It ensures that the voices, concerns, and aspirations of affected communities are acknowledged and integrated into project designs. A more comprehensive understanding of potential environmental and socioeconomic disruptions can be gained by involving local inhabitants who intimately understand the landscape, water resources, and traditional land uses.

Stakeholder consultation provides insights into the potential loss of livelihoods, cultural sites, and traditional knowledge. This feedback can guide the creation of effective rehabilitation and resettlement plans, ensuring equitable compensation and assistance for transitioning to new livelihoods.

It can foster trust and collaboration between project developers and local communities. This mutual understanding can reduce conflicts, project delays, and the potential costs associated with social unrest or litigation. In the context of environmental impacts, stakeholder feedback can highlight less obvious consequences, such as subtle shifts in local microclimates, has implications on non-commercial species, or threats to medicinal plants and herbs.

Involving a broad range of stakeholders, including environmental experts, scientists, local NGOs, and indigenous representatives, ensures a multidisciplinary approach. Such a diverse consultation can help identify sustainable construction practices, better site selection, and potential mitigation measures that may be overlooked in a more limited assessment. Stakeholder consultation provides a platform for holistic, inclusive, and forward-thinking decision-making, crucial for minimizing the adverse impacts of dam constructions in the sensitive ecosystem of the Indian Himalayas.

4.3.3 Infrastructure Development in Resettlement Colonies

Infrastructure development in resettlement colonies can significantly mitigate the environmental and social impacts of large dams in the Indian Himalayas. Before initiating relocations, the onus lies on project authorities and governmental agencies to establish well-equipped resettlement colonies. Ensuring that these colonies are provided with essential services, from healthcare and education to sanitation and electricity, can significantly attenuate the hardships displaced individuals face.

Adequately designed infrastructure provides a foundation for the sustainability and well-being of displaced communities. For instance, ecologically sensitive waste management, efficient transportation networks, and sustainable energy sources can minimize environmental harm. Simultaneously, creating educational and healthcare facilities ensures community development and health, while agricultural and market infrastructure helps restore livelihoods. Additionally, constructing community and cultural centers fosters social cohesion, preserving traditions, and establishing feedback mechanisms for continued community engagement. In sum, holistic infrastructure development in resettlement areas can transform challenges of displacement into opportunities for sustainable growth and social integration.

4.3.4 Education Continuity

Ensuring education continuity in the wake of large dam constructions in the Indian Himalayan region is vital for mitigating both immediate and long-term socio-environmental impacts. Education provides the tools and knowledge essential for communities to adapt to changing environments and find sustainable solutions to new challenges. By guaranteeing uninterrupted learning, displaced children, especially girls who often face heightened vulnerabilities, can continue to acquire skills and knowledge crucial for their personal and community's future. This educational continuity can foster a sense of normalcy amid upheaval and, in the long run, empower these children to become stewards of their environment and advocate for sustainable development in their communities.

4.3.5 Women's Participation in Decision-Making

Throughout history, women have held significant roles within their communities, contributing extensively to the socio-cultural and economic aspects. They have frequently served as primary caregivers and played crucial roles in agriculture, water management, and household economics. Consequently, they possess unique insights into the nuanced challenges that displacement can introduce. By ensuring women's participation in decision-making, especially concerning compensation allocations, projects can be more attuned to the real-world needs and priorities of the entire community, leading to better-tailored, equitable, and sustainable solutions. Their inclusion fosters a comprehensive understanding of the social dynamics, enabling policies and interventions that reflect the complexities of affected communities.

5 A Closer Look at the Dauliganga Basin Amid the Proposed Large Dams

The Dhauliganga basin stands out for its hydrological significance in the Uttarakhand region. The Dhauliganga is the most prominent headwater tributary that feeds into the Alakananda downstream. Its source, the Kamet glacier above 6060 m, not only breathes life into Dhauliganga but also contributes through its Geldhong (Gal) originating branch. As the Dhauliganga River progresses southwestward, it meets the waters from a right bank tributary near Shepak Kharak, maintaining this course until Khal Kurans. Further downstream, at Gamsali, the river welcomes the Amrit Ganga, which originates from the Deoban glacier, joining the Dhauliganga on its right bank. Upon reaching Kuikuti, the river integrates the flows from Girthi Ganga on its left side. Ultimately, the Dhauliganga meets the Alaknanda River at Vishnuprayag on the left bank at an altitude of 1440 m (THDC, 2011).

The Dhauliganga River, nestled in the ecologically sensitive and seismically active Himalayas, is a pivotal case study for evaluating the ramifications of large dams. Its unique location offers insights into potential ecological shifts, seismic risks, and the impacts on indigenous communities, whose culture and livelihoods could be uprooted by such projects (Jha & Khare, 2016). Moreover, the religious and cultural importance of rivers in this region, the Dhauliganga's role in water supply, and its susceptibility to climate change-driven glacial melting highlight the necessity of investigating its hydrological shifts after dam construction. Assessing the interplay between Dhauliganga's dam construction and its multifaceted implications can guide sustainable and equitable developmental strategies for similar Himalayan projects.

5.1 An Overview of the Hydroelectric Projects of Dhauliganga Basin

In the Dhauliganga basin of Uttarakhand, several significant hydroelectric projects have been developed or proposed. Among these are the Tapovan Vishnugad Hydropower Plant, managed by NTPC and expected to offer a capacity of around 520 MW upon completion. Tehri Hydro Development Corp. Ltd. (THDC, 2011) is planning the Malari Jelam H.E. Project with a 65 MW capacity, while the Jelam Tamak H.E Project is set to harness the hydroelectric potential between the Jelam and Tamak villages in the Chamoli district.

5.1.1 Tapovan Vishnugad Hydropower Plant

The Tapovan Vishnugad Hydropower Plant, located on the Dhauliganga River near Joshimath in Uttarakhand's Chamoli district, boasts a planned capacity of 520 MW. As a run-of-the-river scheme, its key components comprise a barrage, headrace tunnel, underground powerhouse, and tailrace tunnel. Developed by India's state-owned NTPC Limited, the project aims to address the peak energy demands of the northern grid and stabilize the region's electrical infrastructure. However, the initiative had encountered delays due to geological and other challenges. Notably, the project's environmental and social implications, including potential displacement of local communities, ecological disturbances, and changes in river flow patterns, emphasize the balance needed between meeting energy demands and minimizing adverse impacts.

5.1.2 Malari Jelam H.E. Project

The Tehri Hydro Development Corp. Ltd. (THDC) aims to construct a 65 MW hydroelectric power plant in Uttarakhand, India. This ambitious project encompasses the development of a substation, powerhouse, access roads, a barrage, a water conductor system, a horseshoe-shaped head race tunnel, an underground machine hall, and a tail-race tunnel. Equipment installation will include generators, transformers, turbines, a gated power intake, a desilting chamber, a surge shaft, and a pressure shaft, complemented by the laying of transmission lines. In 2010, due to opposition from Malari villagers, the project location shifted to Kosa Village, a kilometer from the original site. By April 2011, a power sector task force instructed THDC to ensure timely project completion. The MoEF, in 2012, advised a 1 km gap between the Malari Jhelum's Tail Race Tunnel (TRT) and the Full Reservoir Level (FRL) of the Jelum Tamak Project. The viability report for 65 MW was submitted to the Central Electricity Authority (CEA) by May 27, 2013, initializing the DPR process. In August 2013, a Supreme Court directive halted any environmental or forest clearances for Uttarakhand hydro projects. However, by February 11, 2014, THDC secured clearance from the CEA. A petition was filed in the Supreme Court by THDC on September 6, 2014, to revisit the MoEF clearance issue. The project awaits the Supreme Court's verdict to proceed with DPR preparation.

5.1.3 Jelam Tamak H.E. Project

The Jelam Tamak H.E. Project aims to harness the hydropower potential of Dhauliganga between Jelam and Tamak villages in the Chamoli district. The proposal involves diverting Dhauliganga River through a water conductor system on its right bank. Three 36 MW units, totaling 108 MW, are planned for an underground powerhouse on Dhauliganga's right bank. The blueprint details a barrage, 28 m in height and 83 m in length, at an altitude of 2623.50 m, a 4.40 km long horseshoe concrete-lined head race tunnel, an underground powerhouse, and a 308 m long tailrace tunnel. The system aims to utilize a design discharge of 57.58 m^3/s and a drop of approximately 207.54 m for power generation, with an annual energy generation in a 90% dependable year estimated at 505.12 GWh. The catchment area for the Jelam Tamak H.E. Project spans 1666 km^2.

5.1.4 Lata Tapovan H.E Project

The Lata Tapovan Hydroelectric Project is a significant hydroelectric initiative located in the Dhauliganga basin of Uttarakhand. With a planned capacity of 171 MW, it is a run-of-the-river scheme situated approximately 25 km from Joshimath in the Chamoli district. The government of Uttaranchal (now Uttarakhand) allotted the project in August 2003, prompting site-specific studies and investigations to prepare the Detailed Project Report (DPR) and ascertain its techno-economic viability. The project implementation agreement was formalized between NHL and the state government in November 2005. The anticipated cost per MW for this endeavor is projected at 4.63 crore. As of the latest information, the DPR for the project had been formulated, essential project/site-specific clearances were obtained, and land acquisition for the project was underway, with township infrastructure development in progress.

The Dhauliganga basin, situated at the heart of the Himalayan region, showcases nature's abundant resources. Numerous hydroelectric ventures tapping into the river's kinetic energy underscore the importance of sustainable power generation in the area. These undertakings not only contribute to the electricity grid but also play a pivotal role in the socioeconomic advancement of Uttarakhand. However, while their potential benefits are substantial, it remains essential to prioritize ecological balance, local heritage, and community well-being in the quest for developmental progress.

5.2 Forest Types in Dhauliganga Basin

In the Dhauliganga Basin, the diverse topography and altitude variations give rise to distinct forest types, each harboring a unique combination of flora. Moist Deodar Forests are predominantly found at altitudes ranging between 1500 and 2000 m. Characterized by more or less pure stands of deodar trees, these forests play a crucial role in maintaining the region's ecological balance. Their impressive stature and dense canopies make them a key feature of the Dhauliganga landscape.

Moving on to the Dry Temperate Coniferous Forest, this type is primarily composed of coniferous trees punctuated by a few broad-leaved trees and shrubs. Noteworthy species that make up these forests include *Cedrus deodara*, *Fraxinus xanthoxyloides*, *Hippophae salicifolia*, *Pinus wallichiana*, and *Populus ciliata*. The understory, although not as dense, features shrubs like *Berberis aristata* and *Ephedra gerardiana*, adding layers of biodiversity to the forest structure.

The West Himalayan Dry Juniper Forest is another distinctive forest type. These forests are open and evergreen, mainly situated above Malari in the Niti area and spanning altitudes from 2800 to 4300 m. *Juniperus macropoda* dominates these terrains, occasionally forming pure stands. The undergrowth comprises a range of xerophytic shrubs, including *Berberis petiolaris* and *Hippophae salicifolia*, each adapted to the harsher climatic conditions of this altitude.

The West Himalayan Birch/Fir Forests offer a contrasting sight. These irregular forests predominantly occupy regions above 3000 m, particularly in areas like Dronagiri and Malari. Trees such as *Abies pindrow* and *Betula utilis* are common sights, with woody plants like *Rosa sericea* adding diversity to the forest floor.

The Sub-Alpine Pastures represent a unique biome in the Dhauliganga Basin. These expansive meadows are a riot of herbs and grass species found below the timberline in the sub-alpine zone. From *Aconitum atrox* to *Taraxacum officinale*, these pastures not only serve as grazing grounds but also contribute to the region's rich biodiversity.

5.3 Floral and Faunal Diversity in the Dhauliganga Basin

5.3.1 Floral Diversity and Socio-Ecological Interactions in the Dhauliganga Basin

The Dhauliganga Basin has a unique and diverse floral composition shaped by its varying topography and climatic influences. Within the broader spectrum of flora in Uttarakhand, there are about 116 endemic species of flowering plants, such as the herbaceous members of the Caryophyllaceae family, *Arenaria curvifolia* and *A. ferruginea,* found primarily above 3000 m. Notably, the *Geranium polyanthes* of the Geraniaceae family thrive between 2500 to 4500 m (Table 4). Among the shrubs, *Cotoneaster garhwalensis* from the Rosaceae family is prominent between 2700 and 3700 m. Furthermore, the Dauliganaga region hosts unique grasses such as *Calamagrostis garhwalensis* and *Festuca nandadevica* from the Poaceae family, seen between 2500 and 3550 m.

The medicinal plants of this region are equally fascinating. From the Berberidaceae family, the Berberis aristata, locally known as Daru-haridra, thrives up to 2500 m (Table 4). The Violaceae family's *Viola biflora*, named Vanfsa locally, is seen between 2500 and 3500 m. Another notable herb is *Astragalus candolleanus*, or Rudravanti, from the Fabaceae family, found between 2600 and 4000 m. The Rosaceae family offers medicinal plants like *Potentilla fulgens*, locally termed Vajardanti, and *Prinsepia utilis* or Bhenkla, which flourished between 1500 and 2800 m. The Cupressaceae's *Juniperus recurva* or Dhoop can be located from 2600 to 3600 m. Lastly, *Ephedra gerardiana* from the Ephedraceae family, known as Somvalii locally,

Table 4 Detail of endemic plant species and those with medicinal significance found within the Dhauliganga basin

Family	Endemic Species	Habit	Altitude
Caryophyllaceae	*Arenariacurvifolia* *A. ferruginea*	Herb Herb	3300–3650 Above 3000
Geraniaceae	*Geranium polyanthes*	Herb	2500–4500
Rosaceae	*Cotoneaster garhwalensis*	Shrub	2700–3700
Cyperaceae	*Carexnandadeviensis*	Herb	2000–3000
Poaceae	*Calamagrostis garhwalensis* *Festuca nandadevica*	Grass Grass	2500–3500 3500–3550
Family	Medicinal plant	Local name	Altitude
Berberidaceae	*Berberis aristata*	Daru-haridra	Up to 2500
Violaceae	*Viola biflora*	Vanfsa	2500–3500
Fabaceae	*Astragalus candolleanus*	Rudravanti	2600–4000
Rosaceae	*Potentilla fulgens* *Prinsepia utilis*	Vajar-danti Bhenkla	1600–2600 1500–2800
Cupressaceae	*Juniperus recurva*	Dhoop	2600–3600
Ephedraceae	*Ephedra gerardiana*	Somvalii	2500–3500

finds its habitat between 2500 and 3500 m. These plants not only add to the ecological diversity but also hold immense medicinal importance for local and global communities.

While the region's floral diversity is commendable, it's also home to some Threatened Flora. The Red Data Book of India identifies two such species, *Allium stracheyi* and *Taxus baccata*, that reside within the project and catchment area. Their precarious status is exacerbated by habitat destruction and unsustainable harvesting practices, placing many invaluable species on the brink.

The relationship between the local populace and the flora cannot be understated. Many of the basin's plants have Economic Importance. Local communities not only rely on these plants for their basic needs, spanning from food and fodder to fuel and timber, but they also actively cultivate several of these beneficial species, emphasizing their intertwined existence.

Further enriching the basin's botanical tapestry are its Medicinal Plants. Uttarakhand's wealth in medicinal plant diversity is well-documented, and the Dhauliganga Basin is no exception. Indigenous tribes and local residents, especially those near forest areas, have a storied tradition of harnessing these plants to remedy various health concerns. It's noteworthy that even though the project area might be classified as a degraded, dry semi-arid zone, it still offers a haven for many plants with potent medicinal properties.

5.3.2 Faunal Splendors of the Dhauliganga Basin: A Confluence of Biodiversity

The Dhauliganga Basin, spanning from temperate to alpine zones, presents a tapestry of diverse habitats, from snow-covered regions above the timberline in winter to terraced cultivation valleys dotted with settlements. This range of ecosystems hosts a rich variety of faunal species (Table 5). In the mammalian realm, the Rhesus macaque (*Macaca mulatta*) predominantly inhabits areas up to 2500 m and is classified as 'Least Concern' by IUCN, enjoying protection under Schedule II of the Wildlife Protection Act (WPA). The Common langur (*Semnopithecus entellus*), however, residing up to 3500 m, faces more significant threats, being categorized as 'Endangered' by IUCN and safeguarded under Schedule I of WPA. Interestingly, species like the Goral (*Naemorhedus goral*), spanning regions between 2100 and 3000 m, are considered 'Near Threatened' and find their place in Schedule III of WPA.

High-altitude mammals, like the Argali and Blue sheep, reside around the 4000 m mark and are identified as 'Vulnerable' (Table 5). Their conservation importance is emphasized by their placement under Schedule I of WPA. The Common Leopard (Panther pardus) and Snow Leopard (Panther uncia) are equally significant. While the former thrives up to 3000 m, the latter is adapted to regions above this altitude. Both species have been flagged as 'Vulnerable' by the IUCN, with the Snow Leopard additionally bearing an 'Endangered' tag. Their critical ecological roles warrant their protection under Schedule I of WPA.

The Brown bear (*Ursus arctos*) occupies habitats below 5000 m. While it has a 'Least Concern' status by IUCN, the Zoological Survey of India (ZSI) categorizes it as 'Endangered'. Similarly, the Alpine musk deer (*Moschus chrysogaster*), whose habitat ranges between 3000 and 5000 m, is deemed 'Endangered' by both regulatory bodies and is accorded the same protective status as the leopards. The Himalayan tahr (*Hemitragus jemlahicus*), spanning regions from 2500 to 5000 m, also shares this protective status, reflecting its ecological significance.

Turning our attention to avian species, we find the region graced by the presence of the majestic Lammergeier (*Gypaetus barbatus*) (Table 5). Bearing an 'Endangered' status by IUCN, it is safeguarded under Schedule I of WPA. The vibrant Monal pheasant (*Lophophorus impejanus*) shares the same IUCN classification but finds its protection under Schedule IV of WPA. With its distinct calls, the Cheer pheasant (Catreus wallichi) mirrors the Lammergeier's protective status. Lastly, although' Vulnerable', the Koklas pheasant (Pucrasia macrolopha) enjoys protection under Schedule IV of WPA.

The avifaunal spectrum around the proposed JelamTamak H.E. Project area is diverse and vibrant. The region is a haven for various bird species, ranging from the majestic hawks, vultures, falcons, and eagles to the more petite partridges, pigeons, doves, and cuckoos. The lush greenery and unique topography also attract barbets, drongoes, mynas, tits, sparrows, tree pies, magpies, thrushes, bulbuls, flycatchers, finches, wagtails, and forktails, creating an ornithologist's paradise.

Despite the catchment area of the Jelam Tamak H.E. project not being particularly rich in herpetofauna, the influence zone in its lower reaches is believed to

Table 5 Details of threatened mammal and bird species found in the Dhauliganga basin and their conservation status as per guidelines of the International Union for Conservation of Nature (IUCN), Zoological Survey of India (ZSI), and Wildlife Protection Act (WPA)

	Scientific name	Distribution	IUCN status	ZSI status	wpa status
Mammalian species					
Rhesus macaque	*Macaca mulatta*	2500 m	LC	–	II
Common langur	*Semnopithecus entellus*	3500 m	EN	–	I
Wild boar	*Sus scrofa*	1500 m	LC	–	–
Goral	*Naemorhedus goral*	2100-3000 m	NT	–	III
Barking deer	*Muntiacus muntjak*	1500-2400 m	LC	–	–
Argali and blue sheep		4000 m	VU	–	I
Common Leopard	*Panther pardus*	3000 m	VU	VU	I
Snow leopard	*Panther uncia*	above 3000 m	EN	EN	I
Jungle cat	*Felis chaus*	2000 m	LC	–	II
Wolf	*Canis lupus*	Lower and middle part	LC	–	I
Jackal	*Canis aureus*	1200–2100 m	LC	–	–
Common otter	*Lutra lutra*	3600 m	NT	–	–
Indian flying fox	*Pteropus giganteus*	3600 m	LC	–	–
Brown bear	*Ursus arctos*	Below 5000 m	LC	EN	I
Serow	*Capricornis sumatraensis*	1500–4000 m	VU	VU	I
Bharal	*Pseudois nayaur*	4200–4700 m	LC	VU	I
Alpine musk deer	*Moschus chrysogaster*	3000–5000 m	EN	EN	I
Indian porcupine	*Hystrix indica*	Below 2400 m	VU	–	II
Himalayan tahr	*Hemitragus jemlahicus*	2500–5000	VU	EN	I
Avifaunal species					
Lammergeier	*Gypaetus barbatus*	–	–	EN	I
Monal pheasant	*Lophophorus impejanus*	–	–	EN	IV

(continued)

Table 5 (continued)

	Scientific name	Distribution	IUCN status	ZSI status	wpa status
Cheer pheasant	*Catreus wallichi*	–	–	EN	I
Koklas pheasant	*Pucrasia macrolopha*	–	–	VU	IV

(**LC**- least concern; EN- endangered; **NT**- near threatened; **VU**- vulnerable; and **Schedule I**- endangered species needing rigorous protection; **II**- high protection, trade prohibited; **III**- Protected species, the penalty for violation of the act is less; **IV**- vermin, hunting permitted; **- not defined**)

be home to an array of amphibian species, including *Rana annadalei*, *R. blanordii*, *R. leibigii*, and *R. minica.* The reptilian community here is represented by species such as hemidactylus brooks, *H. flaviridis*, *Agama tuberculata*, *Japalura major*, and *Scincella himalayanum*, along with a few others like *Vipera russelli*, highlighting the basin's herpetological significance.

The species mentioned offer a glimpse into the region's ecological richness. Ensuring their conservation is not just a matter of preserving biodiversity but also an imperative for maintaining the health of the entire ecosystem.

5.4 Ecological Vulnerabilities and Impacts in the Dhauliganga Basin

5.4.1 Vulnerability of Dhauliganga Basin

The Dhauliganga basin stands as the youngest chapter in the grand narrative of the Ganga River. Currently in its youthful stage, the river holds immense potential for establishing hydropower plants and dams (Jha & Khare, 2016). However, the pristine environment, mixed major types of forests, and habitats for many vulnerable and youthful animals make ecological decisions complex. Beyond its faunal richness, the basin is a reservoir of medicinal and economically valuable plant species. Fortunately, anthropogenic involvement remains minimal, preserving its delicate balance. Yet, the region has challenges; it's a hotspot for landslides and Glacial Lake Outburst Floods (GLOFs). Further highlighting its ecological significance is the proximity of the Nanda Devi Biosphere Reserve.

5.4.2 Impacts of Hydroelectric Plants in Dhauliganga Basin

Introducing the H.E. plant in the Dhauliganga Basin brings along ecological concerns (Pandey et al., 2021; Thakur et al., 2016). Foremost among these is the anticipated species loss. The direct activities aligned with the project's execution could adversely affect the native species of the construction zones. Adjacent to the issue of species loss is the probable habitat degradation and loss. The continual stream of construction and the various ancillary operations are expected to affect the natural habitats adversely. The rampant disposal of non-biodegradable waste coupled with the emissions of harmful pollutants, such as SPM, NOx, SOx, and CO, would further amplify the threat. Furthermore, the escalating noise levels and sweeping changes in land use patterns underline the gravity of this concern. Even though these negative impacts are severe, a ray of optimism is, as they are perceived to be temporary and reversible.

Yet, the installation of the plant not only threatens to degrade habitats but also fragments them. The surge in human activities and the sheer volume of project-related operations might severely restrict the unhindered movement of the resident fauna. This fragmentation is not just a physical barrier but has profound ecological implications. While geographically localized, these ramifications are distressingly irreversible (Grumbine & Pandit, 2013; Pandit & Grumbine, 2012).

Finally, the basin's diverse wildlife faces a direct challenge from the project. Activities intrinsic to the project, like blasting and road construction, along with increased vehicular movement, are expected to generate noise levels that could surpass the 90 dB mark. The inherent nature of the basin's wildlife, which includes elusive species such as the musk deer, Tahr, and black bear, among others, is to seek tranquillity. Such heightened disturbances could severely impact their natural behaviours, especially critical breeding activities. The fallout of these project activities on the basin's wildlife is devastatingly irreversible.

5.5 Balancing Energy and Ecology in the Dauliganga Basin

5.5.1 Integrated Resource Planning (IRP)

Balancing the Dauliganga Basin's energy ambitions with preserving its unparalleled ecological gems demands a comprehensive strategy, intertwining technological advancements, sustainable practices, and active community participation. An essential step is the development of an Integrated Resource Planning (IRP) that weighs the energy, economic, and environmental facets of diverse energy sources, highlighting those with minimal basin impact.

For example, rather than resorting to vast dams, the focus could shift to smaller, run-of-the-river hydropower schemes, known for their milder environmental and societal repercussions. Moreover, infrastructure should embrace designs that foster fish migration and sediment transport, such as fish ladders and sediment bypass tunnels. Simultaneously, for any habitat disruptions caused by energy endeavors, counteractive habitat restoration within the basin should be an obligation.

5.5.2 Strategic Environmental Assessments

Furthermore, implementing Strategic Environmental Assessments (SEAs) before any project initiation ensures the seamless integration of conservation priorities from the beginning. Implementing continuous, real-time monitoring mechanisms for water quality, sediment, and biodiversity and adopting adaptive management strategies based on current ecological data and feedback can offer a dynamic approach to conservation.

5.5.3 Community Engagement, Public Awareness and Strengthening Legal Framework

Equally vital is the engagement of local communities in conservation efforts, valuing their indigenous knowledge while ensuring they reap direct benefits from projects. By building the capacity of local communities and stakeholders through training in sustainable resource management and establishing economic incentives, such as eco-tourism and payments for ecosystem services, the basin's conservation can become a shared responsibility and benefit. Collaborative efforts involving governments, NGOs, communities, and the private sector can ensure profitable and environmentally sound energy projects. Public awareness campaigns can further rally broader support by emphasizing the basin's ecological significance and the imperative balance between development and conservation. Strengthening the legal framework with rigorous regulations, coupled with penalties for non-compliance and solid project oversight, is another pillar of this balanced approach. Further, an investment in research and development can lead to innovative hydropower technologies and a richer understanding of the basin's unique ecology, ensuring a harmonious blend of development and conservation.

6 Conclusion and Recommendations

While driving development, hydroelectric endeavors also prompt significant social and environmental disruptions. Their establishment often results in families' displacement, imperils traditional livelihood means, fractures communal bonds, and compromises environmental integrity. Uprooted communities encounter challenges accessing vital water, electricity, and sanitation services. The once-lived ecosystem, home to various species, undergoes alterations marked by habitat degradation and water source pollution. A noteworthy issue is the limited access that women experience to fundamental necessities like nourishment, healthcare, and shelter post-displacement. Additionally, marginalized groups frequently remain sidelined during compensation efforts.

Through our in-depth exploration of dam construction, we conclude that while dams are instrumental for a nation's economic trajectory, their implications are profound, particularly in regions like the Dhauliganga basin. With its pristine and unique ecosystems, this basin is on the brink of witnessing severe disruptions due to damming and associated hydroelectric projects. Such infrastructural developments are slated to fracture habitats and, over time, erode biodiversity. It's evident from local dissent, which underscores genuine concerns over the area's rich biodiversity and deeply entrenched cultural beliefs.

Mitigation, then, isn't just an option but a necessity. Focused efforts on implementing effective mitigation strategies and rigorous policy adherence are essential. Policymakers ought to prioritize areas with lower ecological sensitivity. It's imperative for the government to stringently apply Environmental Impact Assessment (EIA) regulations, with an emphasis on post-construction management and monitoring of sanctioned projects. This balanced approach ensures progress while safeguarding the region's invaluable natural and cultural heritage.

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Assessment of the Impact of Big Dams in the Himalayan Mountain Environment System: Management and Sustainability

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Abstract Dams are an ancient innovation for irrigational and household requirement purposes. Nowadays, it is mainly used for irrigation and hydropower electricity generation. Himalayan rivers have more than 600 dams, adding to the upstream flow velocity and causing significant sediment accumulation around the impoundments. Loss of forest cover, animal species, and human settlements are evident due to the construction of dams and reservoirs. An assessment of the Indian Himalayan Region (IHR) is conducted to evaluate the relationship between various factors and parameters which directly and indirectly affect the dam sites and its periphery. The vulnerability of the ecosystem increases because the study area is a seismically active zone, and anthropological impacts accentuate the possibilities of hazards. The focus is to study the large dams in the Indian States, namely, Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, Assam, and Arunachal Pradesh. The three main river basins, Indus, Ganga and Brahmaputra, are included for better understanding. Major problems like sedimentation, lack of nutrients downstream, and hindrance to the mobility of the riverine species, mainly the fish during their spawning period. The changes have shown differences between the designed and observed rate of siltation (Th.Cu.m/sq. km./Yr). Maps have been generated from QGIS (v3.14) software to represent better the different aspects of the analysis—a graphical data representation was prepared with the help of the data provided by the India Water Resource Information System (WRIS-India) and Central Water Commission (CWC) websites. The entire study is done through secondary data and information.

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1 Introduction

1.1 Background

A dam built across a river is an engineering structure designed to benefit the people and an artificial construction that considerably modifies ecosystems and alters hydrological regimes (Valdiya, 1993). Dams primarily benefit hydroelectric energy generation, irrigation, flood control, drinking water supply, and recreational uses. The major river basins of the Indus, Ganga, and Brahmaputra have dams built in the Indian Himalayan Region (IHR), which stretches from the north and northwest to the extreme east of the nation. Earthen/gravity and masonry and rockfill dams are the primary kinds built explicitly in these locations. Dam storage areas and the dam site's sediment profile are interdependent. The reservoir zones are the full reservoir level (FRL), maximum water level (MWL), minimum pool level, dead storage capacity, live/valuable storage capacity (Calculation of Storage Capacity and Safe Yield of a Reservoir, 2021), bank storage, valley storage, and flood/surcharge storage. The storage levels and outputs of the dams are significantly impacted as the silt profile along the reservoir walls grows.

Over 2500 km long, the Himalayan Mountain range directly influences the physical and anthropological factors. The Himalayas (Weidinger, 2011) are separated into three primary, different sections based on the variations in altitude along the mountains. The three primary divisions are the Lower/Shiwalik Himalayas, Middle/Lesser Himalayas, and Greater/Himadri Himalayas. The Indus (36° 59' N and 79° 39' E) (Hewitt, 1968), Ganga (31° 21' N and 89° 5' E), and Brahmaputra (30° 3' N and 96° 57' E) are the three major river basins which make up the whole range. The Tibetan Bokhar Chu area near Lake Manasarovar, Gangotri Glacier, and Angsi Glacier, respectively, is the point of origin of the Indus, Ganga, and Brahmaputra rivers. The upper river course of the corresponding basins is included in the research area. As a result, the river channels throughout its route are extremely deep and narrow, forming V-shaped valleys. Dam locations along these higher river systems must be constantly monitored and maintained because of their geomorphic hazard susceptibility. The consequences of excessive sedimentation (Annandale, 1987; Wang et al., 2005) are dangerous. The greater river water velocity naturally results in higher production of sediments in the middle and lower river courses. However, because the dams operate as a physical barrier and progressively control river flow and sediment deposition, the silt level along the reservoir's walls is highlighted. The pressure on the reservoir walls also grows as the sediment load does. Long-term water flow pressure and sediment loads cause the walls to deteriorate, which can lead to catastrophic wall collapse and flood conditions.

Various techniques and methods are adapted to analyse the variabilities and dynamics of the sediment accumulation, river water inflow, sediment inflow, bathymetry, topography, relief, etc. Remote Sensing techniques are shown in Table 4.1. *Various Sources and Platforms developed by Different Countries for Remote Sensing Surveys* are upgraded for comprehensive visual interpretation over time. The satellite-based data and information could be extracted from numerous software and platforms.

Another technique for primary survey and data extraction as shown in Table 4.2. *Various Instruments and Equipment for Hydrographic Survey and their Applications* for hydrological study is Hydrographic surveys (Hydrographic Survey Equipment, 2022) are carried out by specialists like researchers, oceanographers, marine scientists, hydrologists, hydraulic engineers, fluvial geomorphologists, civil engineers, etc. Instruments required for these procedures include complex manned and unmanned equipment (probes), namely, Remotely Operated Vehicles (ROV), Autonomous Unmanned Vehicles (AUV), Unmanned Surface Vehicles (USV), Profiling Floats, Towed Systems, Underwater Laser Scanners, RTK GNSS Receivers, Tethered ROV, Underwater Altimeters, etc.

Dams and Spillways have sharp positive and negative effects. The Himalayan River basins (Lu et al., 2009; Mishra et al., 2019) support ecosystem services and

Table 4.1 Various sources and platforms developed by different countries for remote sensing survey

Free satellite imagery sources	Sources developed by countries
USGS earth explorer	USA
EOSDA land viewer	USA
Copernicus data space ecosystem	EU (European Union)
Sentinel hub	EU (European Union)
NASA earth data search	USA
INPE image catalogue	Brazil
Google earth	USA
NOAA data access viewer	USA
NOAA CLASS	USA
Earth on AWS	USA
Zoom earth	UK
Maxar open data program	USA
NASA worldview	USA
JAXA's ALOS World 3D	Japan
VITO vision	EU
Global land cover facility	USA
UNAVCO	USA
Bhuvan Indian geo-platform Of ISRO-NRSC	India

Source EOS data analytics (Sergieieva, 2023)

Table 4.2 Various instruments and equipment for hydrographic survey and their applications

Hydrographic survey instruments	Application
Remotely operated vehicles (ROV)	Offshore Oil and Gas Industry, marine science and exploration, underwater construction and infrastructure, search and rescue operations, military and defence, archaeological exploration, and environmental monitoring
Autonomous unmanned vehicles (AUV)	Pipeline and cable inspection, military and defence, and search and rescue operations
Unmanned surface vehicles (USV)	Hydrographic surveys, port and harbor management, aquaculture, surveying and mapping, and military applications
Profiling floats	Climate studies, weather forecasting, ecosystem monitoring, and modelling and validation
Tethered boats	River crossings, emergency situations, environmental monitoring, maintenance and construction and military applications
Bathymetric LiDAR	Habitat mapping and fisheries management, disaster response and emergency management, and coastal and ocean mapping
Towed systems	Seismic surveys, cable laying, fishing, hydrographic surveys, search and rescue operations
Underwater altimeters	Underwater archaeology, environmental monitoring, and underwater vehicle navigation
RTK GNSS receivers	Surveying and mapping, agriculture, autonomous vehicles, monitoring and geodesy, surveying for utilities, and marine and offshore applications

Source Unmanned systems technology, hydrographic survey equipment (Hydrographic Survey Equipment, 2022)

contribute to the "Himalayan biodiversity hotspot." The building of dams and the operation of reservoirs have changed the natural landscape, harmed local species, and led to the removal of dams. This research evaluates the ecosystem services provided by reservoirs in the Teesta River basin of the Eastern Himalayas. The environmental services offered by RBWs, which include 13 significant dams and a diversion barrage, are evaluated in research. The report names reservoirs worldwide, including the Himalayas and Teesta basins, and suggests management and conservation measures to preserve these resources. No new dams, little regulation, and water-sharing policies are examples of conservation techniques that may turn environmental risks into assets. The Current Science Association conducted a study using GIS and remote sensing to analyse land use and land-cover changes in the Tehri dam catchment in Uttaranchal, India. The research found that large dams (High Dams in the Himalayas, n.d.) negatively impact life-support strategies, affecting 2687 ha of agricultural land and making 3347 ha around the reservoir rim unfit for cultivation. The Himalayan terrain offers cost-effective conditions for dam construction, but its fragility raises concerns about water scarcity. The study focuses on the reservoir rim area, expected to produce 2000 MW of electricity, irrigate 270,000 hectares, and provide drinking water to New Delhi (Himalaya et al., 2002). India's dam-building program aims to meet energy demand, power the largest population, and reduce CO_2 emissions. Biodiversity impacts are assessed, but dam construction could lead to habitat loss and climate change impacts (Ahmad et al., 2021; Grumbine & Pandit, 2013; Khan et al., 2020; Richer et al., 2019).

The research gap in this study is that the entire Indian Himalayan Region (IHR) has not been considered for vulnerability assessment with the help of a primary or hydrographic survey. Primary impacts include bank erosion and landslides, which can aggravate erosion and sedimentation problems depending on the river segment's topography and geology (Higaki & Sato, 2012). The remote sensing survey data of the reservoirs (Biresaw et al., 2021) in the IHR as secondary data must be sufficient for the analysis. This study's research limitations are acquiring the river discharge data from the Indian Government websites, namely, CWC (Central Water Commission) and WRIS (India Water Resources Information System). This parameter would help construct the supporting diagrams of sedimentation in the reservoirs. A deductive approach has been conducted by studying multiple research works, which has concluded that due to the heavy sedimentation rate, the weakening of the reservoir walls increases, increasing the risk of destruction of the dam site, which leads to regional floods, settlement shift and loss of flora and fauna. The security of people and infrastructure (Zheng et al., 2023) is seriously threatened by the damming of rivers caused by landslides. Predicting landslide-induced river damming is extremely important for quantitative risk assessment (Valyaev et al., 2005) and emergency response planning. A credible physically based forecast of landslip dam development is still difficult to make because of the significant uncertainties contained in the input parameters and dynamic numerical models. In this study, we suggested a probabilistic framework to forecast river damming brought on by rockslides and the barrier lake that goes along with it (Zeng et al., 2022). In examining hydrologic processes and river basin management (Schleiss et al., 2016), sediment load is crucial. Few studies have examined the combined influence of rainfall and reservoir on changes in downstream sediment load. Many studies have individually examined the effects of rainfall or reservoirs on the downstream sediment load. The sediment load change in the Wujiang River Basin (WRB) between 1952 and 2017 was measured using a Rainfall-augmented Sediment Trapping Index (RSTI) that takes into account the effects of adequate rainfall and reservoir sediment trapping capacity in order to determine the optimum way to use the suggested RSTI to disclose the combined influence of rainfall and reservoir on the downstream sediment load of WRB, eight linear or nonlinear regression models were built (Xiong et al., 2020).

1.2 Statement of Problem

The problems addressed (Kothyari, 2011a, b) by the large dams in the Indian Himalayan Region (IHR) are the location, size and association with the actively seismic zones (Valdiya, 2014), which are prone to destruction and disaster. The

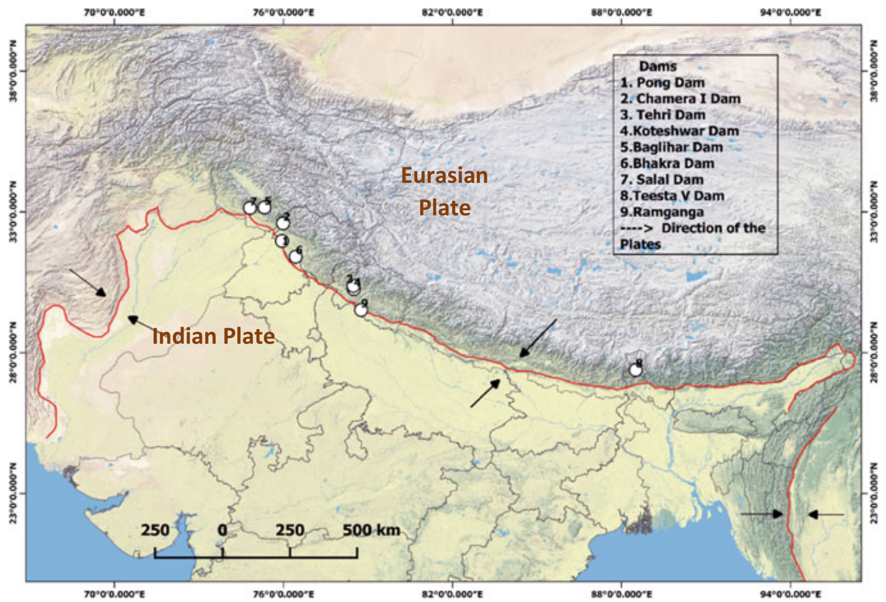

Fig. 4.1 Location of Large Himalayan Dams in the Upper Himalayan Region (Himadri) showed on ESRI Terrain Map

vulnerable population (Fort et al., 2010) and human settlements are alarmed by this fact. A new form of dam that combines the benefits of both the gravity dam and the rockfill dam is the Cement-Sand-Gravel (CSG) dam. Low shear strength and high dispersion characterise the materials utilised to construct the CSG dams. Using finite element software, static analyses of the 100 m gravity dams and SCG dams were performed to evaluate the stability and reliability of these dams. The analytical results were then utilised to calculate the reliability of the dams using the JC technique (Agarwal et al., 2022).

Figure 4.1 depicts the position of the dams on the Eurasian Plate and the tectonically active line taken from the USGS Tectonic Plates (Quick Map Services Plugin). However, because Pong Dam and Ramganga Dam are roughly on the plate edge, there is more danger of calamities, including earthquakes (Jatana, 1999b), landslides, dam failures, and floods caused by failed dams (Hewitt, 1982). Another indicator of heightened catastrophe susceptibility is the presence of other dams close by.

1.3 Objective of the Study

To analyse the sedimentation yield (Fan and Morris, 1992; Jain et al., 2010; Froehlich, 2018; Asthana and Khare, 2022) of the Himalayan dams in the following Indian states: Jammu and Kashmir, Ladakh, Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, and Assam.

To assess the ecological imbalance, biodiversity loss, and Carbon Dioxide (CO_2) and Methane (CH_4) gas emissions from the Himalayan reservoirs, which significantly impact global climate change.

To investigate how different the dam's construction impacts species (flora and fauna) in the riverine system.

1.4 Significance of the Study

It facilitates the government, decision-makers (Bandyopadhyay, 2002), experts, and local citizens to understand the environment and what actions must be made to reduce the deterioration of biota.

Learning more about the dangers and susceptibility of the areas where dam building or population relocating is planned is beneficial.

1.5 Location of the Study Area

The whole Indian Himalayan Region (IHR), which includes the Indian states of Jammu and Kashmir, Ladakh, Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, and Assam, makes up the research area location.

The Indian Himalayan Region (IHR) spans roughly 36°10′55"N and 72°33′58'E and 28°05′44"N and 97°22′54"E (Fig. 4.2).

The specific dam sites in the IHR which surpasses the criteria of *Commission Internationale Des Grands Barrages-International Commission on Large Dams (CIGB ICOLD)* classification of large dams have been chosen for analysis.

As per International Commission on Large Dams (ICOLD) Specification

A large dam is classified as one with a maximum height of more than 15 metres from its deepest foundation to the crest.

A dam between 10 and 15 metres in height from its deepest foundation is also included in the classification of a large dam provided it complies with one of the following conditions:

a) length of crest of the dam is not less than 500 metres or

b) capacity of the reservoir formed by the dam is not less than one million cubic metres or

c) the maximum flood discharge dealt with by the dam is not less than 2000 cubic metres per second or

d) the dam has specially difficult foundation problems, or

e) the dam is of unusual design.

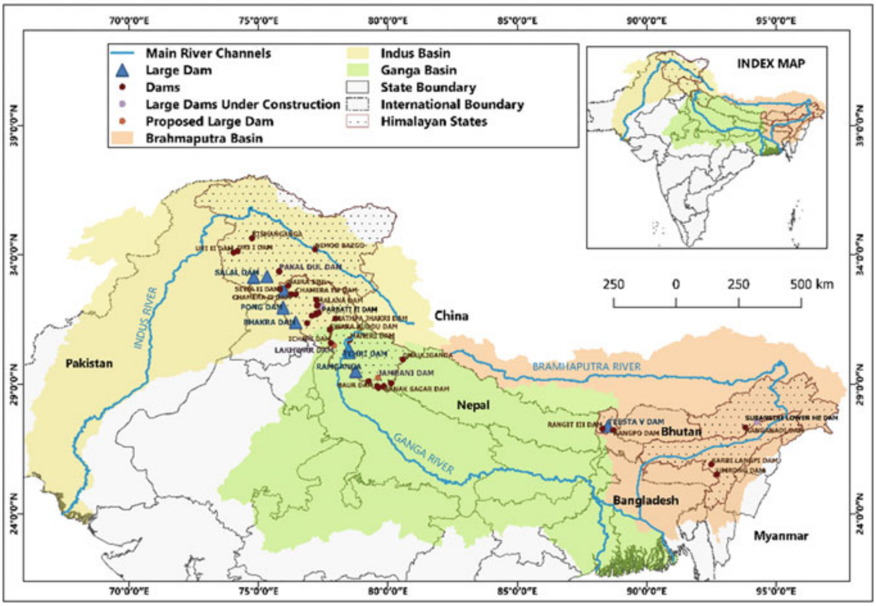

Fig. 4.2 Study Area Map prepared in QGIS v3.14 showing the Three main River basins of Northern Indian Subcontinent with its main river channels, namely, Indus, Ganga and Brahmaputra

2 Methodology

2.1 Datasets

This methodology outlines the steps in conducting a secondary survey using remote sensing imagery from various sources such as USGS Earth Explorer, ESRI Terrain, ISRO Bhuvan, GSI Bhukosh, and DIVA-GIS. The objective of the survey is to gather relevant information for research or analysis purposes. The methodology includes steps for data acquisition, image processing, data analysis, and interpretation. Using multiple remote sensing platforms and tools ensures comprehensive coverage and enhances the accuracy and reliability of the survey results.

The secondary survey aims to gather information and derive insights from existing remote sensing imagery available through different platforms. The combination of USGS Earth Explorer, Google Earth Pro, and DIVA GIS provides access to a diverse range of satellite data, elevation models, and geospatial information for comprehensive analysis. QGIS 3.14. used for the preparation of maps for visual interpretation.

2.2 Data Acquisition

2.2.1 USGS Earth Explorer

Access to the USGS Earth Explorer platform and registration of an account was done for downloading the SRTM DEM images (Fig. 4.3).

Only the specified study area images were selected based on the desired satellite sensor, imagery type, and date range.

The relevant satellite imagery in the GeoTIFF format was downloaded.

For downloading Geological map of study area USGS Cert Mapper websites has been used, https://certmapper.cr.usgs.gov/data/apps/world-maps/ (Fig. 4.4).

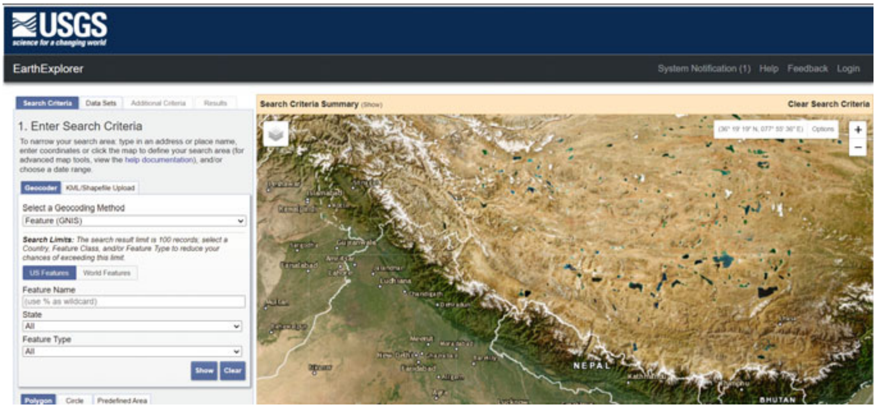

Fig. 4.3 USGS Earth Explorer Webpage (Screenshot Retrieved on May 6, 2023)

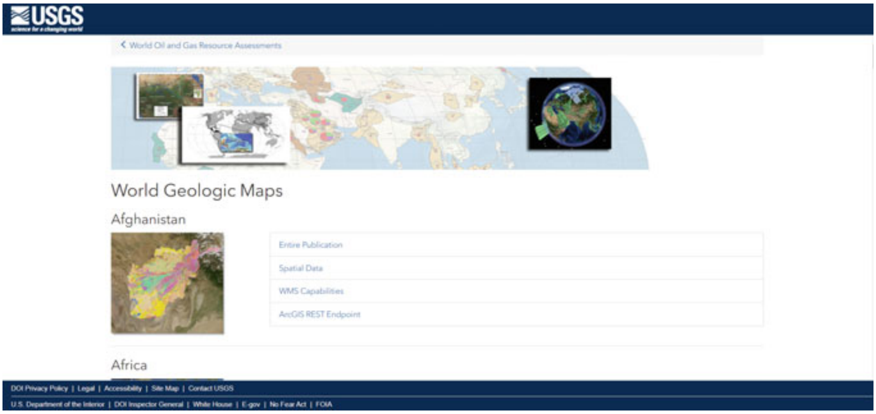

Fig. 4.4 USGS Cert mapper webpage (Screenshot Retrieved on May 2, 2023)

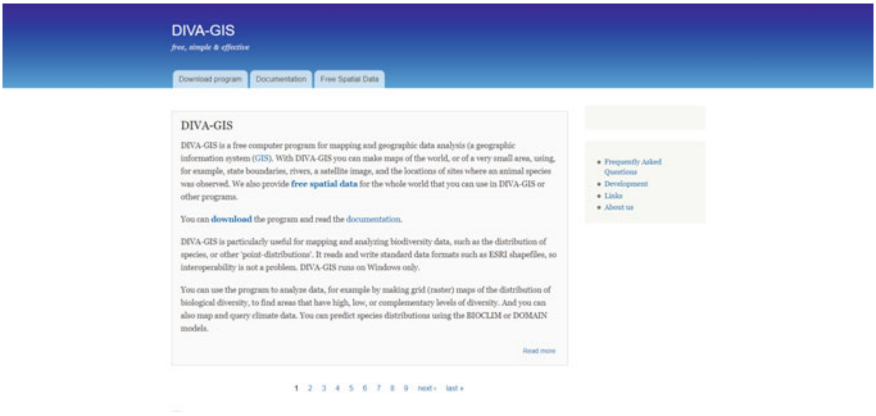

Fig. 4.5 DIVA GIS Webpage (Screenshot Retrieved on May 1, 2023)

1. geo8ag file has been extracted which shows the geological provinces of Indian subcontinent. The entire data has been modified in the QGIS v. 3.14. Software for the data extraction of the exact geology of the study area.

2.2.2 DIVA GIS

DIVA-GIS has been chosen for downloading the shape files of HydroBasins of Indus, Ganga and Brahmaputra (Fig. 4.5).

A file named 'hybas_as_lev01-12_v1c' has been downloaded, showing Asia's river basins. It comprised 12 levels of river basins from macro to macro, ranging in various spatial extent. The shapefile was edited to extract only three river basins for the study. The three river basin files are as follows:

- hybas_as_lev04_v1c.shp for Indus Basin
- hybas_as_lev05_v1c.shp for Ganga Basin
- hybas_as_lev04_v1c.shp for Brahmaputra Basin

2.2.3 Google Earth Pro

In order to export the information in QGIS and make additional changes, the online edition of Google Earth Pro was used to extract KML (Keyhole Markup Language) format files of the pathways of the main channels of the Rivers Indus, Ganga, and Brahmaputra (line); and position of large dam sites (point). Additionally, Google Earth Pro was used to analyse the proposed and currently under construction dams (Fig. 4.6).

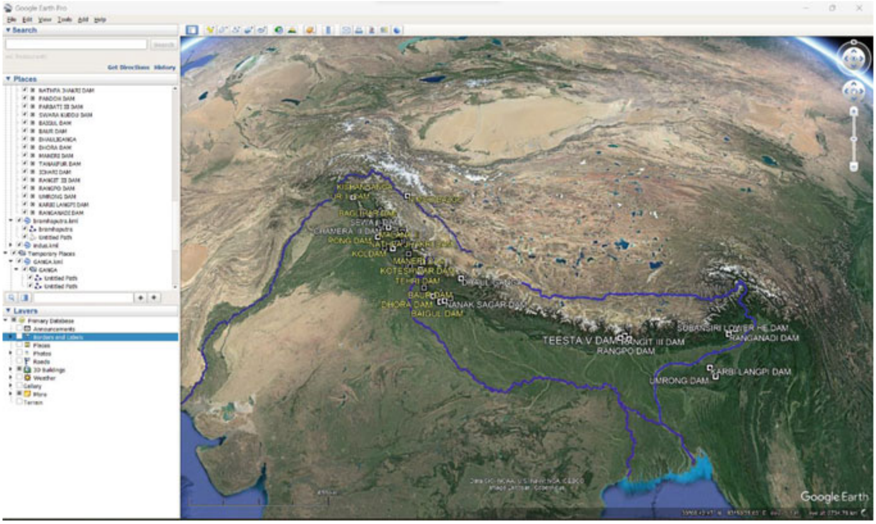

Fig. 4.6 Google Earth Pro Version 7.3.6.9345 (64-bit) Application showing the selected KML layers of River Indus, Ganga and Brahmaputra and 9 Selected Large Dam Sites of IHR (Screenshot Retrieved on May 2, 2023)

2.2.4 QGIS version 3.14

The research area map, geology map, and position of the huge dams on the tectonically active zones in the Indian Himalayan Region were prepared using significant QGIS (Saha et al., 2002) tools and plugins. The maps mentioned above were created using Quick Map Services and Profile Tool Plugins.

2.2.5 India-WRIS (Water Resources Information System)

Data and information about the dams, classified by state and ICOLD (International Commission on Large Dams), have been gathered. The India-WRIS website has also been used to study the literature pertaining to the dams and hydrology of the IHR. Table 4.3a, b. are the data collection results from the India-WRIS website (Table 4.4).

2.3 Image Processing

2.3.1 Data Preprocessing

The downloaded KML river channel data, SRTM DEM pictures, and shapefiles of river basins have all been combined, cropped, and then overlaid in accordance

Table 4.3 a. Large dams according to ICOLD, India WRIS

Sl. No.	Name	Purpose	River	Nearest city	District	State	Basin
1	Tehri Dam	Hydroelectric, Irrigation	Bhagirathi	Pratapnagar	Tehri Garhwal	Uttarakhand	Ganga
2	Lakhwar Dam	Hydroelectric,Irrigation	Yamuna	Dehradun	Dehradun	Uttarakhand	Ganga
3	Bhakra Dam	Hydroelectric, Irrigation, Recreation	Satluj	Bilaspur	Bilaspur	Himachal Pradesh	Indus up to International Border
4	Pakal Dul Dam	Hydroelectric	Marusudar	Kishtwar	Kishtwar	Jammu and Kashmir	Indus up to International Border
5	Baglihar Dam	Hydroelectric	Chenab	Ramban	Ramban	Jammu and Kashmir	Indus up to International Border
6	Chamera I Dam	Hydroelectric	Ravi	Bhattiyat	Chamba	Himachal Pradesh	Indus up to International Border
7	Pong Dam	Hydroelectric, Irrigation	Beas	Dera Gopipur	Kangra	Himachal Pradesh	Indus up to International Border
8	Jamrani Dam	Irrigation	Gola	Naini Tal	Nainital	Uttarakhand	Ganga
9	Subansiri Lower HE (Nhpc) Dam	Hydroelectric	Subansiri	Lower Subansiri	Lower Subansiri	Arunanchal Pradesh	Brahmaputra
10	Ramganga Dam	Hydroelectric, Irrigation	Ramganga	Lansdowne	Garhwal	Uttarakhand	Ganga
11	Salal (Rockfill And Concrete) Dam	Hydroelectric	Chenab	Gool Gulab Garh	Reasi	Jammu and Kashmir	Indus up to International Border
12	Koteshwar Dam	Hydroelectric	Bhagirathi	Pratapnagar	Tehri Garhwal	Uttarakhand	Ganga

(continued)

Table 4.3 (continued)

Sl. No.	Name	Purpose	River	Nearest city	District	State	Basin
13	Teesta -V (NHPC) Dam	Hydroelectric	Teesta	North	North	Sikkim	Brahmaputra
14	Parbati II Dam	Hydroelectric	Parbati	Kullu	Kullu	Himachal Pradesh	Indus up to International Border

b. Large dams according to ICOLD, India WRIS

Sl. No.	Name	Status	Completion Year	Type	Length (m)	Max Height above Foundation (m)	Design Gross Storage Capacity (MCM)
1	Tehri Dam	Completed	2005	Earthen/Gravity and Masonry	575	260.5	3540
2	Lakhwar Dam	Proposed		Earthen/Gravity and Masonry	451	204	587.84
3	Bhakra Dam	Completed	1963	Earthen/Gravity and Masonry	518.16	167.64	9867.84
4	Pakal Dul Dam	Proposed		Earthen/Gravity and Masonry	305	167	0.1254
5	Baglihar Dam	Completed	2009	Gravity and Masonry	364.362	143	475
6	Chamera I Dam	Completed	1994	Earthen/Gravity and Masonry	295	140	242.3
7	Pong Dam	Completed	1974	Earthen/Gravity and Masonry	1950.7	132.59	8570
8	Jamrani Dam	Proposed	1990	Gravity and Masonry	465	130.6	
9	Subansiri Lower HE (NHPC) Dam	Under Construction	2014	Gravity and Masonry	284	130	1643

(continued)

Table 4.3 (continued)

b. Large dams according to ICOLD, India WRIS

Sl. No.	Name	Status	Completion Year	Type	Length (m)	Max Height above Foundation (m)	Design Gross Storage Capacity (MCM)
10	Ramganga Dam	Completed	1974	Earthen	630	127.5	2448
11	Salal (Rockfill And Concrete) Dam	Completed	1986	Earthen/Gravity and Masonry	487	113	28.5
12	Koteshwar Dam	Completed		Gravity and Masonry	300.5	97.5	88.9
13	Teesta -V (NHPC) Dam	Completed	2007	Gravity and Masonry	176.5	86.8	13.5
14	Parbati II Dam	Under Construction		Gravity and Masonry	101.5	85	6.55

Source indiawris.gov.in (Government of India Compendium on Sedimentation of Reservoirs in India, 2020); A list of 12 dams have been selected on the basis of the parameters of ICOLD from the selected Indian Himalayan states

Table 4.4 List of downloaded SRTM DEM images for this study

Sl. No.	Name of large dams	State	Entity ID SRTM DEM	Coordinates	Resolution	Date of acquisition
1	Salal Dam	Jammu and Kashmir	SRTM1N33E074V3	33°08′35.11″ N; 74°48′40.29″ E	1-ARC	2000–02-11
2	Baghlihar Dam	Jammu and Kashmir	SRTM1N33E075V3	33°09′45.28″ N; 75° 19′41.55″ E	1-ARC	2000–02-11
3	Chamera-I Dam	Himachal Pradesh	SRTM1N32E075V3	32°35′49.67″ N; 75°59′10.07″ E	1-ARC	2000–02-11
4	Pong Dam	Himachal Pradesh	SRTM1N31E075V3	31°58′00.61″ N; 75°56′49.28″ E	1-ARC	2000–02-11
5	Bhakra Dam	Himachal Pradesh	SRTM1N31E076V3	31°24′40.21″ N; 76°26′00.56″ E	1-ARC	2000–02-11
6	Tehri Dam	Uttarakhand	SRTM1N30E078V3	30°22′38.67″ N; 78°28′49.20″ E	1-ARC	2000–02-11
7	Koteshwar Dam	Uttarakhand	SRTM1N30E078V3	30°15′36.88″ N; 78°29′52.54″ E	1-ARC	2000–02-11
8	Ramganga (Kalagarh) Dam	Uttarakhand	SRTM1N29E078V3	29°31′03.24″ N; 78°45′21.55″ E	1-ARC	2000–02-11
9	Teesta-V Dam	Sikkim	SRTM1N27E088V3	27°23′12.47″ N; 88°30′14.38″ E	1-ARC	2000–02-11

Source USGS Earth explorer Selected SRTM DEM Meta Data

with the size of the research region. The altered USGS geology map has also been superimposed over the map of India. The USGS Tectonic Plates and ESRI Terrain were the foundation maps in the position map (Fig. 4.1) of the big dams on the tectonically active zones in the Indian Himalayan Region (Fig. 4.7).

To better depict the analysis, data fusion of several images collected from diverse sources has been carried out.

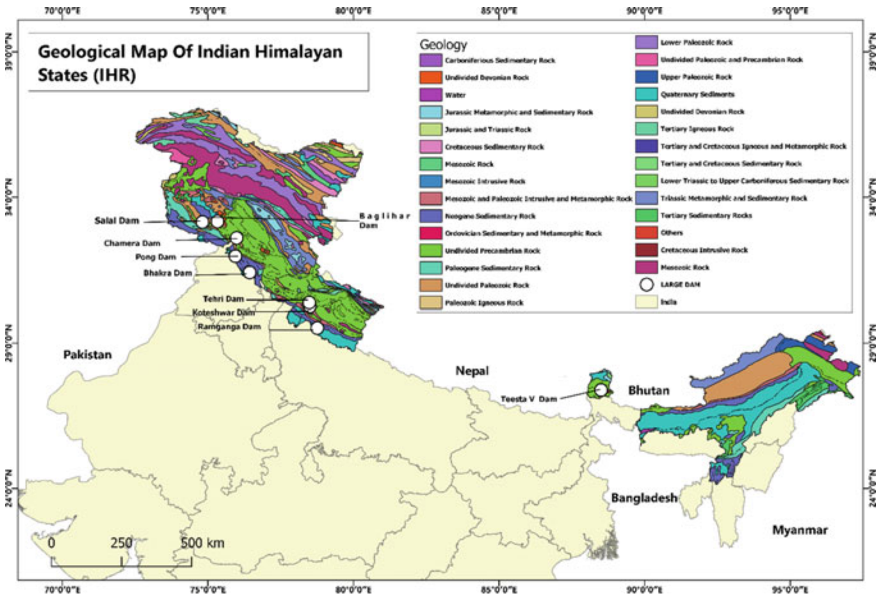

Fig. 4.7 Geological map of the study area prepared in QGIS Software (v. 3.14) showing the variety of rock composition of the large dam sites in IHR (Indian Himalayan Region)

With the aid of the Profile Tool plugin for QGIS, long and cross profiles have also been created. Cross-reservoir profiles have been created upstream and downstream (Li et al., 2020) to compare the topography and sediment deposition (Zakwan & Ahmad, 2021). Long profiles have been produced along the reservoir from upstream to downstream to compare the cross profiles with the extended profile.

2.3.2 Data Analysis and Interpretation

Based on secondary data and sources, all the prepared maps were created. Inferred from satellite photos of the potential dam locations are the cross profiles of the reservoirs upstream and downstream. The cross profiles are interpreted, and a visual analysis is conducted.

- **Salal Dam**- The impoundment of this dam is located on the Chenab River, Jammu and Kashmir (33°08′35.11" N; 74°48′40.29" E). Construction of the Salal Dam (Salal Project, 2023) began in 1971 and was completed in 1987. The dam stands at approximately 113 m (371 ft) and spans the Chenab River, creating a large reservoir known as Salal Lake. The reservoir has a storage capacity of 347 million cubic metres (281,000 acre- ft) of water (Compendium on Sedimentation of Reservoirs in India, 2020).

By examining the satellite image (Fig. 4.8), it is possible to see that the reservoir has reached its maximum storage capacity, the downstream is smaller than the upstream, and the pace of silt buildup (Zhou et al., 2023) has accelerated, as evidenced by the deposits of sediment (Jain et al., 2003) along the river banks (Bhattacharyya & Singh, n.d.). The quantity of silt carried by the river that feeds a reservoir determines the pace at which it silts up, which in turn relies on the rate of soil erosion in the river's catchment region (Kanwal, n.d.).

The upstream cross profile shows the water storage depth with an elevated river bed on both sides below water, as per Fig. 4.7. Geological Map of the Study Area: The Salal Dam site comprises Undivided Precambrian rock and Undivided Paleozoic rock compositions. Precambrian rocks are highly diverse and exhibit a wide range of lithologies, including igneous, metamorphic, and sedimentary rocks. They are often characterised by their intricate structures and compositions, reflecting the dynamic geological processes (Overview of the Geology of the Himalayas Amber Madden-Nadeau Geology for Global Development, n.d.) that occurred during this era. Undivided Precambrian rocks are generally devoid of fossils or contain very limited and poorly preserved fossil remains. This absence of complex life forms is because multicellular organisms had yet to evolve during this early period of Earth's history. The Paleozoic era witnessed significant tectonic activity, including the formation of mountain ranges through processes like continental collisions and volcanic activity. A significant example of the collision of Indian and Tibetan plates can be mentioned. Undivided Paleozoic rocks consist primarily of sedimentary deposits formed in various environments such as oceans, shallow seas, deltas, and swamps. These sediments include limestone, sandstone, shale, and coal, among others, indicative of the environmental conditions during that time. These sedimentary rocks are exposed to fluvial erosion by the Chenab River (Rao et al., 1997) (Indus (Up to Border) Basin Version 2.0, n.d.) at 1627 ft above mean sea level (Salal Project, 2023).

Therefore, a high concentration of sediments was transported from the upstream region of the Chenab River.

- **Baghlihar Dam**- The Baghlihar Dam, also known as the Baglihar Hydroelectric Power Project, is a notable dam and hydroelectric power plant on the Chenab River in the Indian-administered state of Jammu and Kashmir. It is located in the Ramban district, approximately 90 kms (56 miles) downstream of the state's capital, Srinagar.

Construction of the Baghlihar Dam began in 1999 and was completed in 2008. The dam stands at approximately 143 m (469 ft) and spans the Chenab River, creating a reservoir known as the Baghlihar Lake. The reservoir has a storage capacity of about 8,400,000,000 cubic meters (6,820,000 acre-ft) of water (Compendium on Sedimentation of Reservoirs in India, 2020).

By observing the cross profiles of upstream and downstream (Fig. 4.9) of the Baghliar Dam site, both the river beds are smooth and have gentle slopes. However, the sedimentation rate (Kothyari, 1996) is also high in this region due to the rock

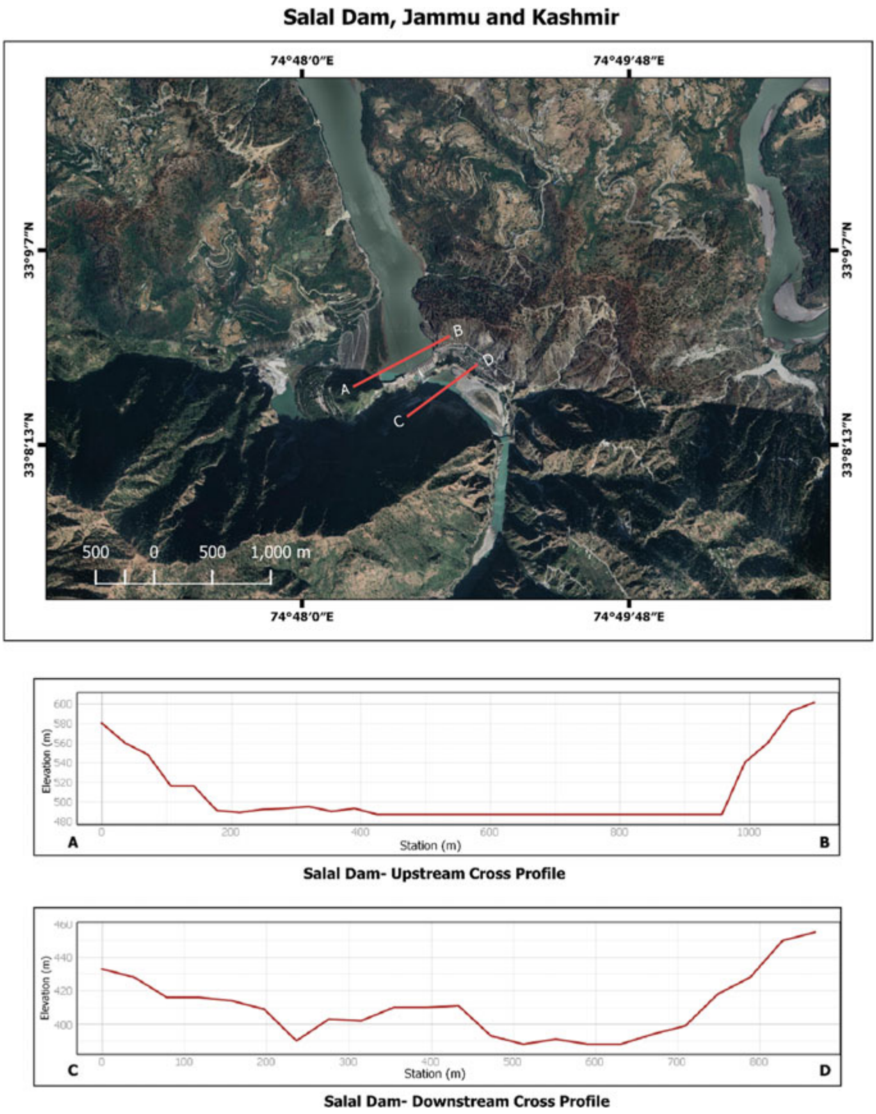

Fig. 4.8 Cross profile of upstream and downstream of Salal Dam (Jammu and Kashmir), image extracted from Google Earth

composition and high river flow velocity where the dam is located at an elevation of 840 m (2755.91 ft) mean sea level.

The geology (Fig. 4.7. Geological Map of the Study Area) of this region is composed of Undivided Paleozoic rock, Tertiary and Cretaceous Igneous and Metamorphic rock, Paleogene Sedimentary rock and Undivided Precambrian Rock. Due

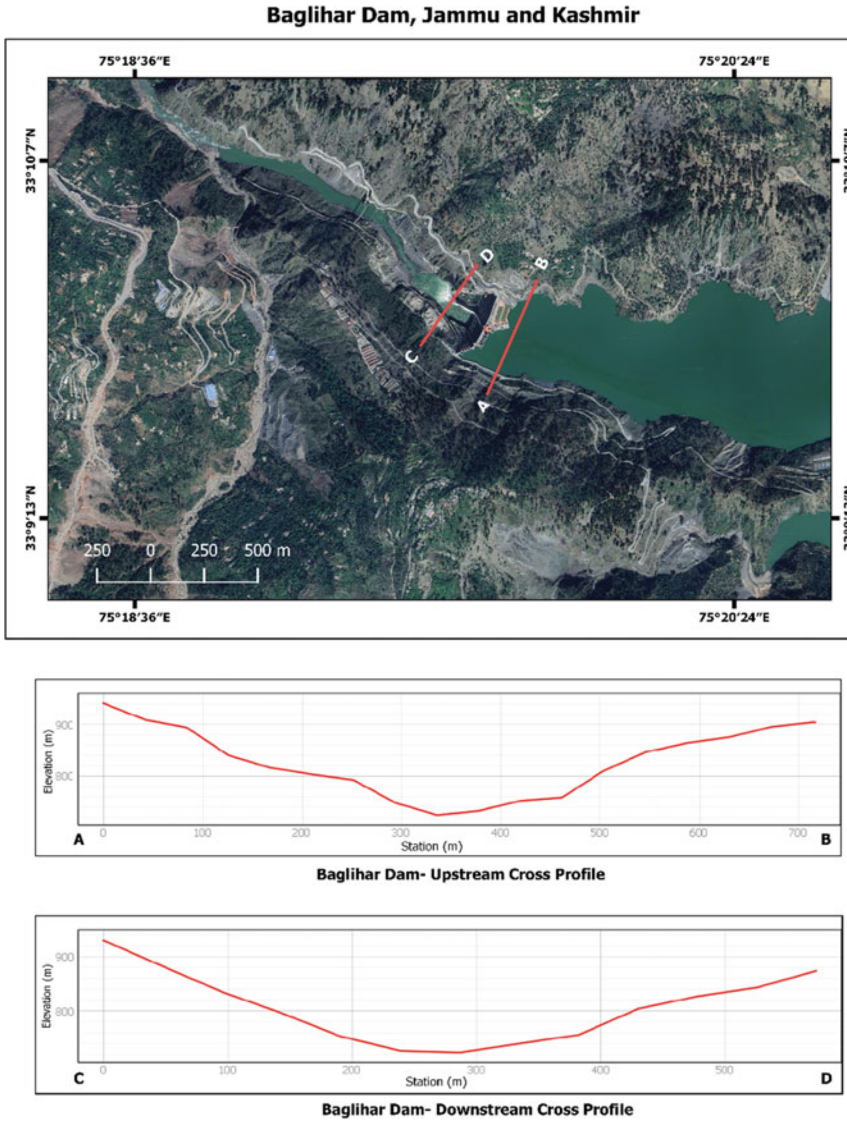

Fig. 4.9 Cross Profile of upstream and downstream of Baghlihar Dam (Jammu and Kashmir), image extracted from Google Earth

to the proximity to the Salal Dam Region, it shares the similarity of rock composition. The Tertiary period occurred approximately 66–2.6 million years ago, while the Cretaceous period preceded it, from around 145–66 million years ago. Igneous and metamorphic rocks formed during these periods are assigned to their respective timeframes. Tertiary and Cretaceous igneous rocks can be found in various compositions, including granite, basalt, and andesite. These rocks often display distinct mineral crystals and textures from their volcanic origins. Tertiary and Cretaceous metamorphic rocks can include gneiss, schist, and marble. These rocks typically exhibit foliated textures and show evidence of intense geological forces acting upon them. Paleogene Sedimentary rocks are sedimentary formations deposited during the Paleogene period from approximately 66–23 million years ago. Paleogene sedimentary rocks encompass a wide range of lithologies, including sandstone, shale, limestone, and conglomerate. Sandstone typically represents ancient river or beach deposits, while shale is formed from fine-grained sediments like clay and silt. Limestone may comprise marine fossils or chemical precipitates, while conglomerates are rounded pebbles or cobbles cemented together. (Overview of the Geology of the Himalayas Amber Madden-Nadeau Geology for Global Development, n.d.).

The constant rate of geomorphic processes of erosion-transportation-deposition (Dutta, 2016) accumulates a high sedimentation rate in the region (Jain et al., 2010). However, there appears to be little sedimentation (Kothyari, 1996) in the downstream when viewing the satellite image.

- **Chamera-I Dam**- Chamera I Dam is a prominent hydroelectric power project situated on the Ravi River in the Indian state of Himachal Pradesh. It is one of the significant dams in the region and plays a vital role in generating electricity and meeting the energy demands of the state and the surrounding areas.

The construction of Chamera I Dam began in 1994 and was commissioned in 1994. The dam stands at a height of approximately 82 m (269 ft) and has a length of about 235 m (771 ft). It creates a reservoir known as the Chamera Lake, which spans an area of around 40 km^2 (15 square miles) and has a storage capacity of approximately 1150 million cubic meters (934,000 acre- ft) of water (Compendium on Sedimentation of Reservoirs in India, 2020).

The primary purpose of the Chamera I Dam is hydroelectric power generation. It has an installed capacity of 540 megawatts (MW) and consists of three generating units, each with a capacity of 180 MW. The power station utilizes the flow of the Ravi River to generate electricity through the process of water turbine rotation.

The satellite image from Fig. 4.10 clearly shows the siltation in the Chamera-I dam's downstream area. Even more so, the waterway has exposed river banks. The river's short depth can be seen in the downstream cross profile, and the reservoir that retains the water is upstream. The upstream cross profile, however, additionally demonstrates the dam site's shallow depth.

The geology of the region (Fig. 4.7. Geological Map of the Study Area) comprises entirely of Undivided Precambrian rock, similar to the dam sites of Salal and Baghlihar. The Undivided Precambrian rocks in the Himalayas provide valuable information about the region's ancient continental growth and crustal evolution. They represent the basement rocks upon which younger sedimentary, volcanic, and metamorphic rocks were subsequently deposited (Overview of the Geology of the Himalayas Amber Madden-Nadeau Geology for Global Development, n.d.).

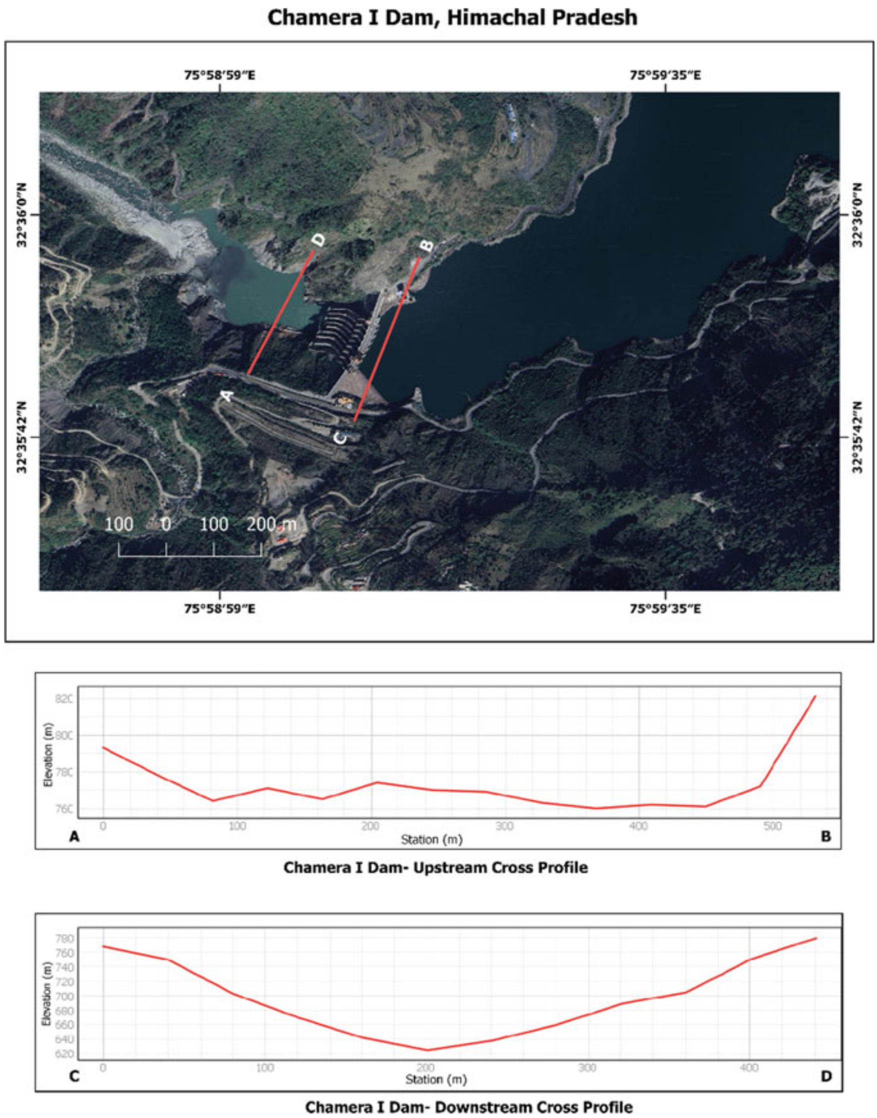

Fig. 4.10 Cross Profile of Upstream and Downstream of Chamera-I Dam (Himachal Pradesh), Image extracted from Google Earth

- **Pong Dam**- Pong Dam, also known as Maharana Pratap Sagar, is a significant dam and reservoir located on the Beas River in the Indian state of Himachal Pradesh. It is named after the revered Rajput warrior Maharana Pratap. The construction of the Pong Dam began in 1961 and was completed in 1974, making it one of India's earliest multipurpose river projects.

The primary purpose of Pong Dam is water storage, irrigation, and hydroelectric power generation. The dam has a height of approximately 133 m (436 ft) and creates a vast reservoir known as Pong Lake. The reservoir has a storage capacity of around 12.4 billion cubic meters (10 million acre- ft). It covers an area of about 45,000 hectares (111,000 acres) when complete (Compendium on Sedimentation of Reservoirs in India, 2020).

The irrigation potential of Pong Dam is substantial, and it serves as a lifeline for agricultural activities in the region. The stored water from the reservoir is released to irrigate agricultural fields, enhancing crop productivity and supporting farmers' livelihoods in the surrounding areas.

An island exists, as seen in Fig. 4.11, in the Pong Dam Lake, which serves recreational purposes. The islands and bars that have formed suggest that there is also substantial siltation in this area. By studying the satellite image, significant deposits of finer particles have been seen in the downstream region. Due to the exposed river beds that can be seen in the picture, the upstream and downstream cross profiles exhibit a modest degree of ruggedness.

The geology of this region (Fig. 4.7. Geological Map of the Study Area) is seen of Neogene sedimentary rocks entirely. The sediments may have been derived from the erosion of pre-existing rocks within the Himalayas or transported from distant sources through rivers and other geological processes. These rock types include sandstone, shale, conglomerate, limestone, and siltstone. The composition and characteristics of these rocks provide clues about the paleoenvironment and depositional history of the region. The Himalayas are known for their complex geological structures, including thrust faults, folds, and uplifted blocks. Neogene sedimentary rocks in the Himalayas have undergone significant deformation and folding due to the compressional forces associated with the ongoing tectonic activity (Overview of the Geology of the Himalayas Amber Madden-Nadeau Geology for Global Development, n.d.).

- **Bhakra Dam**- Bhakra Dam is one of the largest multipurpose dams in India, located on the Sutlej River in the northern state of Himachal Pradesh. It is a monumental engineering project that has played a crucial role in the region's water resource management, irrigation, and hydroelectric power generation.

Construction of the Bhakra Dam began in 1948 and was completed in 1963. The dam stands at a height of approximately 226 m (741 ft) and has a length of about 518 m (1699 ft). The reservoir created by the dam, known as the Gobind Sagar Lake, has a capacity of around 9.34 billion cubic meters (7.56 million acre- ft) of water (Compendium on Sedimentation of Reservoirs in India, 2020).

The primary purpose of the Bhakra Dam (Jain et al., 2002) is to store water for irrigation in the arid regions of Punjab and Rajasthan. The stored water is released through a network of canals, including the Bhakra Main Line and the Nangal Hydel Channel, to irrigate vast agricultural areas, significantly boosting agricultural productivity in the region. This has contributed to the Green Revolution in India, transforming the agricultural landscape and improving food security.

The Bhakra Dam site can be seen in the satellite picture (Fig. 4.12) to have a healthy water flow level and storage in the reservoir. As a result, silt along the river

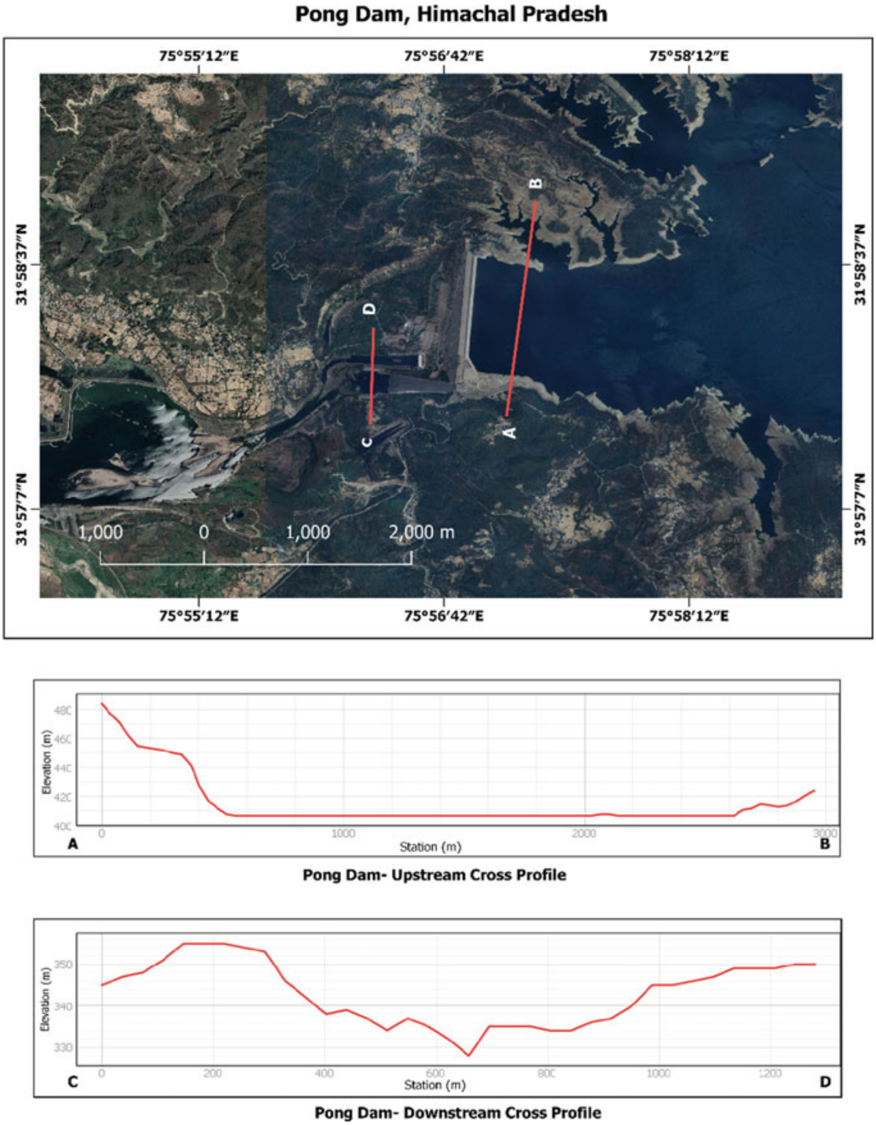

Fig. 4.11 Cross Profile of Upstream and Downstream of Pong Dam (Himachal Pradesh), Image extracted from Google Earth

could be more noticeable. However, the cross profiles of the river's upstream and downstream directions reveal a severe slope on both sides. The downstream generates a U-shaped valley, resulting in a deep channel.

Similar to the terrain around Pong Dam, the geology (Fig. 4.7. Geological Map of the Study Area) of the Bhakra Dam site comprises Neogene Sedimentary Rocks. It

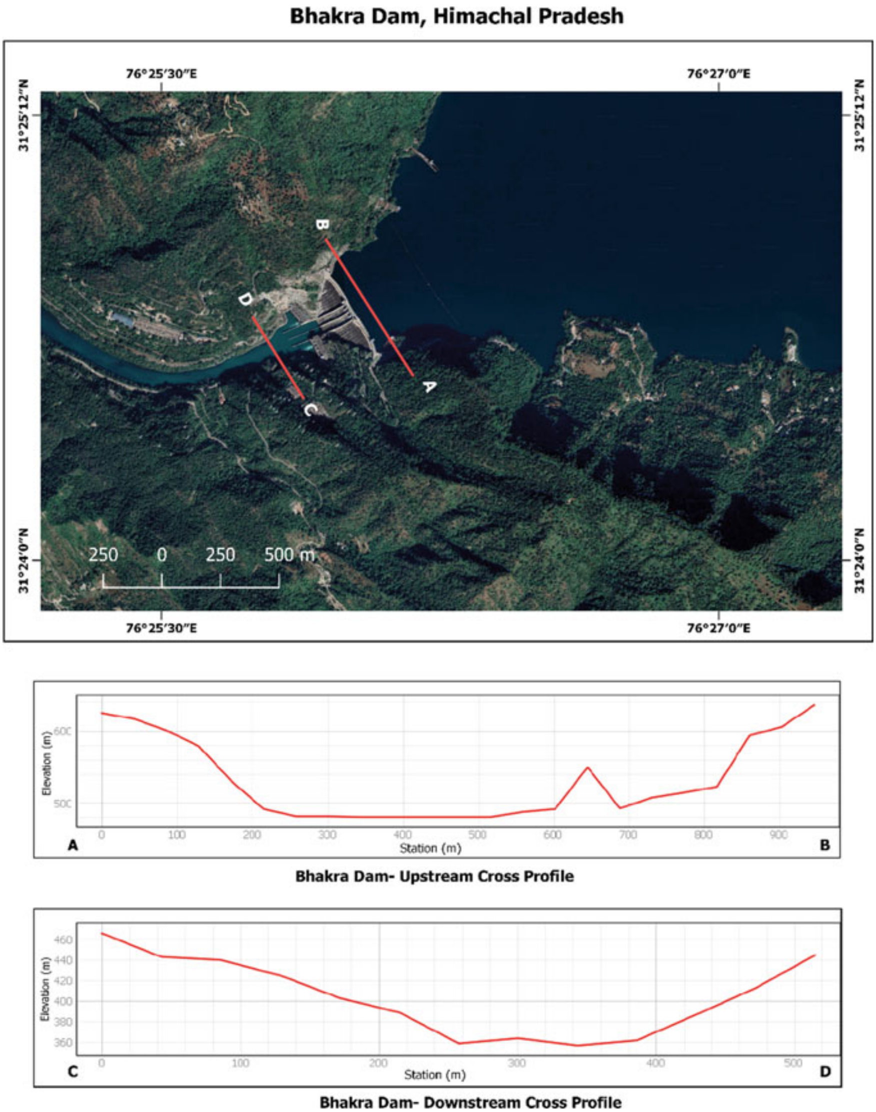

Fig. 4.12 Cross Profile of Upstream and Downstream of Bhakra Dam (Himachal Pradesh), Image extracted from Google Earth

has similar traits to the area around the Pong Dam. A moderate rate of silt deposition is produced due to the more incredible river flow velocity cutting rocks like sandstone, limestone, shale, siltstone, and conglomerate.

- **Tehri Dam**- The Tehri Dam, also known as the Tehri Hydroelectric Complex, is a multipurpose dam project located on the Bhagirathi River near Tehri town in the Indian state of Uttarakhand. It is one of the largest dams in India and serves multiple purposes, including hydroelectric power generation, irrigation, and water supply.

Construction of the Tehri Dam began in 1978, and the first phase was completed in 2006. The dam stands at 260.5 m (855 ft), making it one of the tallest dams in the world. It has a length of approximately 575 m (1886 ft) and a width of 1128 m (3701 ft). The dam creates a reservoir called Tehri Lake, with a storage capacity of about 2.6 billion cubic meters (2.1 million acre- ft) of water (Compendium on Sedimentation of Reservoirs in India, 2020).

The dam has also raised concerns about its potential impact on the region's ecology (Vidal, 2013), particularly on the downstream flow of the Ganges River. Measures have been taken to manage the ecological and environmental effects (Bandyopadhyay and Gyawali, 1994), including implementing environmental flow (Yin et al., 2022) releases to maintain the downstream river ecosystem (Compendium on Sedimentation of Reservoirs in India, 2020).

As the banks of the rivers are visible, the satellite view (Fig. 4.13) reveals a large concentration of sediments along the banks of the upstream Bhagirati River close to the Tehri Dam (Rautela et al., 2002). The Tehri reservoir also has several islands and bars, demonstrating the fast pace of silt buildup. Compared to the downstream cross profile, the upstream cross profile is rough. The downstream cross profile exhibits a mild slope with ongoing river activity.

(Abu El-Magd et al., 2021).

The area of Tehri (Himalaya et al., 2002) has a complicated pattern in its geology (Fig. 4.7. Geological Map of the Study Area). This area in Uttarakhand has intrusive and metamorphic rock from the Mesozoic and Paleozoic, as well as undivided Precambrian rock. Magmatism (Overview of the Geology of the Himalayas Amber Madden-Nadeau Geology for Global Development, n.d.) is how intrusive rocks from the Mesozoic and Paleozoic eras are created. In the upper mantle or lower crust, molten rock is created underneath the Earth's surface, called magma. Heat, pressure, or tectonic action are some physical processes that cause this molten material to ascend. Magma may invade existing rock formations once it has risen to shallower depths, displacing and melting the nearby rocks as it does so. Intrusive rocks are created as the lava solidifies and progressively cools inside the Earth's crust. The texture of the final rock depends on how quickly the lava cools; slower cooling produces bigger crystal sizes. Mesozoic and Palaeozoic metamorphic rocks are created through the process of metamorphism, which entails the modification of pre-existing rocks as a result of changes in temperature, pressure, and chemical conditions. Metamorphism mainly occurs in the Earth's crust, typically at great depths or during tectonic events like the formation of mountains.

High temperatures and pressures cause rocks' minerals to recrystallize and reorganize, producing new minerals and altering the texture and structure of the rock. Sedimentary, igneous, or even metamorphic rocks can transform into metamorphic rocks, with the transformation ranging from low-grade (slight alterations) to high-grade (intense changes).

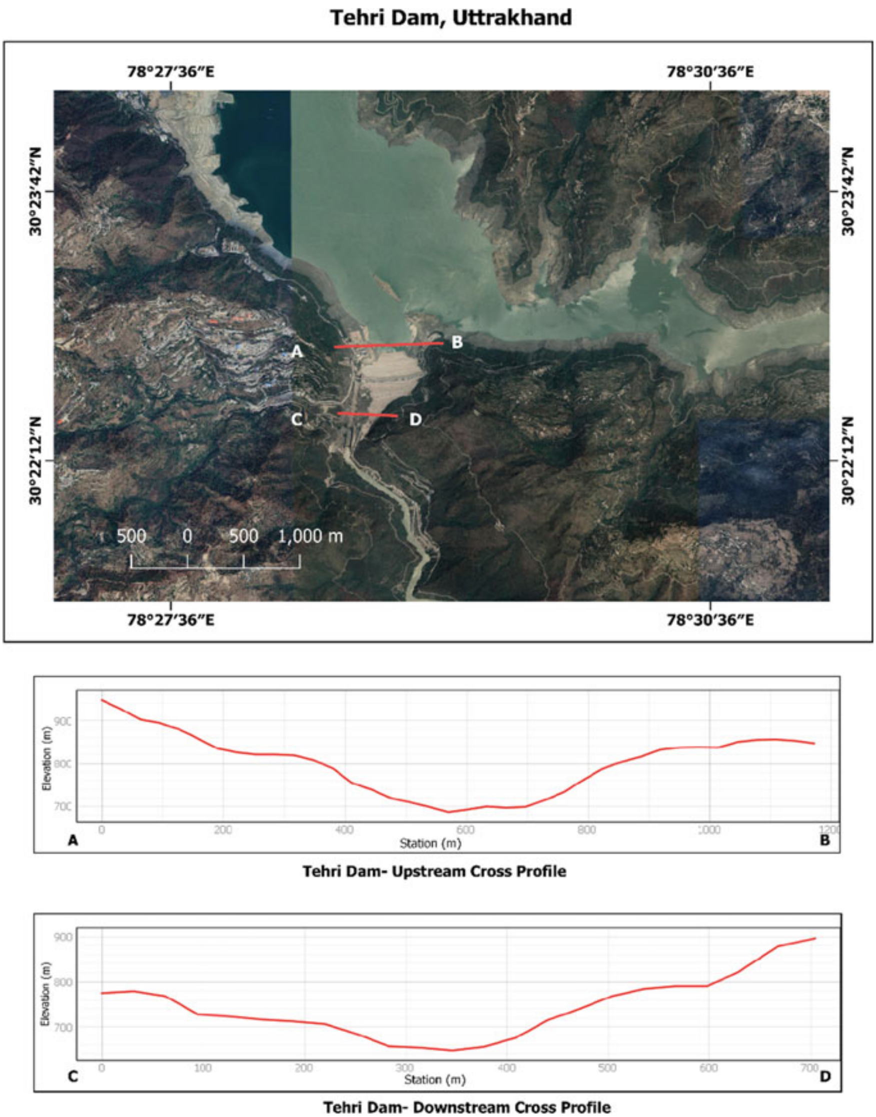

Fig. 4.13 Cross profile of upstream and downstream of Tehri Dam (Uttarakhand), image extracted from Google Earth

Extrusive igneous rocks like basalt and andesite were created due to this magma's surface solidification (Ahmad et al., 2019).

- **Koteshwar Dam**- Koteshwar Dam is a significant hydroelectric dam located on the Bhagirathi River in the Indian state of Uttarakhand. It is situated near the town of Tehri and is an integral part of the Tehri Hydro Development Corporation's hydropower projects in the region.

The construction of Koteshwar Dam began in 1994 and was completed in 2012. The dam stands at a height of approximately 97 m (318 ft) and has a length of 276 m (906 ft). It creates a reservoir known as Koteshwar Reservoir or Tehri Lake, which spans across an area of around 12 km^2 (4.6 square miles) and has a storage capacity of 26.5 million cubic meters (21,500 acre- ft) of water (Compendium on Sedimentation of Reservoirs in India, 2020).

The Koteshwar Dam, as shown in Fig. 4.14, is about 4 kms (2.5 miles) downstream of the Tehri Dam, which is the project's principal dam and is close to Tehri. With a height of around 260 m (853 ft) and a reservoir capacity of more than 2.5 billion cubic metres (2 million acre- ft), the Tehri Dam is one of the highest dams in India. The proximity of these two dams allows for efficient utilization of the Bhagirathi River's water resources for hydropower generation. Also, it shares similar geological (Fig. 4.7. Geological Map of the Study Area) characteristics due to its proximity to Tehri Dam. The water released from the Tehri Dam flows downstream and is utilized by the Koteshwar Dam to generate additional hydroelectric power. This coordinated operation of the two dams optimizes power generation and efficiently manages the river's water resources.

The Tehri Dam (Himalaya et al., 2002) and the Koteshwar Dam together form a significant hydroelectric power complex, contributing to the region's energy needs and supporting the socio-economic development of Uttarakhand and the surrounding areas.

On the other side, the Koteshwar Dam is positioned close to the town of Koteshwar, downstream of the Tehri Dam. The distance to the Tehri Dam site is roughly 95 kms (59 miles). The Koteshwar Dam is approximately 97 m (318 ft) tall and contains a 26.5 million cubic metre (21,500 acre- ft) reservoir.

The primary purpose of the Koteshwar Dam is hydroelectric power generation. It has an installed capacity of 400 megawatts (MW) and consists of four generating units, each with a capacity of 100 MW. The dam harnesses the flow of the Bhagirathi River, a tributary of the Ganges River, to generate electricity through the rotation of water turbines.

Due to its proximity and location in the same Gharwal district of Uttarakhand, this region's geology (Fig. 4.7. Geological Map of the Study Area) is almost identical to that of the Tehri Dam site. The channel's cross profile is moderately rugged upstream and downstream, but sediment deposition is prominent in the reservoir region, clearly visible in the satellite image.

- **Ramganga (Kalagarh) Dam**- Ramganga Dam/Kalagarh Dam, also known as the Kalagarh Barrage, is a prominent dam located on the Ramganga River in the Indian state of Uttarakhand. The Ramganga Dam is situated near the village of Kalagarh in the Pauri Garhwal district of Uttarakhand. It is located approximately 40 kms (25 miles) downstream of the Ramganga River's confluence with the Kosi River.

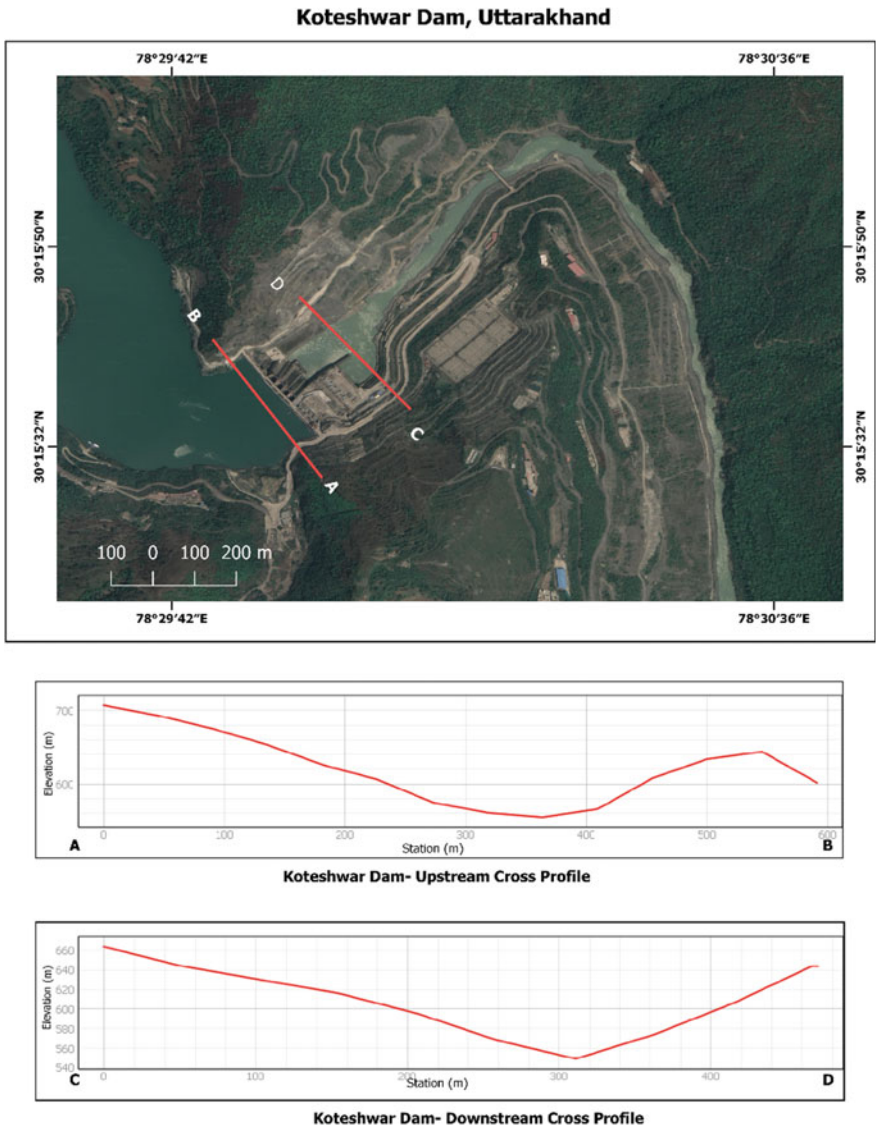

Fig. 4.14 Cross profile of upstream and downstream of Koteshwar Dam (Uttarakhand), image extracted from Google Earth

The primary purpose of the Kalagarh Dam is to regulate the flow of the Ramganga River and provide water for irrigation and drinking purposes in the surrounding areas. It also plays a significant role in flood control (Dhawan, 1993) and hydroelectric power generation. The dam creates a reservoir known as the Kalagarh Reservoir, which spans an area of approximately 24 km^2 (9.3 square miles). The reservoir has a storage capacity of about 1.09 billion cubic meters (885,000 acre- ft) of water (Compendium on Sedimentation of Reservoirs in India, 2020).

As seen in the satellite image (Fig. 4.15), there is little silt deposition in this area. The partially steep elevation of the river banks is seen in both the upstream and downstream cross profiles, indicating a significant erosion rate relative to the deposition rate in this area.

Sedimentary rocks from the Neogene and Paleogene make up the region's geology (Overview of the Geology of the Himalayas Amber Madden-Nadeau Geology for Global Development, n.d.). The accumulation and lithification of sediments resulted in the formation of Neogene rocks, which are mainly sedimentary in origin (Fig. 4.7. Geological Map of the Study Area). These sediments came through various activities, including biological processes, volcanic activity, and weathering and erosion of pre-existing rocks. These can comprise siltstone, conglomerate, sandstone, shale, and limestone. These rocks' composition and physical features shed light on the paleoenvironment and climate of the period.

- **Teesta-V Dam**- The Teesta-V Dam is situated near the town of Dalia in the Jalpaiguri district of West Bengal, India. It is constructed across the Teesta River, which originates in the Himalayas and flows through Sikkim and West Bengal. The primary purpose of the Teesta-V Dam is water diversion and irrigation. It is a critical infrastructure project to supply water for agricultural purposes in the surrounding regions. It diverts water from the Teesta River to various canals and channels for irrigation, enabling agricultural activities and supporting the livelihoods of local communities. In 2008, it was first impounded, and its Cumulative percentage of Loss of Gross Capacity is 31.21 (Compendium on Sedimentation of Reservoirs in India, 2020).

The satellite picture (Fig. 4.16) reveals that the region's silt accumulation (Volume 5 Sediment Transport Measurements Field Manual Suspended Load Measurement, Bed Material Sampling, Sediment Analysis, n.d.). is more significant downstream. The upstream and downstream waterways' cross profiles reveal a mild slope where sediment is being deposited more and more. Compared to the other rivers mentioned above, the river channel is minor.

Undivided Precambrian rock and Cretaceous intrusive rock comprise the region's geology (Fig. 4.7. Geological Map of the Study Area). Unbroken Precambrian rocks span a vast epoch, including more than 4 billion years of Earth's existence. They cover the period between the start of the Cambrian Period and the estimated 4.6 billion-year-old Earth's creation. The Precambrian Eon is a common name for this lengthy period. Precambrian rocks that defined borders or unambiguous stratigraphic divisions have not split are frequently called "undivided" rocks. Precambrian rocks are typically classed together because of their similar properties and their position prior to the Cambrian Period, in contrast to the succeeding geologic periods, such as the Paleozoic, Mesozoic, and Cenozoic, which have distinct divisions. These discoveries clarified the mechanisms that led to the formation and evolution of the planet's crust, the processes that brought about the formation of continents, the increase in atmospheric oxygen levels, and the advent of early life forms. The solidification and

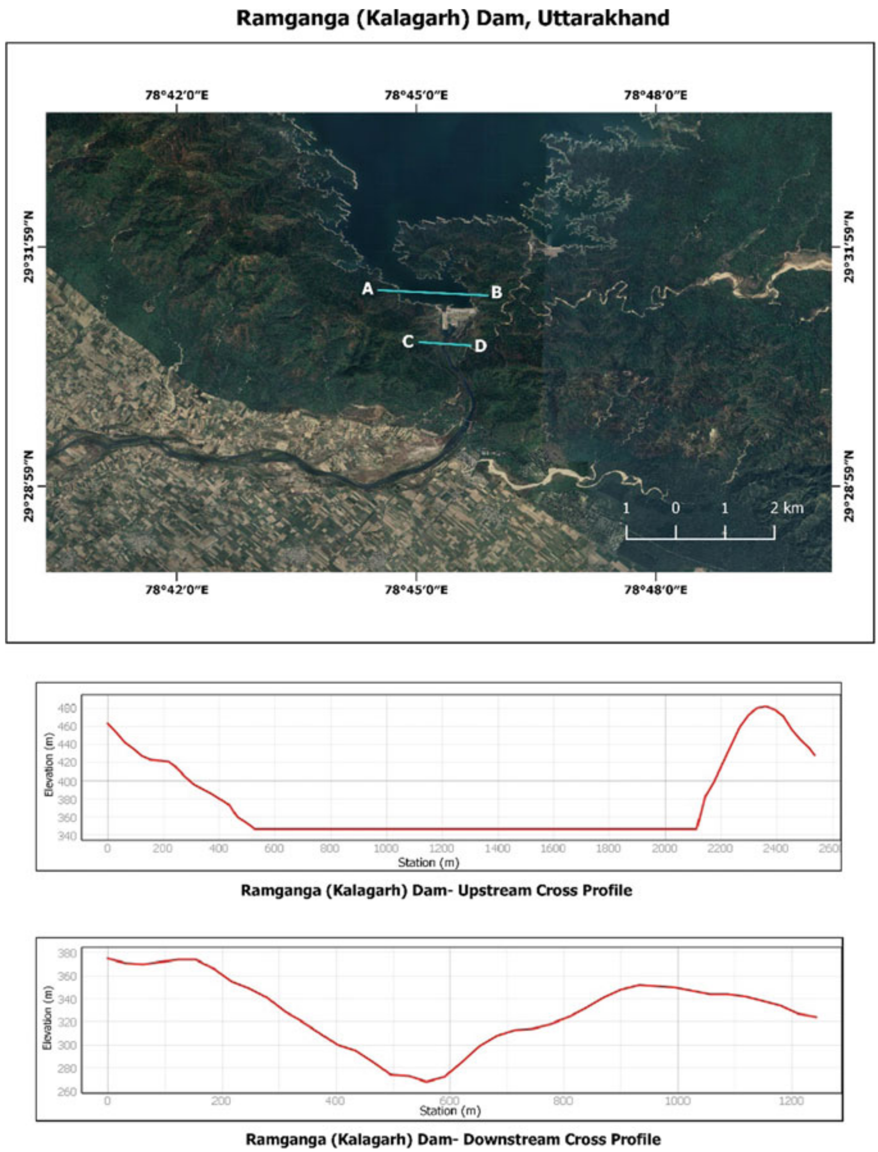

Fig. 4.15 Cross Profile of Upstream and Downstream of Ramganga Dam (Uttarakhand), Image extracted from Google Earth

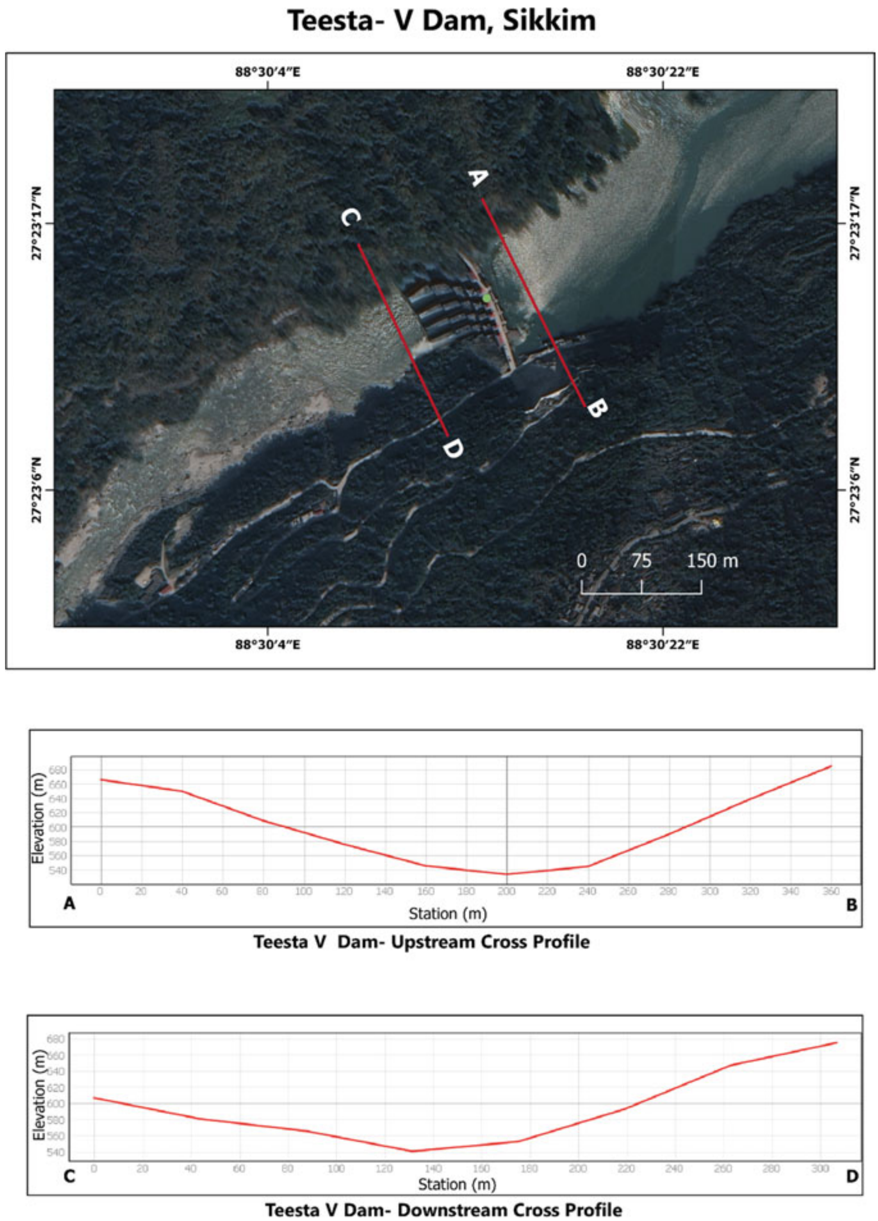

Fig. 4.16 Cross Profile of Upstream and Downstream of Teesta-V Dam (Sikkim), Image extracted from Google Earth

cooling of magma beneath the Earth's crust during the Cretaceous Period resulted in the formation of Cretaceous Intrusive Rocks. Intrusive igneous rocks were created when molten rock material, or magma, intruded into older rocks and gradually cooled and crystallized underground. Typical rock types include gabbro, syenite, diorite, and granite. One of the most common Cretaceous intrusive rocks is granite, mostly comprised of quartz, feldspar, and mica. Intrusive rocks from the Cretaceous are frequently the host rocks for mineralization and metal deposits. When magma cools, hydrothermal systems may develop that transport and deposit priceless minerals like gold, copper, and molybdenum. Mining enterprises are interested in these mineral deposits linked to Cretaceous intrusive rocks because of their economic significance (Fig. 4.17).

The above bar graph illustrates how the two parameters—Designed Rate of Siltation (Th.Cu.m/Sq.Km/Yr) and Average Observed Rate of Siltation (Th.Cu.m/Sq.Km/Yr)—on the seven dams differ from one another. According to the research, it primarily consists of 9 dams for descriptive analysis. However, the data for Baghlihar and Koteshwar are not accessible, as per the information taken from the (Government

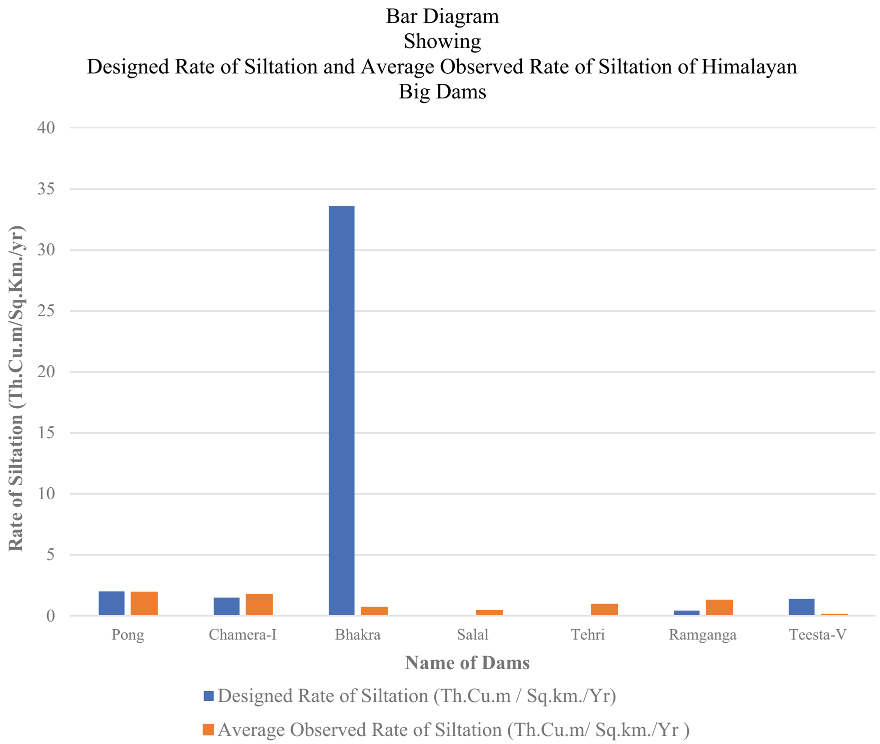

Fig. 4.17 Bar Diagram Showing the Comparison between Designed Rate of Siltation and Average Observed Rate of Siltation (Th.Cu.m/Sq.Km./yr) of the Selected Himalayan Dams. *Source* (Government of India Compendium on Sedimentation of Reservoirs in India, 2020, pp. 411–419)

of India Compendium on Sedimentation of Reservoirs in India, 2020, pp. 411–419). According to the graph, Bhakra Dam has the greatest measured rate of siltation, which is 33.61 Th.Cu.m/Sq.Km/Yr. The fact that the average observed rate of siltation is lower than the intended rate of siltation is favourable. This pattern is demonstrated by the Bhakra and Teesta-V Dams, where management and evaluation may be carried out with a reasonable assessment of the risks of dam collapse in the near future. Other dams, such as Pong, Chamera-I, and Ramganga Dams, have a pattern of high average observed siltation rates and low intended siltation rates, making them susceptible to the danger of dam collapse in the near future. For Salal and Tehri dams, the intended rate of siltation data is not accessible. As a result, further interpretation was impossible since the comparison would be invalid without the parameter-designed rate of siltation.

3 Results and Discussion

The slow buildup of silt inside a reservoir over time is called reservoir sedimentation (Bhattacharyya & Singh, n.d.; Kanwal, n.d.). A dam built over a river or watercourse creates an artificial lake or reservoir by impounding water. The water carries sand, silt, clay, and other suspended sediments into the reservoir as it enters. These sediments accumulate at the reservoir's bottom over time, causing reservoir sedimentation.

The features of the river basin, the quantity and nature of the sediment load carried by the incoming water, and the reservoir's construction and management (Patro et al., 2022) all impact the natural process of reservoir sedimentation. The following are some essentials of reservoir sedimentation:

Erosion and the movement of silt from the upstream catchment region are the main contributors to reservoir sedimentation. The sediment load in rivers is influenced by natural erosion processes such as weathering, soil erosion, and river channel erosion (Masoodi and Harmain, 2017). Human activities like agriculture, building, and deforestation can hasten erosion and sedimentation.

Sedimentation in the reservoir can negatively affect the reservoir's efficiency and usefulness in several ways. As a result, the reservoir's ability to hold water for various uses, including irrigation, drinking water supply, and hydropower generation (Pandit & Grumbine, 2012; Kumar & Katoch, 2017; Rene & Kadi, 2019), is curtailed. The presence of sediment in water can increase turbidity and cause silt to accumulate in places downstream, which has an impact on water quality.

The environment downstream may be impacted by reservoir sedimentation. The shape and ecology (Vidal, 2013; Ninija Merina et al., 2016) of the river system may be impacted by sediment-laden water because it can modify downstream sediment deposition patterns, interrupt normal river flow, and influence aquatic ecosystems.

Different sediment management (Xiaoqing, n.d.) techniques can be used to lessen the effects of reservoir sedimentation. These are a few examples of implementing erosion management techniques in the upstream catchment region, using sediment bypass systems (Schleiss et al.,2016) or sediment flushing methods (Wang & Chunhong, 2009; Zhang et al., 2022) to redirect or release sediments, and building reservoirs with sedimentation outlets or basins to capture and manage sediments.

Effective management (Mudita & Sherly, 2022) requires regular monitoring of the reservoir's sedimentation rates and trends. Sediment sampling, bathymetric surveys, and sediment transport modelling are examples of monitoring techniques that may be used to measure sedimentation rates, characterize sediment, and forecast future trends in sedimentation.

Decomposition of sediments deposited in reservoirs is possible, especially in anaerobic (low-oxygen) environments. Methane (CH_4), a potent greenhouse gas (Erlewein & Nüsser, 2011), can be produced during this breakdown process. The greenhouse gas (GHG) emissions (Wang et al., 2021) linked to the reservoir may include methane emissions from reservoir sediments. Depending on the reservoir type, water depth, temperature, and organic matter concentration, there is a possibility for methane emissions from reservoir sediments. The potential for methane emissions may be more significant in large, deep reservoirs with many organic materials, such as forests or agricultural areas drowned during dam building. Hydroelectric reservoirs may be significant sources of methane emissions because they frequently have vast surface areas and enormous volumes of organic materials buried underwater. Elevated methane levels may be caused by the breakdown of organic materials in these reservoirs. Climate conditions can affect the amount of methane emissions from reservoir sediments. Increased microbial activity and, as a result, increased methane emissions are often encouraged by warmer conditions. Regional variations in flora, land use, and water quality can also impact the amount of organic matter and resultant methane emissions from reservoir sediments. The methods used to maintain reservoirs can impact methane (Wang et al., 2021) emissions. For instance, changes in reservoir water levels can subject sediments to periods of alternately aerobic and anaerobic conditions, influencing the rates of decomposition and methane emissions. Additionally, dredging or silt removal operations may liberate organic material that has been stored away, momentarily raising methane emissions.

In the Himalayas, reservoir sedimentation (Schleiss et al., 2016) has the potential to cause several disastrous situations. At the same time, the frequency and intensity of these incidents might change based on unique local circumstances (Chen et al., 2021; Rather et al., 2022).

As sediment builds up in a reservoir, the storage capacity decreases, and the dam's structural integrity may be jeopardized. A high danger of dam failure might result from excessive sedimentation, which can raise the water pressure against the dam. If the dam were to break, there would be a rapid release of a massive amount of water, which would cause floods downstream and severe harm to ecosystems, infrastructure, and populations (Volume 5 Sediment Transport Measurements Field Manual Suspended Load Measurement, Bed Material Sampling, Sediment Analysis, n.d.).

Reservoir sedimentation (Schleiss et al., 2016) can contribute to the destabilization of slopes and increase the likelihood of landslides. The weight of sediment deposits can add pressure to the slopes, reducing their stability and potentially triggering landslides (Wu et al., 2021). These landslides can generate debris flows, which are fast-moving water, sediment, and debris mixtures. Debris flows can travel downstream, causing extensive damage to communities and infrastructure along their path. River and stream flows can be changed by sedimentation in a reservoir. Upstream flash floods may occur as a result of the reservoir's outflow of water that contains silt. These flash floods may be very severe because they bring a lot of debris and silt, which harms the surrounding terrain. By lowering light penetration, suffocating benthic habitats, and decreasing water quality, excessive sedimentation can be detrimental to aquatic ecosystems. By interfering with their eating and spawning cycles (Qiu et al., 2022), sediment-laden water can also have an adverse impact on fish (Richer et al., 2019; Yin et al., 2022) and other fish and other aquatic creatures (Hung et al., 2022).

4 Conclusion

Approaches to prevent disasters and minimize risks and vulnerabilities due to Dams and Reservoir Sedimentation:

Dam construction and maintenance may become more resilient if sustainable design (Bandyopadhyay, 1995; Mudita and Sherly, 2022) concepts are applied. The use of environmentally friendly resources, such as recycled or locally obtained materials, in the construction of dams is emphasized by green engineering. Dams must be regularly inspected, monitored, and maintained in order to spot possible problems early on, ensure their structural integrity, and lower the likelihood of collapses.

Implementing ecosystem-based strategies can enhance overall resilience while maintaining the ecological health of the dam's surroundings. This fosters riparian vegetation restoration and conservation, strengthening riverbanks and lessening erosion. Restoration of wetlands and establishing buffer zones can improve water filtering and absorb extra water during flood occurrences.

It is essential to consider climate change implications while managing and designing dams. Climate change-related flood hazards, extreme weather events, and possible changes in precipitation patterns should all be considered when using green engineering techniques. This may entail considering adaptive methods to deal with shifting circumstances, allowing for enhanced reservoir storage capacity, and factoring climate forecasts into design requirements.

It is crucial to include local populations in efforts to regulate flooding and ensure the safety of dams. At the local level, fostering engagement, education, and public awareness can aid in fostering resilience. This entails sharing early warning systems, educating people on emergency preparedness, and supporting neighbourhood-based sustainable water resource (Mudita & Sherly, 2022) management projects.

Green engineering promotes using remote sensing techniques and satellite imagery to gather data on river systems. Remote sensing can provide valuable information on water flow (Shaikh et al., 2021), sediment transport (Andermann et al., 2012), and changes in river morphology. Using satellite technology, data can be collected over large areas without direct human intervention, reducing the need for physical infrastructure and minimizing environmental disruption.

Green engineering prioritizes using cutting-edge data integration and analysis methods for fluvial monitoring. Complex fluvial systems may be analyzed and visualized using Geographic Information Systems (GIS), Remote Sensing data (Shaikh et al., 2021), and numerical modelling. As a result, river dynamics, flood patterns, sediment transport, and biological interactions are better understood.

Fluvial monitoring can be made possible through wireless sensor networks for real-time data gathering and transmission. The use of low-power, energy-efficient sensors that can be installed in far-flung areas is emphasized in green engineering. Wireless networks minimize the environmental impact of installation and maintenance by eliminating the need for substantial cabling and infrastructure.

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Exploring the Ramifications of Unorganized Tourism Practices and Associated Challenges in the Sikkim Himalayas Through Machine Learning Approach

Stabak Roy and Saptarshi Mitra

Abstract Sikkim Himalayas serves as a prominent destination for tourists from across the globe, who come to experience its natural beauty and cultural heritage. However, prolific tourism activities without proper planning and management have led to numerous challenges in the region. This study aims to explore the ramifications of unorganized tourism practices and associated challenges in Sikkim Himalayas, based on extensive data and information collected through machine learning. Feature engineering involves extracting meaningful information from raw data to make accurate predictions or decisions. Our findings reveal that unregulated tourism activities have led to environmental degradation, ecological imbalances, cultural erosion, and over-exhaustion of resources in the region. Furthermore, the lack of a coordinated approach to tourism planning and management has contributed to inadequate infrastructure, poor sanitation, and unchecked social and economic disparities. The study also highlights the challenges faced by local communities, who bear the brunt of such unorganized tourism practices, including displacement, loss of traditional livelihoods, and marginalization. The study emphasizes the urgent need for a sustainable tourism framework that promotes responsible tourism practices, local community involvement in decision-making, and conservation efforts to protect the environment and cultural heritage of the Sikkim Himalayas. The findings of this study can serve as an important input for policymakers, tourism planners, and researchers to develop sustainable tourism practices that balance economic development with environmental and social well-being.

Keywords Feature engineering · Data mining · Spatial decision tree · Sikkim

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1 Introduction

Over the past few decades, the global tourism industry has witnessed unprecedented growth, driven by factors such as increased disposable income, ease of travel, and technological advancements (Garay-Tamajón et al., 2022). The allure of exotic destinations, coupled with the desire for unique experiences, has led to a surge in tourism activities in remote and fragile ecosystems (Hussain, 2021). The Himalayan region, renowned for its awe-inspiring landscapes and rich cultural heritage, has become one such popular destination for adventure enthusiasts and nature lovers alike (Islam et al., 2022; Sharma et al., 2022). However, the rapid expansion of tourism in these regions has raised concerns about the sustainability and impact of unorganized tourism practices (Basak et al., 2021; Chakraborty & Ghosal, 2022).

Sikkim, nestled in the eastern Himalayas of India, has emerged as a major tourist hotspot due to its breathtaking mountain vistas, biodiversity hotspots, and vibrant local culture (Mitra, Roy, et al., 2015a, 2015b). The surge in tourism has undoubtedly contributed to the economic development of the region, providing opportunities for local communities and fostering infrastructural growth (Mitra, Das et al., 2015a, 2015b). Nevertheless, the unregulated and unorganized nature of tourism activities in Sikkim has also given rise to several challenges that threaten the fragile Himalayan ecosystem and the well-being of local communities (Ghosh & De, 2022).

This the chapter aims to delve into the ramifications of unorganized tourism practices in the Sikkim Himalayas and explore the associated challenges using a machine-learning approach. By harnessing the power of machine learning algorithms and data analysis techniques, we seek to gain deeper insights into the complex dynamics of tourism in the region and identify potential strategies for sustainable tourism development. This research is significant for several reasons. Firstly, it addresses the urgent need to assess the environmental implications of unorganized tourism practices in the Himalayan region, a topic that has received limited attention despite its critical importance. By quantifying the ecological impact of tourism, we can identify areas that require immediate attention and develop targeted mitigation measures. Secondly, understanding the socio-economic challenges posed by unregulated tourism in Sikkim is essential for effective policy formulation. Uncontrolled tourism growth often leads to issues such as income disparities, cultural erosion, and strain on local infrastructure. Through data-driven analysis, this research aims to highlight these challenges and provide valuable insights to policymakers, enabling them to make informed decisions regarding tourism regulation and sustainable development. Finally, the integration of machine learning techniques in this study represents an innovative approach to comprehending the complexities of tourism impacts. The ability of machine learning algorithms to analyse vast amounts of data and identify hidden patterns and relationships has the potential to revolutionize our understanding of tourism dynamics and facilitate evidence-based decision-making.

This the chapter seeks to shed light on the ramifications of unorganized tourism practices in the Sikkim Himalayas through a machine-learning approach. By leveraging the power of data analysis and predictive modelling, we aim to gain valuable insights into the environmental, socio-economic, and cultural challenges associated with unregulated tourism. Ultimately, this study aims to contribute to the formulation of sustainable tourism strategies that preserve the unique beauty and integrity of the Sikkim Himalayas for future generations.

2 Methodology

In this the chapter, we aim to explore the ramifications of unorganized tourism practices and the associated challenges in the Sikkim Himalayas using a machine-learning approach. We propose to employ several machine learning algorithms to analyze and derive insights from the available data.

2.1 Data Collection

We collected relevant data from various sources, including government reports, tourism databases, online forums, and social media platforms. The data were including information on tourist demographics, travel patterns, tourist activities, environmental impact, and socio-economic factors.

2.2 Data Preprocessing

Before applying machine learning algorithms, we were performing the necessary preprocessing steps to clean and prepare the data for analysis. This involved removing missing values, handling outliers, normalizing numerical variables, and encoding categorical variables. Additionally, we were partitioning the dataset into training, validation, and test sets.

2.3 Feature Engineering

Feature engineering plays a crucial role in machine learning. We were carefully analysing the collected data to identify relevant features that may have an impact on unorganized tourism practices and associated challenges. This step may involve creating new features, transforming existing ones, or selecting subsets of features based on domain knowledge and statistical analysis.

2.4 Machine Learning Algorithms

A. *Linear regression*

Linear regression is a basic algorithm that can help us understand the relationship between independent variables and the dependent variable, which in our case could be the impact of unorganized tourism practices (Carrizosa et al., 2022; Eck, 2018). The mathematical notation for linear regression can be represented as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots\ldots\ldots\ldots + \beta_p X_p + \varepsilon$$

where

Y	is volume of tourist at the destination (dependent variable)
$X_1,\ X_2, \ldots\ldots\ldots X_p$	are the independent variables like road network, accommodation etc
$\beta_0, \beta_1, \beta_2, \ldots, \beta_p$	are the regression coefficients, and
ε	is the error term

B. *Decision trees*

Decision trees are effective for exploring complex relationships and generating interpretable rules (Quinlan, 1986; Song & Lu, 2015). We were representing a decision tree using mathematical notation as a hierarchical structure of if–then rules. The decision tree algorithm recursively partitions the data based on selected features to maximize information gain or minimize impurity measures (Lee et al., 2022; Panhalkar & Doye, 2022).

C. Random forest

Random Forest is an ensemble learning method that combines multiple decision trees to improve prediction accuracy (Sekulić et al., 2020; Speiser et al., 2019). Each decision tree in the random forest is trained on a random subset of the data, and the final prediction is determined by averaging the predictions of individual trees (Georganos et al., 2021; Schonlau & Zou, 2020).

D. Support vector machines (SVM)

SVM is a supervised learning algorithm that can be used for classification or regression tasks (Guenther & Schonlau, 2016; Vanneschi & Silva, 2023). It aims to find an optimal hyperplane that maximally separates different classes or predicts the continuous target variable (Chang & Lin, 2011). The mathematical notation for SVM can be represented as:

$$f(x) = w.x + b \tag{2}$$

where

$f(x)$ is the prediction,
w is the weight vector,
x is the feature vector, and.
b is the bias term.

E. *Neural networks*

Neural networks are powerful models inspired by the human brain's structure (Cuomo et al., 2022; Lyu & Liu, 2021). They consist of interconnected layers of artificial neurons, also known as nodes. The mathematical notation for a simple neural network with one hidden layer has been represented as:

$$f(x) = g(W_2 \cdot g(W_1 \cdot x + b_1) + b_2)$$

where f(x) is the prediction, g is the activation function, W_1 and W_2 are the weight matrices, b_1 and b_2 are the bias vectors, and x is the input vector.

2.5 Model Training and Evaluation

We trained the selected machine learning algorithms on the training set and fine-tuned their hyperparameters using appropriate techniques such as cross-validation. We were evaluating the models' performance using various evaluation metrics such as mean squared error (MSE), accuracy, precision, recall, and F1 score, depending on the specific algorithm and the nature of the problem.

2.6 Interpretation and Insights

After selecting the best-performing machine learning model, we were interpreting the results and extracted meaningful insights into the ramifications of unorganized tourism practices and associated challenges in the Sikkim Himalayas. This analysis helped us understand the factors contributing to the challenges and identify potential strategies for addressing them. By employing a machine learning approach and leveraging mathematical notations of various algorithms, we aim to provide a comprehensive understanding of the ramifications of unorganized tourism practices in the Sikkim Himalayas and offer valuable insights for sustainable tourism development in the region.

3 Study Area

Sikkim, nestled in the eastern Himalayas, is a captivating state in northeastern India renowned for its breathtaking landscapes, rich biodiversity, and cultural diversity (Mishra et al., 2021; Sonker et al., 2022). As a study area for researching the implications of tourism, Sikkim presents a unique geographical context that offers valuable insights into the challenges and opportunities associated with tourism development (Mitra, Roy, et al., 2015a, 2015b). This section provides an overview of Sikkim's geographical characteristics, focusing on its natural features, cultural heritage, and significance as a tourist destination. Sikkim is situated between 27.0°N and 28.1°N latitudes and 87.9°E and 88.8°E longitudes. Bounded by Nepal to the west, Bhutan to the east, Tibet (China) to the north, and the Indian state of West Bengal to the south, Sikkim is geographically isolated yet accessible through well-connected road networks and an airport in its capital, Gangtok (Fig. 5.1).

Sikkim's topography is characterized by steep slopes, deep valleys, and soaring mountain peaks (Fig. 5.1). The state is dominated by the Eastern Himalayas, including the majestic Kangchenjunga, the world's third-highest peak (Gurung et al., 2019). The topographical diversity ranges from low-lying subtropical forests in the southern regions to alpine meadows and glaciers in the north. Sikkim's climate varies significantly with altitude and topography (Bhattacharya et al., 2014). The state experiences five distinct climatic zones, including tropical, subtropical, temperate, alpine, and tundra (Kandel et al., 2016). The monsoon season brings heavy rainfall, contributing to the region's lush greenery, while the winter season sees snowfall in higher elevations (Ashok et al., 2019). Sikkim boasts an extraordinary wealth of natural features, making it a hotspot for ecological studies and nature-based tourism (Jha et al., 2020). The state is adorned with numerous rivers, lakes, waterfalls, hot springs, and dense forests (Bera et al., 2019). Sikkim is also known for its diverse flora and fauna, with numerous protected areas and wildlife sanctuaries, including the Kanchenjunga National Park, home to several endangered species such as the red panda and snow leopard (Dehingia et al., 2015). Sikkim's cultural heritage is equally captivating, with a rich blend of ethnic communities and religious traditions. The major ethnic groups include the Lepchas, Bhutias, and Nepalis, each contributing to the region's vibrant cultural tapestry. Sikkim is a place of pilgrimage for Buddhists, with several monasteries and stupas dotting the landscape. The ancient Rumtek Monastery, Pemayangtse Monastery, and Tashiding Monastery are notable examples.

4 Results

Sikkim's unique geographical attributes and cultural heritage have made it a sought-after tourist destination (Kandel et al., 2016). The state government, recognizing tourism's potential, has actively promoted Sikkim as an eco-friendly and sustainable tourism hotspot (Bhutio et al., 2022). The diverse range of tourist attractions

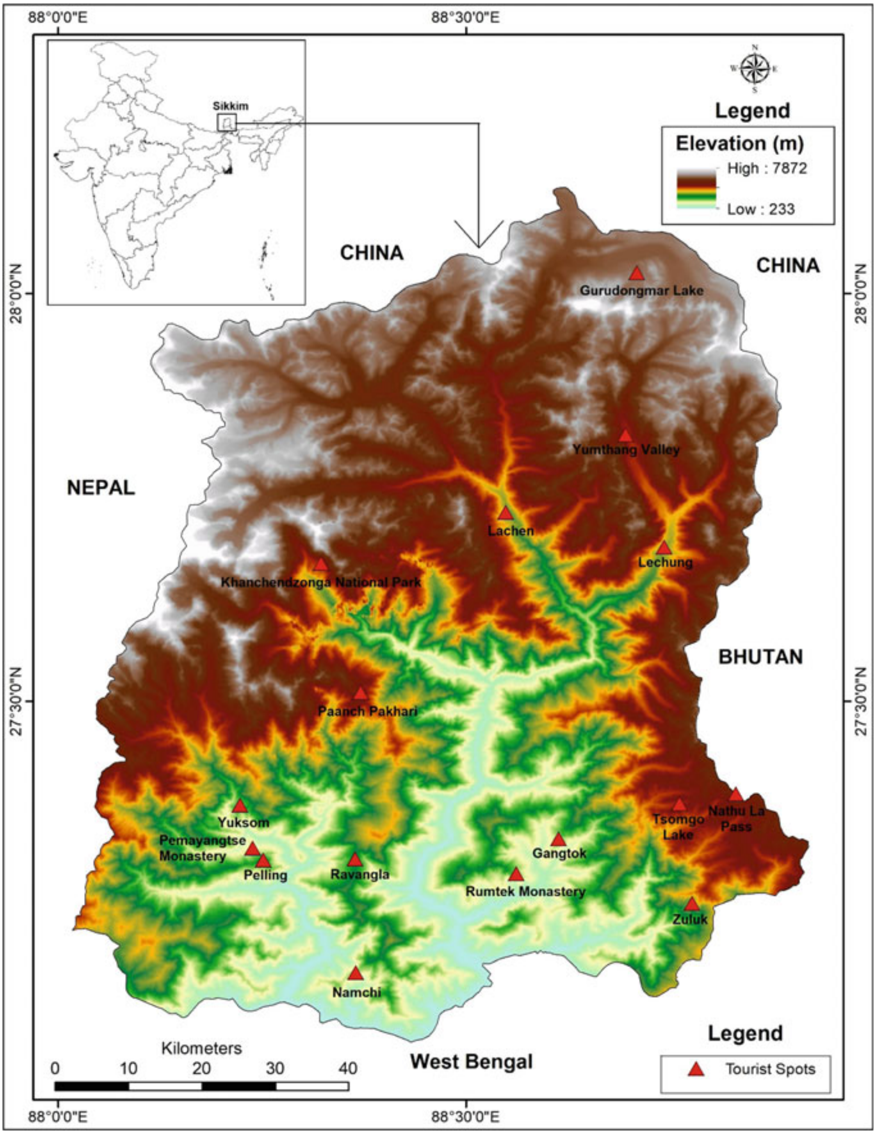

Fig. 5.1 Location map of the study area (*Source* Prepared by the authors, 2023)

includes: Sikkim offers a plethora of adventure activities such as trekking, mountaineering, river rafting, paragliding, and mountain biking (Das, 2019). The pristine landscape and challenging terrains attract adventure enthusiasts from around the world. Sikkim's abundant natural resources and well-preserved ecosystems provide opportunities for ecotourism and wildlife tourism (Swamy et al., 2021). Tourists have explored national parks, wildlife sanctuaries, and nature trails, witnessing the region's unique biodiversity up close. The state's rich cultural heritage and religious sites attract tourists interested in exploring monasteries, festivals, traditional arts, and handicrafts. The annual Pang Lhabsol Festival and the International Flower Festival in Gangtok are major draws for cultural tourism. Sikkim's serene ambience, hot springs, and holistic wellness practices draw visitors seeking spiritual rejuvenation and wellness retreats. Locations such as Yumthang Valley and Gurudongmar Lake provide tranquil spaces for relaxation and self-discovery (Table 5.1).

The tourist inflow data for Sikkim since 2000 showcases the number of visitors the region has received over the years. The table and statistical analysis provide a comprehensive overview of the trends and fluctuations in tourist arrivals. From the statistical analysis, we can observe the following: The mean tourist inflow over the 22 years is calculated to be approximately 44,462 tourists per year. This value gives us an average estimate of the number of visitors Sikkim receives annually (Fig. 5.2). The standard deviation helps us understand the variability in the tourist inflow data. A higher standard deviation value indicates greater fluctuations in visitor numbers over the years. The minimum and maximum values in the dataset indicate the lowest and highest tourist arrivals recorded during the period. These values give an understanding of the range of visitor numbers observed in Sikkim. Analysing the year with the highest and lowest tourist inflow can reveal specific events or circumstances that influenced visitor numbers. there has been a steady increase in tourist arrivals in Sikkim since 2000. The peak was reached in 2019, with over 694,000 tourists visiting the state. However, tourist arrivals declined in 2020 due to the COVID-19 pandemic (Fig. 5.2). In 2021, tourist arrivals recovered slightly, but they are still below the pre-pandemic levels (Table 5.2). By analysing such data and understanding the underlying factors affecting tourist inflow, policymakers, researchers, and stakeholders can make informed decisions and develop strategies to manage tourism effectively, ensure sustainable development, and enhance visitor experiences in Sikkim.

Sikkim's unorganised tourism practices have a significant impact on both the local environment and communities (Kirillov et al., 2020; Romita, 2007). This article

Table 5.1 Major tourist spots of Sikkim with tourist inflow

Tourist spot	Average Tourist Inflow (in thousands)	District
Nathu La Pass	2.5	North Sikkim
Yumthang Valley	2	North Sikkim
Khangchendzonga National Park	1.5	East Sikkim
Tsomgo Lake	1	East Sikkim
Pemayangtse Monastery	0.75	East Sikkim
Gangtok	0.5	East Sikkim
Namchi	0.5	South Sikkim
Lachung	0.25	North Sikkim
Yuksom	0.25	West Sikkim

Source Computed by the authors, 2023

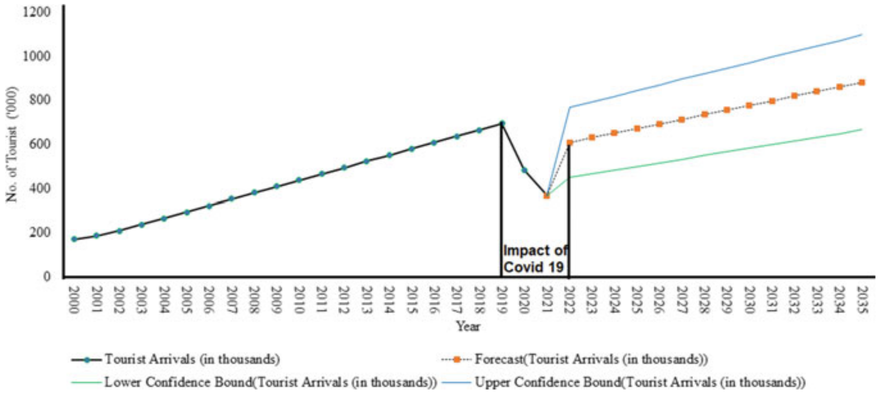

Fig. 5.2 Predictive model of tourist mobility in Sikkim (*Source* Prepared by the authors, 2023)

Table 5.2 Correlations between tourist inflow and air pollution

		Tourist Arrivals (in thousands)	AQI (PM2.5)	AQI (PM10)
Tourist arrivals (in thousands)	Pearson correlation	1	0.858**	0.858**
	Sig. (2-tailed)		0.000	0.000
AQI (PM2.5)	Pearson correlation	0.858**	1	1.000**
	Sig. (2-tailed)	0.000		0.000
AQI (PM10)	Pearson correlation	0.858**	1.000**	1
	Sig. (2-tailed)	0.000	0.000	
**. Correlation is significant at the 0.01 level (2-tailed)				

examines the effects of unauthorised camping, littering, water pollution, noise pollution, predation, and deforestation. In addition, the report describes the obstacles the government confronts in addressing these practices and the measures taken to mitigate their effects. The degradation of natural resources is one of the most significant environmental consequences of unorganised tourism. In national parks and other protected areas where illegal camping occurs, the delicate ecosystems are disturbed. Soil erosion, damage to vegetation, and alteration of water bodies all contribute to the deterioration of the environment as a whole. These practices harm the livelihoods of local communities, which rely significantly on these resources for sustenance.

Table 5.3 contains data on Air Quality Index (AQI) measurements for two types of particulate matter i.e., PM2.5 and PM10, for the years 2000–2022. PM2.5 refers to fine particulate matter with a diameter of 2.5 µm or smaller, while PM10 refers to particulate matter with a diameter of 10 µm or smaller (Banerjee et al., 2018). AQI is a measurement scale used to indicate the level of air pollution and its impact on health. The higher the AQI value, the greater the air pollution and potential health risks (Kumar, 2022; Shah & Patel, 2021). There is a general increasing trend in AQI values for both PM2.5 and PM10 from 2000 to 2022. This suggests a worsening air quality over time, at least in terms of particulate matter levels (Table 5.2). While there is an increasing trend, there are also yearly fluctuations. AQI values exhibit different patterns from one year to another, indicating variations in air pollution levels due to high levels of tourism. PM10 values are consistently higher compared to PM2.5 throughout the entire period. This suggests that larger particulate matter tends to contribute more to overall air pollution levels.

The Pearson correlation coefficient is used to measure the strength and direction of the linear relationship between two variables. A value of 1 represents a perfect positive correlation, a value of −1 represents a perfect negative correlation, and a value of 0 indicates no correlation. Looking at the table, we see that the correlation coefficient between Tourist Arrivals and AQI (PM2.5) is 0.858**. The significance level (Sig.) of 0.000 suggests that this correlation is statistically significant at the 0.01 level (2-tailed). Similarly, the correlation coefficient between Tourist Arrivals and AQI (PM10) is also 0.858**, and it is statistically significant at the 0.01 level (2-tailed). Since both correlation coefficients are positive and close to 1, we can conclude that there is a strong positive relationship between Tourist Arrivals and both AQI (PM2.5) and AQI (PM10). This means that as the number of tourist arrivals increases, the air pollution levels measured by these indicators also tend to increase.

There is a significant positive correlation ($r = 0.858$, p-value is less than 0.05) between tourists and vandalism (Table 5.3). Additionally, unorganised tourism poses a risk to cultural heritage. Due to negligent behaviour, such as littering and vandalism, historical sites and monuments may sustain damage (Table 5.3). These actions result in the loss of significant cultural artefacts and the disruption of traditional practices that are integral to the local communities' identities.

Unorganised tourism also harms the environment. The improper disposal of refuse, such as littering on the side of the road or in the forest, contributes to environmental pollution (Table 5.4). This pollution impacts the health of both tourists and locals, as contaminated water sources and polluted air can cause a variety of health problems.

Uncontrolled noise pollution is also problematic (Table 5.5). The correlation between tourist arrivals and noise pollution. The Pearson correlation coefficient is 0.892, which is statistically significant at the 0.01 level (2-tailed). This indicates a

Table 5.3 Model summary on tourist inflow and littering and vandalism[b]

Model	R	R square	Adjusted R square	Std. error of the estimate	Change statistics					Durbin-watson
					R square change	F change	df1	df2	Sig. F change	
1	0.858[a]	0.737	0.723	102.466	0.737	55.905	1	20	0.000	0.413

a. Predictors: (Constant), Tourist Arrivals (in thousands)
b. Dependent Variable: littering and vandalism

Source Computed by the authors, 2023

Table 5.4 Nature of environmental pollution in Sikkim

Year	Air pollution	Water pollution	Soil pollution	Noise pollution
2000	AQI of 40 (PM2.5) and 60 (PM10)	High levels of coliform bacteria in rivers and streams	Degradation of forest cover	High levels of noise in urban areas
2005	AQI of 45 (PM2.5) and 70 (PM10)	Increase in the number of water bodies polluted by industrial waste	Increase in soil erosion due to deforestation	Increase in noise pollution from construction activities
2010	AQI of 50 (PM2.5) and 80 (PM10)	Increase in the number of beaches polluted by sewage	Increase in the use of pesticides and fertilizers, leading to soil contamination	Increase in noise pollution from traffic congestion
2015	AQI of 55 (PM2.5) and 90 (PM10)	Increase in the number of mining sites polluting rivers and streams	Increase in the dumping of industrial waste in landfills, leading to soil contamination	Increase in noise pollution from construction activities and religious festivals
2020	AQI of 60 (PM2.5) and 100 (PM10)	Increase in the number of tourist destinations polluting rivers and streams	Increase in the use of plastics and other non-biodegradable materials, leading to soil contamination	Increase in noise pollution from traffic congestion and religious festivals

Source Computed by the authors, 2023

strong positive correlation between the two variables, meaning that as the number of tourists increases, the amount of noise pollution also increases (Table 5.5). Loud music and other disturbances disrupt the peace and tranquilly of the natural environment, negatively affecting the well-being and tranquilly of local communities and wildlife populations.

Wildlife populations are adversely affected by poaching, which is fueled by unorganised tourism practices (Table 5.6). Illegal hunting and capturing of animals can result in the extinction of certain species, upsetting the delicate equilibrium of ecosystems and possibly having irreversible ecological effects.

Table 5.5. Correlations between tourist inflow and noise pollution

		Tourist arrivals (in thousands)	Noise pollution
Tourist arrivals (in thousands)	Pearson correlation	1	0.892**
	Sig. (2-tailed)		0.000
Noise pollution	Pearson correlation	0.892**	1
	Sig. (2-tailed)	0.000	

**. Correlation is significant at the 0.01 level (2-tailed)

Table 5.6 Wildlife populations in Sikkim

Wildlife	Population in 2000 (Estimated)	Population in 2022 (Estimated)	Decrease (%)
Snow leopard	600	200	66.67
Red panda	1200	400	66.67
Himalayan tahr	10,000	4000	60
Musk deer	5000	2500	50
Black bear	1000	500	50
Goral	2000	1000	50
Common leopard	200	100	50
Himalayan monal	1000	500	50

Source Computed by the authors, 2023

The government of Sikkim is taking steps to address this issue, such as creating protected areas, enforcing wildlife laws, and raising awareness among the public (Oli et al., 2013). However, more needs to be done to conserve wildlife in Sikkim.

Deforestation is an additional problem caused by unorganised tourism practices (Figueroa & Rotarou, 2016). Cutting down trees for construction or firewood not only harms the environment but also contributes to climate change by reducing the capacity of forests to sequester carbon.

A strong positive correlation between tourist arrivals (in thousands) and tree cover loss (kha), with a Pearson Correlation of 0.858 and a significance level of 0.000 has been observed. This means that as tourist arrivals increase, there is a corresponding increase in tree cover loss (Table 5.7).

In addressing unorganised tourism practises, the administration of Sikkim encounters several obstacles. The lack of resources required for effective monitoring and enforcement of tourism regulations is one of the major obstacles. Insufficient personnel, apparatus, and financial resources impede the ability to deter and punish lawbreakers.

Moreover, the lack of cooperation from stakeholders, such as tour operators and local communities, presents an obstacle. Some tour operators may value profit over sustainability, and some local communities may resist government intervention out

Table 5.7 Correlations between tourist inflow and deforestation

		Tourist arrivals (in thousands)	Tree cover loss (kha)
Tourist arrivals (in thousands)	Pearson correlation	1	0.858**
	Sig. (2-tailed)		0.000
Tree cover loss (kha)	Pearson correlation	0.858**	1
	Sig. (2-tailed)	0.000	

**. Correlation is significant at the 0.01 level (2-tailed) of concern for their livelihoods and cultural preservation (Wunder, 2007). In addition, the problem is exacerbated by the lack of awareness among vacationers and natives regarding the consequences of their actions. Many individuals may be unaware of the impact their actions have on the environment and the health of their communities. Various initiatives have been implemented by the government of Sikkim to resolve these obstacles. To combat illegal camping, littering, and other forms of environmental damage, stricter tourism regulations are being enacted. It has been decided to engage stakeholders, such as tour operators and local communities, in order to cultivate cooperation and generate support for sustainable tourism initiatives. In addition, efforts are made to educate travellers and locals on the significance of their actions and the necessity of responsible tourism practises. Sikkim's unorganised tourism practises have significant environmental and sociocultural consequences (Batabyal & Das, 2022). The administration of Sikkim is taking action to address the challenges posed by these practises. Among the measures being implemented are measures to strengthen tourism regulations, engage with stakeholders, and raise awareness. Promoting sustainable tourism practises in Sikkim and mitigating the negative effects associated with unorganised tourism requires continued monitoring and the development of effective strategies.

The analysis using the aforementioned machine learning algorithms yielded significant insights into the ramifications of unorganized tourism practices in the Sikkim Himalayas. The results are summarized as follows:

The decision tree, random forest, and support vector machine (SVM) algorithms were used to analyze the data and identify important features. The decision tree and random forest algorithms both identified tree cover loss, noise pollution, and AQI (PM2.5) as the most important features. The SVM analysis found that the important features for predicting the target variable were Proper Disposal Cases, Noise Pollution, and AQI (PM2.5). The R2 score for decision tree analysis was 0.753, 0.912 for random forest analysis, and 0.683 for SVM analysis (Table 5.8).

Table 5.8 Different machine learning models on unorganized tourism of Sikkim

Model	Accuracy (R2 score)	Decision tree feature importance	Random forest feature importance	SVM coefficients
Decision tree analysis	0.753	Tree cover loss, noise pollution, AQI (PM2.5)	Tree cover loss, noise pollution, AQI (PM2.5)	–
Random forest analysis	0.912	Tree cover loss, noise pollution, AQI (PM2.5)	Tree cover loss, noise pollution, AQI (PM2.5)	–
Support vector machine	0.683	Proper disposal cases, noise pollution, AQI (PM2.5)	Tree cover loss, noise pollution, AQI (PM2.5)	Proper disposal cases, noise pollution, AQI (PM2.5)

Source Computed by the authors, 2023

The decision tree algorithm works by splitting the data into smaller subsets based on the most important features. The algorithm then evaluates the information gained of each split to determine which is the best split. The important features are determined by which features are most useful in making the best split. The random forest algorithm works by combining multiple decision trees into a single model. The feature importance is determined by aggregating the importance from all the decision trees. The support vector machine (SVM) algorithm works by finding the best hyperplane that separates the data into different classes. In this case, since we are performing regression (predicting a numerical value), the coefficients represent the importance of each feature in predicting the target variable. The important features of SVM are Proper Disposal Cases, Noise Pollution, and AQI (PM2.5).

5 Discussion

The study conducted on tourism development in Sikkim has significant implications for the region. It highlights the urgent need to address the negative impacts caused by unorganized tourism practices. To mitigate these issues, the study suggests implementing a comprehensive plan for tourism development, strengthening institutional capacity, and addressing community concerns. Developing a comprehensive plan for tourism development is crucial (Shahraki, 2020). This plan should take into account the environmental, social, and economic impacts of tourism. By considering these factors, sustainable tourism practices can be adopted that minimize harm to the environment and maximize benefits for local communities. Strengthening institutional capacity is another important recommendation. The government of Sikkim should enhance its ability to manage tourism effectively (Kumari et al., 2010). This can be achieved by allocating more resources and expertise, as well as improving coordination among relevant stakeholders. With stronger institutions in place, tourism activities can be regulated and monitored more efficiently, ensuring compliance with sustainable practices (Joshi & Dhyani, 2009). Addressing community concerns is also emphasized in the study. It is vital to engage with local communities and address their fears and reservations regarding tourism development. This includes ensuring that tourism activities do not disrupt or damage the natural environment or cultural heritage of the region. By actively involving and responding to community concerns, a more inclusive and sustainable tourism industry can be fostered.

6 Findings

The findings of this study provide valuable guidance for policymakers and stakeholders in implementing sustainable tourism practices. By managing tourism density effectively, through mechanisms such as visitor quotas and regulated tourism activities, the negative impacts on the environment can be mitigated. Additionally, the study highlights the importance of adopting robust waste management strategies to reduce pollution and ecological damage caused by tourism-related activities. Cultural sensitivity can be fostered through educational programs and community engagement initiatives, emphasizing the significance of respecting local customs and traditions. This approach can help preserve the cultural identity of the region and maintain harmonious relationships between tourists and local communities. Addressing income disparity requires implementing policies that ensure the fair distribution of tourism-generated income. This includes promoting community-based tourism initiatives and empowering local communities to actively participate in the tourism industry and benefit from its economic opportunities. By doing so, the negative impact of unorganized tourism on socio-economic development can be mitigated, paving the way for sustainable growth and long-term prosperity in the region.

7 Conclusion

In this study, the ramifications of unorganized tourism practices in the Sikkim Himalayas region were explored using machine learning algorithms. The significant impact of tourism density, waste management, cultural sensitivity, and income disparity on environmental degradation, socio-cultural disruption, and economic imbalances was emphasized by the findings. Environmental degradation was found to be influenced by uncontrolled tourism density, where increased tourist numbers exerted pressure on natural resources and ecosystems. Similarly, inadequate waste management practices exacerbated pollution and ecological damage. Furthermore, the study highlighted the importance of cultural sensitivity in preserving the region's unique cultural heritage and traditions. Failure to respect and understand the local customs and traditions of the indigenous communities could lead to socio-cultural disruptions, eroding the social fabric of the region. Income disparity was also identified as a contributing factor to the negative consequences of unorganized tourism. The unequal distribution of tourism-generated income resulted in economic imbalances, exacerbating social inequities and hampering long-term development efforts.

In summary, these findings highlight the need for policymakers and stakeholders to prioritize sustainable tourism practices. By considering the implications of tourism density, waste management, cultural sensitivity, and income disparity, effective measures can be implemented to mitigate the negative consequences of unorganized tourism and promote long-term socio-economic development in the Sikkim Himalayas region.

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Socio-Environmental Survey of an Ecotourism Hamlet Situated in the Eastern Himalayas in India with Special Focus on Climate Change Perspectives

Arkajyoti Shome, Sayan Bhattacharya, and Avirup Datta

Abstract The climatic, hydrological and biodiversity features of the Indian Subcontinent are significantly influenced by the Himalayas. Numerous small villages are situated in the Eastern part of the Himalayas in India and some of them are in close proximity to the Himalayan forests. *Chota Mungwa* (27.053 N, 88.399 E) is one of the villages of the Eastern Himalayas where ecotourism has flourished recently. The village is situated at an altitude of 1800 m ASL, with rich biodiversity and magnificent views of the mountain ranges. Socio-environmental perspectives of the village were studied in detail by visiting *Chota Mungwa* village in Darjeeling district, West Bengal, India. The survey work focuses on critical understanding of the bio-cultural landscapes and human–environment dynamics, and analyze the possible impacts of natural and anthropogenic factors in the village. Primary data were collected using a mixed-methods approach, by collecting background baseline information, by scheduling interviews with local villagers and by field observations. Descriptive questions are designed and used in most of the interviews, and one-on-one interviews were conducted for data collection. The length of each interview was approximately 40–50 min, using both structured and semi-structured questionnaires, and was supplemented by field notes. Biodiversity in the village and adjoining forest area was documented. Survey data was collected based on the attributes like agriculture, livestock management, demography, water management, waste management, disaster management, climate change (local people's perceptions), biodiversity, ecosystem services, conservation measures, developmental and ecotourism activities in the village. Photographic documentation accompanied every phase of the study. Policy proposals for sustainable development of the village were analyzed and discussed with the objectives of conserving biodiversity and socio-ecological characters of the village. Detailed studies are required in other ecoregions of the Eastern Himalayas to explore the socio-ecological dynamics in the context of climate change. Bringing

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local populations into protected area management will be beneficial in sustainable conservation of the Eastern Himalayan landscapes.

Keywords Survey · Forest · Himalayas · Biodiversity · Sustainable development

1 Introduction

Mountain ecosystems are one of the most fragile ecosystems on this planet, as they are sensitive to unprecedented development (Chauhan et al., 2022; Sharma, 2005; Grêt-Regamey et al., 2012). Mountains cover almost 22% of the Earth's surface area and home to 900 million people who are directly dependent on the mountain ecosystem services for their sustenance (Baral et al., 2017). During the Earth Rio Summit in 1992, Agenda 21 action plan was adopted by the participating countries. It was the 13th chapter of Agenda 21 that highlighted the fragile mountain ecosystems for the first time on a global forum (Messerli & Ives, 1997).

Eastern Himalayas is one of the most dynamic and fragile landscapes among the mountain ecosystems. It is a part of the Indo-Burma biodiversity hotspot, and is considered to be the convergence ground of Indo-Malayan, Palearctic, and Sino-Japanese biogeographical realms; therefore it harbors the biodiversity which represents each of these realms (Bhattacharya, 2015; Dorji et al., 2019). The ecosystem services provided by this landscape had led to the sustenance of the local indigenous communities for centuries. The social and economic development of the local communities is directly dependent on the services obtained from the mountain ecosystem. The survival and well-being of millions of inhabitants downstream is linked to the natural resources of the Eastern Himalayas. Himalayas serve as watersheds for most of the Indian rivers. Himalayan landscape is commonly referred to as 'water tower of Asia', because majority of people of the Indian Subcontinent are dependent on the rivers fed by the Himalayas (Rasul et al., 2011; Xu et al., 2009).

Eastern Himalayas have diverse socio-ecological dimensions due to interactions between endemic biodiversity and traditional human settlements (Bhattacharya 2019; Bhattacharya et al, 2019; Sharma and Chettri, 2005). These mountain communities and their cultural perspectives are highly influenced by the Himalayan ecosystems. The local communities of the Eastern Himalayas are benefited from diverse ecosystem services, including provisioning (ex. food, fodder), cultural (ex. religious, aesthetic), supporting (ex. soil development, hydrological cycle), and regulatory (ex. climate) services (Bhattacharya et al., 2016; Bhattacharya et al., 2014; Chaudhary et al., 2011; Gupta et al., 2019).

But the whole landscape is changing unprecedently since the past century due to the change of interactions between the people and the landscape. Increase in anthropogenic activities which include, intensive cash crop cultivation (Tea, large cardamom, orange) mostly accredited to the British government, followed by the expansion of unplanned tourism activity has impacted the landscapes in several dimensions. Several other negative interactions like hunting, deforestation, overexploitation of groundwater or spring water and other developmental activities have led to massive degradation and deterioration of the fragile landscape. The impact of these changes is very much evident from the natural calamities in the past few years like the increase in the frequency of floods and landslides in the Eastern Himalayas. The shift in the weather patterns has considerable impact on local agriculture and tourism, which are the two major sources of income of the local inhabitants (Bhattacharya et al., 2019).

Relatively few numbers of research works have highlighted the importance and relevance of ecosystem services, changing socio-ecological systems and climate change in conserving the natural, social and human capital of North Bengal and Sikkim state (Anonymous).

Many small villages are situated in the Eastern Himalayas; several among them are proximate to the forest areas with rich biodiversity. *Chota Mungwa* (27.0537N, 88.399 E) is an emerging ecotourism destination in the Eastern Himalayas, situated at an altitude of 1800 m ASL, in the district of Darjeeling of the state of West Bengal in India. The name of 'Chota Mungwa' has been derived from the Finger millet that was cultivated by Lepchas who had settled in this region since the sixteenth century (in Nepali language, 'mungwa' means finger millet). The beautiful view of the mount Kanchenjunga range from the hamlet and incredible diversity of birds and medicinal plants have made the hamlet as an attractive destination for tourists, nature lovers, photographers and ecological researchers.

The study was conducted in November, 2019 by visiting *Chota Mungwa* village in India (Fig. 1). The survey work focuses on critical understanding of the bio-cultural landscapes and human–environment dynamics, and analyze the possible impacts of natural and anthropogenic factors in the Eastern Himalayan village.

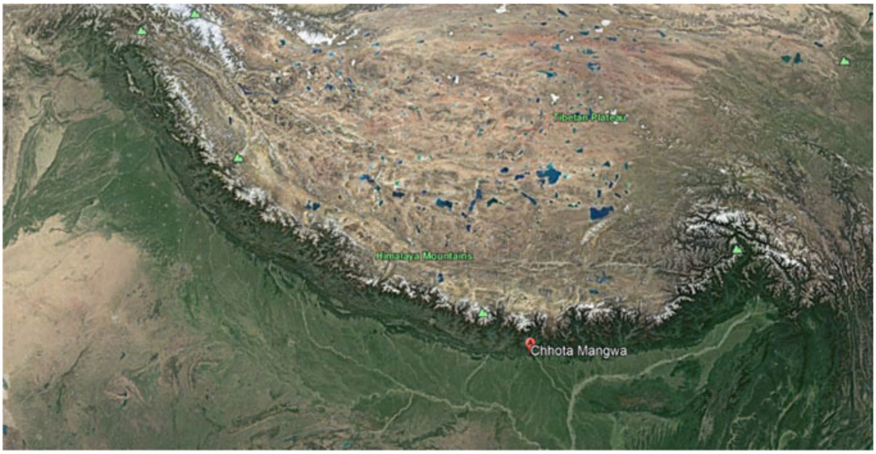


Fig. 1 Location of *Chota Mungwa* village in the Eastern Himalayan landscape in India

2 Methodology

The survey was carried out in November, 2019 by visiting *Chota Mungwa* village situated in Darjeeling district, West Bengal, India. The study focused on integrating several perspectives related to social ecology, ecosystem services and conservation.

Data were collected using a mixed-methods approach, collecting background baseline information, scheduling interviews with members of the local villages and field observations. In several hamlets situated in the Eastern Himalayas, the head of the family holds the rights regarding social and economic decision-making. In this regard, each household head of the family was interviewed. Based on the study framework and research objectives, both structured and semi-structured questionnaires are used, and was supplemented by field notes. Descriptive questions are designed and used in most of the interviews, and one-on-one interviews were conducted for data collection. PRA (Participatory Rural Appraisal) methods were applied for collecting data and methods like key informant interviews (KIIs), focus group discussions (FGD) and field observations are included and followed. The average length of each interview was approximately 40–50 min. The interviews were conducted in local languages (Bengali and Hindi) and English. The questionnaires were also developed in English, Hindi and Bengali languages.

Biodiversity in the village and adjoining forest area was studied and documented by taking field notes. Survey data was collected based on the attributes like agriculture, livestock management, demography, water management, waste management, disaster management, climate change (local people's perceptions), biodiversity, ecosystem services, conservation measures, developmental and ecotourism activities in the village. Demographic information was collected by interviewing the villagers and from the local *Panchayat* office. Information education was noted from local schools and public health information was collected from the local sub health centers. Information regarding transportation facilities was collected from the local transport syndicate. Photographic documentation accompanied every phase of the survey (Bhattacharya et al., 2015; Chaudhary et al., 2011). Policy proposals for sustainable development of the village were analyzed and discussed with the objectives of conserving biodiversity and socio-ecological characters of the village.

3 Results & Discussions

3.1 Social and Demographic Dimensions

In *Chota Mungwa* the dominant ethnicity is being the tribes of Lepchas and Tamang which comprises about 41% of the population. The commonly spoken language is Nepali and, followed by various other ancestral tribal languages. Though, they do speak in Hindi, which is one of the widely spoken languages to communicate with visitors and tourists.

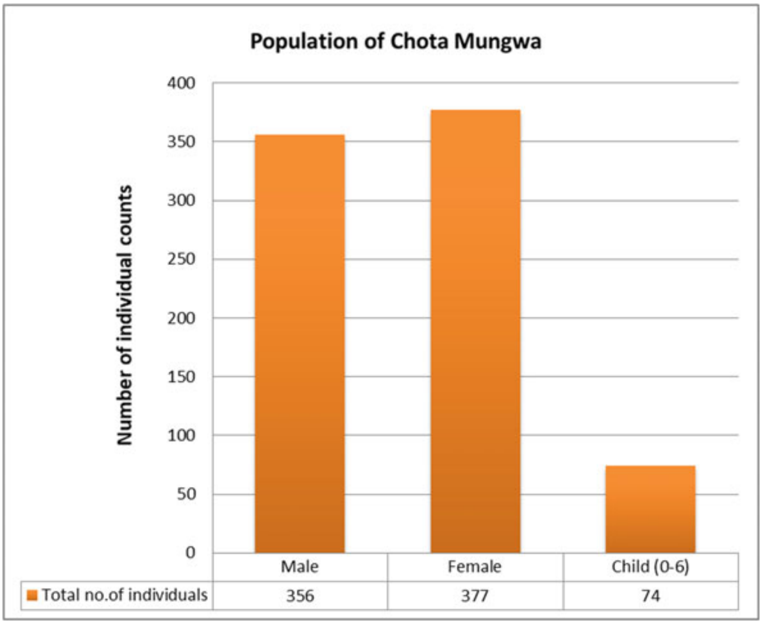


Fig. 2 Bar graph showing the numbers of individuals in each category

As per the 2011 census report published by the Government of India (Fig. 2), about 161 families are residing in the hamlet. The total population of the village is 807, of which 51% (411) is female and 49% (396) is male respectively. The children population between the ages of 0–6 years is around 74 which makes up almost 9% of the total population.

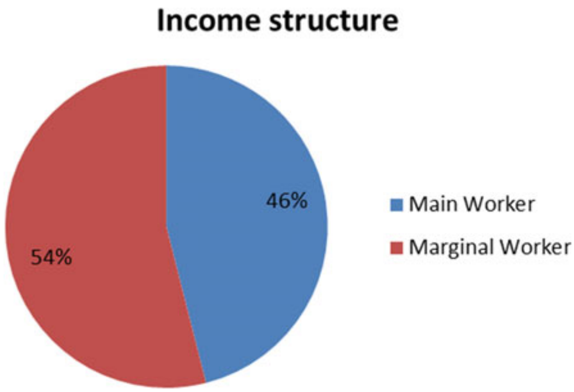
About 75% of the population in the village practices Hindu religion with the rest of the population mostly practicing Christianity and Buddhism respectively.

The overall literacy rate of the population is 82.4%, with male literacy rate being 85.4% and female being 79.6%. The overall literacy rate stands better when compared with the literacy rate of the state of West Bengal which is 76.3%. The education level is going up since there has been an increase in high school with nearly 7 high schools that have been newly built in the neighbouring villages. Private night schools and day-care centres have also been established with the help of local villagers.

In the village of *Chota Mungwa*, approximately 60% (506) of the population is employed or waged (Fig. 3). The majority of them are categorized as 'marginal workers', as they are employed for less than 6 months of the year. The marginal workers mostly include landless farmers who are employed by the landowners in their field. About 70% of the agricultural community was found to be landless farmers.

The male members of the families are occupied in tourism, transportation, and agricultural activities. The female members are involved in household work, agricultural activities and tourist hospitality in the homestays.

Fig. 3 Pie chart unveiling the share of marginal and main workers among the total worker population (n = 506) of *Chota Mungwa*



Terrace cultivation or step cultivation is practiced in *Chota Mungwa* village. Agricultural activities in *Chota Mungwa* are divided into cultivation of two major crop types

1. Cash crop, which includes large cardamom and orange plantation. Though in recent years the production of both these crops has gone drastically due to various ecological (pest attack, the shift in the climatic pattern) and economical (reduction in import, surplus production) problems.
2. Food crop, which includes mostly Legumes (beans), root crops (onion, garlic, radish, turmeric), tuber crops (potato), chili, tomato, coriander, cauliflower. Most of the food crops in the village are cultivated by organic farming.

Since the practice of organic farming increases the production cost, therefore most of the crops produced are for personal consumption. The meal served to the tourists by the home stay owners also includes organic vegetables. Practice of organic farming has been developed in the last 30 years. Application of cowdung and vermicompost are common techniques of organic cultivation in *Chota Mungwa.* Rainwater and pipe water irrigation methods are followed in the agricultural fields. Rainfed Irrigation is commonly practiced in the agricultural fields. At times, water is brought from the local springs (*jhoras*) to the agricultural fields, especially during the period of water shortage. Irrigation by pipes is commonly practiced in vegetable farming.

Most of the houses at *Chota Mungwa* have cultivable lands adjacent to the houses.

The common livestock at *Chota Mungwa* are local breeds of cows and pigs. Livestock is also a part of income sources for a few of the households. Majority of them has cow as livestock for milk production. Meat, milk and eggs are the main livestock products, and are the significant sources of earnings. Organic manure is produced from the wastes generated by the livestock; manures are applied in the agricultural fields to increase productivity. Bee-keeping has also been observed in a few of the households during the survey, but it is not a common practice in the village.

About twenty years back, the main sources of income in *Chota Mungwa* were agriculture, livestock and manual labour work. However, with the increase of tourism in

Table 1 Population and land area data of *Chota Mungwa* (Census, 2011)

Area (in hectares)	203.6
Population	807 (Male: 396; Female: 411)
House	161
Children (0–6 years)	74 (Male: 40; Female: 34)
Literacy (percentage)	82.40
Forest land (in hectares)	80
Non-agricultural land (in hectares)	21
Culturable waste land (in hectares)	0
Total irrigated land area (in hectares)	32.6
Total unirrigated land area (in hectares)	70

recent years, more people have shifted towards tourism business which now becomes the main source of income in the village, followed by agriculture and daily labours work. Currently, there are about 6 homestays in the village; with most of them have the capacity to accommodate about 10 people at a time with the exception being Darjeeling Blossom, the oldest homestay with the capacity to accommodate 50 people at a time. Local transportation business, engagement of the local villagers as tourist guides and local shops also have increased with the development of tourism.

Educated young villagers migrate to other places for job and business opportunities. Majority of the migrated individuals join in defence.

A summary of the population, occupation and land area data of *Chota Mungwa* is shown in Table 1.

3.2 Ecological Dimensions

Chota Mungwa sits equidistant to Senchal Wildlife Sanctuary and Mahananda Wildlife Sanctuary which is about 45 km on the opposite side to each other. Takdah reserve forest is the closest reserve forest which is approximately 5 km from the hamlet *Chota Mungwa* is surrounded by Peshok tea garden and Takling Khasmahal (Fig. 4).

Khasmahal is the unclassified forest area that has been exploited for generations by the local inhabitants. The marginal communities have been dependent on these forest patches since they have settled since centuries. The major dependency on these forest lands is due to collection of firewood, medicinal herbs, fruits, and resins. However, the forest resources have been decreasing accordingly to the villagers of *Chota Mungwa.* The firewood consumption has reduced significantly since most of the households have been able to procure LPG (Liquefied Petroleum Gas) cylinders due to various cost-effective initiatives from the Government. Resins and wild fruits are rarely collected nowadays as most people have shifted to alternative occupations.

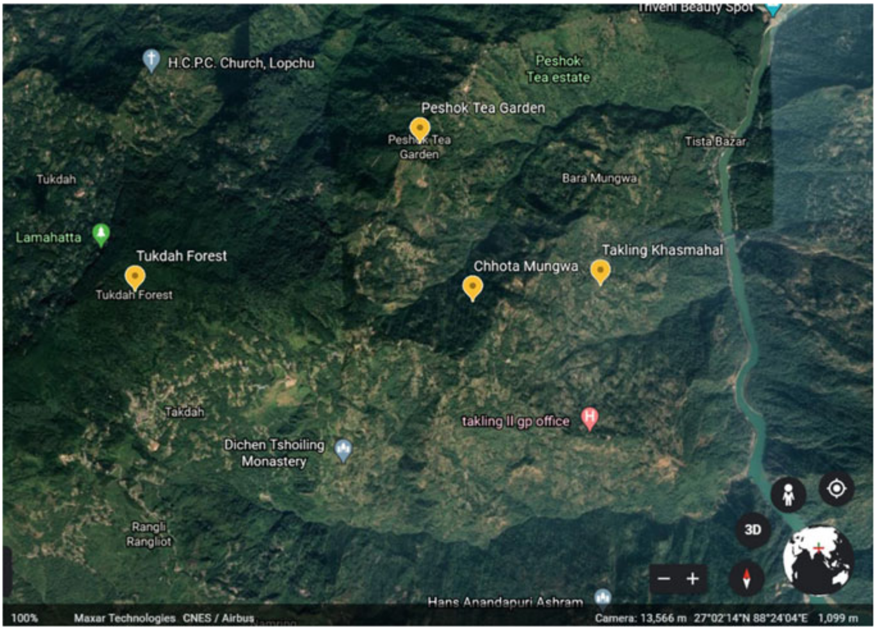


Fig. 4 Highlighting (pointers) the Takdah forest, Peshok Tea estate, *Chota Mungwa*, and *Takling Khasmahal*

Uses of medicinal herbs from the forest also have decreased with an increase in the availability of synthetic drugs in the local medicine shops. However, in some places, use of timbers for construction has increased significantly in response to growth in tourism and development of homestays.

The locals reported about the issues related to deforestation such as changes in local rainfall patterns and weather over the decades and largely in the past few years. Less rainfall has led to drying up of some local springs during the peak summer, causing water scarcity. As per the opinion of some elderly interviewee during the survey, there has been an overall rise in the temperature during the summer season, which has also prolonged over the past few decades.

The intensive pressures on the forest patches of *Khasmahal* have led to a change in the nature of the biophysical attributes over the past few decades. The satellite image in Fig. 4 highlights the degraded and fragmented landscape across the region. The only dense vegetation that can be observed in the proximity of *Chota Mungwa* is the Takdah reserve forest since it is devoid of encroachment because of being classified as a forest reserve by the Government of West Bengal.

The biodiversity of the Takdah forest and the surrounding Khasmahal region haven't been studied in the near past and therefore no literature is available, which could have provided the detailed biodiversity status and to acknowledge the effect of fragmentation and degradation in the region. The resilience of the ecosystem has till now sustained it from collapsing, it is indeed necessary for an adaptive sustainable conservation strategy to revive this landscape before the tipping point arrives to topple down the ecosystem.

3.3 Socio-Ecological and Economic Dimensions

Indigenous communities of the region have been living in harmony with nature since the 16-seventeenth century. The indigenous communities are largely dependent on the ecosystem services obtained from this landscape for their day-to-day needs, which has led to the evolution of an intricate socio-ecological linkage. The linkage is an example of a sustainable livelihood that has led to the conservation of the landscape till the recent past, but over the past few decades, this linkage has been compromised due to degradation of the habitat caused by the unsustainable consumption of natural capital and climate change, which has led to the loss of biodiversity, agricultural loss, and loss of social and human capital which are all inter-dependent to each other (ICIMOD, 2020).

Two of their main sources of income—tourism sector and agriculture sector have major roles in recent times in stabilizing local economy by transforming their development strategy from anthropocentric to eco-centric, with the underlying belief being humans are embedded within nature. Apart from the income sources, socio-ecological dimensions are also connected and simultaneously influenced by cultural practices of the indigenous communities.

3.4 Tourism

Tourism started in *Chhota Mungwa* in 2003, with only one homestay. In the last decade, it has gained momentum like other ecotourism destinations in the Eastern Himalayas (Bhattacharya, 2015; Bhattacharya et al, 2014, 2015, 2019). The practice of tourism in these hamlet can be termed as 'slow tourism', which can be considered as a modified version of the concept of 'slow travel', where the tourists spend leisure time by observing nature; hiking and trekking in small groups, while spending a substantial amount of time to indulge oneself towards understanding the landscape and the socio-cultural dimensions of the surroundings (Sharma, 2020). 'Slow tourism' is contrasting to 'fast tourism', which is more commonly practiced tourism that can be found more or less in every popular tourist destination across the world. Slow tourism is the concept that is intertwined with the eco-centric development approach that is indeed necessary for the development of the indigenous communities.

In *Chota Mungwa*, the major attractions of tourism are the scenic view of Mt. Kanchenjunga, incredible diversity of birds and butterflies and hospitality of the traditional local inhabitants. Tourism is largely dependent on the cultural services of an ecosystem.

Most of the tourists are dependent on the hospitality provided by the home-stays. However, the tourists often carry dry food packs and bottles with them. Waste generation increases during the peak tourist seasons of April–May and September–October.

3.5 Agriculture

Agriculture is undoubtedly the most primitive and significant example of a socio-ecological linkage that exists today. Though initially, when the Lepcha community first settled in during the sixteenth-seventeenth century at *Chota Mungwa*, their survival depended on collection and consumption of wild fruits and meat procured from the Himalayan forests. Finger Millet was the first food crop that was produced by the Lepcha community in *Chota Mungwa*. Orange and large cardamoms are the main cash crops that have been cultivating since the past century. However, with change in environmental conditions (e.g., climate change, degradation of soil fertility, shift in rainfall patterns) there has been considerable impacts on cultivation of both the cash crops over the years, especially in the last three decades. Production of oranges has gone down considerably in the area. Besides, the selling prices for large cardamom has significantly in recent times.

The production of large cardamom has declined in recent times in many areas of the Eastern Himalayas (Sharma et al., 2009). According to a study conducted by Sikkim's Department of Agriculture, Govt. of Sikkim, large cardamom farming has decreased recently in yield per hectare. Another reason effect of viral diseases like *chirkey* and *phurkey* on the plantations (MoAC, 2008; ECCOS, 2010; Stoep, 2010). Improved curing methods, which are able to produce higher quality capsules are difficult to adopt by the local farmers because of high cost. The quantity of large cardamom traded from India in 2010–2011 decreased in compared to the trading in 2008–2009. However, the export value was higher in 2010–2011, which indicates higher value and demand for this cash crop. An increase in production of large cardamon by developing effective management structure and implementing proper pricing of the high-quality products can improve the livelihoods and economic condition of local inhabitants in the sub-Himalayan region.

Besides, the local communities gradually have developed and integrated system of organic farming, livestock management and collection of forest resources, which effectively increases self-sufficiency of the local inhabitants, and less dependency on the external markets for consumption. The socio-ecological linkages developed in *Chota Mungwa* are based on sustainable and pragmatic approaches towards achieving an eco-centric socio-economic growth.

4 Policy Recommendation for Sustainable Conservation

In modern age, humans have altered or impacted ecosystems all across the globe through their various socio-economic activities. Therefore, while dealing with the intricate ecosystems of the Himalayas and the indigenous communities residing in the landscape, researchers often consider them as robust socio-ecological systems, with human and ecosystem elements integrated within it. The policy recommendations, therefore, need to develop strong objectives towards sustainable benefits of the socio-ecological system as a whole, by considering it as a continuous entity instead of considering a discrete one (Dyson et al., 2023; Ramakrishnan, 2007).

Chota Mungwa village has emerged recently as one of the popular tourist spots in the Eastern Himalayas for family and educational tours, nature camps, trekking, hiking and research. Ecotourism can be considered as one of the significant driving factors in accelerating socio-economic growth and development of the village. Formulation and implementation of sustainable development policies are essential in order to safeguard the socio-ecological characters of village, ethno-cultural conservation and protection of the biodiversity (Bhattacharya, 2020). The following perspectives can be considered for sustainable conservation and management of *Chota Mungwa* village are as follows:

a. Water and energy management—According to the experience of the local people, there is periodical water crisis in recent times in the summer because of drying up of the local springs. In monsoon, the water gets murky because rainwater flows towards the mouth of the supply line, while washing and eroding the adjacent soil layers.

   Some of the homestays have installed water filtration systems to provide clean water for the tourists, however, most of the local households are devoid of such amenities since the maintenance is costly. Rainwater harvesting has been initiated by very few households by self-funding. Since most of the families don't have strong economic support, therefore institutional motivation in terms of policy reforms and funding is required to develop and maintain rainwater harvesting structure in the village houses.

   The power supply in terms of electricity is largely non-uniform, especially during the monsoons. Solar panels would be a better alternative in such condition, which can, therefore, be independently managed by each of the households and even at community level. Subsidies can be helpful for in this regard, which can, therefore, provide clean power supply even to the remote households in the hamlet

b. Ecological management—Deforestation is considered to be one of the major reasons for ecological crisis in the eastern Himalayan biodiversity hotspot (Sheth et al., 2020). Deforestation can lead to fragmentation of habitat, loss of biodiversity, the shift in local weather patterns. According to the villagers, In 1985–86, approximately 50–60 hectares of forests was lost in the adjacent areas of *Chota*

Mungwa; since then a major change in local rainfall pattern has been observed by the villagers.

Reforestation programs needs to be carried out at a massive scale, by planting indigenous species which can be ecologically and culturally important. However, selection of appropriate species is essential for this vulnerable landscape.

Large scale biodiversity survey by Government and Non- Government agencies should be arranged to understand the change in biodiversity in the forest patches, and a comparative database can be developed by studying the historical records, villagers' perceptions and present experimental data.

c. Agricultural management—The decrease in the production of orange and large cardamom cultivation supports the idea that monoculture is never ecologically sustainable.

   Subsistence organic cultivation adopted by farmers in the landscape has reduced their dependency on the external market to some extent. The practice of organic farming is not common yet since it's costly and needs a different approach than the commercialized farming methods. Support from Governmental institutions in the form of subsidies and loans can really help the farmers in practicing organic farming, thus can popularize the concept among other farmers in their respective communities.

d. Tourism—Tourism can uplift the socio-economic condition of the indigenous communities residing in the landscape of *Chota Mungwa*. Ecotourism is a recent practice that is being strived for in these biodiversity hotspots, however, proper implementation and practice of 'slow tourism' can help to reduce the ecological footprint, as mentioned earlier. In this scenario, tourists would spend much more time indulging themselves in different socio-cultural activities at their perusal, thus leading to less ecological footprint and can support sustainability.

   Corporations and Government institutions can invest and provide subsidies to encourage more such practices in these landscapes, which can, in turn, promote global environmental awareness and sustainability.

e. Education & health management—The education and health sector at *Chota Mungwa* village need to be ramped up by Government as soon as possible since social wellbeing is strongly related with education and health. Implementation of private public partnership projects on health and education and making them affordable to the local people in these would be beneficial.
f. Waste management—In the village area, waste segregation is practiced at household level, based on segregation of organic and inorganic wastes. Organic wastes are majorly used for feeding the livestock and for preparing organic fertilizers. However, the inorganic wastes are mostly burnt in regular intervals, on weekly and monthly basis. Waste management, with special focus on plastic and other inorganic wastes should be implemented in the village area. Proper methods of waste

collection, transportation, storage, disposal and processing should be established in the villages of the eastern Himalayas. Waste management is also relevant for the local economic growth, since accumulation of wastes can significantly affect the aesthetic beauty of the Himalayan landscape on which the tourism sectors are largely dependent; therefore it needs serious interventions from both individual and government level.

The recommendations put forth needs serious implementation after rigorous groundwork to maximize the benefits among the stakeholders. CoVID-19, the socio-ecological and epidemiological disaster has brought in a major upset in the dynamic socio-economic structures of human societies. Himalayan landscape is no exception, where the rural societies have been facing significant problems in tourism, health and social wellbeing due to this pandemic. While reviving ourselves post-COVID, we should transform our socio-economic activities in a way to re-establish and sustain our robust socio-ecological connections, before we are struck by more such pandemics.

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Trouble in Paradise: Evaluating the Effects of Unorganized Tourism on the Himalayan Ecology

Chandranshu Tiwari and Mala Rani

Abstract The Indian Himalayan Region (IHR) has drawn visitors and pilgrims from all over the world due to its towering peaks, majestic landscapes, rich biodiversity and cultural heritage. Tourism not only provides valuable economic and business opportunities and jobs for local mountain people, but also generates revenue and profits for state governments and private entrepreneurs. The modern tourism industry is closely linked to development, and frequently includes a strategy aimed at covering as many new destinations as possible. Tourism in the IHR has grown steadily and diversified over the last few decades to become one of India's fastest growing economic sectors. Tourism in the IHR range is currently viewed as a source of environmental damage and pollution, a threat to socio-cultural heritage, a heavy user of scarce resources, and a potential source of negative externalities in society. The uncontrolled growth of tourism resulted in a construction boom in hazardous areas such as river valleys, floodplains, and landslide-prone slopes, exacerbating the disaster. Erratic rainfall and environmental degradation caused by land use change for infrastructure development are already having an impact on mountain aquifer systems. These internal tourism development dynamics, including the effects of climate change, are significant change agents influencing sustainable tourism development in the IHR. In this review we analyze the current trend of environmental impacts associated with rampant tourism and consequent infrastructure, we conclude the discussion with possible mitigation measures.

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1 Case Study-I: Disaster in the *Devbhoomi*

June 2013, The Monsoon came early that year and in plenty. IMD reported an unprecedented increase in rainfall (440% more than usual for that time of the year). Meteorologists blamed the phenomenon on the collision between the advancing monsoon winds and the westerlies.

On June 16 and 17, 2013, the Gaurikund-Rambara-Kedarnath region was more crowded than usual for this time of the year. Gangotri and Yamunotri were opened to the public only a month ago, and the holy shrines of Kedarnath and Badrinath followed suit; the opening was delayed by almost two weeks. The delay, with the pleasant pre-monsoon weather and ongoing vacations resulted in a record breaking gathering of devotees. Uttarakhand High Court had suspended the use of horses and mules, owing to the hygiene for the pedestrians. Forcing people to move slowly or stay back at Rambara or Kedarnath, even people who could have gone back to Gaurikund if they could travel on horseback or mules. The persistent rains made air travel difficult. This included suspension of the helicopter service between Guptakashi and Kedarnath. Passengers who could have opted to travel by air had little option but to proceed further on foot with the procession. One that was already grinding to the halt at most places due to incessant rain and the low visibility that came with it. People returning from the shrines had no choice but to wait out the rain at Rambara or Kedarnath. In the face of heavy rains, plans had to be altered. More people continued to gather in the area. At the peak of pilgrimage season and with no pre-registration system, there is no way to be sure of how many people were in the region when the "Himalayan Tsunami" struck.

Heavy rain combined with increasing pace of melting glaciers triggered a lake outburst flood, landslides and flash floods. The resultant disaster ravaged Uttarakhand, with worst damage in Rudraprayag, Chamoli, Uttarkashi, Bageshwar and Pitthoragarh. Rough estimates put the human casualties in the upwards of 4000. Besides the massive loss of lives, the disaster was an unimaginable blow to the state's economy. The large scale destruction of infrastructure and costs of search, rescue and evacuation spelled a terrible loss of livelihood for most survivors. The aftermath saw a steep decline in the tourist foot fall in the region, yet another insufferable blow to the state's economy so dependent on the tourism and pilgrimage for their revenue. Government tried to bail out small businesses and victims through tax exemptions and fiscal aid even for loss not directly under the purview of the intended fund. An act of goodwill that only worsened government's financial woes.

It wasn't long before the media trial started, and people looked for someone to blame. Widespread public discourse included everything from climate change to divine wrath, yet peculiar by its absence was the topic of ever-expanding tourism in the state. Tourism and pilgrimage have a longstanding history in the Himalayan states, yet somehow ever-expanding urban growth and socioeconomic dependencies and vulnerabilities it entails escaped public eye. This ignorance becomes especially important when we remember how many of the victims in the Uttarakhand tragedy were actually tourists and pilgrims.

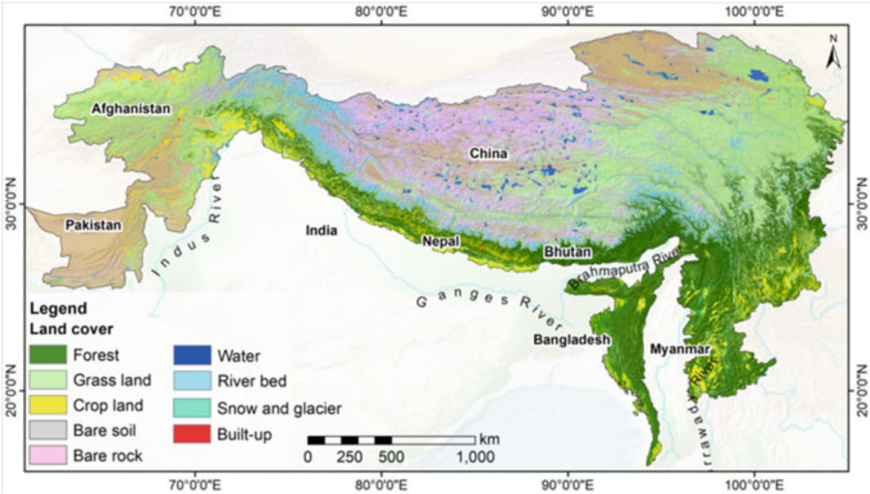

Fig. 1 Geographical depiction of Hindukush Himalayas (HKH) including Indian Himalayan Region

1.1 The Abode of Snow: A Primer to Himalayas

The Himalayan Mountain chain runs in an arc that passes through northern Pakistan, Nepal, Bhutan and India. A roughly 3000 km arc houses the tallest mountain peaks in the world, including Mt. Everest (*Sagarmatha* in Nepalese, *Chomolungma* in Tibetan) and some of the deepest river canyons in the world (Fig. 1).

The Yangtze,[1] Indus, and Ganges are just a few Asian rivers that have their primary sources in the Eastern Himalayas. Water from the Himalayas serves people all over the continent for drinking, agriculture, manufacturing, and power production. The rivers from the region serve no less than a billion people in the ten countries they flow through (Wester et al., 2019; Bhagirath, 2023).

Indian Himalayan Region (henceforth IHR) starts from the Indus River in the west to Brahmaputra in the east and spans 500,000 sq. km along the northern border for an estimated 2400 km. IHR has significant influence over the physiography and climatic conditions of the Indian subcontinent. Geographically, IHR has two distinct parts, viz. Eastern Himalayas cover the northeastern states of West Bengal, Sikkim, Assam, and Arunachal Pradesh, and Western Himalayas span Kumaon-Garhwal and northwest Kashmir. Owing to the abrupt rise in elevation in the region, less than 500 m to over 8000 m, IHR houses a wide diversity of ecosystems, often in a relatively small spatial area. These include Alluvial grasslands, some of the tallest in the world, and

[1] Mankabir, W. (2021). *A land cover map of the HKH region was developed using Landsat 30-m data.* https://commons.wikimedia.org/. Wikimedia Commons. Retrieved June 4, 2023, from https://commons.wikimedia.org/wiki/File:A_land_cover_map_of_the_HKH_region_was_developed_using_Landsat_30-meter_data..png.

subtropical broadleaf forests along the foothills that give way to temperate broadleaf forests in the mid hills, mixed conifer and conifer forests, and alpine meadows above tree line in only a few hundred kilometres (Bhattacharya, 2019; ENVIS 2022).

Biogeographically, IHR represents a meeting point for the Indo-Malayan, Palearctic, and Sino-Japanese domains. The resultant diversity has an intricate connection with the welfare of the billions of people around it. From a cultural perspective, the ecosystem diversity of the region has given rise to a wide range of ethnocultural diversity. Individual communities in the IHR are closely attuned to their local surroundings.

These communities are intimately dependent on IHR for several ecological services not limited to supplying essential commodities to support and regulate environmental cycles (soil formation and water cycle). That said, despite the abundance of natural resources, these mountain communities remain one of the marginalized groups in terms of socioeconomic growth. The resource utilization and the resulting social structures are a direct function of the geographical features. Compared to the plains, land is a limited commodity in the hills. Conventional wisdom of the plain finds little appeal among the hill folks. Incompatibilities between economic activities and environmental conditions can result in changes that may adversely affect social and ecological order. To better understand the socioeconomics of communities. We must study the five specificities: inaccessibility, fragility, marginality, diversity, and niche (Jodha, 1991). All of these directly impact the lives of people in IHR. Let us talk briefly about each of these points.

- Caused by the geographic conditions (altitude, steepness, unpredictable weather) and associated natural hazards, lack of access stemming from the isolation results in limited mobility, poor communication, and absence of basic amenities. The expensive transportation forces local communities to an even greater degree of dependence on the region's natural resources. The inaccessibility of the mountain communities creates an artificial close-loop economy derived entirely from the local resources. If not managed properly, these may result in severe depletion of the very resources essential for the communities in the first place.
- Despite its immense size and biological diversity, IHR is extremely vulnerable to degradation. This primarily stems from their low carrying capacity for resource-intensive economies (See Sect. 2).
- Inaccessibility combined with fragile geographic structure prone to natural disasters so commonplace in IHR create feedback loops of poverty. An inadequate resource base due to frequent natural disasters, and lack of institutional support due to the remoteness of these locations forces the communities into low-productivity practices that continue to push them into poverty over time. Historically, communities in IHR have been marginalized by policymakers who blame the remoteness and the accompanying socio-political instability for it.
- A combination of geographic and climatic facts makes IHR habitat to a wide diversity of flora and fauna often with rapid transitions between vegetation types. At the higher altitudes especially, the flora and associated hydrology changes are hard to

predict and may undergo severe fluctuations between seasons. Mountains consequently exhibit quick transitions from flora to snow and ice. The resultant landscape of ethical and cultural communities is deeply entwined with their surroundings. Thus, issues and their solutions become context-specific. The complex socioeconomic paradigm makes any attempts at generalization redundant.

- The unique climate conditions of IHR and the wide diversity of flora and fauna in the region create a market for goods, services, and activities that give IHR a competitive edge over the plains. Owing to its heterogeneous structure, locals have specialized niches for products derived locally such as traditional medicinal herbs, exotic fruits, and ornamental flora. The distinct geography of IHR is a lucrative tourism market, and communities in the IHR stand to improve their economic prospects if only they utilize the distinctive natural and cultural resources. At the same time, unsustainable use of these resources can also lead to total degradation (Jodha, 2001; Nyaupane and Chhetri, 2009).

1.2 Trouble in Paradise: How Many is Too Many?

The aforementioned factors combine to exacerbate the regional economy of IHR to a subsistence level despite the abundance of natural resources. Added to this, the relentless consumption has accelerated environmental degradation, increasing the risks associated with natural disasters in the region. Any attempt to restore the ecological balance of IHR demands a holistic shift in priorities and to strike a suitable middle ground between economic interests and environmental sanctity (Singh and Kotru, 2018).

The fragile environment of IHR has undergone severe degradation in recent history owing to unplanned land use, including unsustainable farming practices along the steep slopes and overgrazing of the vegetation essential for holding the soil together. Large-scale engineering work in the name of "development" and overharvesting of local resources by the communities have resulted in severe damage in even the most remote parts of the region. The recent loss of environmental quality, mass emigration, and fast deteriorating cultural fabric have been a serious concern for policymakers (Singh and Kotru 2018; Lorenz and Dittmer, 2021; Kuniyal and Negi, 2022).

1.3 Impact of Tourism

[2]As in the case of Uttarakhand, with the advent of connectivity, IHR has experienced an unprecedented flow of tourists over the years. The number of tourist sites, businesses involved, and the resultant capital flow have all grown to massive levels owing to word of mouth and large-scale promotions. Tourism today contributes a significant

[2] By authors.

proportion of the state GDP in the IHR region, employing some local people and businesses. However, the large-scale expansion of influx had severe consequences for the environmental sanctity. With the advent of mass tourism activities, commercialization of the socio-cultural landscape has put the traditional way of life at risk at many of the previously pristine sites (Datta and Banerji 2015; Lorenz and Dittmer, 2021; Bhagirath 2023) (Fig. 2). The relentless flow of people and the resources it accompanies jeopardizes the fragile equilibrium of the local ecosystem and has been a source of worry for the locals at multiple places in the IHR (See case study II).

The alarming rate of tourism in the IHR region has raised several concerns regarding resource management and environmental quality. These include waste management, increased air pollution, depletion and degradation of water resources, accelerated loss of local resources, biodiversity extinction, and loss of ecological services in the region (Kuniyal et al. 2022). In the urban centres of IHR states, average solid waste production is roughly 6,346 tonnes/day. Jammu and Kashmir produces the most rubbish (1792 tonnes), followed by Uttarakhand (1,528 tonnes). This garbage is produced primarily by the tourism industry (Bhagirath, 2023). Sikkim alone, an otherwise small state in the Eastern Himalayas with a population of ~ 6,00,000, has had 5,00,000 domestic visitors in 2011. A number that grew to 1.4 million in 2019.

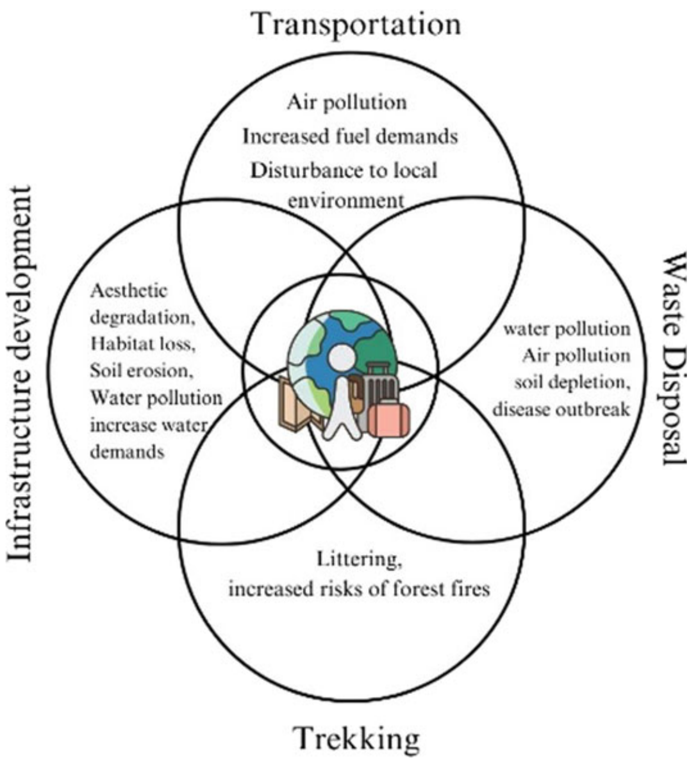

Fig. 2 Multi-dimensional effects of rampant tourism

Similar trends for tourists are observed all over the IHR. Although the rise has a promising effect on the local economy, without proper supervision, this may cause irreparable harm to the local ecology (Datta & Banerji 2015).

2 Case Study-II: Woes of Tourism in Ladakh

Ladakh is one of the largest state/union territories of India. Consisting of both Kargil and Leh Districts, the region has a total length of 54,146 km. With a land area of –1,03,000 sq. km and a population of 274,000, Ladakh is also the region with the lowest population density in the nation (Goering, 2010; Jamphel, 2023). The majority of the population relies on subsistence farming and animal rearing. The climate in Ladakh is extreme, with annual precipitation >4 inches and a minimum temperature that may dip below –40 °C. The region was opened to the international world for the first time in 1974. Government statistics report 527 tourists visited in the first year, of which only 27 were domestic. With the growth in connectivity through the air and now, roads, the traditional way of life has come under great stress. From a little more than half a thousand visitors in 1974 to 15,000 in the 1980s, to 2,50,000 in June-July 2022 alone, Ladakh continues to experience burgeoning tourist numbers every year. A number that most locals and conservationists allege to be a primary contributor to impending severe natural calamities. The distinct natural landscapes and the unique cultural appeal of the region attract visitors from all over the world. Ladakh experienced a large-scale rise in construction, especially in the areas in and around Leh.

2.1 Disproportional Distribution

A significant portion of Ladakh's cash economy comes from tourism and related activities. These benefits, however, are limited to the minority associated with the sector. More than 90% of the Ladakhi population lives beyond Leh, the hub of tourist activities, receiving little to no economic benefits from the business. Few locals operating hotels in Leh profit disproportionately from the trade. Most tour companies and vendors operating in the area are seasonal, arriving before the onset of tourist season in June and leaving afterward. These players take the lion's share of the tourist revenue. The only way the locals outside Leh earn is by hosting individual trekkers and occasional groups not part of the organized sector or renting out pack animals to them (Goering, 2010).

2.2 Consequences

The arrival of mass tourism in the 2020s had massive impacts on the landscape. As per the figures from the Ladakh Taxi Union, anywhere between 300 and 600 cars visit Pangong Lake daily during the tourist season. These cars, often driven by tourists, wade recklessly through some of the most fragile habitats in the area. NGOs and environmentalists have repeatedly flagged the effect of increasing tourists and vehicles on the fragile terrain of IHR (Chakravarty, 2022).

Efforts to cater to modern hospitality standards place excessive pressure on the region's water supply. Leh's total bed capacity was 12,474 in 2016, but by July 7, 2022, that number had risen to 17,104. Between 2016 and 2022, there are approximately 140 restaurants, a 145% increase from the 57 in 2016. Overall number of hotels, guest houses, and homestays has expanded from 520 to 881 in the same period. Most of the hotels and homestays use borewells to supply water and septic tanks for wastewater collection, jeopardizing the local ecology and groundwater resources in the process. Some of these hotels have access to communal water sources and are known to import water via tank trucks during particularly severe dry spells.

Up until recently, the waste was recycled into the soil and used in agriculture. The rapid growth of the hospitality sector has put the region's waste management sector under pressure. Irresponsible disposal of solid waste pollutes the environment and water supply causing disease outbreaks. Poorly constructed sewage systems, for instance, have been shown to contaminate nearby water streams. Local government initiatives for waste segregation and recycling have somewhat alleviated the problem in certain parts. However, due to the limitation of area, open burning is the most common practice for waste disposal, shifting the problem from land to air. Leh's waste management practices continue to raise concerns among locals and environmentalists alike. The problem is expected to grow as the region experiences an ever-growing number of visitors. To put matters in perspective, Leh produces 1.3 tonnes of trash per day during the winters and 12–15 tonnes per day during the summers (Jamphel, 2023).

Furthermore, tourists have higher energy demands than locals. The hotels import fossil fuels, transported via trucks from the plains for cooling, heating, lighting, and transportation needs, adding diesel fumes, coal smoke, and used oil to the growing list of environmental concerns in the region. Trekkers consume already limited fuel and feed in remote settlements, often without proper compensation to the locals.

2.3 Takeaways

While the socioeconomic welfare of the people in IHR cannot be compromised, there is an urgent need to educate the local populace about a sustainable economy. Furthermore, if the indigenous communities are better trained, they would be able to push for greater adherence to rules designed to protect the fragile ecological equilibrium of their area. While the most logical route for economic growth in the IHR is through tourism, it is crucial to address the environmental concerns associated with the sector. With improvements in road connections and transportation, unregulated tourism will continue to impact the Ladakhi landscape. Policymakers must remember that the ecology and landscape are crucial for tourism. If ecology suffers, the economy will follow (Rizaal & Ashokan, 2014).

3 Ecotourism: Boon or Bane?

Ecotourism has had many definitions but there is little consensus over its components. Over the years, terms including ecotourism, alternative tourism, green tourism, and sustainable tourism have been used interchangeably.

Definitions of Ecotourism include:

> ...responsible travel to natural areas that conserves the environment and sustains the well-being of local people- International Ecotourism Society (1991)
>
> ...environmentally responsible travel and visitation to relatively undisturbed natural areas, in order to enjoy and appreciate nature (and any accompanying cultural features- both past and present) that promotes conservation, has low negative visitor impact, and provides for beneficially active socio economic involvement of local population. -IUCN (1996)
>
> All nature-based forms of tourism in which the main motivation of the tourists is the observation and appreciation of nature as well as the traditional cultures prevailing in natural areas. -The British Ecotourism Market, UNWTO (2002)

3.1 Promising Future (?)

Ecotourism is recognized as the symbiotic link between ecology and tourism that safeguards ecological fragility while securing the socioeconomic interests of locals. Recent definitions include elements of environmental impact, the contribution to conservation, and community participation (Batta, 2006). The activity recognizes the stakes of both the locals and the tourists in the human component. Thus, the focus broadens to examining how local communities can adapt to the needs of the tourists and maintain the sector. Hence there is more to the activity than just tourism to natural regions (Chopra 2017).

Conventional tourism practices focus on the customer's leisure, often disregarding sustainability, leading to pollution, habitat degradation, overcrowding, and resource depletion. Ecotourism, if promoted properly, can put an end to this trend. In its essence, the activity encourages responsible travel with awareness about one's responsibility towards protecting the local environment and culture.

Ecotourism is rapidly emerging as a crucial contributor to economic growth and socioeconomic changes in regions with cultural and ecological diversity. Several estimates put ecotourism expenditures in these regions at a number ten times higher than the conservation initiatives by various international organizations (Chopra 2017; Brandt et al., 2019; Ashok et al., 2022). From a purely economic perspective, ecotourism offers a monetary incentive to the stakeholders to preserve the local ecosystems and species that attract revenue to the region (See Case Study III). The feedback loop leads to a net increase in the biomass of the ecosystem in turn attracting more ecotourists over time. By playing to this function, ecotourism activities offer the local communities an alternative source of income, reducing resource extraction from the environment and thereby helping them overcome the challenges brought by climate change (See Case Study IV). By encouraging ecotourism in unprotected areas, locals can be encouraged to safeguard their natural resources for the long term. Things, however, are far from ideal.

3.2 Yet Another Risk (?)

As a direct consequence, the term *ecotourism* is being used willy-nilly with little regard to the actual implications, all to get a competitive edge. Tourists anticipate experiencing the natural landscape and expect a "traditional community" driving many communities to preserve the appearances to cater to these expectations despite the local urges to modernize (Chaturvedi, 2002). The absence of matrices for monitoring the impacts of tourist activities and indicators for assessment are the major hurdles in wide-scale applications of the concept (Batta, 2006).

Expansion of trails, denudation of vegetation, exposing tree roots, rampant littering of high altitude areas, contamination of water streams, unplanned constructions, and the resultant landslides, break down of conventional routes, and climate change-related fires are to name a few of many adverse effects "ecotourism" have been associated with over the years. More recently, construction in the hospitality sectors in IHR has raised concerns over the detrimental effects these economic activities have had on the biodiversity in the region (Ashok et al., 2022).

4 Case Study-III: From Foe to a Friend

Snow leopards (*Panthera uncia*) are apex predators of IHR and evolved over millennia to survive in some of the harshest conditions on the planet (Fig. 3).[3]

Their thick white–grey coat with black rossettes blends them perfectly in the high rocky mountain habitats. Their camouflage renders them nigh invisible thus the moniker of "ghost of the mountains". As the apex predator, the snow leopard is an indicator of the ecosystem health in the mountains and increasingly of the impact of climate change on the mountain environment. The species is thought to be distributed

[3] Irbis1983. (2010). *snow leopard*. Wikimedia Commons. Retrieved June 7, 2023, from https://commons.wikimedia.org/wiki/File:Irbis4.JPG.

Fig. 3 Snow leopard (*Panthera uncia*) is one of the most elusive big cats in the world. Ladakhi's believe the animal doesn't eat flesh but drinks blood similar to its namesake (Balasubramanian, 2018)

across 12 countries in Asia, with 60% of its native habitat concentrated in China. The natural low-density population of the species suffers an increasing amount of duress as climate change increases the events of conflicts with humans.

The high altitude and its elusive nature make studying animals a challenge. While we don't know the exact numbers, estimates vary between 3, 00 to no more than 6500, of which IHR is home to approximately 500. The species is classified as Vulnerable by the IUCN. The leading cause behind this is humans. In the absence of official figures, wildlife trade networks report that between 2008 and 2016, ~ 220–425 cats were killed or traded every year (snowleopard.org, 2018). In India alone, 21 to 45 snow leopards were killed annually till 2016 (Majumdar 2017).

4.1 Roots of Contention

With rising global temperatures damaging alpine productivity, the native territories of snow leopards and their traditional prey species increasingly overlap with the domestic livestock. As illegal trade and poaching reduce the population of its native prey, such as blue sheep, ibex, and Argali wild sheep, the cats increasingly prey on the livestock for survival. For marginalized communities such as herders, such losses are often catastrophic. As such events become more frequent, the animal has grown a negative reputation among the local communities that often trap and kill the cats in retaliation (Desai, 2016; Majumdar, 2017; snowleopard.org, 2018; Jain 2019; WWF.org, 2023).

4.2 Finding Solutions

In efforts to reduce the brewing conflict,[4] The Snow Leopard Conservancy-India Trust (SLC-IT) started the Himalayan Homestay Program (HHP) in 2002. Created in partnership with Hemis National Park and later the State Forest Department, the initiative originating in several valleys of Leh was an attempt to supplement the local income by providing lodging for the tourists. The project aimed to offset the monetary loss due to depredation. HHP trained locals in housekeeping, and several youths were trained as local guides to lead the visitors on environmental tours that might include occassional sightings of the snow leopard.

Since 2002, SLC-IT has trained over 130 families to offer homestays across Ladakh, with over 1200 homestays successfully operating currently (Balasubramanian 2018). Forest departments enabled local stakeholders to devise their own rules and regulations for operation in the region, allowing more autonomy and better management of the resources. Homestay owners in the area today earn anywhere between INR 2–3,00,000 per annum. In the process, the relationship between locals and the “ghost cat” has undergone drastic changes. The animal is now a crucial source of income, worth more alive than dead (Fig. 4). Visitors frequently report sightings from as little as 50 m in Hemis (Majumdar 2017).

HHP gives visitors a first-hand experience of Ladakhi culture and cuisine. Licensed homestays, registered with the tourism department, charge INR 1000 per day for lodgings, three meals, filtered water and tea. Homestays associated with HHP have ecologically sustainable dry toilets that conserve the limited fresh water supply of the region. As an additional effort to improve the social conditions of the resident village, ten per cent of each homestay’s income goes to a village fund managed by a women’s organization for the welfare of the community as a whole. Women participants experience higher economic autonomy. SLC-IT-led handicraft development programme encouraged women to produce woollen goods and souvenirs. In Ulley Village, the money gathered by local homestays was used for installing a solar-powered water heater to offer hot water to local hikers at nominal prices. The money collected is then put back into the fund. Over time, the trust assisted in procuring and installing solar-powered lights to ward off wild predators after dark (Desai, 2016).

As a result of local support, both the snow leopard population and the tourists’ numbers have experienced a period of growth. The most recent camera surveys in 2012 indicate a local rise in numbers from 40 in 2006 to 60 in 2012. Demand for wildlife guides has increased in tandem.

4.3 Cautious Optimism

As part of a study to examine changes in attitudes towards Snow leopards, a team of researchers from the University of Kent (UK) interviewed 49 villagers from seven

[4] By authors.

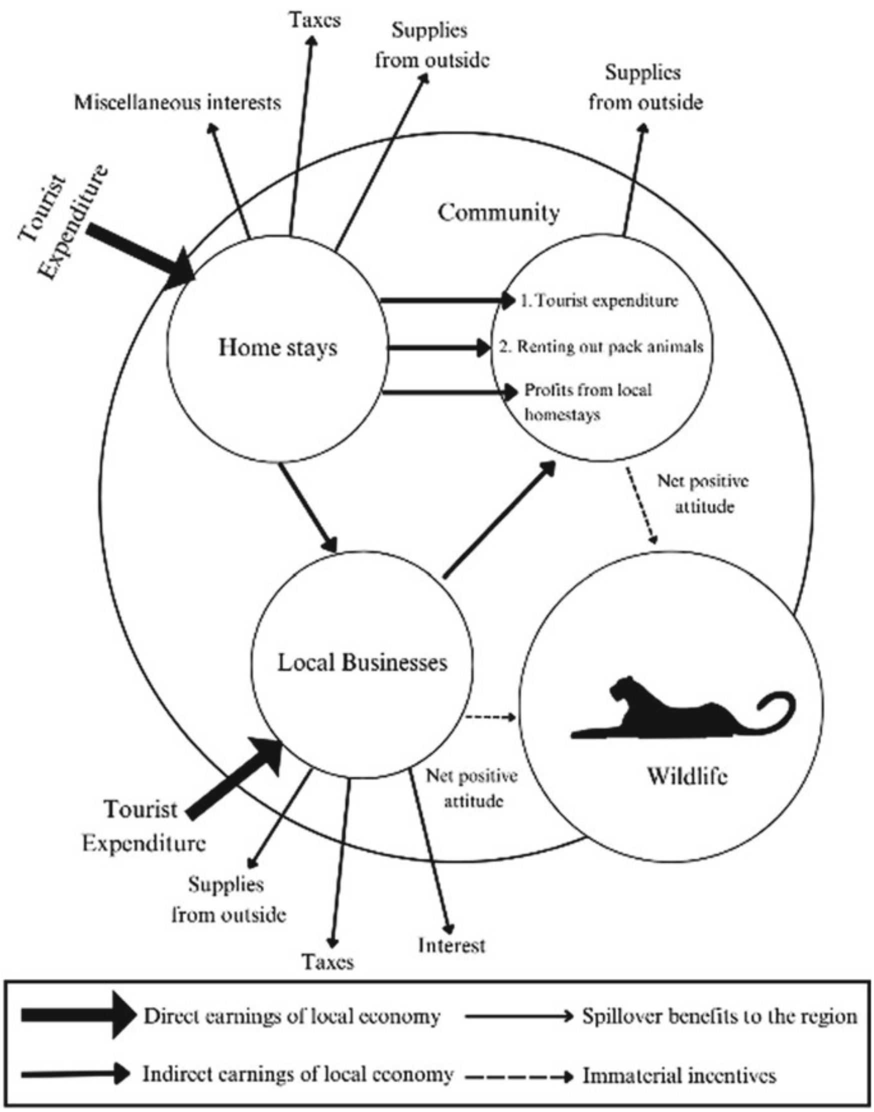

Fig. 4 Impact of Ecotourism on the local economy in HHP

villages in Ladakh in 2018. Four of these villages are in the western Sham Valley, and three are in the eastern Rong Valley (Vanelli et al., 2019). The interviews aimed at understanding if implementing HHP had altered the residents' opinions of the animals and their general opinion about wildlife in their region.

The results found that participants directly involved in the business and (thus stakeholders) held the Snow Leopard in greater regard than non-participants. The stakeholders also placed a higher instrumental value on wildlife, expressing significant pride in their local biodiversity. Even people not directly operating with homestays but living near the initiative appreciated the importance of Snow leopards for the region. In contrast, participants from locations away from HHP and homestays expressed a neutral or negative attitude towards the wildlife, primarily due to frequent economic losses from depredation (Vanelli et al., 2019).

If more communities can be encouraged to adopt HHP and similar initiatives for wildlife tourism, it may help mitigate the conflict situation. Incentivization is essential for changing the general public's attitudes and gaining support for conservation. These incentives can be tangible in the form of financial gains, employment, education or infrastructure or intangible in the form of ecosystem services and maintenance of cultural heritage). While material incentives may be more lucrative, awareness of immaterial incentives becomes increasingly crucial. As people grow solely reliant on tourism, the same wildlife that is the source of pride for the community may become commodities. It is, therefore, essential to educate the stakeholders and the locals about the intrinsic values of wildlife and the role of snow leopards in maintaining ecological equilibrium in IHR (Jain 2019).

5 Case Study-IV: Oak Country and Communal Participation

[5]Binsar Wildlife Sanctuary in Uttarakhand is 30 km north of Almora. The sanctuary was established in 1988 to protect the shrinking population of broadleaf oak forests (Fig. 5). The region was the former summer capital of Chandel kings, and several British officials had estates established inside the forest. Before the official order, villagers in the neighbouring areas relied on the forests for subsistence farming, small-scale logging, pine resin extraction and rearing livestock. All such activities, however, were banned afterwards.

A few years later, several entrepreneurs and the owner of the Khale estate in Binsar came together to found Village Ways, an India-based tourism company (hereafter VW). VW suggested the development of tourist lodges in villages around Binsar Sanctuary. Village Tourism Committees (VTCs) were founded to construct and operate the proposed lodges. The committees would offer guides and porters in addition to meals and lodging. As a pilot for the experiment-guest lodges were constructed in five villages-Satri, Kathdhara, Gonap, Risal, and Dalar (Fig. 5) (Peaty, 2009).

Local landowners leased the land to village committees that built the lodges using regional materials and traditional designs. VW contributed to the construction through a combination of subsidies and interest-free loans. VW further provided guiding and resort management training before the inauguration of the lodges in 2006.

[5] Google Earth.

Fig. 5 Binsar wildlife sanctuary, Uttarakhand

In March–April 2023, VW worked with the village committees to establish an annual birding festival to attract more tourists to the area (Parkes, 2023). With expert-led talks, hikes around the sanctuary's villages, and wildlife film screenings at Khali Estate, a former colonial summer home built in 1874 by Sir Henry Ramsay, a British commissioner of Kumaon, the event aims to draw birding enthusiasts from all over the world to the park. To attract more guests during COVID-19, Risal's community-owned guesthouse became one of the first in Binsar to update its rooms to include en suite bathrooms.

Currently, the majority of tourists travelling to Almora come from the UK. From Almora, they proceed to the Mountain Resort at Khali Estate (Peaty, 2009). From there, tourists travel by foot from village to village, staying in lodges created by *Gram Paryatan Samiti*, village tourism committees supported by grants and loans from VW, and run by the neighbourhood. A comparable product is also available from the business in Supi, a sizable village close to the Nanda Devi Biosphere Reserve.

The five villages have benefited greatly from VW. The biggest one is money. For every visitor night stayed in their community, the VTCs charge VW. The *Paryatan Vikas Samiti* is used to negotiate the fee. The training offered by VW, improved self-esteem, and a desire to learn English and other cultures are further advantages. Additionally, VW has worked to increase possibilities for women and members of lower castes.

There hasn't been a great environmental impact from the lodges and visitors. Each lodge has electricity and hot water, thanks to the solar panels that VW purchased and put in place. The trash is burned. Septic tanks receive sewage flow. Poaching and illicit logging appeared to have increased since Binsar's notification as a sanctuary. The rare barking deer population and other species appeared to have expanded when the VW project started. The "green gold" oak trees, which play a vital part in the forest ecosystem by absorbing water during the monsoon season and gradually releasing it during the dry season, are among its riches. More than 200 different species of birds, including eagles, parakeets, woodpeckers, forktails, and the enormous Himalayan vulture, as well as langur monkeys, Himalayan goral goats, martens, and leopards, make up the abundant avifauna.

It is also said that there will be little cultural impact. To avoid interfering with agricultural activity and relying too much on tourism, VW opted at the outset to limit visitors to six per hamlet, which has helped avoid undesired cultural influences. By ensuring that VTCs include at least two women, training female tour guides, and pushing VTCs to use female porters, VW has made a purposeful effort to empower women (Peaty, 2009; Bhalla et al., 2015).

6 Fragile Geology

The Himalayas sits on the fault line between Indo-Australian and Eurasian plate due to which the region has been vulnerable to seismic activities. The past couple of decades have witnessed unprecedented growth in urban settlements in this geologically sensitive region. Growing connectivity to the erstwhile remote locations in IHR has increased the possibilities for economic growth in the region. In 2022, Joshimath and the surrounding area witnessed a footfall of 41,00,000 tourists by October (Tripathi, 2023). The land subsidence and the social crisis that followed in the area have raised serious concerns about the future of the winter abode of Lord Badrinath.

Data for Uttarakhand in 2013 (20 million) shows that tourist arrivals can decline due to calamities, with numbers falling to an all-time low over five years. Similar to this, J&K has demonstrated a notable fall in visitors over the past few years due to political instability. The region's isolation and lack of attention reflected in fewer visitors, with Nagaland coming in last place (46,658) (Singh & Kotru, 2018). The main draws for tourists to travel to Himalayan sites today are pilgrimage, spirituality, adventure, and summer and winter joys. We must take the lessons from Uttarakhand to heart as urban planners throughout the IHR because the factors at play in Joshimath are also found in Nainital, Champawat, and Uttarkashi to name a few.

7 Conclusions

The Uttarakhand flood has taught us that we must develop viable models for pilgrim-based tourism in the exposed highlands. Pollution, trash, and solid waste management are problems in many high Himalayan tourist locations. Hotels and resorts are commonly constructed in vulnerable areas due to unregulated construction rules. So that the best practices may be discovered and disseminated, the shift to ecotourism needs to be carefully encouraged. The local community must most critically benefit from the tourism business. The government has actively encouraged homestay tourism in Leh for instance, there is a stronger emphasis on environmental protection and pollution reduction. Such actions are required to increase mountain tourism for the benefit of the neighbourhood. Despite numerous natural disasters and political upheaval, tourism in the IHR has steadily increased over the years.

While the interest of the people cannot be ignored, careful planning will be critical for long-term development plans in IHR. One cannot overstate the importance of considering the unique nature of the environment and economy, partnerships with local stakeholders can prove crucial in developing viable strategies. If we must learn one thing from the past let it be that Nature has its way of claiming its resources and it is up to planners and policymakers to keep this in mind as we proceed further.

The development of tourism satellite accounts to fully measure the contributions of tourism tothe state and national economy, cess or higher user charges/levies on service providers and consumers, and an assessment of the carrying capacity of tourist destinations across existing and potential tourism sites are key components towards developing sustainable and inclusive tourism in the Himalayas. Building skills and entrepreneurship in the tourism sector using a value chain approach and resulting in greater engagement of the local workforce; potential business sector reinvestments in conservation and local skill and entrepreneurship development; developing, implementing, and monitoring standards for the tourism sector (e.g., hospitality, hotel, and tour operators compliance standards); The decongestion of tourist locations or hosting of tourists following the local carrying capacity requires visitor awareness, online information on real-time carrying capacity, and the local application of safety and security regulations may go long way in alleviating the environmental stress on the IHR.

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Limestone Mining in the Himalayas: Advancing Adaptive Governance for Ecological and Socioeconomic Resilience

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Abstract The Himalayan region, recognized as a global biodiversity hotspot, faces the dual challenge of promoting economic growth while ensuring ecological sustainability. Within this context, this research explores the impacts of limestone mining, a significant economic driver, on the environment and communities, specifically in Sirmaur. Our objectives were: Firstly, to analyze guidelines for the Impact Assessments of Non-Coal Mining projects and recommend sustainable strategies; and secondly, to discern the effects of limestone mining on crucial parameters such as hydrology, public health, biodiversity, and livelihoods. The findings highlight that while mining propels economic growth, certain practices, notably open-pit techniques, pose significant environmental risks. These risks highlight the importance of long-term commitments to land rehabilitation targeting the creation of self-sustaining ecosystems. Despite the critical nature of reclamation, its implementation remains inconsistent across the region. Waste from mining presents a potential for value addition, especially when repurposed for construction, wastewater treatment, etc.. Enhancing the quality of impact assessments is achievable through technological tools like remote sensing and geospatial analysis. Coupled with community-centric

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air and water quality monitoring, these methods can better inform mitigation strategies and policy decisions. To adopt the sustainable practices, a holistic approach is essential, incorporating environmental science, engineering, social dynamics, and policy-making. While participatory models engaging communities throughout the mining project lifecycle have shown promise, there is an urgent need to transition these models from mere consultation to genuine collaboration. As the Himalayas stand at the crossroads of development and conservation, this research emphasizes the importance of adaptive governance to protect both ecological and community well-being, especially in the face of climate change challenges. The findings provide essential insights and lessons that are globally applicable, emphasizing the potential of collaborative action to harness resources sustainably for future generations.

1 Introduction

The Himalayan mountains span over 2400 km across Asia and form one of the world's biodiversity hotspots, home to over 10,000 plant and 1200 vertebrate species (Pandit et al., 2014). Designated as an Endemic Bird Area and Global 200 Ecoregion, the Himalayas play a vital role in influencing regional climate and supporting diverse ecosystems through processes such as monsoon circulation. Almost a quarter of the global human population resides in mountain regions, with over half dependent on mountain resources, including minerals, water, timber, and food. With intensifying resource extraction, conserving Himalayan biodiversity and sustainably managing resources take on global significance (Gupta et al., 2020).

Mining plays a vital role in India's economic development, contributing approximately 2.5% to the country's gross domestic product (GDP) (Ministry of Mines, 2021). While booting economic growth, mining operations also present considerable environmental management challenges due to resource extraction and landscape modification (Prasad & Bose, 2001). Striking a balance between developmental activities and conservation efforts is paramount, especially given mining's strategic importance to the national economy.

India houses some of South Asia's richest mineral deposits, with the Himalayan states containing significant limestone reserves (IBM, 2020). Globally, India ranks third in limestone production at 224 million tonnes annually, valued at $1.5 billion. The majority of India's output, around 171 million tonnes per year, is sourced from deposits scattered across the Himalayan region. Himachal Pradesh alone contributes approximately 5% to national annual limestone production through 55 operational mines across 12 districts (HPED, 2020). Key producing districts include Sirmaur (estimated reserves 250 million tonnes, annual capacity 25 million tonnes), Solan (reserves 120 million tonnes, capacity 12 million tonnes), and Mandi (reserves 90 million tonnes, capacity 9 million tonnes).

Limestone mining has boosted local economies through direct jobs provided in the mining sector and indirect opportunities generated due to mining in Himachal Pradesh, contributing approximately $80 million annually in state revenue (HPED, 2020). It also facilitates the growth of associated industries like cement, with 13 major plants within the state. Sustainable management of this vital resource sector amid climate change remains an ongoing challenge. Effective post-mining restoration of degraded sites is a crucial factor in achieving this balance. Proper rehabilitation helps restore ecosystem services and promotes biodiversity regain (Maiti et al., 2022a, 2022b). If left unaddressed, the visible success of the Himalayan mines may reveal latent environmental and social issues. The Himalayan geology comprising weak, fractured rock types and steep terrain renders the landscape highly susceptible to impacts from natural hazards and anthropogenic activities like mining (Hakhoo et al., 2019).

There is an urgent need for comprehensive baselines and transdisciplinary research to enable evidence-informed policymaking balancing resource extraction with ecological protection. Existing studies predominantly assess isolated issues rather than adopting a holistic lens considering the region-specific dimensions in Sirmaur.

Through an integrated multidimensional case study, this research aims to (i) analyze the guidelines for Impact Assessments of Non-Coal Mining projects and recommend strategies for sustainable industry, and (ii) synthesise the impacts of limestone mining across key indicators like hydrology, public health, biodiversity, and livelihoods within Sirmaur. Quantitative government data and qualitative community perspectives has been utilized to develop the synthesis. The insights would offer a strategic roadmap for other global mountain contexts increasingly vulnerable to climate impacts.

2 Sustainable Approaches in Non-Coal Mining Sector: Guidelines and Impact Assessments

2.1 Environmental Clearances, Categories and Regulatory Guidelines

To ensure sustainable development, mining projects in India require an Environmental Clearance (EC) as per the EIA Notification, 2006. EC aims to balance economic growth with environmental protection by comprehensively evaluating potential impacts. Projects are categorized as A or B based on scales of operation. Category A projects involving land areas $\geq$ 50 ha or production capacities $\geq$ certain thresholds require central-level clearance from the Ministry of Environment, Forest and Climate Change (MoEFCC). Conversely, Category B projects involving $<$ 50 ha of land or smaller production capacities fall under the purview of State-level Expert Appraisal Committees (SEIACs).

As per the Mines and Minerals (Development and Regulation) Act of 1957 (MMDR), state governments can only grant mining leases after the Directorate General of Mines Safety confirms the presence of minerals. Mining operations must adhere to centrally approved mining plans detailing excavation/beneficiation/transportation activities. The Mineral Concession Rules (1960) mandates a designated officer to verify compliance with approved mining plans before lease renewals. Plans describe geological aspects, natural features, pollution mitigation measures, equipment, and production targets for the next five years. Mining lease applications require submission of a plan within six months outlining proposed reserves, exploration needs, slope stability, etc. Recent amendments aim to bring more transparency through e-auctions of mineral blocks and stricter monitoring of post-mining rehabilitation. However, further sustainable reforms promoting community welfare and eco-friendly practices warrant attention.

2.2 Conducting EIA of Non-Coal Mining Projects

Thorough documentation is essential for carrying out robust EIA. Key requirements that must be addressed include the provision of historical production data highlighting peak annual outputs, which is important for evaluating cumulative impacts over time. Details about the project proponent and operational parameters, such as the mining lease area and extraction methods, must also be furnished. Waste generation estimates should be furnished to facilitate adequate waste management and minimization planning. Land diversion must be validated against state land use policies to prevent arbitrariness. Documentation of adherence to relevant environmental legislation benchmarks regulatory compliance. Geo-referenced maps, diagrams presenting lease boundaries and infrastructure layouts, and natural features aid transparent appraisal. Baseline data collection follows standardized protocols, with bio-physical parameters recorded seasonally to account for variations (Paliwal, 2006). This rigor ensures the scientific robustness of assessments to facilitate informed decision-making to balance developmental goals and environmental protection objectives.

Ensuring the environmental and social integrity of mining projects necessitates meticulous planning and stringent oversight. Foremost, safety evaluations, including slope and blast studies, are paramount. This diligence extends to an encompassing area study, spanning at least 10 km from the lease area's edges, designed to capture the full spectrum of impacts across the mine's operational lifespan. Equally significant is the thorough documentation of any external overburden dumps. In the circumstances entailing forest lands, validation through certificates from state forest authorities becomes non-negotiable. Adherence to the Forest Right Act 2006 is vital, especially regarding the rights of scheduled tribes and traditional forest dwellers. A profound understanding of local vegetation is indispensable, coupled with insights into the probable repercussions of mining on both flora and the adjoining wildlife. Lastly, the close presence of national parks and wildlife sanctuaries, especially if within 10 km of the mining lease, demands clear demarcation and recognition.

Robust baseline assessments of key environmental and social parameters are integral to the EIA process. Mine safety requirements, including studies evaluating slope stability through geotechnical investigations and blast impact modeling, help prevent accidents (Wang et al., 2020). A comprehensive 10 km radius area analysis of the lease encompassing the project lifetime is mandated. This aids the characterization of baseline conditions and cumulative impact forecasting over decades of operations through a holistic regional lens (Lechner et al., 2017).

External overburden dumps posing high sedimentation and contamination risks warrant thorough documentation of geological specifications, dumping locations, and stabilization strategies for effective management. Where mining affects forest land, certification from state forest departments ascertain protective safeguards for these sinks as per the Forest Conservation Act.

Compliance with Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006, validating the rights of Indigenous communities should feature. Assessments of floral and faunal diversity endemic to local ecosystems and potential disturbances mining may instigate on vegetation and surrounding wildlife through habitat degradation are crucial (Dhyani, 2023). Protected areas like national parks and sanctuaries should be delineated within 10 km to aid impact forecasting on vulnerable species. Together, addressing such diverse environmental, social, health, and safety parameters lays the groundwork for science-backed consensus on sustainability.

2.3 Integrating Expertise and Advanced Technologies to Post-Mining Rehabilitation

For optimal restoration outcomes, India could consider establishing a specialized wing within the relevant regulatory body solely focused on post-mining site rehabilitation (Downing, 2002). Personnel with multidisciplinary expertise in ecology, soil science, and engineering could facilitate systematic restoration planning and monitoring. Furthermore, as biodiversity recovery at reclaimed minescapes progresses, advanced technologies should be leveraged to aid the rehabilitation process and minimize residual environmental impacts. For example, remote sensing and geospatial tools allow high-resolution monitoring of revegetation patterns and enable timely interventions if restoration targets are not met (McKenna et al., 2020). Precise drone-based hyperspectral imaging can also accurately assess biochemical properties and structure of recovering vegetation communities.

2.4 Infrastructure Design for Protecting People and Place

Unprecedented scholarly attention spotlights regions like the Himalayas, where extractive activities intersect sensitive environments supporting biodiversity and cultural heritage. While mining promotes national progress, true development uplifts all segments of society equitably without compromising the ecosystems and natural assets we depend on. Holistic infrastructure design within impact assessments exemplifies this vision.

Baseline monitoring networks distributed factoring topography and seasonal fluctuations generate high-resolution maps of airsheds and waterscapes. Modelled under changing conditions, they empower evidence-based plans, minimizing uncertainty faced by frontline communities. Surveys uncover complex hydrogeological interconnections between surface and subsurface flows. Robust protections respect these intricacies, safeguarding aquatic ecosystems and downstream communities (Soni, 2016). Indigenous plant selection driving selective revegetation stabilizes land, sequesters emissions, and restores ecological services and landscape integrity (Maiti et. al., 2022). Public participation ensures local knowledge complements scientific tools in holistic impact oversight and emergency response training. Multi-tiered workforce housing meets all living standards through medical facilities promoting wellbeing. Protecting health uplifts dignity.

Addressing such multidimensional factors transforms extractive projects into ones jointly progressing people and nature interdependently. If diligently upholding these balanced priorities, minin's imprint on these mountains need not remain an open question for future generations. The cumulative lessons offer a roadmap for global contexts where sustainable resource governance remains unrealized.

2.5 Mining Infrastructure Design and Community Health Safeguards

Thorough baseline assessments underpin responsible infrastructure design and occupational health protection. Comprehensive air quality monitoring networks informed by local meteorology generate high-resolution baseline pollution maps. Time-series data fed into air dispersion models empower planning proactive mitigation for varying operational and climate scenarios, minimizing uncertainty faced by frontline communities.

Holistic water resource investigations factoring waterscape characteristics like elevation, hydrology, and aquifer vulnerabilities through field surveys and modeling anticipate diverse mine water management demands. Robust infrastructure preserves underground and surface flows, supporting healthy ecosystems and downstream dependents (Rasul, 2014).

Multi-layered living facilities for the mining workforce respect national accommodations standards, while on-site first aid centers and routine medical check-ups safeguard the physical wellbeing of those powering development. Studies forecasting health outcomes from chronic occupational exposures to particulates and emergencies like flash floods trigger proactive community education. Low-cost sensors help monitor impacts, aiding curriculum revisions.

Greenbelt establishment guided by growth rates of native floral species and soil stabilization functions protects locals from dust noise and restores landscape aesthetics post-closure (Maiti et al., 2022a, 2022b). Land rehabilitation through soil regeneration and indigenous revegetation marking ecological recovery remains the final, most important milestone. Its success determines whether mining remembers its human hosts or vice versa. Our study exemplifies how diligent infrastructure design and health safeguards can transform an extractive project into one where the environment and society mutually progress.

2.6 Resource Planning and Community-Centric Management

Robust costing support sustainability throughout mining's lifecycle. Itemized project budgets account for infrastructure development, personnel, protective measures, waste handling, and progressive reclamation to avoid cost overruns compromising best practices (Dwivedi and Soni, 2021).

Incorporating technological tools and field experts is crucial for an effective and efficient EIA process. Environmental management plans detail standard operating procedures addressing routine and emergency pollution scenarios through a mitigation hierarchy prioritizing avoidance, minimization, and offsets. Disaster response protocols leveraging predictive modeling anticipate flashfloods or slope failures through early warning networks and community training (Basher, 2006).

Moreover, considering the input of local communities with traditional knowledge of regional flora could aid in conservation. Participatory monitoring involve traditional ecological knowledge alongside scientific tools for holistic impact oversight. Low-cost sensors augment authority monitoring, catching lapses threatening remote locals. It is also vital for reports to undergo rigorous multi-level checks to ensure accuracy and reliability. Multi-stakeholder reviews integrating experts and public transparency safeguard report integrity essential to balanced consensus.

Streamlining approvals while maintaining rigor prevents unnecessary project delays that impede sustainable growth. But the sacrifice of diligence defeats the purpose. Many improvements remain, yet this balanced, innovative subsection exemplifies envisioning mining not just as extraction but as an opportunity to enhance livelihoods for generations to come. Addressing these facets can expedite the often lengthy EIA process, which remains a prominent concern in contemporary mining.

2.7 Financial and Management Aspects

Resource extractive projects require prudent long-term financial planning to balance economic, social and environmental considerations. Comprehensive cost projections power sustainability goals when implemented properly. Itemized capital budgets cover critical mining infrastructure, pollution abatement technologies, occupational health facilities, and housing designed to safeguard worker wellbeing. Lifecycle analyses factor in recurring expenses for continuous environmental monitoring networks, emergency response preparedness, and multi-stage site rehabilitation extending beyond mine closure (Suppen et al., 2006).

Community development funds directed through participatory needs assessments uphold equitable benefit-sharing with frontline project-impacted populations. Crisis management protocols leverage advanced modelling capabilities and scenario-based community simulations to strengthen preparedness for low-probability, high-consequence events like industrial accidents or natural disasters.

Open-access geospatial and industrial data platforms expand technical and local traditional ecological knowledge to aid holistic impact oversight. Ground-truthing by independent monitoring committees enhances integrity by detecting less obvious issues. Knowledge co-production workshops cultivate shared understanding between project proponents and all stakeholders to facilitate consensus-based solutions addressing regulatory and oversight gaps. If diligently implemented, robust financial planning and participatory management safeguards can help transition extractive activities from short-term profit motives toward the higher purpose of intergenerational social and ecological wellbeing.

3 An Integrative Exploration of Limestone Mining Industry in Sirmaur

With its unique geotechnical conditions, the Himalayan region has been historically associated with small-scale mining, contributing to roughly 50% of non-fuel mineral production in India. These mining activities, although economically rewarding, pose significant environmental challenges. Waste generated accounts for a considerable land fraction, causing environmental degradation. The regional geological uniqueness and unsystematic mining have exacerbated environmental challenges in areas such as the Mussoorie Hills (Ghosh, 2003). Despite the challenges, mining remains crucial for local communities, offering compensation and wage avenues. However, existing policy inconsistencies have curtailed potential benefits for local livelihood and environmental preservation (UNDP, 2018). Limestone, vital to various industries and crucial to this research, underscores the need for an integrated mining approach, ensuring economic and environmental sustainability.

The study area, Sirmaur was purposively chosen based on its ecological representativeness and socio-economic importance. It harbours 250 million tonnes of limestone reserve. The area lies within a tropical dry deciduous forest biome, with the Sal trees being the predominant flora. Located at 1552 m elevation in the lesser (FSI, 2019). Sustainable management of this sector, considering climate change, is a continuous concern. In fact, India's policy think tank, NITI Aayog, recognizes the sensitive environmental and societal trade-offs, emphasizing the need to carefully balance inclusive development and ecological security through rights-based approaches in mountain regions (NITI Aayog, 2018).

3.1 Biodiversity of Sirmaur Region

Tables 1 and 2 present an overview of major floral and faunal diversity reflective of the region's ecological sensitivity as a Seismic Zone 5 area with moist sal forests at 1552 m elevation (Chandel & Brar, 2010). Typically, pre-mine studies assess feasibility, impacts, land needs, and displacement. Surface and vast deposits utilize opencast mining, while deep-seated reserves employ underground techniques based on deposit characteristics.

Table 1 Details of floral taxa documented from the case study area of Sirmaur, Himachal Pradesh, India

Scientific name	Common name	Status
Shorea robusta	Sal tree	LC
Abrus precatorius	Rosary pea	NA
Mallotus philipus	Kumkum tree	NA
Easearia tomentosa	NA	NA
Aegle marmelos	Bael	NT
Acacia catechu	Black cutch	**LC**
Pinus roxburghuii	Chir pine	LC
Toona cilianta	Red cedar	NA
Terminalia chebula	Chebulic myrobalan	NA
Pyrus pathia	Wild Himalayan pear	**LC**
Syzygium cumini	Jamun	NA
Helinus lanceolatus	Lanceleafhelinus	NA
Rhododendron arboran	Burans	NA
Quercus leucotrichophoem	Banj oak	NA
Sapium insigne	Khirum	NA
Cassia fistula	Golden shower tree	NA
Tinospora cordifolia	Guduchi	NA
Pueraruia tuberose	Indian kudzu	NA
Dodonea viscose	Hop bush	NA
Rungia pectinata	Comb rungia	NA
Eclipta prostrate	False daisy	NA
Helinusanceolatus	Lanceleafhelinus	NA
Carissa opaca	Garanda	NA
Diospyros Montana	Bombay ebony	NA

Table 2 Details of faunal taxa documented from the case study area of Sirmaur, Himachal Pradesh, India

Mammals	Scientific name	CITES	IUCN
Jackal	*Canis aureus*	III	V
Flying fox	*Pteropus*	II	LC
Hedgehog	*Frinancecinae*	NA	LC
Rhesus macaque	*Macaca mullata*	II	LC
Common langur	*Semopithecus entellus*	I	EN
Indian wolf	*Canis lupus pallipes*	I	LC
Red fox	*Vulper vulpes*	III	LC
Indian wild dog	*Cuon alpines*	NA	EN
Mongoose	*Herpestidae*	III	LC
Himalayan wessel	*Mestela sibirica*	III	CR
Brown bear	*Urcus arctos*	I	LC
Asiatic black bear	*Urcus thibetanus*	I	CR
Leopard	*Panther pardus*	I	V
Indian pangolin	*Manis crassicaudata*	II	EN
Tibetian wild ass	*Equus kiang*	II	LC
Sambhar	*Rusa unicolor*	NA	V
Bharal	*Pseudoisnayar*	I	LC
Goral	*Naemorhedus*	I	NT
Nilgai	*Boselaphus tragocamelus*	NA	LC
Yak	*Bos grunniens*	I	V
Porcupine	*Erethizontidae*	NA	LC

The region hosts rich botanical diversity comprising trees, herbs, and shrubs important for local livelihoods (Table 1). Here is a mention of some of the most noteworthy ones. *Shorea robusta* is primarily sought after for its timber. *Abrus precatorious* is notably used in contraceptive medicine formulations. *Mallotus philippus*, apart from being a source of dye, has therapeutic effects against skin diseases. *Aegle marmelos* offers relief from ailments like diarrhea and dysentery. In contrast, *Acacia catechu* is essential in crafting ropes and fishnets. With its distinctive aromatic traits, *Pinus roxburghii* is apt for deodorants and also doubles as a liver tonic and diuretic. *Toona cilianta* stands out for its efficacy in alleviating joint pain. *Terminalia chebula* boasts a dual purpose: as a dye and a medicinal remedy. For instance, *Syzygium cumini* bark has medicinal uses like treating throat issues, bronchitis, and dysentery. Also, *Syzygium cumini* is a preferred choice for furniture craftsmanship while *Pyrus pathia* commonly serves as fuel. *Helinus lanceolatus* is harnessed for its medicinal and dyeing properties. *Rhododendron arboran* is utilized as fuel and a prime source for charcoal. *Quercus* L. is predominantly used for fuel wood. Rounding off the list, *Sapium insigne* is esteemed not just for its timber but also for its health advantages. This diversity highlights the region's ecological fragility, warranting a science-backed approach to development.

The rich mammalian biodiversity of Sirmaur district include the Common langur (*Semopithecus entellus*), Indian wild dog (*Cuon alpines*), Indian pangolin (*Manis crassicaudata*), and the Sambhar (*Rusa unicolor*) are marked as Endangered (EN) bu IUCN. This designation accentuates the immediate need for region-specific conservation strategies. Even more concerning is the status of the Himalayan wessel (*Mestela sibirica*), and the Asiatic black bear (*Urcus thibetanus*) which are listed as Critically Endangered (CR), reflecting their perilous state in the district. In addition, species like the Otter (Lutrinae), Hyaena (Hyaenidae), and Himalayan Goral (*Naemorhedus goral*) are categorized as Near Threatened (NT), suggesting imminent risks if appropraite measures aren't undertaken. The interplay between mining activities and wildlife conservation presents a unique challenge, emphasizing the need for sustainable mining practices that can coexist with conservation initiatives in Sirmaur.

3.2 Mining Impact and Production Analysis

Quarrying, blasting, dumping, and transport have degraded over 600 springs and water sources across the region through increased turbidity and heavy metals. Studies around four major limestone mines in Sirmaur observed groundwater contamination up to 2 km downstream, coupled with reduced agriculture, livestock health issues, and elevated cancer incidence among communities solely reliant on these resources (Prasad and Bose, 2001; Nath & Singh, 2020). Additional impacts involve the loss of 2500 ha of forested areas critical for landslide prevention, reduced groundwater recharge and biodiversity declines of species like the endangered *Barbet*.

Within Banour-Shiva are 18 operational (296 ha) and 20 inactive mines (180 ha) (Nath & Singh, 2020). In contrast, Solan has two larger active mines (793 ha), indicating that Sirmaur mines tend to be smaller. Banour mine's significantly contributed (peak 44%) to Sirmaur's limestone production during last decade, emphasizing its economic relevance. Limestone output of Sirmaur rose consistently post-2008, motivating socio-environmental analyses.

Consumption trends from 2015–2018, indicate cement and iron/steel as top users. Given India's global leadership in cement manufacture, limestone plays a vital role, with additional significance in the coal and iron/steel sectors (CRC, 2022). Limestone mining demands substantial manual labour, accentuating the importance of local unskilled jobs. Employment grew from 19,500 in 2010–11 to 23,449 by 2016–17 as production value, increasing steadily since 2008–09, peaked at ₹7388 crore that year (IBM, 2021). This output from Himalayan mines promotes national economic growth and job creation across all skill levels.

Key industries consuming limestone is dominated by cement production. India ranks second globally in cement output, highlighting limestone's strategic importance to this industry (Morrow et al., 2014). Coal also relies heavily on limestone, with 76% used by the coal industry due to coal satisfying 55% of national energy needs.

Limestone primarily feeds the power, fertilizer, textiles, paper, and brick industries. As a predominant form, mining necessarily balances conservation with sustainable development, given irreversible socio-ecological impacts requiring prudent management. Recent efforts promote "green mining" practices, leveraging advanced technologies for optimized resource extraction with minimal environmental disturbance. However, impact mitigation and long-term restoration strategies need strengthening in vulnerable Himalayan contexts.

3.3 Ecological and Socio-Economic Consequences of Limestone Mining in the Himalayas

Mining introduces profound environmental and socio-economic changes, particularly when employing open-pit methodologies. Initially, the land itself is transformed as these operations dramatically reshape geomorphological structures, leading to disturbances in both vegetation and soils—a scenario reminiscent of the impacts of quarrying. The tree loss resulting from mining decreases carbon dioxide uptake, intensifying the greenhouse effect. Mining is a highly energy-intensive industry, and regions with dense mining activities contribute to global climate change. The method of mining largely depends on the mineral deposits' location. Opencast methods are preferred for surface deposits, while underground mining is chosen for deep-seated minerals.

As the expanse of mining areas grows, there is a marked transformation in original land usage, deviating from its primary ecological functions (Wang et al., 2020). Infrastructure integral to mining, such as roads, further complicates the scenario, causing habitat fragmentation and consequently jeopardizing wildlife connectivity (Dhyani, 2023). The repercussions are not land-bound. Atmospheric quality deteriorates with rising levels of noise, dust, and particulate emissions, collectively enhancing pollution levels (Ganapathi & Phukan, 2020).

Vital water sources face contamination risks with elevated heavy metal concentrations, compromising both their ecological function and its potability. The increased concentrations of certain metals, possibly from rock erosion, dumping, or other external causes, require further examination (Prasad & Bose, 2001). Untreated mining discharge could spread pollution if not regularly monitored and managed.

Waste generation consumes considerable land, degrading ecosystems Unsystematic practices, combined with the region's unique geology, have exacerbated impacts in areas like Mussoorie Hills (Bandyopadhyay & Shiva, 1985). However, mining remains crucial for uplifting local livelihoods through compensation and jobs (Soni, 2016). Yet prevailing policy inconsistencies have undercut the potential dual benefits of development and conservation.

Amidst these challenges, the technological advancements emerge as saviors. Innovations like remote sensing and LiDAR offer critical insights for terrain analysis and sustainable project planning, ensuring minimized ecological disruptions (Werner et al., 2019). LiDAR technology provides detailed topographical data, aiding in the meticulous planning of mining projects. By embracing such technological tools, combined with rigorous standards, consistent monitoring, and community involvement, a more harmonious balance between development and conservation becomes achievable.

Limestone's importance to strategic industries highlight the need for balanced approaches to ensure mining's ecological and economic sustainability. Advanced practices like selective mineral excavation, concurrent reclamation, and community-focused policies can promote this balance. Despite efforts, knowledge gaps remain in integrating social, technical, and regulatory dimensions across diverse Himalayan contexts. Addressing this through collaborative action among stakeholders could operationalize more sustainable mining models.

3.4 Transforming Waste from Limestone Mining into Valuable Resources

The pressing challenge of waste management invariably marks the global mining landscape. Limestone mining, despite its multitude of benefits, contributes to this problem by generating significant overburden—an often-underutilized byproduct with scarce immediate economic benefits (Mohd Isha et al., 2021). This waste, predominantly viewed as a burdensome offshoot of mineral extraction, harbors a plethora of sustainable, value-added applications.

At the confluence of agriculture and mining, limestone waste emerges as a potential resource for enhancing soil fertility (Oliveira et al., 2014). When judiciously integrated into soils, this waste rejuvenates its chemistry and structure, invigorating plant growth and agricultural productivity. From an environmental standpoint, the climate crisis offers an unexpected avenue for limestone waste utility (Kusin et al., 2020). When infused into brick compositions, limestone waste has the dual advantage of augmenting material strength while concurrently serving as a carbon sink, offering a tangible solution to climate change concerns.

Urbanization and rapid infrastructural development spotlight another crucial application. When repurposed as sand substitutes in concrete formulations, limestone mining byproducts hold the promise of quality construction without exacerbating sand shortages. Similarly, in public health, wastewater treatment processes harness the potential of lime derived from mining, ensuring safe water by precipitating hazardous pollutants like heavy metals (Ouakibi et al., 2013).

Transportation infrastructure is also benefited immensely. When integrated into the foundation of roads or airfields, mining waste provides enhanced stability, safeguarding surfaces against capricious environmental shifts. Lastly, a pivot towards industrial applications reveals the multifaceted nature of limestone waste. From the chemical industry's broad product spectrum to the pulp and paper sector's bleaching processes, lime remains an indispensable resource.

The principles of the circular economy come to the forefront in addressing mining's environmental ramifications. Re-envisioning waste as an asset, with potential value-addition through refined downstream processing, encapsulates a pragmatic waste management strategy. This approach holds particular promise for isolated mountainous regions, mitigating their waste burden while fostering economic upliftment. Dedicated research endeavors will undoubtedly refine and optimize these transformative avenues as we surge ahead.

3.5 Strategic Management Plans for Sustainable Limestone Mining

In the complex arena of sustainable limestone mining, management strategies anchored in robust, science-driven frameworks are of paramount importance. Fostering a culture of ecological awareness stands out as an elemental strategy. Here, deploying training programs highlighting the intertwined nature of biodiversity conservation with socio-economic value can cultivate stakeholder buy-in, ensuring a collective effort towards sustainability (Ghosh, 2003). Scientifically managed infrastructure is the next logical step. Employing advanced planning tools to meticulously delineate ecologically sensitive zones ensures their sanctity against expanding infrastructure, such as roads or mining facilities. The participatory nature of this delineation process galvanizes community interest and involvement, achieving co-management objectives.

Air quality, often a casualty of mining activities, requires rigorous attention. Herein, integrating community participation in air monitoring using affordable sensors provides real-time insights, ensuring particulate concentrations remain within nationally accepted standards In tandem, wildlife conservation demands acute attention. Instituting co-management systems prohibiting hunting and harnessing local knowledge about the ecosystem ensures a conservation approach. Adherence to stringent emission standards safeguards local fauna from the emissions, ensuring the biota's health. Additionally, a holistic approach to mining necessitates ecological rejuvenation efforts. Creating tailored reforestation blueprints sensitive to both mining- and climate-specific factors is imperative. These frameworks, accompanied with native species, should be validated via long-term monitoring to ascertain efficacy and impact.

At the core of these strategies, compliance mechanisms form the backbone. Institutionalizing third-party environmental audits and strict adherence to legal statutes, coupled with transparent safety protocols, fosters an environment of trust and regulatory conformity. Integrating traditional ecological insights with state-of-the-art technological tools shapes a balanced trajectory for mining, particularly in climate-vulnerable mountain terrains. Such adaptive, inclusive management not only ensures ecological integrity but also bolsters the resilience of local livelihoods.

4 Concluding Remarks

As a globally critical biodiversity hotspot and regional watershed, the Western Himalayas exemplify the complex interplay between development, ecology, and interconnected human wellbeing. Limestone mining fuels strategic industries while demanding prudent oversight, as extraction poses risks of degraded water quality, habitat fragmentation, and respirable emissions if left unmitigated. Opencast techniques, in particular, intensify such concerns through drastic landscape transformations challenging restoration. However, opportunities exist to minimize mining's footprint through integrated solutions. Value-addition from waste streams into usable materials supports local communities. Low-cost sensor networks empower participatory impact monitoring. When endorsed by evidence-based land delineation and conservation-centered policy reforms attentive to socio-ecological vulnerabilities, such balanced approaches hold promise to realize prosperity in durable harmony with the natural heritage upon which it depends. More holistically, the Himalayas offer a learning ground for reconciling resource stewardship with planetary stewardship, which is vital for impending global disruptions disproportionately threatening mountain regions. Sustainable paths remain within reach if guided by collective long-term vision over narrow self-interest.

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Impacts of Mining and Quarrying Activities in the Himalayas: An Overview

Anita Punia and Saurabh Kumar Singh

Abstract The hills of Himalayan region are rich in flora and fauna diversity. The recent developmental activities (specifically industries and tourism) are adversely impacting the biodiversity of fragile ecosystem of Himalaya. Small scale mines of limestone's are prominent in the hills of Himachal Pradesh and Uttarakhand. The mines of phosphorite, soapstone and magnesite are also active in these hills. The blasting, drilling and excavation of steep slopes of hills for mines is triggering the landslides and earthquakes. The application of bioengineering techniques or introduction of exotic species for the stabilization of steep slopes hinder the growth of native plants leading to change in the floral diversity. The north-eastern Himalayan states such as Meghalaya and Nagaland are enriched in coal reserves and extensive mining is being carried out at small and large scale. The conflict on the rights of coal reserves in the Meghalaya and Nagaland are highly reported and sometimes it also results in violence and loss of human life. The recent studies show the loss of forest cover, degradation in quality of soil and water in the mining landscape. The pollution level of cleaner air of the north-eastern Himalayan is continuously increasing. It is also observed that the coal mines of Meghalaya are generating acid mine drainage and are potential source of metal contamination.

Keywords Mining · Environmental contamination · Landslides · Land subsidence

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1 Introduction

Himalayan region is geologically fragile and prone to natural hazards such as landslides, earthquake and cloudburst (Sharma et al., 2019). Himalaya covers part of countries namely India, Pakistan, China, Afghanistan, Myanmar, Nepal, Bhutan and Bangladesh commonly known as Hindu Kush Himalaya. The anthropogenic activities such as mines, urban settlements and hydropower developments are rising in Hindu Kush Himalayas (Chao et al., 2023; Singh et al. 2016; Hussain et al., 2019). The fragile environment of Hindu Kush Himalayas needs to be preserve to save it from natural disasters. The impacts of natural disaster can be significant beyond the geographical boundary of a country. The developmental activity in one country could impact its neighbouring country (Deka, 2021) so it is important to consider the broader or downstream area while studying the environmental impact assessment.

The adverse impacts of mines are observed in different Himalayan countries. In Bangladesh, land subsidence and change in land use and land cover (increase in settlements for mining or power plants) is observed around Barapukuria Coal Mine (Arifeen et al., 2021). Total 1 km^2 of land is subsidised resulting in cracks in the buildings. Similarly, illegal mines along with other anthropogenic factors such as expansion of agricultural lands, settlements and railway tracks lead to change in LULC at the foothill of Bhutan-Bengal (Chamling & Bera, 2020). Hazara phosphate deposits enriched in phosphorite of lesser Himalayan regions of Pakistan are viable for the production of fertilizers but the concentration of metals i.e. Zn, Pb, Cu and Cr is also high suggesting the probable contamination of agricultural fields in the future (Faridullah et al., 2017).

Landscape of any country covered by different landform features such as mountains/hills, deserts and plain area. The mining activities are carried out in different landforms depending on the mineral resources availability. The landform, geology and climatic factors control the intensity and frequency of landslide, flash floods and land subsidence. The mining activities trigger the intensity and frequency of adverse impacts caused by landslide, flash floods and land subsidence. India is mineral rich country and mines are active in different parts of the country covering mountains/hills, deserts and plain area. The environmental contamination due to metallic and non-metallic is reported across the different parts of the country (Giri et al., 2017; Pattnaik & Equeenuddin, 2016; Punia et al., 2017; Singh & Kamal, 2017; Tiwari et al., 2017). However, the case studies of discussing the natural disasters induced by mines are not significant in number.

Mines are active in Jharkhand, West Bengal, Madhya Pradesh, Chhattisgarh etc. for metallic and non-metallic in the plain areas of country. Contamination and change in LULC are major adverse environmental impacts caused by mines (Yu & Zahidi, 2023). Elemental contamination of soil (Naz et al., 2018; Siddiqui et al., 2020), water (Ruhela et al., 2022; Xia et al., 2023), air (Ruhela et al., 2022; Sharma & Kumar, 2023) and vegetation (Roca-Perez et al., 2023) due to metallic and non-metallic mines are also one of the major problems reported across the globe.

The arid and semi-arid state of Rajasthan and Gujarat are mineral rich and famous for metallic mines likely iron, copper, zinc, lead and non-metallic mines such as petroleum, sandstone and marble (Rebello et al., 2021). The species diversity in the arid/semi-arid regions are less comparative to forest. Similarly, a decrease in species diversity and threat to native species specifically *A. nilotica, Acacia senegal* and *Salvadora oleoides* due to coal mines of Panandhro, Matanamadh and Jadva in the western Kachchh, Gujarat is observed (Patel et al., 2019).

In the Himalayan region, along with the contamination mining activities also lead to natural hazards such as landslide and flash floods. The lives and livelihood of the local residents living in the mining area are at stack due to natural hazards. In the Himalayan region, prolong rainfall leads to landslides and is a major reason for the destruction in the region. The bed load of river depends on intensity and duration of rainfall in the hilly terrain and it is influenced by the anthropogenic activities such as mining, dams and construction of roads (Chauhan et al., 2017).

The present review is carried out to understand the adverse impacts of mines and quarrying in the Himalayan region. To better understand, Himalayas are divided into two parts western and eastern on the basis of geographic location. The main objective of the current review is to assess the environmental impacts caused by mines in the western and eastern Himalayas and their role in natural disaster events.

2 Climatic Conditions of Himalayas

Himalaya spreads in 2500 km of length covering 13 states namely Jammu and Kashmir, Uttarakhand, Himachal Pradesh, Ladak, Sikkim, Arunachal Pradesh, Manipur, Mizoram, Meghalaya, Nagaland, Assam, Tripura and West Bengal. The Indian Himalayan region is divided in two parts i.e. western and eastern (Fig. 1) on the basis of location and climatic conditions. The eastern Himalayas lies in biodiversity hotspot due to variation in altitude and climatic conditions leading to diversity in vegetation cover (Acharya et al., 2011). The diverse and fragile environment of eastern Himalayas needs protection from climate change and anthropogenic activities (Saikia et al., 2017). The main objective of present review is to assess the environmental impacts caused by quarrying or mines in the Indian states covering western and eastern Himalayas.

The western Himalaya covers the parts of Himachal Pradesh, Jammu & Kashmir, Ladak and Uttarakhand. The parts of states such as Meghalaya, Nagaland, Manipur, Assam, Mizoram, Tripura Nagaland, and West Bengal lies in eastern Himalayas. Average annual rainfall of eastern Himalayas are higher comparative to western Himalayas. The annual rainfall of Cherrapunji which is located in Meghalaya state is 10,000–15,000 mm. The rainfall in eastern Himalayan region is caused by monsoon during summers and it is due to western disturbances western Himalayan during winters (Palazzi et al., 2013). At higher altitude i.e. elevation above 4500 m face extreme winter conditions like snowfall and temperature below the freezing point in the western Himalayas (Sabin et al., 2020).

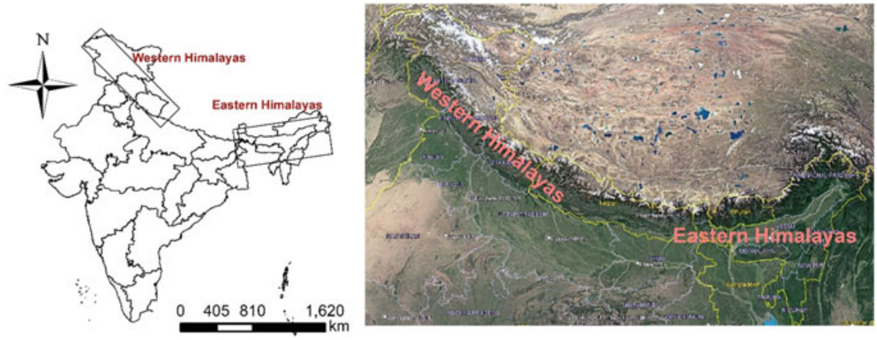

Fig. 1 Map of India and location of Himalayas on google earth

3 Environmental Impacts

Mines are one of major contributor to pollution (air, soil, water and vegetation) and degradation of environment. Himalayan region is rich in biodiversity and pollution adversely impacts its beautiful and scenic valleys. The destruction of upper surface of soil for quarrying disturbs functioning of terrestrial and aquatic ecosystems. Most of people living in the region depends on the natural resources for livelihood. The environmental contamination due to mines in the Himalayan region are discussed in the following section.

3.1 River Ecosystem

Sand mining of river is one of major and regular source of livelihood of poor people living close to rivers (Hatlebakk, 2023). The riverbed mining generate income for the local residents but it also impacts the biodiversity of the region. It is observed that stone and riverbed mining adversely influences the density and diversity of insects living in small tropical Jatinga River passing through Dima Hasao and Cachar district of Assam (Chakravarty & Gupta, 2023). The wildlife sanctuary and forest close to rivers are also prone to adverse impacts caused by riverbed mining. The riverbed mining is one of the main source of income for people living near the Nandhaur Wildlife Sanctuary, Uttarakhand. The overexploitation of forest resources and unsustainable riverbed mining is leading to habitat loss and fragmentation of Nandhaur Wildlife Sanctuary ecosystem (Irengbam et al., 2017).

Sediment mining significantly contributes to narrowing down and deepens (Mitra et al., 2020) the river channel changing its geometry and morphology. Apart from morphological changes, the extraction of river bed material adversely effects the socioeconomic conditions of the local community depended on its ecosystem services for livelihood (Wiejaczka et al., 2018). The illegal mining by local community causes clash with authorities and sand mining is found to be responsible for most of the conflicts (Bisht & Gerber, 2017).

Mining activities disturb the upper surface of land and the riverbed mining at large scale accelerates the erosion and flooding of river plains impacting the flora and fauna of the river ecosystem (Singh & Sidhu, 2016). The impacts of aggregate mining are significant, even short term variations in erosion (Vercruysse & Grabowski, 2021). The erosion of soil from surrounding agricultural and forest land increase sediment load in the river. High siltation impacts the aquatic life of the river. The river bed mining is adversely impacting the diversity of phytoplankton and zooplankton near Haridwar, Uttarakhand which is located at the foothill of western Himalayas (Kamboj & Kamboj, 2020; Kamboj et al., 2022). The implementation of site-specific management policies and identification of potential zones of sand mining locations would solve the problem of erosion and pollution of river (Dar et al., 2023).

3.2 Biodiversity Loss

North-eastern Himalayas lies in tropical climate and covered with thick vegetation cover. The eastern Himalayas is richer in threatened plants compared to western Himalayas (Mehta et al., 2023). However, in recent times studies have reported loss of biodiversity in the region due to climate change and anthropogenic activities (Banerjee et al., 2022). Anthropogenic activities are eroding soil of eastern Himalayas (Choudhury et al., 2022a, 2022b) impacting the vegetation cover and biodiversity. Nagaland lies in the biodiversity hotspot of Indo-Burma region and coal mines are also prominent in the region majorly managed by the local tribes. The dominant species of plants are under threat reducing the vegetation diversity of reserve forests due to coal mining (Semy & Singh, 2023).

3.3 Land Use and Land Cover Change

The bloom of anthropogenic activities in the Himalayan region is changing the land use pattern (Rasool et al., 2021; Ritse et al., 2020). The change in land use and land cover increases the probability of natural hazards like landslides and flash floods in the Hilly terrain. The anthropogenic disturbances to the passage and floodplain of river increases the probability of flood risk. The construction of buildings along the riverside increases the magnitude of flood risks (Dash & Punia, 2019). Slum encroachment within the floodplains of Asan river at the Dehradun of Doon valley, Uttarakahand are prone to flood disaster. The ongoing illegal sand mining and employment opportunity is the reason for the slum encroachment at the banks of Asan river (Gupta et al., 2023).

The mines or ore excavation processes disturb the upper layer of soil accelerating its erosion (Lehmkuhl & Stauch, 2023). The Himalayan region is prone to soil erosion

(Mahapatra et al., 2018) and deforestation for the mining activities would aggravate its intensity and frequency. In the Jaintia hills of Meghalaya, coal mining is harmful to vegetation cover leading to loss of dense forest and rise in open forest (Sarma and Kushwaha, 2005). The unscientific and illegal mines further accelerate the loss of forest cover. The change in land use and land cover impacts the soil properties (Choudhury et al., 2023) and quality (Pandey et al., 2022). In the north-eastern Himalayas, the soil organic carbon content is influenced by the change in LULC, climate change and altitudinal gradient (Choudhury et al. 2016). The disturbance in soil properties hinders the plant growth and influence the biodiversity of the region.

Human activities majorly urbanisation and mining are degrading forest cover in the upper Indus valley of Himalayan region (Yan et al., 2022). The region is prone to adverse impacts of climate change and natural hazards. Similarly, the extreme rainfall in the eastern Himalayas increases the risk of soil erosion under anthropogenic influence and needs proper management strategies (Mandal & Sharda, 2013; Soja & Starkel, 2007). The adoption of appropriate policies to maintain the forest ecosystem by the authorities would reduce the adverse impacts of climate change.

3.4 Pollution

The environment of upper Himalayas is less contaminated compared to lower Himalayas due to low population and lack of industrial development. River Ganga and Yamuna passing through the higher altitude in the Himalayas are less polluted compared to downstream locations in the plain area such as Haridwar, Kanpur, Delhi etc. (Bowes et al., 2020; Kumar et al., 2017). Similarly, River Gola originated from the lesser Himalayas (western Himalayas) is famous for illegal mining and its impact on the biodiversity (Seth et al., 2016). It can be stated that as the river passes through the plain area from hilly terrain its contamination increases due to rise in anthropogenic activities.

The Banor-Shiva limestone mines of Sirmaur, Himachal Pradesh adversely impacting the local environment leading to change in LULC and water pollution (Nath & Singh, 2020). The degradation of local environment and rehabilitation of abandoned mines also increases the limestone production cost. The contaminants released from industrial sites travel with wind and deposit at distant locations. The anthropogenic source of Cu and Zn in soil samples of Jammu district, India is atmospheric deposition from mining and smelting sites (Kaur et al., 2018). The concentration of Cu exceeds the USEPA guidelines limit in the region.

In North-east India specifically in Nagaland and Meghalaya, coal mines are owned by the local tribal communities leading to conflict among the communities and authorities (McDuie-Ra & Kikon, 2016). The water quality of Tsurang river, Nagaland close to mining sites is highly degraded during the periodic rainfall during summer and autumn compared to winter season due to drainage of AMD from coal mines (Semy & Singh, 2021). The water quality index calculated using parameters such as pH, turbidity, total dissolved solids, electrical conductivity, total alkalinity, total hardness, dissolved oxygen, biological oxygen demand, cations (calcium and magnesium) and anions (sulfate, chloride and nitrate) shows positive correlation with the seasonal drainage from coal mines indicating rise in deterioration of water quality during rainfall with increase in runoff from mining.

4 Natural Disaster

Himalayan region is prone to natural disasters such as earthquake, landslides and flash floods. The climate change and anthropogenic activities are increasing the intensity and frequency of extreme events. The physical and chemical changes caused by mining and quarrying disturb the Himalayan ecosystem and contribute to rise in extreme events. In the following section, landslide and land subsidence are discussed for better understanding the role of mines in enhancing the intensity of impacts caused by extreme events.

4.1 Landslides

Himalayan region is landslide prone area and heavy rainfall is one of the main cause for the landslides in Himachal Pradesh (Kahlon et al., 2014). In future, the probability of heavy to extreme rainfall is expected to increase over the western Himalayas due to rise in global warming (Das & Meher, 2019). The ore excavation process removes the upper surface of earth and the waste is mainly dumped at nearby location after the beneficiation of ore. Rise in extreme rainfall events increase the probability of washing away of waste dumps to the downstream locations, especially in the hilly terrain where the slope is steep. The deposition of waste in the river rises its bed resulting in change in river-course and extensive erosion of soil from agricultural fields and forests (Bandyopadhyay & Shiva, 1985). Reuse of waste material will solve the problem of waste disposal and its impacts on the environment. The waste from marble mines are being studied for manufacturing of construction material i.e. bricks, concrete and cement (Thakur et al. 2018; Shukla et al., 2020; Kushwaha et al., 2022).

Mining accounts 12% of total 829 landslides in India occurred between 2004 and 2016 (Parkash, 2023). In the Himachal Pradesh, sandstone mines very common and lithology controls the slope stability as the structure and strength of different rocks varies from each other. The soft rocks (sedimentary and low grade metamorphic) are more prone to landslides compared to hard rocks (high grade metamorphic and igneous). The abundance of sandstone in the Himalayan region increases the susceptibility of area for landslides. Apart from lithology, faults, fractures and slope plays an important role in triggering the landslides. The faults and cracks in the rock formations of phyllite, slates, and sandstone are more prone to landslides compared to granite and dolomite rocks of the Kullu region, Himachal Pradesh (Banshtu et al., 2020). In contrast, slate and phyllite (steep slope) of the Dharamshala region are more susceptible to landslides compared to shale and sandstone (gentle slopes) (Sweta et al., 2022). It suggests that faults, cracks and slope are controlling and important factors for landslides than geology or lithology of the area. Blasting during ore excavation process create fissures and fractures in the steep rocks increasing the susceptibility of landslides.

In the Kullu district of Himachal Pradesh falling in the western Himalayas mining activities are one of the major cause for the landslides along with the other anthropogenic factors likely rise in infrastructure and population (Banshtu et al., 2020). The construction of new roads or widening of existing roads is commonly observed in the mining area for transporting the ore from excavation to beneficiation site. The construction and widening of roads disturb the slope stability increasing the probability of landslides (Sangeeta & Singh, 2023). In addition to construction of roads, the establishment of built-up infrastructure for the ore beneficiation and residential building increases the construction activities in the region. Cutting of slopes and mountains for the construction of building increases the risk of landslides. The incidences of landslides are more frequent in the steep slope area (Singh & Sharma, 2022) and excavation of ore leads to natural disaster.

4.2 Land Subsidence

The underground mine workings create cracks, voids and sinkholes in the ground leading to land subsidence. The areas neighbouring mines are prone to land subsidence due to decline in groundwater table. During 1999 to 2000 land subsidence was reported in Rainawari approximately 4 kms from Srinagar, Jammu & Kashmir creating potholes on the roads and cracks in the buildings. The sinkholes, cavities, voids, room and pillar structures of old mine workings induce land subsidence in the region (Bali et al., 2021). Lack of information regarding the incidences of land subsidence due to mines in the Himalayan region is main constraint of the study.

The land subsidence is mainly reported over the large scale underground mines (Meinan et al., 2023). Western Himalayan is fragile and large scale mining is not prominent in the region. The artisanal mining by local community is prominent in the Himachal Pradesh and Meghalaya states from western and eastern Himalayas respectively (Deb et al., 2008). Jaintia Hills lying in the eastern Himalayas is famous for rat hole mining for coal and no land subsidence incidences are reported from the region. Potholes are reported nearby the limestone mines in East Khasi Hill district of Meghalaya close to Cherrapunjee Mawsynram belt which is known for high rainfall ranges from 2000 to 5000 mm (Prakash et al., 2015). Thus, the mitigation and adaption strategies should be adopted to avoid the land subsidence incidences in the fragile Himalayan region.

5 Discussion

Western Himalayas are steep slope on average and very fragile to climate change. The extreme events and natural disaster in the Uttarakhand and Himachal Pradesh are continuously rising in recent decades (Kala, 2014). However, eastern Himalayan ranges are comparatively stable and less polluted due to lack of developmental activities for tourism. So, the adverse impacts due to mines in the western Himalayas would be more dangerous comparative to eastern. The mining activities at larger scale are banned or less reported in western Himalayans. At few locations, mining activities are carried by local community such as gold mining at Rampur, Himachal Pradesh and sand mining at Dharamshala and River Gola, Himachal Pradesh. However, mines in eastern Himalayas are carried by local community at larger scale in their private lands such as Janitia hills which is famous for the rat hole coal mining.

In the Doon valley of Uttarakhand, quarrying of limestone was banned in 1985 by Supreme court of India following the public-interest litigation filed by local residents (Shiva & Bandyopadhyay, 1985). The valley is rich in high grade limestone and these deposits store the rainwater (Bandyopadhyay & Shiva, 1984). The quarrying was disturbing the hydrological balance and flow of springs/streams in the valley. Quarrying and waste debris from mine was impacting internal hydrological processes and the spring sources decreased by 50% in the villages (Bandyopadhyay & Shiva, 1985).

Environmental impacts such as deforestation, landslides, soil erosion and chemical pollution due to small scale mines of limestone, phosphate, magnesite and Zn-Pb-Cu in the fragile region of western Himalaya are reported 20 years back by Ghose (2003). Similarly, Gupta (1978) reported visible damage caused by the spoils of surface mines of phosphate (near Maldeota) and limestone (Dehradun-Mussoorie road) on river water quality. The disposal of mine waste in the hilly terrain is threat to downstream agricultural lands and siltation of streams. The large scale mines are banned in the western Himalayas and reclamation activities would help in restoration of lost biodiversity. Reclamation of abandoned limestone mine of western Himalayas via growing fast growing leguminous plants on stabilizes the slope stability but adversely impacts the biodiversity (Raizada & Juyal, 2012).

The north-eastern states of India are comparatively less polluted than rest of country due to lack of developmental activities. Meghalaya and Nagaland are well known for the artisanal mining by the local tribal community. It is observed that sand mining is one of major source of income for the people living on the river banks but it leads to the destruction of environment in the Meghalaya (Shymbin & Nongbri, 2022). In addition to sand mines, coal mines are major source of income for indigenous people and the rat hole mining is very prominent in the region polluting the environment significantly. The growth of heavy metal tolerant bacteria i.e. *Bacillus* sp. could be used for bioremediation of acid mines drainage from rat hole coal mines (Ka-ot et al., 2018). Streams are major source of water for the tribal communities in the Jaintia Hills, Meghalaya, North-eastern India and is being polluted by the coal mines (Das & Semy, 2023). Similarly, the ecology of Simsang River is affected by the inflow of untreated waste from open cast coal mines. The genotoxic damage is observed in the fishes and threat to food web of the river ecosystem (Talukdar et al., 2016).

Considering the geographical and climatic conditions, it can be stated that in the semi-arid and arid the scarcity of water is a major problem and use of available fresh water resources for mining further aggravate the situation. In the mountains or hilly terrain, mine trigger the intensity of natural hazards such as landslides and flash floods. The dense forest of Terai region of Himalaya is continuously converting into open forest due to anthropogenic activities such as rise in human settlements or agricultural land (Deb et al., 2018). Himalayan region is rich in biodiversity and even small scale mines have a capacity to degrade its environment at significant level. Mitigation measures such as awareness should be created among the local communities to save the fragile Himalayas. Additionally, native community knows and understand better fragile ecosystem of Himalayas and their knowledge should be used during the preparation and adoption of management policies and strategies.

6 Conclusion

The elemental contamination of soil, air, water and vegetation are very common in the mining region. However, the adverse impacts of mines in the hilly terrain are beyond the elemental contamination and loss of biodiversity. In the hilly terrain, mining activities or quarrying of upper surface leads to rise in natural hazards such as landslides and flash floods resulting in washing away whatever comes to its path. The soils and upper surface of Himalayas are prone to erosion or landslides. Thus, excavation or quarrying the upper surface leads to landslide during the rainfall. Landslides damages infrastructure and danger to life of people living in the area.

In western Himalayas large scale mines are not prominent and small scale quarrying is being carried out by the local community. The environment of Himalayas are fragile and even small mines could prove dangerous in future. In eastern Himalayas, rat hole mining by local community in their private lands is very common. It leads to conflicts among the local tribal community and large scale mining industries. Recent studies reported environmental contamination in the Meghalaya and Nagaland states of India due to mines. The proper management and adoption of mitigation strategies would prevent the further degradation of eastern Himalayas environment. The prevention of contamination in the initial stages is very important and easy to mitigate the adverse impacts.

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Assessment of Shifting Cultivation in the Context of Anthropogenic Environmental Burden in Eastern Himalaya

Olivia Halder and Arindam Sarkar

Abstract In the eastern Himalayan area, shifting farming is very common. Approximately 83% of the area is being farmed in a shifting manner. In India, slash-and-burn agriculture, or "jhum" farming, is the principal kind of shifting cultivation. It is primarily the most ancient traditional culture of cultivating. The whole north-eastern Himalayan region, including Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, and Tripura, is the research area for this essay. This report largely draws on secondary data collecting and already published research papers and publications. This paper's major objective is to categorize the research region into various altitudes and to represent the present scenario of the seven different states of the north east region. The literature that has been examined has mostly been used to analyze the fundamental social aspect and traits of this form of horticulture as well as government policy initiatives. Additionally, to assess the loss of biodiversity as well as the overall area under cultivation. My focus is on emphasizing that this kind of farming cannot be a way of life in the present since it does not promote sustainable development need to look at alternatives to this kind of farming. And because multiple assessments will be made, the results may show that as the population grows, the locals are forced to shorten the period of time they spend shifting agriculture as a result of the demand for resources and today, much other stable farming may be done in that height, especially when it comes to income crops.

Keywords Biodiversity · Cultivation · Environment · Jhum cycle · North east India · Shifting

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1 Introduction

India is known for its cultivation all over the world. Almost every part of India deals with different kinds of cultivation techniques according to the climate, elevation, morphology, geology, irrigation facilities, and other factors influence too. One kind of traditional and primitive way of cultivation is shifting cultivation which is mainly seen in the northeastern Himalayan region including the seven sister states Arunachal Pradesh, Assam, Manipur, Mizoram, Tripura, Nagaland, and Meghalaya. These seven states of India still contribute to the shifting cultivation as a major part of the source of cultivation in India. Thus, the northeast Himalayas can be known for its unique type of primitive cultivation which is known as shifting cultivation locally known as the "Jhum" cultivation. It is a primitive practice of cultivation across the hilly terrains of the region (Borthakur, 1992). Thus, as it shows a primitive method of cultivation and with time it is becoming harmful to the environment. It is mainly carried out.

because of the sociocultural traditional beliefs of the local's community (Tripathi & Barik, 2003). Many papers contents of the fact that this type of cultivation is practiced at the cost of biodiversity loss and can be replaced through farm forestry so as to sustain the environment (Ranjan & Upadhyay, 1999). The shifting cultivation is being studied in a different way still now and different aspects have come into consideration (Panda et al., 2017). The cycle which is carried on in the shifting cultivation of burning and clearing forests and then again leaving the land for regeneration of the vegetation (Ramakrishnan, 2007). This cyclic way of cultivating land is responsible for soil degradation and affects the ecosystem (Nath et al., 2016). Thus overall, it can be seen that this type of cultivation cannot be sustainable and it needs to replace as soon as possible. Thus, the local community is coming up with some strict measures such as charging fine in case of the destruction of natural resources, controlling fire, and to make people aware of its harmfulness, and taking the initiative to adopt new methods (Tiwari, 2014). The national institution of transforming India (NITI Aayog) is welcoming a vast dimension to discuss the different aspects of shifting cultivation and to come up with suggestive measures and views in negative as well as positive ways.

This cultivation has definitely been dissolved in many parts of the world but still in the northern Himalayan region this type of cultivation is mainly done by the local tribal people(Pandey et al., 2019). Thus, the main perspective of this type of cultivation is to eradicate this way of livelihood and to adopt some better and inducing way of cultivation (Ray et al., 2020). This whole northeast region mainly comes under the economically unstable region where the people of this region mainly depend on the traditionally cultivated crops grown. But in the present scenario of different government plans and policies, there is a decline in this kind of cultivation. Different agroforestry programs, high-yielding varieties of seeds, integrated farming systems, and better fallow management have been adopted to improve the shifting cultivation. The shifting cultivation is highly exploited with the minimum use of natural resources in the northeast region. this cultivation is not just a way of livelihood

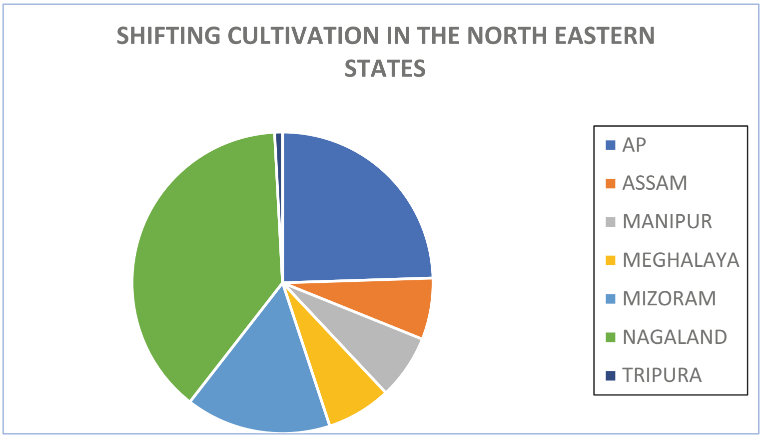

Fig. 1 *Source* Wastelands atlas of India, 2011

but rather a feeling of culture, customs, and ethnicity which develops in the people living over there by cantering this kind of cultivation.

According to the Westlands Atlas of India, 2011 it can be seen that there is a huge change jhum condition of the present scenario. there are the states where the present jhum land per sq. km has fallen considerably. But the data shows that among all the northeastern states Nagaland has the highest number of the current jhum area because mainly of the tribal population and their traditional mindset of livelihood and the poor economic status which is the major drawback of this region to still practice this type of cultivation (Fig. 1.)

And another state which is followed is Arunachal Pradesh who's current Jhum status per sq. km is also considerably high is also because of their lower economic value their tribal ethics and the main constraints is the rugged topography and the very high elevation which enables a huge climatic barrier in this region and poor transport and communication which restricts this place to develop themselves and come out if the old traditional way of livelihood. And the other states have shown a much lower area of current jhum status whereas Tripura has shown a remarkably lower area which can be considered that this state is entering the modern and Sustainable way of living.

2 Overview of Shifting Cultivation in the North Eastern Himalaya

The northeastern hill region of India occupies more than 0.76 m ha of land out of 0.94 m ha of jhum land (Anon, 2011). Shifting cultivation is very much dominant in the whole northeastern region. Besides the terrain topography climatic barrier poor economic condition, the other factor which influences the shifting cultivation is the older and non-educated farmers who are very much rigid and has an emotional feeling towards this kind of traditional practice because of their lifestyle food habit ethnicity revolves around this.

In India, shifting cultivation has been confined to a low category and unstable equilibrium and are mainly practiced at the conventional level and which leads to a wasteful and dysfunctional system leading to wastage of natural resources, soil erosion, and other unstable condition (Das et al., 2021) thus, it is time to eradicate the old traditional type of cultivation by introducing the new modern method of farming (Chakraborty et al., 2015). This will also provide the locals with maximum production and this will lead to economic stability in these states as well the approach towards sustainability can also be seen.

3 Assessment of Shifting Cultivation in Relation to Elevation

The elevation in the northeastern Himalayas region varies from a lower altitude to a higher altitude. The states like Meghalaya, Tripura, Manipur, Mizoram, and Assam show a comparatively less altitude than the states like Nagaland and Arunachal Pradesh. And the shifting cultivation is mainly found from a gentle slope to a steep slope and also in the foothills of the Himalayan range. The elevation of the northeast region ranges from 700 m to above 5000 m. This wide variety of the sloping surface gives access to a wide range of cultivation along the sloping surface. Nagaland has an elevation of above 200 m where mainly the high elevation shifting cultivation can be found other than this Arunachal Pradesh which has a much higher elevation than any other state but on a very high altitude the cultivation is not possible because of the climatic barrier and the poor communication facilities. Therefore, most of the cultivation is practiced in moderate-sloping ranges to the foothills.

The northeastern part of India due to its terrible terrain, climate, a wide variety of slopes and altitude, cultivation practices, land tenure system, and poor communication facilities makes this area to be dependent on subsistence farming. Different varieties of crops and fruits are being grown on the slope and also flowers are grown over there (Fig. 2) This type of farming includes a suitable combination of crops grown along with some horticulture crops enabling the poor farmers to become self-sufficient and to become economically stable. The present cultivation of this region is not exposed to an adequate scientific base and thus leading to land degradation, soil erosion, and the exploitation of other natural resources.

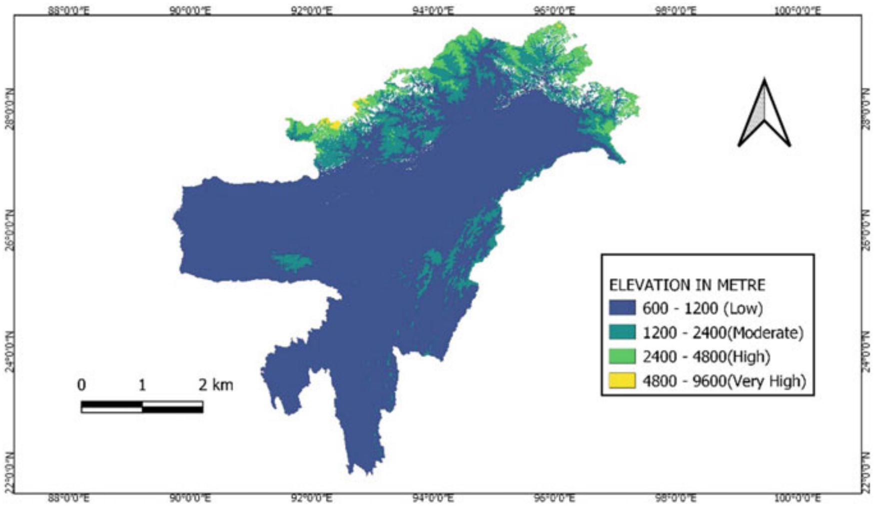

Fig.2 Digital elevation model of North East India

4 Present Status of Shifting Cultivation in the 7 States of North East India

4.1 Arunachal Pradesh

4.1.1 Present Scenario

Around 52% of the area is under shifting cultivation (Prakash et al., 2017). As this area is highly undulating in nature with great altitude therefore many areas are out of agricultural facilities. Paddy is their stable food and different varieties of rice are grown in the jhum fields. and other food crops such as maize and millet are also grown as complementary to paddy and as traditional substitutes. the sowing is mainly done by the local tribal women. The main activities involve the terracing of steep slopes and in the higher areas along with contours with half-burnt logs, weeds, stems, etc. Some crops are also grown on the contour bunds where the wooden poles are laid along the contour to prevent soil erosion (Teegalapalli & Datta, 2016). The crops grown in other crops are grown are beans, chili, soybeans, brinjal, cabbage, etc. these root crops are grown on a comparatively sloping surface as it helps in soil conservation. other than these some fruits like kiwi, pineapple, banana, and apple are also grown. cash crops that are found are turmeric, ginger, and large cardamon for commercial purposes.

4.1.2 Policy Initiative

Jhum cultivation is fully an exploited natural resource way of cultivation thus many programs and action plans have come into existence to make a technically skill-based, rational, and sustainable use of resources and also to increase the way of production. Govt. of Arunachal Pradesh has adopted many plans such as the Integrated Community Large Cardamom and Orange Plantation in Jhum land at Restoring, Koraput, Tarak Langdi, and Galang Putung Villages under Tarak Circle of Kurung Kumey District in the year of march 2012 in order make the jhumming sites under the commercial production. Establishment of the Biotechnology Training and Development Centre at Ziro in the year 2013 to take advantage of the huge biodiversity available in this state (Teegalapalli & Datta, 2016) thus, in this way, the old traditional way of cultivation is coming under the new scientific way of development and sustainability.

4.1.3 Production

In Arunachal Pradesh, the production of main food crops, and vegetables are quite low because of its climatic barrier and unskilled laborers following traditional use of technology. the production of paddy is the highest which is around 1550(kg/ha) including the rainfed and the irrigated cultivation of paddy. and which is followed by the production of maize which is 1006 (kg/ha) and which is only rainfed. And this is followed by the production of Millet which is 1000(kg/ha) and the rest is followed by the pulse and the oilseed which is 810 and 870 (kg/ha) respectively. There is also the production of vegetables which is around 42,500(kg/ha) (Prakash et al., 2017). The production is shown according to the average of the 5 years from 2009 to 2014. But there is no production of any plantation crop which can be seen and make the state economically strong by exporting such crops whether the agriculture is very much subsistence and are localized.

4.2 Tripura

4.2.1 Present Scenario

A total area of about 1,08,824 ha is under shifting cultivation (Prakash et al., 2017). The local tribe adopts a mixed cropping which varies from one locality to the other depending upon the tribal community their way of cultivation and obviously the climate and the terrain in that region. Among the food grains coarse varieties of rice, millet, and maize are grown and this area is also suitable for cash crops like jute, cotton, and pineapple. These crops are grown at different periods of the year which provides them with a wide variety of crops almost throughout the year. Occasionally some residual crops are also grown and collected from the nearby abandoned nearby fields by the local tribal people. Rice is the predominant jhum crop. Though the jhum cultivation in Tripura has decreased a lot as to the other northeastern states is because of the different developmental programs taken by the govt. of Tripura. Different kinds of settled farming initiatives were taken by the government in early 1954 with a small amount of payable grants to support this kind of farming (Das & Das, 2014). Soil and water conservation schemes in the year 1974 and other different integrated plan have been adopted and thus is on the verge of entering and adopting the new scientific and sustainable method of cultivation.

4.2.2 Policy Initiative

An estimate was made by a team of experts from the Central Water Commission and State Water Resources Department to ascertain the irrigable land in the state. It was primarily assessed that 1,17,000 hectares of land could be brought under assured irrigation availing feasible components of non-monsoon run-off and groundwater storage, which may now likely increase up to 1,78,000 hectares. Irrigation infrastructure so far has been developed in the state through various projects which include, lift irrigation, diversion, Dynamic Time Wrapping (DTW), medium irrigation, shallow tube well, artesian well, tank, 5HP pumps etc., for covering 1.13 lakh hectares. A recent assessment of the Central Ground Water Board has revealed that the overall exploitation of groundwater in the state is about 10 percent of the total potential only. Agriculture Department has taken steps for tapping the groundwater potential for irrigation purposes and accordingly, 1814 small bore deep tube wells have been installed till 2014- 2015.

4.2.3 Production

The activities of agriculture and the other sectoral are mainly in the hand of the marginal and small cultivators. the production of rice is the highest which is 3493(kg/ha) followed but wheat which is 1900 (kg/ha) and potato at 15,969 (kg/ha) and the other crops which are mustard, and pulse maize are also grown in a decent amount. In comparison to the previous year, food grain production increased by 6% in 2014–15. During 2014–15, 7.68 lakh tonnes of food grains were produced, compared to 7.27 lakh tonnes the year before. 2013–14, while 8.79 lakh tonnes of food grains were anticipated to be needed in 2014–15.use chemical fertilizers growing rapidly (Datta et al., 2015).

The secret to enhancing crop productivity is Integrated Nutrient Management, which uses macro and micronutrients along with organic manures, vermicompost, and bio-fertilizers to ensure sustainable production and preserve soil health and fertility. Chemical fertilizers were used more frequently in the state, increasing from 46,000 MT in 2013–14 to 58,432 MT in 2014–15, a 27% increase.

4.3 Meghalaya

4.3.1 Present Scenario

In Meghalaya around 448.99 km^2 of area is under shifting cultivation (Prakash et al., 2017). jhum cultivation is practiced. The criteria for the selection of the crops are based on the priority that is already grown on in the area, the crops such as different spices, pea potatoes, etc. are grown in the irrigated area. On the steep slopes mainly the leguminous plants and the deep-rooted plants are grown such as soybean, pea, and guinea apart from these five essential crops which are grown are different kinds of fruits and vegetables and other Kharif crops like cowpea, sesamum, groundnut, etc.

4.3.2 Policy Initiative

Different integrated approach has been taken to improve the jhum cultivation in this area the soil and water conservation department took up the scheme of jhum control in 1975 (Jeeva et al., 2006) under the state plan in order to improve the jhuming facilities to provide land for settled farming and to make people aware about the adverse effect of shifting cultivation. The NERCORMP project supported by the international agricultural department has done remarkable work in west Garo Khasi hills (Kumar et al., 2006) in order to control and optimize the jhum cultivation through monitoring, planning, and implementation and by giving new approaches to their way of cultivation (Sharma, 2017).

4.3.3 Production

Jhum farming was practiced by a significant decline in families in Meghalaya, however, the effectiveness of this effort was difficult to judge due to a lack of valid data. The implementation of the plans to regulate jhum cultivation shouldn't be done in a vacuum, but rather with a comprehensive strategy (Tumuli & Bora, 2022). This type of farming is perhaps the best fit for the Meghalaya hills and possibly the entire northeastern area, barring the reduction in the jhuming cycle from 20–30 years to 3–6 years (Kumar et al., 2010). Due to the terrain and rainfall in Meghalaya, the current funding allotment of Rs. 10,000 per hectare for treatable regions was insufficient for the required treatment (Pandey et al., 2021).

4.4 *Mizoram*

4.4.1 Present Scenario and Production

In Mizoram, about 16.9% of the total area is under shifting cultivation (Prakash et al., 2017). This cultivation is mainly dominated in the highlands. This cultivation is dominated by subsistence crops. Some of the most common crops grown are rice and maize. Chilies, mustard, etc. vegetables, and fruits are also grown but are consumed domestically. The principal crop is paddy which is grown in a way of many varieties almost throughout the year. Different initiatives and strategies have been taken by the govt. to control shifting cultivation such as NLUP (New Land Use Policy) in the year 2010 to decrease the population depending on the shifting cultivation and to make this state an economically stable one. According to the Agriculture Department Report (2009–2010), more than 20% of the population of Mizoram is involved in shifting farming, both directly and indirectly. For them, it is their main source of income. Shifting farming in Kalimantan, Indonesia, provides 23 persons per km^2, more than twice as many as is provided by commercial cultivation. As Jhum is woven into the culture and traditions of more than 200 tribal races that are inhabited in the northeast region, shifting cultivation aids in the preservation of the regio's unique cultural variety.

4.4.2 Local Initiative

In Mizoram, the pattern of land use is changing, resulting in a labor force that is distinct from what has been practiced historically and other types of human resources. This has led to the appearance of a new type of agricultural worker or wage employee class (Swami, 2018). In addition, the labor pool for shifting agriculture, particularly at the community level, has shrunk as a result of the decline in the number of shifting cultivators brought on by a variety of factors. As previously indicated, shifting cultivation depends on local methods for sharing labor, and neither the idea nor the need for contracting labor for cultivation is present (Prakash et al., 2017). As opposed to a reciprocal type of participation in the agriculture process for the villages or nearby shifting blocks, there was traditionally no sense of labor. As previously indicated, shifting cultivation depends on local methods for sharing labor, and neither the idea nor the need for contracting labor for cultivation is present. In the past, there was no concept of labor; instead, participation in activities was reciprocal the farming procedure for the locals or nearby moving blocks. The workforce's reciprocity and sense of community have been weakened by recent privatization (Lalliantluanga et al., 2020) migration, and cash crop plantations. It has created wage labor and benefited some of the daily wage earners, but it has had a significant negative impact on impoverished households who rely on merger means of subsistence and cannot afford to hire labor for farming.

4.5 Manipur

4.5.1 Present Scenario and Policy Initiative

In the state of Manipur, the crops which are grown are very less in number because of the lack of other mechanized facilities. rice is the main crop that is grown mainly in the highlands. some other potential crops which are along the hillslopes are mainly pulses crops which help to add to the fertility of the soil. The economic backward condition of this state also restricts the locals from further improvement in terms of agricultural conditions and production (Maring & Pillai, 2023) the crops which are grown are mainly Indian corn, pumpkins, chilies, yam, etc. (Thong et al., 2018) The people of Manipur currently face major dangers from the destruction of the land and forest caused by jhum or shifting farming. The cultivation of undesirable, harmful weeds have a significant negative impact on biodiversity (Thong et al., 2019) soil, water resources, and land or forest productivity. Even after applying fertilizers and pesticides, crop yield has consistently dropped to 50% over the past ten years (Singh, 2022) The energy inputs are greater than the energy outputs of the crops. In order to control jhum cultivation especially in the hillside areas the ICAR and central university of Agriculture in Imphal conducting various programs and initiatives to eradicate this kind of farming and to think about sustainability (Khesoh, 2022) another international fund for agricultural development NERCORMP is working in the area of Ukhrul and Senapati districts.

4.6 Nagaland

4.6.1 Present Scenario and Production

Nagaland is located comparatively in a higher elevation where the tribal influence is primarily dominant all over the state. Thus, the tribals fully indulge in this cultivation and a variety of crops and fruits are grown throughout the year mainly mixed cropping is practiced over here. the crops which are grown on the high hills (900–1200 m MSL) are mainly potato, cabbage, and beans. the crops grown on the mid hills (below 800 m MSL) are mainly ginger, chillis brinjal, Bean, and also, other varieties of fruits such as citrus, and papaya are also grown (Prakash et al., 2017). in the foothill fruits like jackfruit, and banana is grown. Although shifting cultivation practices have a number of drawbacks and environmental effects, a sizable portion of tribal farmers continue to use this approach. Low agricultural yield is caused by conventional farming on muddy terrain (Saplalrinliana et al., 2016) using locally accessible seeds, tools, and implements, without taking action to conserve soil and water. Despite a number of drawbacks, the lack of viable alternatives for a living makes total elimination of this technique of farming almost impossible. The current typical jhum farming operational systems, including the yield of the primary growing jhum crops (paddy, maize, [Ramkrushna et al., 2022] local beans, Colocasia, ginger, soybean, rice bean, cucumber, tapioca, and chili), as well as the crops' growth season, cultivar utilized, seed rate, sowing techniques, and weed control, are listed below. Some programs and initiatives taken by the government are Integrated land development projects Govt. of Nagaland. Soil and water conservation program Govt. of Nagaland. ICAR-projects on jhum improvement.

4.7 Assam

4.7.1 Present Scenario

Assam is a state where a wide variation of elevation can be seen. the crops grown here are also of mixed cropping and grown throughout the year starting from the foothills till the higher elevation. Apart from food crops that are grown there are also cash crops such as groundnut, cotton, and cashew which are almost packed for marketing (Singh K, 2022) Various planning initiatives have been taken in order to decrease shifting cultivation (Misra & Rajan, 2020) and to make people dependent on settled farming and to make people aware of the hazardous effects of shifting cultivation. Variations in production result in variations in people's standards of living. Therefore, it is crucial to understand how people's standards of living differ under the two different production systems. About 40.68% of the population of Assam is considered to be poor (Prakash et al., 2017). As a result, Assamese' standard of living is significantly lower than the national average. The main contributors to poverty appeared to be limited access to agricultural land, a lack of employment opportunities on the land, a lack of educational opportunities, a low cost of living, and a significant reliance on traditional crop production. The study of income disparities between the two production systems and how they affect people's quality of life is therefore crucial.

4.8 Effect on Environment

The jhum is a special agroecology with distinctive agrobiodiversity that is exclusively adapted to the delicate hill ecosystem and is sustained by tribal tribes. It is thought to be a significant natural resource. The diversity of this agroecosystem in Jhum includes edible and medicinal plants as well as cereals, millets, tuber crops, vegetables, oil seeds, spices, sauces, and culinary herbs. In the jhums, farmers grow more than 40 different kinds (Pandey et al., 2022). Within the species, there is a significant amount of genetic variety. Farmers also exploit wild plant species as food plants associated with food security in addition to agrobiodiversity (Panda et al., 2017). Through jhum practice, traditional varieties of these crops (Malik, 2003) have been preserved from the dawn of time. These conventional cultivars either do not respond to fertilizer or respond very little to it. There isn't much room to replace these cultivars with crops that are fertilizer-responsive HYV (Prakash et al., 2017). Because the farmers are hesitant to fertilize the jhum fields, HYVs cannot provide the projected yield. Additionally, the region's heavy rainfall will result in a low fertilizer use efficiency, as the majority of the applied fertilizers would be lost to surface runoff. Therefore, efforts to create varieties with good yield potential and minimal inputs using the genetic resources of current traditional cultivars are worthwhile (Kant P, Katwal R.,2003) Additionally, it will assist prevent the degradation of soil and water resources and preserve the diversity of traditional cultivars.

Due to soil erosion, loss of organic matter, and leaching of plant nutrients, shifting cultivation has a negative impact on the soil fertility of jhum fields. Studies on steep slopes have shown that there is nutrient loss along with soil loss from hill slopes (Nath et al., 2016) By implementing soil conservation techniques such as contour trenches, contour bunds, vegetative bunds, grass waterways, etc., soil loss can be effectively reduced. In addition to increasing cash revenues (Sain, 1978) the introduction of leguminous cover crops in the current jhum field will reduce soil loss, enhance soil health, suppress weeds, and provide food for humans and animals (Laskar Sileshi Pathak K et al.,2021).

4.8.1 Environmental Degradation

In jhum fields, crops experience extreme moisture stress, especially in the winter, which significantly lowers crop output. Even though the North East receives substantial monsoon rains, there is a severe water deficit throughout the winter. The geological structure prevents water from being retained; runoff is swift, and springs and tiny streams dry up in the absence of rain. Options for water/moisture conservation that are suitable for sloppy land must be investigated in order to increase jhum productivity (Punitha et al., 2018) Depending on the availability of adequate space in muddy soil, the construction of inexpensive micro water harvesting structures with minimal seepage and evaporative losses will be a viable option for the irrigation of crops that can save lives (Nath et al., 2016).

There have been major environmental degradations during the past 20 years as a result of a variety of anthropogenic influences, such as the extensive Jhuming in upland and some valley regions. Jhuming and deforestation are undoubtedly causing a number of natural disasters, such as the frequent mudslides and landslides in the hills of northeast India (Dobhal S, Kumar De H et al., 2022) which are impeding transportation and posing serious health risks to the state's population in both the hills and valley. However, due to a lack of knowledge, the general public does not take the effects of Jhum cultivation seriously (Paul et al., 2017) Once the rainy season begins, flash floods, mudslides, soil degradation, and the loss of fertile topsoil become yearly occurrences due to deforestation caused by the short cycle of jhum farming. Ecologists and environmentalists claim that jhum is both ecologically and economically unsustainable (Prakash et al., 2017). However, jhum, or shifting agriculture in the state's hill regions, particularly among the tribal populations, is a method that must be stopped to prevent soil deterioration and other ecological and environmental problems (Saikia, 1998) After burning, the ash's liming effect causes the pH of the soil to rise (Bhaduria & RamaKrishnan, 1996) while leaching causes it to fall over time. The extent of the shift varies depending on the soil characteristics. After burning, the basic cations in the ash generate significant increases in the exchangeable calcium, magnesium, and potassium (Mishra, 2022) These are then gradually reduced as a result of leaching and crop uptake during the cropping period. Burning has little impact on soil organic matter, (Ramakrishnan, 1994) even though it volatilizes the majority of the carbon, sulphur, and nitrogen that is present in the vegetation. Following clearing and burning, a soil's accessible phosphorus level rises due to the ash's phosphorus content (Giri, 2019). The soil microflora is significantly altered by fire and clearing.

5 Results and Findings

Jhum or shifting cultivation is nevertheless a dominating system of agriculture in the northeastern region. The people who are engaged in this type of cultivation in mainly the local tribal people and the rural villagers who are totally dependent on this type of cultivation. As these states mainly have a poor condition of economic status thus the problem of lack of basic information, lack of proper monitoring system, lack of implementing machines, complex land tenures, and also their rigid, customs, traditions, and beliefs are also playing a major part in following such type of agricultural practices. shifting cultivation was found to be a good initiative by the locals when it emerged. least disturbance of soil and the soil is recovering in a fully natural way within the span of 20 to 25 years, mixed cropping under the rainfed condition totally depended on the locally natural recourses as a whole this was the most well-maintained naturally equipped way of cultivation. But as time is passing the pressure on the land and the resources increases and the need to conserve resources became the main priority. But on the other hand, the shifting cultivation causes a loss of biodiversity, soil erosion, land degradation, losses of valuable flora and fauna, and animal resources creating an ecological environment not suitable for this kind of agriculture.

Almost all the parts of the northeast region have a huge hotspot of biodiversity. And thus, this cultivation is leading to the loss of such biodiversity, and soil and land upliftment become minimum which leads to the people over there lacking in terms of livelihood generation and lacking behind as a state of production which in turn makes these states remain economically backward. And therefore, there is no further implementation of scientific ways and methods to compete with any other state of India. And the most important phenomenon which is coming into existence is that due to the huge pressure on resources and production to meet the need of the people of this huge population the fallow cycle is being decreased gradually which was 20 to 25 years at the time of beginning now it has been decreased to 2 to 3 years it is now much more intensive and frequent which results in the loss of soil fertility the quality of the soil is decreasing as it is not getting enough time to recover the loss nutrients thus it results are seeing in the case of production of crops which is also decreasing considerably. As a whole many initiatives and planning have been encouraged by the government of different states to control, monitor and reduce this kind of cultivation and to move forward toward sustainability and the use of scientific methods.

The shifting cultivation due to its ways and how it is practiced affects the environment severely. Clearing of the forests causes a huge loss of biodiversity, and again, burning that area causes the release of several gases into the atmosphere and thus increases the acidic content of the soil, which ultimately results in a loss of production. One of the most negative impacts of shifting cultivation is the huge damage it causes to the soil system. It acts as a catalyst for the degradation of land and soil erosion. especially on steeply sloping grounds, the rate of loss of soil nutrients becomes much higher. As the Jhuming cycle has been reduced to only 2 to 3 years due to the pressure on the natural resources, the vulnerability of shifting cultivation has increased. It has been blamed on the huge loss of forest cover and some tropical hotspots in the region. Large-scale deforestation is, as a whole, causing the ecological imbalance.

6 Conclusion

Jhuming refers to the practice of only having crops grow on the land once every few years (5–19 years, depending on the jhum cycle). However, in established farming, the same area can be used for several crops under irrigation and scientific management, which might two or more crops should be grown. As a result, jhum cultivation has a much lower productivity per ha than settled cultivation. The typical family income among agricultural households is trivial due to the low yield of jhum land. Jhum land is free, and capital outlay is little. The primary capital input, seeds, are completely produced domestically. Considering these factors, the productivity, value of the products, and return on investment per man-day are all relatively poor. In light of current wage rates, the level of income from Jhuming thus seems to be quite low. The drawbacks of primitive technology were thus felt through Jhuming in terms of both the productivity of the land and the return of labor. Because these lands are not utilized properly in terms of the land use land cover and not in the proper cultivation method which can lead to the betterment of the environment as well as the livelihood of the people living over there.

Since there is no private ownership and the land is free, farmers are not encouraged to take appropriate steps to develop and conserve the soil. Low productivity means that there is no surplus to be ploughed back. The increasing population has created a cycle where more land is being Jhumed, which causes the fallow season to be shorter and the soil fertility to decline, necessitating the Jhuming of more land.

For the North East region, sustainable agriculture should require the creation of management structures that guarantee an adequate supply of food, fibre, and fuel for the expanding population. These mechanisms must simultaneously guarantee that people's living conditions are improved. via practical and lucrative effective use of all natural resources, including land, water, and external inputs, while promoting environmental safety. It is necessary to make these regions' alpine ecosystems, where shifting farming is practiced, environmentally sustainable. Making an environmentally sustainable eco-development strategy for the area could take enhancing jhum practice and land usage into consideration. Unscientific farming methods are causing a decline in biodiversity; estimations show that each unit of energy used in agronomic production results in a larger loss of energy from the woods. Farmers, however, Rehabilitating the Jhum practice calls for a collaborative convergence-based approach with new land use regulations for site-specific and farmer-centric technologies.

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Climate Change Implications in the Himalayas

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Abstract The entire world is affected by climate change and variability, and the consequences are more pronounced in mountainous areas and their inhabitants. Himalayas is a huge mountainous region covering an area of 2400 km, includes parts of eight nations: Nepal, Bhutan, Bangladesh, China, Afghanistan, Burma, Pakistan and India. The Himalayan region is warming faster than the world average (0.08 °C per decade), and during the past six decades, precipitation has also increased dramatically. As a consequence, climate—induced disasters have also increased in terms of frequency and intensity. Additionally, climate-dependent sectors have already been impacted by changes in precipitation and temperature and will continue to do so. Hence, understanding the implications of climate in Himalayan region is vital since it's impact is not only region—specific but has a trans—boundary effect. In this regard, this chapter addresses state of knowledge concerning the current status of climate change, draws out implication on water resources, forest, biodiversity, human health and tourism; along with adaptation and mitigation measures in Himalayas. To summarize, Greater Himalayas' climate change issues can only be solved by enhancing regional cooperation in scientific research and policy decisions.

Keywords Climate change · Water resources · Biodiversity · Human health · Tourism

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1 Introduction

The mountains, which are delicate, serve as crucial reservoirs for water and biodiversity. Specifically, the Himalayas, often referred to as the "roof of the world", possess a breathtaking and picturesque landscape featuring alpine meadows, lush green forests, deep gorges, agricultural fields, cascading river valleys, waterfalls, and human settlements situated on perennial streams or unstable slopes of major rivers. According to the theory of continental drift, the Himalayas were formed approximately 50 million years ago as a result of the collision between the Indian and Eurasian plates (Haq et al., 2023; Kious & Tilling, 1996). Spanning across eight countries in Asia, the Himalayas hold significant importance as they are the origin for major rivers, aids in irrigation, provides water for drinking, and hydroenergy for a global population of nearly 20% (Sharma et al., 2019). Renowned as the world's tallest mountain range, the Himalayas constitutes majority of the highest peaks worldwide, whereas the Hindu Kush and Karakoram are normally considered as separate ranges. The Tibetan Plateau (TP) and the Hindu Kush Himalaya (HKH) mountain range collectively form the "Third Pole", possessing the largest freshwater reserve outside the North and South Poles. The melting of glaciers in the Himalayas supplies streams and rivers in the region, including the Ganges, Brahmaputra, and Indus river systems in India, which jointly contribute to nearly 50% of the India's surface water (Srivastava & Misra, 2012). Various studies indicate that most of the glaciers prevailing in the HKH region are experiencing volume and mass loss due to rising temperatures caused by climate change (Kulkarni & Karyakarte, 2014; IPCC SR, 2019). However, fully comprehending and quantifying the consequences of these changes in the mountain ranges remains a challenging task.

The foothills of the HKH's climate is characterized by subtropical/tropical conditions; whereas at higher altitudes, the region is covered by permanent snow-covered peaks (Pant et al., 2018). The fauna and flora in the Himalayas diverge based on various factors such as climate, rainfall, altitude, and soil composition. Rainfall escalates along the southern front from west to east, resulting in the Himalayan climatic condition being divided into several sub-zones owing to the varied geographical features, closely related to the topographical distribution of the region (Haq et al., 2023). The annual precipitation and temperature patterns vary significantly across these zones. The average summer temperature in the valley ranges from 15 to 25 °C, while winters are considerably colder. Regions greater than 4500 m encounters harsh winters, with temperatures dropping well below the freezing point. In the Karakoram range for instance, during summer the mean maximum temperature is nearly 20 °C; while the mean minimum temperature during February is less than –3 °C (Kapnick et al., 2014). The Himalayas north western peaks experiences dry climatic conditions; wherein the temperature ranges from –20 to –35 °C and 3 to 35 °C during winter and summer respectively. Since twentieth century, the HKH's climate has undergone substantial changes in temperature, with a warming trend of approximately 0.10 °C (0.16 °C) per decade (Krishnan et al., 2019). Hence, this chapter addresses the current status and projected climate change, impact on several sectors (agriculture, forest, water and food insecurity, biodiversity, tourism, human health, and economic status), and the adaptation and mitigation approaches to alleviate climate change.

2 Climate Change—Current Status in Himalayan Region

Climate change poses a significant threat to the water resources. Current projections indicate that by 2050, more than 57% of the global population will face water shortage (Boretti & Rosa, 2019). Rapid population growth, industrialization, and urbanization will further dwindle the availability of freshwater. The changing climate will have noticeable effects on hydrology of the Indian sub-continent, affecting its agricultural economy and water resources. The Indus river and its tributaries are vulnerable to climate change as they heavily rely on snowmelt and glaciers. The region's rich biodiversity and its fragile nature make it susceptible to natural hazards triggered by climate change, evident through increasing occurrence of floods, drought, landslides, shift in biodiversity, endangered species, and threats to food security (Mir et al., 2015, 2018).

2.1 Temperature

In the past 60 years, the HKH region has experienced a significant rise in surface temperatures (Kulkarni et al., 2013; Rajbhandari et al., 2017). Both the western and eastern Himalayan river basins have gradually warmed, and the overall trend of lowest temperatures is substantially greater than the pattern of maximum temperatures (Rajbhandari et al., 2015). Ren et al., (2017) used historical time series spanning a century to demonstrate that the mean temperatures inclined from 1901 to the early 1940s after which it dropped from 1940 to 1970, and then it again started increasing. According to the spatial distribution of annual mean temperature trends over the HKH region between 1901 and 2014, the eastern side of the HKH range observed an increase in temperature at a rate of roughly 0.2 °C per decade, whereas the TP region warmed at a rate of more than 0.3 °C per decade. Additionally, the annual warming signal consistently displayed a positive trend in the majority of the grids, but the warming rates varied greatly. According to several research (IPCC, 2007; You et al., 2017), the observed warming signal is due to a rise in the concentrations of anthropogenic greenhouse gases. Furthermore, research showed that in recent decades, the rate of temperature increase was comparatively less in regions below 500 m (0.2 °C per decade) than at regions greater than 2000 m (0.61 °C per decade) (Ren et al., 2017). The Sichuan Basin of China, Northern India, and the Karakoram range during the northern summer all displayed the feeblest warming trends, with annual rate of increase less than 0.10 °C per decade (Forsythe et al., 2017).

Over the past three decades, the HKH has also experienced a major spike in extreme warm events and a sizable decline in extreme cold events (Sun et al., 2017).

Particularly, the significance of trends in warm events is greater than that of trends in cold events. Beginning in the early 1990s, a noticeable increase in the amount of warm nights and a decline in the amount of frosty days can be noticed (Sun et al., 2017). In the HKH region, the average DTR (diurnal temperature range) anomalies appeared to be declining before the 1980s, but after that point, they began to rise. According to the spatial distribution of linear trends for extreme temperature indices, the number of extremely cold days and nights decreased by 0.85 and 2.3 days per decade, respectively, in the Tibetan Plateau (TP) region, while the number of extremely warm days increased by 1.2 days per decade; whereas warm nights increased by 2.5 days per decade (Sun et al., 2017). It was also observed that, the amount of frost days significantly declined at the rate of 4.3 days per decade and the number of ice days dropped at the rate of 2.4 days per decade. According to studies by Liu et al. (2006) and Sabin et al. (2020), the length of the growing season has been expanding at a pace of 4.5 days per ten years.

2.2 Precipitation

In tropical highlands, precipitation is one of the primary forces influencing regional biogeography, land surface processes, and water security (Wohl et al., 2012). According to Krishnan et al. (2019), large-scale atmospheric circulations, steep elevation gradients, and geomorphology interact nonlinearly to influence precipitation patterns in topographically complex mountains. Precipitation is therefore the most difficult meteorological variable to model in studies of climate change from mountains, with additional challenges brought on by changes in regional atmospheric moisture circulations brought on by global warming (Körner, 2007; Krishnan et al., 2019). Modelling studies from the Himalaya show decreasing precipitation patterns in the Western Himalaya, especially at low elevations, whereas precipitation is predicted to increase in the Eastern Himalaya, notably in mid-high elevations (Krishnan et al., 2019; Ren et al., 2017). However, the accuracy of such forecasts is largely reliant on the availability of fine scale ground precipitation data. In the Eastern Himalaya in particular, there is a dearth of geographically distributed long-term meteorological station data (Krishnan et al., 2020; Li et al., 2018, Ren et al., 2017). This restricts our capacity to characterise the regional hydro-climatology, comprehend ecosystem-climate interactions at finer scales, and precisely forecast extreme precipitation events (EPEs) and geohazards such flash floods and landslides in the Himalaya (Jena et al., 2020; Krishnan et al., 2020; Zhan et al., 2017).

Since 2010, numerous catastrophic flooding events have happened in the Himalayan region, primarily over the Indus basin, northern Pakistan, and along the western side of South Asian Monsoon. These occurrences have been caused by excessive rain during the summer monsoon. Among them, the devastating floods in Pakistan in 2010 and India's Uttarakhand in 2013 have emerged as model cases for studies on high rainfall (rainfall over 100 mm per day) in the Himalayas and its potential causes. For instance, Rasmussen et al. (2015), and Krishnamurti et al.

(2017), all point to the formation of an anomalous moisture supply over the region as the primary cause of storms that have occurred in the western HKH in recent decades. Upon examining the rainfall data since 1950s, it was interpreted that variations in the historical circulations in the western Himalayas might have been the reason for the increased occurrence of cyclonic troughs (Filippi et al., 2014; Priya et al., 2017). In a separate study that examined precipitation data collected between 1961 and 2012, Zhan et al., (2017) discovered that the Tibetan Plateau experienced a more pronounced increase in the quantity and frequency of intense precipitation (defined as precipitation above the 90th percentile), compared to the rest of the HKH, which showed a more heterogeneous signal of change. Since the 1960s, there have been considerable improvements in the maximum 1-day, 3-day, and 5-day precipitation levels on average across the whole HKH as well as consecutive rainy days in much of the region (Sabin et al., 2020).

2.3 Glaciers

According to numerous studies (Bolch et al., 2019; King et al., 2019; Zemp et al., 2019), glaciers have been widely retreating during the past few decades in the Himalaya and most other mountainous regions of the world. According to Zhang et al. (2015) and Nie et al. (2017), the Himalaya has a total glaciated area of about 22,990 km^2 and more than 4000 glacial lakes. The ten major river systems in Asia, which run from Afghanistan to Myanmar, are supplied with water by the snow and glacier resources of HKM (Gurung et al., 2017; Scott et al., 2019; Vaidya et al., 2019). These river systems are home to significant populations in their downstream basins. However, as in most other mountainous areas globally, the widespread retreat of glaciers has increased over the past few decades in the Himalaya (Bolch et al., 2019; Zemp et al., 2019). According to geography and meteorological factors, Kulkarni & Karyakarte (2014) demonstrated that the Himalayan glaciers can retreat anywhere between a few metres and nearly 61 m every year. A map of over 20,060 km^2 of glaciated land in the Himalayas, scattered across all major climate zones, shows a loss of glacier area of about 13% over the previous 40 years (Kulkarni et al., 2021). According to a three-component hydrograph separation using field-based ablation measurements and oxygen isotope fingerprinting for one of the glacier basins (Sutri Dhaka), the melting of glaciers accounts for between 65 and 80% of the river water input, with snowmelt accounting for between 20 and 35% (Singh et al., 2019). According to Joya et al. (2021), between 1990 and 2015, the Kokcha subbasin of the Himalayas range's glacier cover and glacier count decreased from 576 km^2 and 1007 km^2 to 492 km^2 and 998 km^2 correspondingly, losing 84 km^2 (about 15%) of the entire glaciated area. Similarly, according to Bahugana et al. (2021), over a 17-year period, 3091 glaciers covering an area of 11,451.53 km^2 in the Himalayan region showed a loss of 1.44%, whereas 2143 glacier bodies in the Karakoram region showed a gain of 0.026%. The glacier loss was about 0.76, 2.2, 0.84, 2.16 and 2.15%

in subbasins present in the left of Indus River, Sutlej and Chenab, Ganga basin and Tista sub—basin.

2.4 River Response

In a study by Du et al. (2019), the SWAT model was employed to evaluate the impact of various climate change and land use scenarios on the runoff of the Dagu River, China. According to the findings, runoff was more significantly impacted by climate change than by changes in land use. Floods and other natural calamities are frequently brought on by climate change. In the past thirty years, there has been a rise in the frequency of large-scale flooding in the rivers of the North Western Himalayas. For instance, the upper Indus basin experienced a 100% increase in stream flows during the winter and a 50% rise during the summer (Yaseen et al., 2022). Although winter precipitation did not increase, the boost in winter temperatures allowed for higher stream flows. These conclusions have been supported by a number of studies, including the one by Nazari-Sharabian et al. (2018) in Iran's mountainous Mahabad Dam watershed, which found that urbanisation and climate change were responsible for an early rise in peak runoffs and an increase in runoff and subsequent pollutant load. Similar conclusions were also reached by Nepal (2016), and Shrestha et al. (2017) in their respective research. The presence of excessive sediment loads in rivers as a result of shifting climatic circumstances has also been noted in various research conducted worldwide (Fakhri et al., 2014; Zalaki-Badil et al., 2017). These excessive sediment loads have a negative impact on the health of rivers, disrupting natural river systems and putting additional strain on the planning and design of hydraulic structures, necessitating more protective and design measures (Mir et al., 2018, 2020; Rather et al., 2017, 2022).

3 Observed and Projected Changes

The Himalayan region is experiencing significant climate change impacts, which are observed through various indicators and projections. This section aims to provide a comprehensive overview of the observed and projected changes in the Himalayas. Climate related disasters in Hindu Kush Himalayan regions were frequently increasing over the last three decades compared to Andes, European Alps and Central Asian mountain regions (Froude & Petley, 2018; Stäubli et al., 2018) .

3.1 Observed Changes

According to Dad et al., (2021), temperature over Kashmir Himalaya between 1980 and 2017 increased by 0.035 and 0.022 °C on an annual scale for maximum and minimum temperature, respectively. Moreover, precipitation showed an annual increase of 0.4 mm a^{-1} and revealed a 10% increase of Indian Summer Monsoon (ISM) due to climate variability. Sabin et al. (2020) stated that the anthropogenic climate change increased the annual mean surface-air-temperature at a rate of ~0.1 °C per decade since 1901, while faster rate of warming ~0.2 °C per decade was observed during 1951–2014 in HKH. In addition, higher elevations (> 4000 m) have experienced faster and strong warming of about 0.5 °C per decade. Rafiq et al. (2022) stated that, Himalayan region showed extreme precipitation increase by almost 77.52% per unit of temperature increase in India over the past 113 years, resulting in a wave of disasters. As temperature hikes in the regions of Himalayas, so does the number of disasters such as snow avalanches, flash floods, glacial lake overflows and landslides. Air temperatures are trending upward in the Himalayan region and are consistent with decreasing snowfall. In the Himalayan region, an estimate of 25% reduction in snowfall was associated with an increase in temperatures thereby resulting in 71.24% decrease in snow depth. Dileepkumar et al. (2018) reported that the anthropogenic aerosol emissions are the dominant sources of recent surface temperature increases over Western Himalayan region since the mid-twentieth century. Yu et al. (2017) used climate datasets LSAT-V1.1 and CGP1.0 for studying the long term changes in temperature and precipitation over the HKH region. The results revealed a 0.104, 0.077 and 0.176 °C increase per decade for mean temperature, mean maximum, and minimum temperature respectively between 1901 and 2014; wherein, the highest increase was observed over the Tibetan Plateau (TP) and south of Pakistan. Similarly, annual precipitation showed an increasing trend with a rate of 5.28% per decade during 1961 to 2013. Jaswal and Rao (2010) reported that over the time series 1967–2010, temperature increased from + 0.04 to + 0.05 °C a^{-1} over Jammu and Kashmir Mountain regions (Hock et al., 2019). The observed physical changes and human systems in Himalayan mountain regions over the past decade is presented in Table 1.

Drastic changes in seasonal precipitation pattern alters the timing and availability of water for agricultural activities in Hindu Kush Himalayan regions. Moreover, in many of these regions, demand for water exceeds the supply (Bharti et al., 2020; Sharma et al., 2020a, 2020b). Additionally, springs are prominent source of water in Himalayan mountain region. Studies showed that in recent years, water provision from springs significantly decreased in Himalayan regions, eventually decreasing the groundwater availability, which is caused by multiple causal factors including climate change and human interaction (Suwal et al., 2016). Most of the regions around HKH have shown declining extreme events of glacier retreating and winter snowfall; whereas, parts of Karakoram Himalayas (Higher elevation) exhibited an increased precipitation in winter time Sabin et al., 2020). In addition, localized decline in crop yield have also been observed in HKH regions due to changes in snow cover and glacier retreat (Hock et al., 2019).

Table 1 Observed changes in high Himalayan mountain regions over past decades

Himalayan high mountain regions (Hindu Kush, Karakoram, Hengduan Shan, and Tien Shan)	**Parameters**		**Increase/ Decrease**	**Positive/ Negative impacts**	**Attribution confidence (Cryospheric changes)**
	Physical changes	*Water availability*	Increase and decrease	–	High
		Flood	Increase	–	Low
		Landslide	Increase	–	Low
		Avalanche	Increase	–	Low
	Eco-systems	*Tundra*	–	Positive and negative	High
		Forest	–	Positive and negative	Medium
	Human systems and ecosystem services	*Tourism*	–	Negative	Medium
		Agriculture	–	Negative	Medium
		Infrastructure	–	Negative	High
		Migration	–	Positive	Low
		Cultural services	–	Negative	Medium

Furthermore, increased avalanche activity became more frequent in some slopes of the Western Himalaya over past few decades, which directly correlated with increased frequency of wet-snow events (Ballesteros-Cánovas et al., 2018). Results of the Weather Research and Forecasting (WRF) along with the use of Multi Point Statistics prediction reported that the changes in precipitation (2.87–8.0 mm and 1.45–3.27 mm) and temperature (0.65–1.13 K and 0.51–0.83 K) are a good indicators of climate change, which triggers the occurrence of avalanches (Singhal & Jha, 2022). These extreme climatic events also play a major role in deciding the Himalayan flora and fauna. For example, in the past two decades apple production in Himalayan region reduced by 9.4 tonnes per hectare due to climate change (Das, 2021). Similarly, the reduced Ophiocordyceps (mushroom) productivity (Hopping et al., 2018) and decreased fruit size of Myrica esculenta (Munt et al., 2016; Shah and Tewari, 2016) in Himalayan region have also been reported. Likewise, strong climatic factors have also altered the distribution of sensitive medicinal plants species in Himalayas with few species at risk of extinction. The observed changes in Himalayas is given in Table 2.

Table 2 Observed changes in precipitation and temperature at Himalayas

Location	Event period	Precipitation	Temperature	Reference
upper Indus basin (Pakistan)	1961–2000	Increased	0.07–0.51 °C	Fowler and Archer (2005)
Hindu Kush Himalayan	1901–2014	5.28% ↑	0.077–0.176 °C	Ren et al., (2017)
Western Indian Himalayas	1901–2003	Increased	0.9 °C	Dash et al. (2007)
Kashmir valley, North Western Himalayas	1980–2014	10.3 mm/year ↓	0.05 °C/year	Shafiq et al., (2019a, 2019b)
Indian Himalayan region	1971–2005	Increased (↑)	0.5 °C	Diodato et al. (2012)
Upper Indus Basin	1967–2005	Increased (↑)	0.45 °C	Khattak et al. (2011)
HKH	1951–2014	Increased (↑)	0.5 °C/decade	Sabin et al. (2020)
Kashmir	1980–2017	–	0.022–0.035 °C	Dad et al., (2021)
Bhutan Himalaya	1985–2002	Increased (↑)	0.5 °C	Tshering et al. (2012)
Northern Himalaya Region	1979- 2018	Increased(four decades)	0.56 °C/decade	Han et al. (2021)
Upper Indus Basin, Hindukush-Karakoram-Himalaya	1955–2016	2.74 mm/ decade	0.14 °C/decade	Hussain et al. (2021)
Jhelum basin	1980–2010	4.75–2.4 7% ↓	1.39–2.37 17 °C (t max) and 2.14–4.34 °C (t min)	Ahsan et al. (2023)

↑* -Increased Precipitation ↓-Decreased Precipitation

3.1.1 Future Projections

Compared to the global mean warming rate, HKH regions depicted much higher rate of warming in recent decades (Shrestha et al., 2015; Sabin et al., 2020). With the substantial increase in warming, projected future temperature and precipitation are expected to modify the nature of Himalayan cryosphere (Shrestha & Aryal, 2011). Faster and strong warming over high elevated Himalayan regions exert prolonged impact on climate-dependent activities such as agriculture (Sharma et al., 2019). According to Tyagi et al. (2022), Coordinated Regional Climate Downscaling Experiments in South Asia (CORDEX-SA) based projections showed a decrease in annual precipitation by 5.92% at mid-century (2021–2050; RCP 4.5) and an increase of 5.97% at end of the century (2070–2099) over the Himalayan regions, Uttarakhand.

Projection studies based on several CMIP5 scenarios suggested that warming rate over HKH region projected to 2.6–4.6 °C at the end of twenty-first century and also an increase in annual precipitation was observed over high elevated Karakoram Himalayas (> 4000 m) (Sabin et al., 2020). Similarly, CORDEX projection (multi-RCMs analysis; RCP8.5 scenario) depicted a substantial warming of about 5.4 and 4.9 °C during the winter and summer season, respectively over the whole HKH and its sub hill-regions by the end of twenty-first century (Sanjay et al., 2017a, 2017b).

In Hindu Kush and Himalayan region, future projections of mean annual precipitation denoted a 5 to 20% increase over twenty-first century; while intensity and frequency of extreme events differ along with season (Hock et al., 2019). Correspondingly, across the Himalayan–Tibetan Plateau mountain regions, numerous episodic and intense summer monsoon occurred especially in the easternmost part of the mountain range throughout the twenty-first century. Further, the intensity of extreme precipitation events is projected to intensify during the summer monsoon in Himalayan chain (Palazzi et al., 2013; Sanjay et al., 2017a, 2017b). By the end of twenty-first century, projected precipitation showed a similar pattern in both RCP4.5 and RCP8.5 scenarios (CORDEX and NEX simulations) i.e., increase in the amount of precipitation of ∼16% over the north-eastern regions of HKH (Sanjay et al., 2017a, 2017b; Singh et al., 2017a, 2017b).The High-resolution Regional Climate Model—PRECIS (Providing Regional Climates for Impact Studies) projections indicated that a significant surface warming would be observed over HKH region and 20–40% higher summer monsoon precipitation is expected during 2071–2098 compared to the baseline period (1961–1990) (Kulkarni et al., 2013). Mishra et al. (2023) mentioned that based on the projection using Coordinated Regional Climate Downscaling Experiment-South Asia (CORDEX-SA)—Coupled Model Inter comparison Project Phase 5 (CMIP5) climate data, it was reported that the mean surface temperature would increase by 1.39 to 6.39 °C in the Eastern Himalayan region during the twenty-first century with summertime drying and winter precipitation. Additionally, the Regional Hydro-Ecological Simulation System (RHESSys) predicted that the total streamflow in Nuranang watershed, eastern Himalayan region increased by 1.97% in 2020s; whereas it would decrease by ~0.60 and 3.54% during 2050s and 2080s, respectively.

Romshoo et al. (2022) found that the western Himalayan Drass basin's snow shrinkage and depth decreased due to rising greenhouse gas and black carbon concentrations. The multi-data satellite image from 2000 to 2020 provides proof that 77 glaciers in the Himalayan region exhibited reduced thickness and mass loss. The total area of the glacier cover has decreased by 5.31 ± 0.33 km^2 over the time period (2000–2020). The average thickness change and mass loss for the glaciers are -1.27 ± 0.37 and -1.08 ± 0.31 m of water equivalent per annum respectively. Due to the present snow melting and continuous mass loss of the glaciers, the average glacier velocity has decreased from 21.35 ± 3.3 m a^{-1} in 2000 to 16.68 ± 1.9 m a^{-1} by 2020. Gul et al. (2021) reviewed light-absorbing aerosols of black carbon are deposited on snow or ice, the surface might become darker, which increases the absorption of solar radiation and considerably lowers the surface albedo. As a result, the Himalayan region has atmospheric Black carbon deposition, which has an effect on snow albedo and causes fast melting of snow and ice. In this connection black carbon influence on the cryosphere, which either directly or indirectly affects the local temperature as well as the monsoon and hydrological cycle. At lower elevations of Himalayan range, the snow depth and snow mass are projected to decline between the range of 10 and 40% during the period between past (1986–2005) and future (2031–2050) (Hock et al., 2019). A summary of predicted changes in Himalayan regions are given in Table 3.

4 Impact on Agriculture

Agriculture is one of the domains of human endeavour that has been most negatively impacted by climate change in the Himalayan region (Dahal et al., 2022a, 2022b). Himalayan region's 90% of agriculture are rain-fed, and hence, climate change poses a significant concern due to fluctuations in rainfall pattern. The severity and frequency of droughts and floods may vary, which could influence growing season, crop duration, and soil moisture regime leading to decreased agricultural outputs. Crop damage from landslides, soil erosion, and flooding is more likely to occur with more frequent and intense precipitation. Moreover, increase in soil temperature had led to decrease in soil moisture content. Soil temperatures are influenced by long-term effects of both air temperature and precipitation patterns (Bradford et al., 2019). This in turn increased the requirement of water for irrigation, an upsurge in insect pests and diseases, and weed infestation that results in low crop output or even crop failure. In recent years, The native people of Himalayas indicated that the shift in rainy season and unpredictable rainfall pattern caused a negative impact on their agricultural practises and output (Kc et al., 2022). Nowadays, a lot of people in the Himalayan region had shifted to grow economic crops, especially vegetables, in place of food crops. The initiation of dormancy, bud break, and optimal flowering in apples are susceptible to wintertime temperature and precipitation, particularly snowfall. Dahal et al., (2022a, 2022b) reported that temperature above 26 °C or below 15 °C during the flowering phase limits the apple production. As a result, peach cultivation is becoming more popular among farmers since it is thought to be less susceptible to climatic stressors than apple farming.

As farmers embraced contemporary crop varieties in an effort to improve income from market sales, recent studies have seen a decline in the area planted with traditional crops in the Himalayas and Trans-Himalayas (Sharma & Chauhan, 2013; Sharma et al., 2009a, 2009b). Modern crop varieties, including black pea, horse gram, millet, buckwheat, soybean, amaranthus, barley, sweet potato, potato, and chenopods, have replaced traditional and staple food crops (Lamsal et al., 2017). These traditional crops are highly valued for their nutritional and medicinal properties as well as their commercial worth. Alternately, beans and minor millet can tolerate less fertile soil and drought, they are also seen as compensating for the negative economic effects of globalisation and environmental change (Kc et al., 2022). These commercial crop adoptions can have negative environmental effects, even

Table 3 Predicted changes of climatic events in Himalayas

Location	Event period	Prediction model	Precipitation	Temperature	Reference
Indian Himalayan region	21st century	COordinated Regional Climate Downscaling EXperiment- South Asia (CORDEX-SA) and Regional Climate Model (RCM)	–	0.23–0.52 °C/decade	Dimri et al.(2018)
Kashmir Himalaya	2071–2100	Statistical Downscaling Model (SDSM) and ClimPACT2	2.09–6.61% ↓ (2080s)	0.36–1.48 °C(T_{max}) and 0.65–1.07 °C (T_{min})	Ahsan et al.(2022)
Kashmir Himalaya	2030s, 2060s, and 2090s	Global and regional climate models (GCMs/ RCMs)/Statistical Downscaling Model (SDSM) and Canadian Earth System Model (CanESM2)	-	0.3–2.3 °C (T_{max}) and 0.3–1.9 °C (T_{min})	Shafiq et al.,(2019a, 2019b)
Teesta River basin in Indian Himalayan	1951–2100	General Circulation Models (GCMs)	Precipitation is likely to increase in both monsoon and non-monsoon seasons	1.92 °C (2011–2040) 0.5 °C–1.2 °C (2041–2070), and 2 °C (2071–2100)	Sharma and Goyal (2020)
Himalayas and the Tibetan Plateau	21 century	CMIP5Coupled Model Intercomparison Project Phase 5 (CMIP5)	Precipitation (Karakoram Himalayas) ↑ Snowfall (HKH)↓	2.6–4.6 °C	Sabin et al. (2020)
Tamor River Basin, Eastern Himalayas of Nepal	2030-2080	SWAT model	8.5% ↓	4–5.5 °C	Bhatta et al.(2019)
Gandaki River Basin, Central Himalaya	2015–2100	Coupled Model Intercomparison Project phase 6 (CMIP6)	Precipitation ↑	Tmax $\geq$ 30 °C and Tmin $\geq$ 20 °C	Sigdel et al. (2022)

(continued)

Table 3 (continued)

Location	Event period	Prediction model	Precipitation	Temperature	Reference
Sikkim Himalayas and West Bengal	2021–2060	regional climate models (RCMs) from Coordinated Regional Climate Downscaling Experiment (CORDEX)	Precipitation ↑	Temperature ↑	Biswas and Bhattacharya (2023)
Koshi Basin, Nepal	2020–2100	CMIP5 GCM (RCP 8.5)	33% ↑	1.1 °C	Bajracharya et al. (2023)
Uttarakhand, India	2021–2099	CORDEX-SA (RCP 8.5)	2.83% to 15.89%	0.30 °C to 5.86 °C	Tyagi et al. (2023)

↑* -Increased Precipitation ↓-Decreased Precipitation.

though it might have some short-term financial benefits. The extensive cultivation of contemporary crop varieties, especially industrial potato farming, is also linked to increasing soil loss and run-off (Kc et al., 2022). Therefore, a decline in traditional crops has detrimental effects on both financial and food security in near future.

5 Impact on Water Resources

More than 1 billion population live in the downstream of glacier-fed river basins, like the Ganges, Brahmaputra, Indus, Yellow, Yangtze, Mekong, and Salween, which originate from the Himalayan mountains (Chaudhari et al., 2018). The climate change had impacted the hydrological cycle in most ways by influencing the rainfall pattern. For instance, between 1982 and 2006, the annual mean temperature increased by 1.5 °C while the average annual precipitation hiked by 1.63 mm (Salunke et al., 2023). With the continuous rise in temperature, there has been a considerable fluctuation in precipitation patterns (Banerji & Basu, 2010). In addition, from 2010 to 2019 the rate of water surface warming increased to 0.280 ± 0.068 °C per decade, which is 4.5 times faster than the long-term average (Garcia-Soto et al., 2021). This increase in water temperature could lead to reduction in dissolved oxygen availability, alterations in ice-free periods and thermal mixing patterns in water bodies contributing to anaerobic conditions that culminate in eutrophication.

In comparison to the rest of the world, Himalayan glaciers as a result of "precipitation decline coupled with temperature increase" are currently retreating more rapidly due to warming of the Earth. According to Kranaijenbrink et al. (2017), a 1.5 °C rise in global temperature will warm Asia's high mountains by 2.1 ± 0.1 °C, causing glaciers to melt by 49 ± 7% to 64 ± 5% by the end of the century. Similarly, Li and Xu (2023), also observed that 82% of the glaciers in western China have receded in the second half of the twentieth century. On the Tibetan Plateau, the glacier area has shrunk by 7% over the past 40 years and 4.5% over the past 20 years, indicating a faster retreat rate. High intensity rainfall episodes have been caused by increased temperature over the Tibetan Plateau (Sabin et al., 2020). The entire Himalayas is expected to have high rainfall events on occasion, seasonal fluctuation, and irregular monsoon rainfall (Turner & Annamalai, 2012). Wetlands are extremely susceptible to hydrological changes in terms of water availability, including frequency, duration, and timing, as well as water quantity and quality. The most important and pronounced effects on wetlands in the Himalayan region would be induced by changes in hydrological regimes brought on by glacier melting and changes in precipitation regimes. Additionally, wetlands serve as a source and sink for greenhouse gases, and changes in hydrology have an impact on this equilibrium (Lamsal et al., 2017). Further, climate change would also prompt glacier and permafrost related hazards.

Cloudbursts are difficult to predict in terms of their location and timing in and around the southern rim of the Indian Himalayas. They are primarily linked to flash floods as a result of the heavy rain. Studies are currently witnessing a change in monsoon extremes and cloudbursts as a result of the 1°C increase in global surface temperatures (Gupta et al., 2022a, 2022b). A mid-day cloudburst, multiple episodes of rainfall, and a Glacial Lake Outburst Flood (GLOF) caused a disastrous flood and landslide in the state of Uttarakhand in 2013. A cumulative rainfall of > 300 mm was recorded, which resulted in a flash flood and a landslide (Rawat et al., 2022). Similar to the above, a cloudburst on the Hari Maharaj Parvat caused massive debris flows and flash floods that affected 143 houses in four villages in downstream areas (Sati & Kumar, 2022).

6 Impact on Forests

Climate change, the modern agricultural development, and a number of other anthropogenic stresses are all causes of forest degradation and biodiversity loss. Since climate change is expected to have a greater impact in higher-elevation places, the mountainous forests (Sub-Alpine and Alpine forest, Himalayan Dry Temperate forest, and Himalayan Moist Temperate forest) are more vulnerable to its negative impacts (Upgupta et al., 2015). The habitat of Himalayan pine has been shifting upwards (19 m per decade on the south slope and 14 m per decade on the North Slope), which indicates a high susceptibility to global warming (Gret-Regamey et al., 2019). According to studies, the presence of oak woods is associated with higher water quality and abundance in the Himalayan region, while pine forests are associated with lower water holding capacity (Dhamala et al., 2020). Depletion of water resources can also be linked to different forest distribution patterns as well as retreating glacier cover, illuminating the complex relationship between hydrology and climate in the Himalayan region that influences the phenology and growth of numerous species. In eastern and central Nepal, Chhetri and Cairns (2015) documented an upslope migration of the alpine tree Abies spectabilis by 0.17 and 2.6 m each year respectively. Meanwhile, Lamsal et al. (2017) documented the upslope migration of Juniperus indica, Betula utilis, Rhododendron sp., Alnus nepalensis, and Berberies sp., in the western and central sub-alpine middle mountains of Nepal in addition to Abies sp. In India's Arunachal State, a similar Abies sp. migration phenomenon has also been documented (Qamer et al., 2016). Since most species are thought to shift their distribution upwards by 300 m for every 1 °C increase in temperature, an increase in temperature in mountainous areas may cause the snowline and the biota it supports to shift upward (Lamsal et al., 2017). According to Forrest et al. (2012), tree line shift by 2050 will cause a 40% decrease in the snow leopard's habitat in Nepal, which is expected to be taken by other species including the Asiatic wild dog and common leopard. The Range shift and the invasion of non-territorial species may have an impact on predator–prey interactions and disrupt the balance of such delicate high-altitude ecosystems.

Indian flora consists of about 40% of alien plant species, of which 25% are invasive in nature (Sharma et al., 2005). The Himalayan region alone consists of 190 invasive species from throughout the region (Chandra Sekar et al., 2012). The invasion by exotic invasive plants due to warming trend in the Himalayan forests could be vulnerable to the restricted habitat fauna. For instance, according to Alamgir et al. (2015), climate change and its associated problems, such as forest fragmentation, would cause a significant decline in Asian elephant habitat range in Bangladesh by the year 2070. Similarly, Ursus arctos, Mustela altaica, and Bos mutus in the alpine and sub-alpine forests of middle mountains, and Ursus thibetanus and Neofelis nebulosa in the mid temperate forests, are examples of restricted fauna that may be susceptible to climate change (Lamsal et al., 2017). Besides, forest habitats are being invaded by invasive plants like Argertum conyzoides, Senna tora, Argemone mexicana, Erigeron karvinskianus, Ageratina adenophora, Ageratum houstonianum, Anthemis cotula, Cassia tora, Amaranthus spinosus, and Rubus niveus (Thapa et al., 2018; Gupta et al., 2021).

7 Impact on Biodiversity

The Himalayan region is home to 330 vital biodiversity areas, 60 eco-regions, and 4 biodiversity hotspots. This area is known as the “global biodiversity hotspot” and is a significant origin to some the of largest river systems in Asia (Kotru et al., 2020). Although it can be difficult to differentiate between anthropogenic and natural effects of climate change on biodiversity, variations in migration patterns, abundance, severity and frequency of the outbreak of pest and diseases have become crucial implications for loss in biological diversity in the Himalayan region. With a shift in the growing season of grasses and vegetation, climate warming has impacted the functional and phenological features, as well as the fitness or ability of plants to produce ecosystem services (Kattel, 2022). The resilience and biodiversity of native ecosystems, primarily scrublands and meadows, have been severely threatened by the rapid expansion of invasive alien plant species in Nepal and the Indian Himalaya. These species include Ageratum houstonianum, Ageratum conyzoides L., Ageratina Adenophora L., Erigeron karvinskianus, Bidens pilosa L., Amaranthus spinosus L. Niche model-based studies from the Himalaya anticipated an upslope range shift of alpine specialists, including Snow Leopards, and Blue Sheep, taking into account the predictions. The current warming should lead to an upward increase in the habitable areas of highland shrubs, with their steady spread replacing herbaceous ecosystems in the eastern Himalaya, according to species distribution models (Manish et al., 2016).

Biodiversity loss due to climate change may have a significant impact on how well an ecosystem’ functions. The Himalayas have historically provided pastoral people with important ecosystem services like water storage, carbon sequestration, food security, and biodiversity preservation. For instance, the Sikkim Himalaya alone is home to 10% of all alpine genera and 60% of all alpine plant families worldwide (Ingty, 2021). Similar to this, the oak forests in the Bhutan have become important to produce socio-cultural ecosystem services when managed under agriculture, community-based forestry, and a combination of shrub land and forests (Dorji et al., 2019). However, a decline in habitats and biodiversity has led to a major loss of ecosystem services in the Himalayas. The decrease in the value of carbon storage, greenhouse gas sequestration, nature-based recreation and water quality by 60, 74, 94 and 88%, respectively, was observed in the Shivapuri-Nagarjun National Park of Nepal over the most recent decade (Peh et al., 2016).

8 Impact on Mountain Tourism

Travelling to undisturbed ecosystems with the intention of enjoying in the natural surroundings is referred to as nature-based tourism, which is a significant and expanding subset of tourism. Through a variety of activities, such as hiking, bicycling, and snow sports, mountain tourism has the advantage of drawing in a variety of tourists throughout the year (Romeo et al., 2021). It's interesting to note that the distinctive characteristics of high mountain regions—such as nature, wildness, topography, remoteness, and climate conditions are also what draw tourists to these areas. However, because mountain tourism infrastructure and activities depend on the alpine temperature, topography, beauty, and seasonal cycles, climate change is already having an influence on and will continue to have an impact on present-day and future mountain tourism development (Palomo, 2017; Steiger et al., 2022). Examples of climate induced effect on mountain destinations in give in Table 4.

Table 4 Examples of climate-induced effects on mountain destinations

Types of impacts	Geographical region	Tourism implications
Long—term glacier melt and retreat	Himachal, Uttaranchal and Sikkim Himalaya in India Khumbu and Langtang regions in Nepal	Exposure to natural hazard due to glacial lake outburst and flooding (GLOF) Visually less appealing destination
Seasonal wet weather	Throughout High Himalaya	Higher altitudes necessitate more fuel wood Periods of heavy snowfall can cause avalanches that result in loss of life, property, and damage to nearby roads and routes
Seasonal dry weather	Mountains in Western Nepal, Southwest China	Loss of agricultural productivity has an impact on the connections between tourism and agricultural outputs Exposure to fire hazard Threats to threatened species have an impact on wildlife-based tourism

Climate change might affect not only the number of tourists but also the time of year of their visits. High-elevation trekking in Bhutan, for example, might expand from spring and autumn to include winter due to higher temperatures, but greater precipitation might shorten the spring and autumn tourist seasons (Hoy et al., 2016). The Indian Himalayan Region (IHR), attracts millions of tourists and provides multiple ecosystem services. Yet, the progress and contribution of IHR in mountain-tourism remains relatively unknown due to a lack of integrated approaches. The findings show that uneven, centralized and unrestricted tourism development has already interrupted the human environmental balance in Western-IHR (Chakraborty & Ghosal, 2022). Globally, between 2004 and 2017, there were 5318 non-seismic landslides, of which 3285 were precipitation-related. In the Indian Himalayas, there were 580 landslides during that time, of which 477 were precipitation-related, accounting for 14.52% of all landslides (Dikshit et al., 2020). These events have reduced the tourism in Himalayan regions.

9 Impact on Human Health

By fostering conditions that are favourable for forest fires, disease vectors, heavy snowfalls, avalanches, floods, major storms, and droughts, as well as changes in sunlight availability and cloud cover, climate change-related effects on mountain ecosystems may have an adverse effect on population health. Extreme precipitation brought on by climate change contaminates water sources, disrupts power, closes health facilities, and ruins roads, all of which have an impact on public health. The biological, chemical, or physical stressors that can be exposed to climate-related risks vary in time, location, population, and severity. These are referred to as exposure pathways and are discussed as follows.

9.1 Infectious Diseases

According to the IPCC (2014), and Bongaarts (2019), climate change is a factor in the emergence of infectious diseases since it forces the migration of people and animals, who harbours vectors and hosts of many diseases. In general, it has been observed that that a rise in temperature increases the epidemic potential of vector-based diseases in Himalayas. In the Himalayan region, higher rainfall may also have an impact on the rate of disease vector reproduction. The ability of microbes to quickly expand their host range and colonise new hosts is also made possible by climate change (Brooks et al., 2019). Climate change has been linked to the increased spatial distribution and incidence of dengue and chikungunya during the past few decades in the Himalayan region. Climate change has been associated to an increase in the number of confirmed cases of Japanese encephalitis in the Himalayan highlands, which were formerly limited to the lower southern plains (Dhimal et al., 2021). In addition to encephalitis, other mosquito-borne illnesses like dengue, chikungunya, and, malaria thrive in the hot, humid southern lowlands (Acharya et al., 2018). A survey conducted in the higher altitutes of eastern and central Nepal also found the occurrence of various vectors like dengue and lymphatic filariasis vectors Aedes albopictus andAedes aegypti, the Japanese encephalitis vector Culex tritrinorinchoes, the malaria vectors A. maculatus, A. annularis and Anopheles fluviatilis, complex, as well as the vector of Japanese encephalitis (Dhimal et al., 2021).

A growing body of research indicates that climate variability in terms of temperature, humidity, and rainfall, as well as recurring events like El Nino and disasters owing to climate change like floods, have a significant impact on the transmission of food—and water -borne diseases (Liu et al., 2017). In South Asia, including the nations in the Himalayan region, children living in rural highlands have a higher death rate and a greater prevalence of childhood diarrhoea (Reiner et al., 2020). For instance, Wangdi and Clements (2017) examined state—wise datasets on diarrheal cases in Bhutan over the course of a decade and found that the chance of developing diarrhoea increased by 0.6 and 5% for every increase in maximum temperature of 1 °C and every increase in rainfall of 1 mm, respectively.

9.2 Mental Health and Non—Communicable Diseases (NCDs)

According to Cianconi et al. (2020), the incidence of NCDs such as malnutrition, injuries, and mental illness will increase due to climate change. According to studies, being exposed to extreme cold or hot temperatures, increases the risk of cardiopulmonary death (Alahmad et al., 2023). For pulmonary disease, the underlying physiological process could be directly linked to elevated blood pressure, viscosity, and heart rate (Meng et al., 2021). Increased temperatures reduce agricultural output in the less developed tropical regions, which in turn could increase the risk of NCD.

Mountain populations are also susceptible to mental health problems brought on by climate change, which are exacerbated by natural disasters like drought (Cianconi et al., 2020). Many people who are exposed to climate- or weather-related natural disasters are said to experience stress and psychological disturbance due to the loss of a family members, social networks, resources, or wide relocation, and they may also experience depression, post-traumatic stress disorder (PTSD), increased substance use, general anxiety, and suicidal thoughts. There are few researches on how climate change affects the mental health in the Himalayan region, but the information that does exist shows how severely it affects the health and well-being of the communities there, making it urgently necessary to pay attention to the problem (Dhimal et al., 2021).

9.3 Water and Food Insecurity

According to Rasul et al. (2018), the region's most important contributing reasons to food and nutrition insecurity are climate change and a decline in agro-ecological environment. Unprecedented climate change, including rising temperatures, fluctuating precipitation patterns from year to year, and frequent floods, along with other factors like commercialization of agriculturally productive lands and deforestation, are negatively affecting agriculture and food security in the Himalayan region (Hussain et al., 2016). In the Himalayan region, ground water extraction is being done to deal with the unpredictability of surface water availability in expectation of rising energy demand and significant losses to groundwater resources (Rasul & Sharma, 2016). Western and far-western Himalayan regions of Nepal, Baluchistan Province in Pakistan, Chin State in Myanmar, Afghanistan, and Meghalaya State in India all have high rates of food and nutritional insecurity (Kc et al., 2022). For the native Himalayan populations, decreased food production and farm revenue have resulted from climate-induced changes such as droughts, floods, livestock diseases, landslides, and increasing biological invasions such as crop pests (Shrestha & Shrestha, 2019). Due to increased occurrence of natural disasters, physical barriers to infrastructure, agricultural productivity, high transportation costs, and restricted access to food markets, the state of food security in the Himalayan region is unreliable, particularly in remote mountain areas (Bocchiola et al., 2019).

Malnutrition and food insecurity in the Himalayan region are also made worse by decreased agricultural output brought on by climate change. According to Rasul et al. (2019), the causes of malnutrition and food security are different in the highlands and the plains. Due to decreased water availability for rangeland production andagriculture, drought has an impact on people's quality of life in the Himalayan region. Inadequate health care systems, a lack of access to clean drinking water, inadequate sanitation, contaminated food, a lack of knowledge of nutrition at the household level, and the inability to empower women are a few of the numerous issues that make food security and nutrition in the Himalayan region worse (Rasul et al., 2019). The problems with food security that already exist have been made worse by climate change.

10 Economic Implications

The socio-economic system of the people residing in the Himalayan region has been disrupted due to climate change. The economic activities in this region, such as agriculture, cattle rearing, trade, tourism, and fisheries, have been adversely affected, leading to harmful effects on human health and natural resources. The loss of biodiversity caused by climate change is particularly impacting the poor and deprived sections of society who heavily rely on natural resources for their livelihood. Furthermore, climate change is affecting the agricultural sector, resulting in a reduction in the production of cash crops like rice, maize, and barley. The presence of offensive insect species in the fields is increasing, causing further harm to crop production. The diminished production of fodder seedlings has led to a decrease in income from cattle rearing and related jobs. Moreover, the change in the flowering time of crops like Saal, Amla, and Maize has forced many people to abandon farming as their livelihood and seek alternative means of earning (Srivastava, 2022).

The decline in agricultural crop production due to climate change has resulted in a significant problem of food shortage, leading to diseases and malnutrition among the population. Additionally, climate change has increased the threat of vector-borne diseases, including malaria, bortonalasis, and tick-borne diseases, in the Himalayan region. With the rise in surface temperature and changes in rainfall patterns, there has been a shift in the dispersal of mosquitoes and vector species, affecting even higher altitude areas. This temperature rise has created a favorable environment for malaria-carrying protozoans, resulting in a higher mosquito population. Furthermore, there have been reports of increased cases of problems related to menstruation and vaginal infections in women, as well as skin and eye problems in children, which can be attributed to climate change (Srivastava, 2022).

The significance of Himalayan forests in the well—being of native communities has led to several studies evaluating the goods and services provided by these forests. The relationship between the native people and forests plays a significant role in balancing the ecology and economy of the Himalayas (Chakraborty et al., 2018). However, with the predicted influence of climate change, ensuring a constant supply of ecosystem services for communities in the mountainous region becomes a difficult task (Joshi & Joshi, 2019). Climate change not only directly and indirectly affects forests but also impacts the local population relying on forest-based resources, as well as pastoral and agrarian communities (Negi et al., 2022).

Forest self- sufficiency is a metric that describes how well a household meets its food needs through crop yield (Hanna et al., 2017). Shukla et al. (2018) reported that climate change has significantly reduced the crop yield and productivity, which in turn dwindled the household self—sufficiency of the farmers in Himalayan region. Additionally, the study has also reported that the annual expenditure of water increased with climate change since expenses were incurred in purchasing higher quantity of agricultural inputs and in maintaining the livestock health. Furthermore, studies have indicated that climate change posed a substantial negative impact on livestock production thereby affecting the economic status of the farmers (Koirala & Shrestha, 2017). Predicted changes in forest distribution patterns due to climate change would invariably alter the benefits derived from forests (Kattel, 2022). However, empirical studies quantifying the changes in ecosystem services specifically focusing the climate change impacts on Himalayan forests are lacking. The quantification of goods and services varies based on region-specific species composition and forest management practices. More research efforts are required to assess the long-term changes in forest goods and services to address the knowledge gap (Devi et al., 2023). The overall impact of climate change is summarized in Fig. 1.

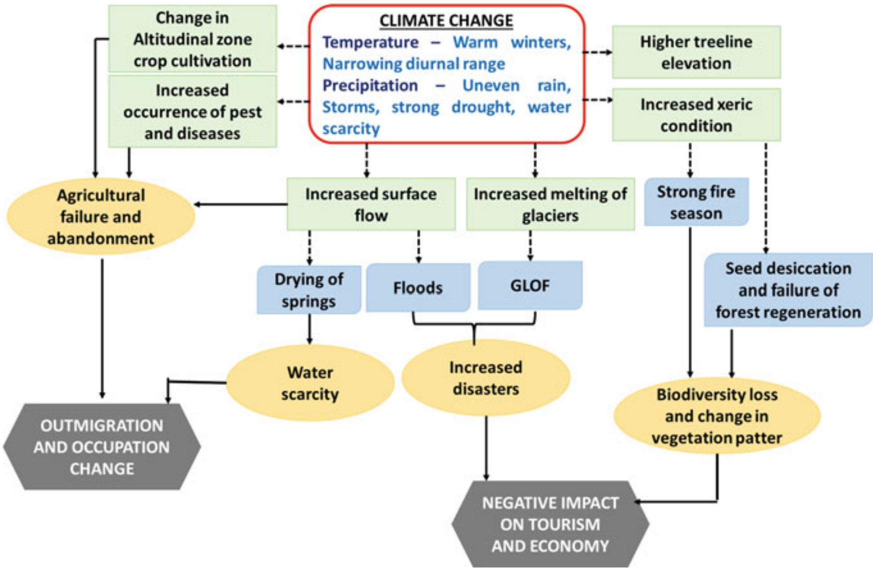

Fig. 1 Impact on climate change in Himalayan region

11 Adaptation and Mitigation Measures

While climate change serves as a natural driving force, other factors such as population migration, urbanization, economic growth, and globalization also contribute to rapid socioeconomic transformations in the HKH region. These transformations often introduce conditions of uncertainty due to the complicated interactions among these driving forces. In order to plan for and take action on adaptation in the face of large-scale and uncertain changes, the HKH countries must move beyond incremental strategies and embrace adaptation and transformative development. An urgent example of transformative change needed in the HKH is empowering mountain women, who are often left behind due to out-migration of male population, to transition from being "frontline victims" to becoming "risk and resource managers" (Mishra, 2017). Meeting this capacity requirement for policymakers in the HKH will only be possible when political leaders push for intensified adaptation responses within a broader framework of transformative development.

According to UNFCCC documents submitted by HKH countries (National Adaptation Programmes for Action (NAPA)), adaptation priorities commonly focus on agriculture, forests, water, health, biodiversity, and disaster management. Mountain-specific adaptation concerns have received varying degrees of emphasis in country priorities. For instance, in Bhutan, a mountainous country, all NAPA priorities address mountain specific climate risks and vulnerabilities. Strengthening early warning systems for floods and glacial lake outburst floods (GLOF) risk reduction is identified as requiring a higher density of stations due to micro variation in topography and climates in the mountainous environment. Nepal's NAPA and Local Adaptation Plans of Action (LAPA) specifically recognize the risks and vulnerabilities of fragile mountain ecosystems, prioritizing adaptation interventions in rain shadow regions of far- and mid—western regions. Another mountain specific policy response is India's National Mission for Sustaining the Himalayan Ecosystem, which is part of the country's National Action Plan on Climate Change (NAPCC). This mission, with a geographical focus, aims to increase forest cover, conserve biodiversity, and other ecological values in the Himalayas by evaluating the region's susceptibility to climate change in a scientific perspective. Below are a few examples of adaptation measures implemented in various sectors.

11.1 Agriculture

There are several evidences regarding the adoption of several autonomous strategies towards climate change adaptation by the farmers. For instance, Paudel et al., (2020) observed that owing to climate change, farmers in Himalayan region employ various adaptive measures like intensifying the use of pesticides, crop rotation, crop diversification, short—labor migration and even changing their occupation. Besides, subsidies like loan, provisions of irrigation systems can also aid the farmers to adapt climate change. In addition, a study by Bhattarai et al. (2021) suggested an ecosystem-based adaptation approach (EbA) that utilizes ecosystem services to reduce human vulnerability to climate change by improving adaptation. Furthermore, nature-based solutions (NbS) and natural climate solutions are the other possibilities for mitigating vulnerability to climate change (Chausson et al., 2020; Keith et al., 2021). These solutions involve protecting, conserving, managing, enhancing, restoring, and imitating natural ecosystems (Mishra et al., 2019; Osaka et al., 2021). Various retrospective and prospective adaptation measures in agricultural sector is given in Table 5. Besides, other examples towards climate change adaptation is listed below.

- In China, farmers facing drought conditions are selecting crops that can adapt to stress, and provide better economic returns. Additionally, farmers are willing to invest in irrigation infrastructure and adopt water-saving technologies to mitigate the risk of water scarcity and climate change impact (Wang et al., 2010).
- In the Uttarakhand hills of, India, farmers respond to variations in rainfall patterns by cultivating to less water intensive crops and diversifying their livelihood sources. Similarly, farmers in Sikkim have introduced crops like maize, cabbage, pumpkin, and carrot, which were previously unsuitable for high altitude cultivation (Ingty & Bawa, 2012).

    o In Rupan Valleys of Himalayas, cultivation dominant crops like wheat and barley declined; whereas, cultivation of cash crops like potatoes significantly increased (Nüsser & Schmidt, 2017).

Table 5 Various retrospective and prospective adaptation measures in agricultural sector

Climate risk	Retrospective adaptation	Prospective adaptation
Increasing temperature	Changing the cropping pattern Introducing new crops	Adoption of crop mulching Terrace wall farming Integrating legumes with maize Community—managed drinking water systems
Rainfall and floods	Changing the time and method of planting Migrating to safe places	Raised seedbeds Cultivating flood—tolerant crops Fencing orchards, land Planting deep—rooted grass along the contours
Drought	Direct seeding Collecting wild edible foods Building local institutional structures	Dry seedbeds Cultivating drought—tolerant crops and mixing with high yielding varieties Varying the date of sowing in different plots
Biophysical damage	Bamboo fencing Migration and occupation change	Adoption of shifting cultivation

- In Nepal, farmers commonly practice mixing several varieties of maize and beans seeds as an option to mitigate risk. This approach ensures that at least some genotypes can withstand environmental stresses and extreme events. The sowing dates are also being modified to prevent the water shortage during critical growth stage (Piya et al., 2012). Furthermore, local communities have developed various agroforestry practices to address frequent landslides, droughts, and soil erosion. They have also built low-cost bamboo fence to safeguard themselves from recurring floods (Paudel et al., 2020).
- In the mountain areas of Myanmar, farmers commonly practice traditional rotating fallow systems or shifting cultivation. Irrigated and terrace farming using water from natural springs are also autonomous adaptations employed by hill tribes in Northern Shan (Thet & Tokuchi, 2021).
- In Pakistan, farmers have been adjusting their cropping calendar and sometimes changing crop varieties in response to increased uncertainty in rainfall patterns. Field level studies in districts of Southern Punjab and Sindh have documented this practice and provided policy recommendations (Abbas et al., 2021).

11.2 Livestock/Pastoral

In terms of livestock management, farmers reduced the size of their herds, occasionally switching from cattle to less expensive goats due to a lack of pasture. Because there were fewer cattle, the burden on humans and their health rose because animal power to plough fields was no longer accessible. Even when cattle were kept, milk yield decreased because people had to feed them dry grass and leaf litter instead of green grass. The scarcity of fodder also hampered traditional pastoralists, who began shifting their herds to higher altitudes in search of healthier pastures (Uprety et al., 2017). The variety of these adaptations, as well as their widespread adoption in the region, illustrates the increasing difficulty that people face in sustaining agricultural or subsistence-based livelihoods (Kuruppath & Tamma, 2022).

- In Nepal, pastoral communities have employed various proactive and reactive adaptation strategies to cope with climate change impacts. These include changing grazing areas and transhuman routes, reducing the duration of stay at points along the route during unfavorable stall-feeding animals, biophysical conditions, growing forage and fodder, feeding livestock crop stubbles, reducing herd size, and hay during dry periods, preserving native breeds adapted to ecological stresses, digging ponds for water storage, and even relocating houses, animal sheds, or entire villages in response to ecological risks (Aryal et al., 2014).
- In the Inner Mongolia region of China, the privatization of land and rigid land tenure systems have undermined traditional practices of herd and pasture management, reducing the resilience of pastoralists to climatic abnormalities like drought. The shift away from common property regimes, which allowed for greater mobility and mutual aid, has negatively impacted the ecology of natural grasslands (Nori, 2019).
- In Sikkim, pastoralists have adapted to changes in rainfall and snowfall patterns by substituting sheep with yak and implementing collective bans on the slaughter of sheep (Luxom et al., 2022).

11.3 Water Resources

- In the hills of Nepal, communities have taken initiatives to address water scarcity during dry seasons by constructing community managed water tanks fed by natural springs. However, with the drying up of springs, the sustainability of this practice is at risk, and alternative solutions may not be readily available to the affected communities (Piya et al., 2013).
- In northern areas of Pakistan, where water supply relies on glaciers and slope side channels, local communities have adopted the practice of artificial glacier grafting to create new glaciers as a response to water scarcity (Cao et al., 2013).
- Bhutan is experiencing the significant impact of climate change on water resources, with reports of drying water sources in various parts of the country. Small-scale farmers in Punakha Valley are adapting to insufficient water for irrigation from traditional sources by resorting to river pumping (Tariq et al., 2021).
- In Rupan Valleys of Himalayas and the upper Hunza Valley of Western Karakoram, gravity—dependent and meltwater diversion channels have been constructed enabling the farmers to cope with channel destruction and water scarcity owing to

natural hazards. Other local strategies to mitigate water scarcity includes regular excavation to align the intakes and channels to complete restructuring the irrigation systems in response to constant changes in glacier surface, tongues and supraglacial lakes (Nüsser et al., 2019).

- In Igoo catchment of the Trans—Himalayan region, Ladakh, various ice reservoirs called the 'artificial glaciers' have been introduced in different catchment areas to cope with climate change. The classical type consists of a cascading series of rock walls in the river beds to reduce runoff velocity and to facilitate the process of icing under conditions of frequent freeze–thaw cycles (Nüsser et al., 2019).

11.4 Forests

- In Nepal, a community forestry program has been implemented to engage communities in the sustainable management of forest resources. This initiative has led communities to adopt various practices aimed at ensuring the long term sustainability of forest ecosystems and deriving benefits from them, particularly during periods of agricultural failures and droughts (Dahal & Cao, 2017).
- With increased productivity, multiple cropping is yet another adaptation practices followed in many Himalayan region which increases the income of farmers thereby contributing to agrobiodiversity (Aase et al., 2019).

11.5 Disasters

- In Nepal, prolonged and recurring droughts in recent years have resulted in extensive abandonment of land and significant reductions in crop yields in various districts across the country. People have resorted to relocating to neighbouring urban centres as a result. Labour migration has emerged as a popular method for diversifying livelihoods and guaranteeing income streams that are immune to bad local conditions and shocks (Moktan et al., 2008).
- Indigenous communities in Sikkim are adapting to unpredictable rainfall patterns and unexpected landslides and floods by leveraging local ecological knowledge and traditional practices. These includes the terracing, construction of riverbank retaining walls, and using rocks and native plants to stabilize slopes (Ingty & Bawa, 2012).
- For successful monitoring, a reliable and scientific seismic hazard analysis are required. Several models have been developed to anticipate seismic activity rates. Ramkrishnan et al. (2021) established a prediction equation that predicted PGA more correctly than prior studies.
- Various stochastic methods, such as Autoregressive moving average, Autoregressive Integrated Moving Average and Seasonal autoregressive integrated moving average (Parvaze et al., 2021; Valipour et al., 2013), have been widely used

for forecasting temperature, rainfall, hydrological time series and water level. These models must include crucial characteristics such as snowmelt modelling, precipitation generation mechanisms, flood routing and catchment runoff. Satellite photography have revealed the presence of glacial lake outburst floods. These measures would aid in providing an early warning system before the onset of any natural disasters (Ramya et al., 2023).

11.6 Urban Settlements

- Recent studies indicate that even the urban poor, such as those living in slum areas, are well aware of the climate change impact and are willing to take actions to mitigate its impacts. A case in point comes from beyond the HKH area, specifically in El Salvador, where residents of 15 slum areas prone to disasters have made significant investments in various strategies aimed at reducing risks, self-insurance, and facilitating recovery, despite the considerable costs involved. Similarly, wealthier households in cities like Pakistan, Vietnam and India which are closer to the HKH region, have been reported to invest in housing upgrades as adaptation measures against floods, heatwaves, and typhoons, respectively. This demonstrates that individuals across different socio-economic backgrounds recognize the importance of adapting to climate change and are taking action accordingly (Olokeogun and Kumar, 2020; Joshi, 2021).

11.7 Diversification of Livelihood

With reduced profit in herding and farming, people have started earning through selling small livestock herds, eggs, milk, fishing and hunting (Pandit et al., 2016; Singh et al., 2017a, 2017b; Sujakhu et al., 2016). Marketing non-timber forest products, shifting to tourist business, harvesting forest foods, manufacturing weaving, handicrafts and ethnomedicines, masonry, and carpentry were all examples of off-farm labour (Singh et al., 2017a, 2017b). People also quit traditional locations to work in hotels, as daily wage workers, or to relocate to metropolitan areas in quest of more profitable job (Chhogyel et al., 2020; Paudel et al., 2020). Out-migration was a common occurrence in the area, notably in Nepal, where a fifth of the overall population migrated to other cities. While it was caused by a complex combination of variables, the negative impact of climate change on crop quality and quantity was a significant component, as agriculture became less productive and hence less profitable. As a result of migration in quest of better jobs, arable land was abandoned, resulting in a further considerable decline in livestock and agricultural productivity across Nepal and Uttarakhand (Pandey, 2021).

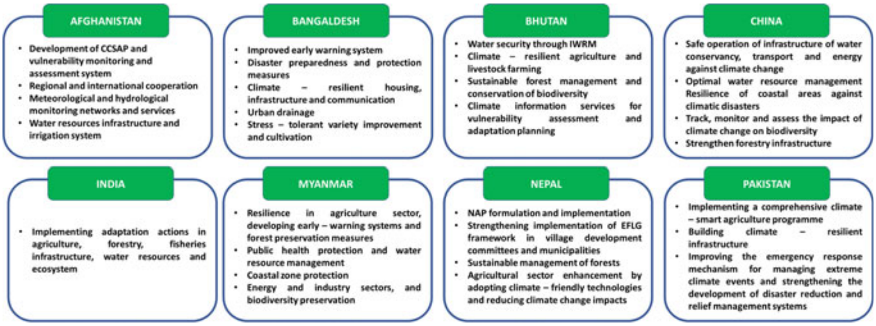

Fig. 2 Various adaptation responses at national and subnational levels towards climate change management in Himalayan regions

In addition to the aforementioned strategies, the HKH countries have implemented a range of adaptation responses at subnational and national levels through policies, programs, and projects. Other adaptative strategies should include the values of traditional knowledge, inclusion of gender—specific policies and integration of customary practices. These initiatives cover various areas, with a majority of them focusing on climate-resilient agriculture, watershed management, better access for disaster risk reduction (DRR) and decision making (Das & Mishra, 2022).

The decentralisation of access to adaptation funds by province and municipal governments is another significant feature of adaptation in the HKH area. This allows for greater local decision-making and application of adaptation measures. India and Bangladesh have established statutory funding mechanisms to facilitate the flow of adaptation finance to the local levels of governance. Similarly, countries like Bangladesh, Bhutan, and Nepal have access to international sources of adaptation funding. Besides, the HKH countries at present have several adaptation responses at subnational and national levels through projects, policies, and programmes (Fig. 2).

However, there is a need for sturdier integration of adaptation efforts with national development plans and programs, including Sustainable Development Goals (SDGs). It is crucial for political leadership to prioritize and intensify the adaptation response within the broader development framework. Additionally, enhancing regional collaboration and substantially increasing adaptation finance are essential. This includes mobilizing funds for risk insurance and social protection to provide greater resilience to climate change impacts. The involvement of the private sector in resilience and adaptation efforts is also critical for effective action. Overall, these measures highlight the commitment of the HKH countries to address climate change impacts and build adaptive capacity, but continued efforts and collaboration are necessary to strengthen adaptation responses and ensure sustainable development in the region. Various policies adopted in different countries towards climate resilience in Himalayan regions is given in Fig. 3.

The various statutory funding mechanisms for the financially supporting the local governance in India and Bangladesh is given in Fig. 4.

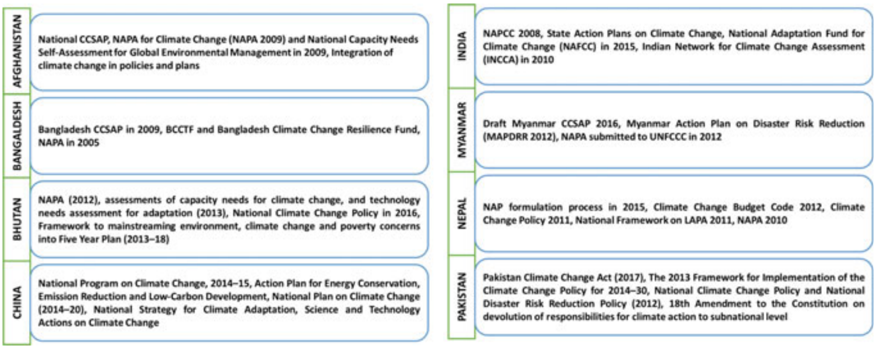

Fig. 3 Various policies adopted in different countries towards climate resilience in Himalayan regions

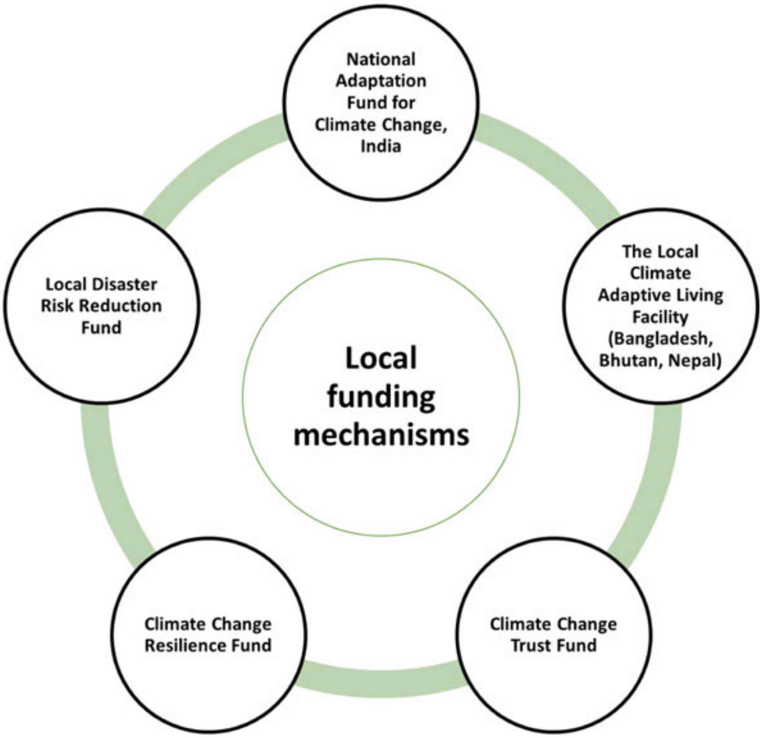

Fig. 4 Various funding mechanisms in Bangladesh and India

12 Conclusion

During the twenty-first century, the broader Himalayan area is predicted to be more sensitive to climate change. The expected changes in temperature and precipitation, as well as their impact on the surface hydrology and cryosphere, would vary regionally due to its huge area, complicated terrain and elevation gradients, and diverse interactions with multiple large-scale air circulations. The increased temperature will typically increase precipitation events and the rainfall-to-snowfall ratio, decrease glacial mass, and have an impact on agriculture, water resources, biodiversity, tourism, the economy, and human health. Most of the local people's adaption tactics are essentially transitory, and the region's climatic fluctuation will ultimately harm the huge population directly or indirectly. As a result, evidences on long-term climate change based on observational records and tree-ring proxies would be valuable for improving knowledge of climate variability over a much greater region and assisting in the development of sustainable forest and water management plans.

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Anthropogenic Impacts in the Himalayas and the Sustainable Development Goals (SDGs)

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Abstract The world leaders and policy makers globally agree on fighting against to the climate change for sustainability of living conditions for people. The rapid continuation of climate change is mostly a result of human activities nowadays. In other words, anthropogenic impacts on climate change have become a common issue for both academic, scientific and political platforms. Therefore, the era we live in has also left its mark as the Anthropogenic era. The Himalayan Mountains, where glaciers are located, contain forty percent of the world's fresh water. With this aspect, considering various different environmental riches, the sustainability goals of this field, which is among the main backbones of the world's ecological sustainability, is a critical research topic. In this context, it is vital to make future predictions by looking at the relationships between Sustainable Development Goals and anthropogenic effects and the Himalayas. The main aim of the study is to explore the relationships between the effects of climate change and human activities in the Himalayas under the 2030 Sustainable Development Goals. In this study, it is planned to present a conceptual perspective by interpreting economic, ecological and social indicators with the help of some global statistical data.

Keywords Sustainable development goals (SDGs) · Anthropogenic impacts · Ecological indicators

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1 Introduction

Climate change is a natural phenomenon that has occurred in various periods of the world. However, today's climate change and accelerating global warming, which is the result of anthropogenic effects, has caused some sudden separation in the world. "Anthropogenic features such as urbanization, roads, and power lines, are increased by rapidly growing human populations" (Leu et al., 2008). The human factor, which affects the environment and climate, also creates a multiplier effect with the world demography and population growth. Along with population increases, technological development, environmental pollution and the problems of directing large volumes of capital accumulation to investments are the factors that trigger the human impact on global climate change (İslamoğlu & Akkuzu, 2023).

The concept of Anthropocene has emerged as a result of the combination of the Greek origins of "human" and "new" concepts. Also, scientific roots come from anthropology, which describes the human history (Usher, 2016). "Considered as a category and concept, the term inspires fear, revelations, skepticism, and all manner of predictions and projects" (Moore, 2015). The effects of human impacts on climate change vary from environmental pollution to excessive consumption of natural resources and energy usage. It certain that we must stop seeing anthropogenic release of CO2 as something detached from future energy supply questions (Höök, & Tang, 2013). "The effects of anthropogenic emissions can now be discerned not only globally, but also at more regional and local scales for a variety of natural and human systems" (Hansen et al., 2016).

The Anthropocene, which was first conceptually defined by the Russian scientist Aleksei Pavlov in the 1920s, the environmental problems that increased exponentially after the second world war, the colonization of the world and the dramatic changes in the human–environment interface brought about by the rise of capitalism, including the age of fossil fuels, made this age more threatening to life on earth than in other periods (Foster, 2016). According to Lewis and Maslin (2015) the year of beginning of this era is 1964. "The key advantage of selecting 1964 as the base of a new Anthropocene Epoch is the sheer variety of human impacts recorded during the Great Acceleration almost all stratigraphic records today, and over recent decades, have some marker of human activity" (Lewis & Maslin, 2015). The most important feature of this age is that climate change occurs faster than expected time estimates in the world. Instead of taking urgent measures to environmental problems, human impacts take superficial measures with greenwashing approaches (Yildirim, 2023; Yıldırım & Kantarcı, 2022), causing irreversible environmental problems. At this point, the sustainability discourse is also a phenomenon that is both supported by its solution-generating aspect and criticized by environmental activists and academics as a global dimension of greenwashing. Taking these criticisms into account, this study is based on the 2030 sustainable development goals as the broadest way of common sense for the future of the world, despite everything. The 2030 SDGs cover the sustainable development goals of the United Nations, which aim to realize the most favorable conditions for the continuation of the world's favorable condition for human life, by considering equality and justice as much as possible. In the study, evaluations on the ecological sustainability of the Himalayas will be made through the 2030 sustainable development goals and policy recommendations will be developed. This study includes an originality in the interpretation of 2030 items regarding the Himalayas and the creation of original tables. It is aimed that this study will be a guide for those who will work in this field in the future in terms of a basic due holistic analysis.

2 The Position of the Himalayas

It is thought when understanding the position and importance of the Himalayas will be helpful to determine why the link between climate change and the Himalayas is important issue among the worldwide. The Himalayas are dominated by a region of about 2400 km stretching from Nanga Parbat (Pakistan) on the west coast and Namche Barwa on the east coast. The Himalayan contains ecological features within the region. For example, the climate is tropical at the foot of the mountains and the climate is formed as permanent ice at higher elevations (McGill School of Computer Science, n.d.).

The Himalayas are considered to be the region with the largest glacier mass in the world after the polar regions. There are approximately 15 thousand glaciers in this area and the glaciers contain 3000 cubic kilometers of fresh water (Himalayas Facts, n.d.).

The most important feature of the Himalayas is being the most important source of fresh water around the Polar regions. 16.6% of India's geographical area belongs to the Himalayas (Kumar et al., 2021).

The Himalayas form the largest and youngest mountain range in Asia. These extend to Bhutan, China, India, Nepal and Pakistan, respectively (Ghosh, 2021). The Himalayas cover the highest part of the world. In other words, it is home to the highest mountain peaks in the world. The highest peak, Everest (8848 m), is located in the Himalayas. Afterwards, high peaks such as Godwin-Austen mountain (8611 m) and Kanchenjunga (8586 m) are also located here. The two main seasons in the Himalayas are transitional and summer–winter. The winter season is very cold in Himalayas, while the summers can be seen as 25–30 ºC in the central parts of the Himalayas. On the other hand, all areas above 4880 m are under snow patterns and are constantly cold (Mount Everest, 2018).

The Eastern Himalayas stand out with the large number and variety of living species in the region. Asia's largest herbivore, the Asian elephant, one-horned rhinoceros and wild hippopotamus live here (WWF, n.d.a). The rich ecosystem of the region can be categorized as Fig. 1.

Unique creatures such as the Bengal tiger and snow leopard also live in this region. Problems such as the climate crisis and environment-human conflict experienced by the Himalayas pose a great threat to the unique ecosystem (WWF, n.d.a).

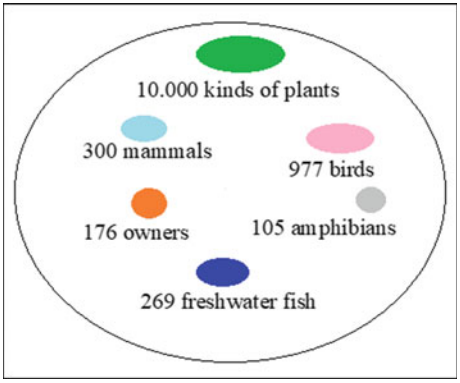

Fig. 1 Ecosystem of the Himalayas. WWF, (n.d.a) *Source* adapted from

3 The Climate Change and the Himalayas

Today, the Himalayas are one of the most important regions where the effects of climate change are felt on a global scale. Food insecurity, water scarcity and energy security problems and biodiversity problems will gradually increase due to the continuation of climate change in the long term. It is a fact that each negative impact on food security and water security in the Himalayas will expand in the Asian region and then the world. As being a water tower of Asia, the Himalayas are a vital source of water for the world. Accordingly, more than 500 million people in South Asia and 450 million people in China depend entirely on the Himalayas, while the lives of more than a billion people depend on the same resource (WWF, n.d.b).

An increase in temperatures due to the climate change has caused the glaciers to melt faster. At this point, the rapid melting of the glaciers in the Himalayas shows that the threat of climate change is at serious levels. The melting of the glaciers in the Himalayas increases disasters such as avalanches and floods and poses a great danger to the population living in the region. In addition, melting glaciers cause sea level rise worldwide (Ntv.com.tr, 2021). The most of studies on the impact of climate change on the Himalayas is seen as "melting of glaciers" in the literature. In other words, the melting of glaciers in the Himalayas is seen as the greatest threat posed by climate change (Shrestha et al., 2012). As seen in Fig. 2, the impacts of the Himalayas can cover all over the Asia region in the future.

As scientists have pointed out, climate change has been anthropogenic in the last century. It is stated that the temperature change experienced in the Himalayas between 1951 and 2014 is human-induced. It can be said that there is a warming of 0.2° every year in the relevant area (Sabin et al., 2020).

Large chunks of ice from the glaciers in the high reaches of the Himalayas have caused many deaths and great destruction in Uttarakhand, India. The sinking of glaciers also increases threats such as floods and landslides in the same region. Between 2016 and 2018, it was observed that the glaciers in the region lost about 0.5–2.5 m of perimeter thickness. Considering that melting glaciers pose a long-term

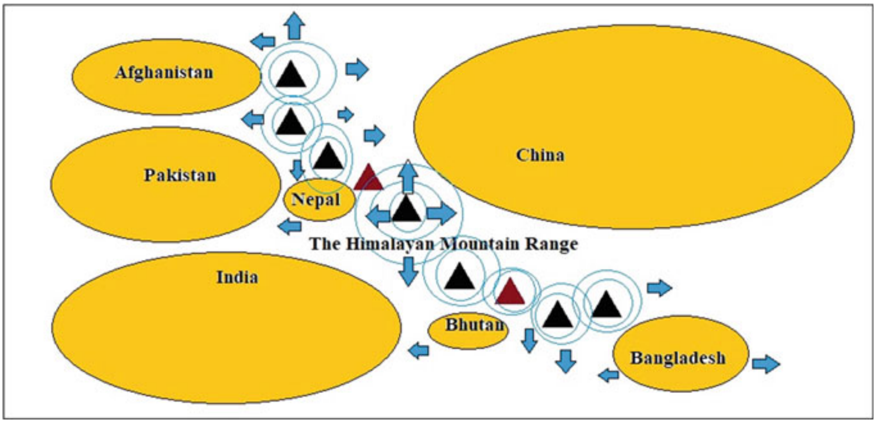

Fig. 2 The Himalayas among the Asia region. *Source* Created by the authors

threat to the region, taking precautions will be a vital necessity (Buchholz, 2021). As a result of global warming and anthropogenic climate change, the ecosystem in the Himalayas is also being destroyed. Factors such as the melting of glaciers, deforestation, excessive consumption of natural resources, the spread of invasive species, and poaching signal that the ecosystem in the Himalayas will not be sustainable in the long run (Ghosh, 2021). Figure 2 shows these locations.

4 2030 Sustainable Development Goals (SDGs) and the Himalayas

Sustainable development aims to achieve economic development when keeping balance between economic growth and environmental quality in the long term (Yildirim, 2023; Yıldırım & Yıldırım, 2020; Yildirim et al., 2023; Yıldırım et al., 2018). The world leaders also noticed that achieving economic growth is not enough without social welfare. At this point, sustainable development is a new guide both for developed and developing countries. By 2015, the UN launched 2030 Sustainable Agenda and 17 main goals planned to be achieved until 2030. These goals include economic, social and environmental issues and each main goal includes some subgoals (Yıldırım et al., 2023). There is a clear gap in knowledge of economic impacts of climate change in the Himalayas (Gautam et al., 2013) (Table 1).

The effects of climate change in the Himalayas region also affect the 2030 SDGs. In particular, accelerating global warming complicates the realization of the 2030SDGs. As a result of the literature review, the following can be said in terms of the Himalayas and 2030SDGs:

Table 1 The 2030 SDGs. *Source* created by the authors

Goals*	Theme*	Prior issue	What is this?
Goal 1	Poverty	Related with Economic issues	Poverty is an essential problem and related with issues of health, education and economic growth in general. Poverty should be reduced in the world to provide better life condition for everybody
Goal 2	Hunger	Related with social welfare	Hunger mostly threats least developed countries and poor or low-income countries in the world. However, twenty-first century showed that the hunger threats every kind of economies in the long term. The Covid-19 pandemic, the Russia-Ukraine conflict and the climate change have shown that the hunger is the biggest problem
Goal 3	Health	Related with social welfare	The world leaders have seen that providing sustainable health of societies is important aim in the long term. Especially, the covid-19 pandemic proved that no country is ready for the pandemic
Goal 4	Education	Related with social welfare	Sustainable education should be provided in the world and it should be provided equally to each girl and boy in the world
Goal 5	Gender equality	Related with social welfare	Gender equality is an important issue in education, work, health and other social and economic issues in the world
Goal 6	Clean Water	Related with environmental quality	In the world, there have been many people who had no any fresh and clean water since decades. Due to the rising global warming, the future will meet more drug and water scarcity
Goal 7	Clean Energy	Related with environmental quality and economic issues	Clean and affordable energy is related with also economic sustainability when it keeps protecting environmental quality. Without energy, economies can't keep economic growth and welfare On the other side, air pollution and environmental destruction are all related with non-green energy plants

(continued)

Table 1 (continued)

Goals*	Theme*	Prior issue	What is this?
Goal 8	Economic growth	Related with Economic issues	Economic growth supports social welfare. Accordingly, societies should keep the optimum level of economic growth to achieve social welfare in the long term
Goal 9	Industry	Related with Economic issues and environmental quality	The industry is responsible for achieving environmental quality when considering their impacts on natural environment since decades
Goal 10	Inequalities	Related with social welfare	Inequalities should be ended in the world. Each individual should reach equal rights and life-standards
Goal 11	Sustainable cities	Related with environmental quality and social welfare	Usual city life pollutes natural environment and it isn't sustainable in the long term
Goal 12	Responsible consumption—production	Related with Economic issues	Sustainable consumption patterns should be adapted in the long term. To achieve sustainable development, sustainable production process and systems should be adapted by the industry
Goal 13	Climate change	Related with environmental quality	The climate change is a fact that changing the usual climate and ecosystem of the Earth. Although it is an natural event, the human factor is more effected on the climate change in recent years
Goal 14	Clean Sea and oceans	Related with environmental quality	Clean sea and oceans will achieve sustainable marine biodiversity and then it will bring sustainable seafood and will support seafood security
Goal 15	Clean Lands	Related with environmental quality	Clean and sustainable land areas are needed to achieve sustainable agriculture and stock in the long term

(continued)

Table 1 (continued)

Goals*	Theme*	Prior issue	What is this?
Goal 16	Peace and Justice, strong Institutions	Related with social welfare	Peace, justice and strong institutions will save communities in the related region and this will prevent migration
Goal 17	Global Partnership	Related with social welfare	Global partnerships can supports countries to achieve some goals in the same region. For example, countries from the Mediterranean region can collaborate with each other to achieve seafood security in this region

*based on UNPD, https://www.undp.org/sustainable-development-goals

- Although the Himalayas are a region rich in biodiversity, it has been exposed to anthropogenic effects. This region is an important livelihood point for the poor people with the terrestrial resources it provides. It can be said that efforts to reduce poverty and protect biodiversity in the Himalayas are not very effective (Sandhu & Sandhu, 2015). In the long term, the focus should be on the sustainability of the biodiversity in the Himalayan region to prevent a migration wave from the region.
- Negative consequences of climate change in the Mediterranean basin (Kaplan & Yildirim, 2023; Kaplan et al., 2022; Yildirim & Kaplan, 2022) have also started to appear in the Himalayas. However, the acceleration of climate change in the Himalayas has increased the melting of the glaciers. Melting glaciers threaten water resources globally (Xu et al., 2009).
- Despite their inaccessibility, the Himalayas are heavily subject to human-induced biodiversity loss. People have lived in the Himalayan mountains for thousands of years, but global accessibility in recent years has increased demand for this region. The ecosystem area is gradually deteriorating and biodiversity is under threat. The proliferation of the human population and the proliferation of residential areas have disturbed the balance in the ecosystem. For example; Forest lands have been destroyed and deforestation has begun to create agricultural and planting areas (CEPF, n.d.).
- Food security differs between mountainous and plain areas in the Himalayan region. Limited accessibility in mountainous areas results in a high level of vulnerability in this region. Therefore, people living in mountainous areas have to contend with food insecurity and other socio-economic challenges. In terms of food security, agricultural activities have also been tried to be supported in mountainous areas, but climate change has also negatively affected these supports (Rasul et al., 2019).
- The most basic principle for food safety can be explained as "self-sufficiency in food". At this point, the lack of self-sufficient food in the mountainous areas of the Himayalas region creates a great food insecurity. For example, between 2012 and 2017, it was seen that the rural mountain population was very vulnerable

to food in the mountainous areas of the Himalayas. In 5 years, food insecurity has increased by 12%. Between 2012 and 2017, the mountain population in Asia increased by 8.1%, but the food-resistant population decreased by 7.5%. About 1.5 billion people live in the mountainous area of the Himalayas and depend on this area for all their basic needs (Khandekar, 2019).

- The mountainous part of the Himalayas (HKH-Hindu Kush-Himalayan), where food insecurity is high, constitutes the smallest area of poor people (Jean-Yves et al., 2015).
- Shyamsundar et al. (2018) examined the relationship between poverty and forest in the Himalayan region. According to the results of the study, per capita income in Nepal is half of the per capita income in India. However, those living in the Himalayas seem to be in a better position in terms of wealth. Having a lot of forest land can be considered as good for the population.
- An old study also shows how farmers in Nepal are affected by the climate crisis. Extreme weather conditions (winter drought 2008–2009) have reduced agricultural yields and the vast majority of the population in Nepal has been affected by the climate crisis. (Oxfam International, 2009).
- The Indian Himalayan part is home to a very rich habitat, but these natural resources have been overused due to high demand. At this point, the problem of sustainability has emerged. Therefore, it would be beneficial to develop alternative strategies and policies for the sustainability of biodiversity in the relevant region (Badola & Aitken, 2010).
- Resurrección et al. (2019) studied on gender divert among the Himalayas region through climate change effect. Women at different socioeconomic levels are also affected differently by the consequences of the climate crisis, due to inequalities based on oppressive cultural rules and norms in the distribution of rights, sprawl, resources and power. As a result, women in the Himalayas are often poorer and less educated than men. Although women gain economic life, there are inequalities between men and women in terms of income and other socio-economic rights.
- The International Center for Integrated Mountain Development (ICIMOD) published a report about climate change in the Hindu Kush Himalaya region. In the report, it was determined that a temperature rise of 2 °C became deadly for the Himalayan glaciers (Bhushal, 2019).
- Gender relations in the Himalayas region vary according to the external migration status of men. The inequality between men and women in the Himalayas region is also seen in farming. Women can farm, but they cannot go to markets or public spaces. In addition, while men show themselves in all kinds of social areas, the social role of women is very limited (Holmelin, 2019).
- The aim of Goal-5 is to achieve gender equality and improve the social rights of women and girls through active participation in social, political and economic development. Following the Sustainable Development goals, Nepal has also focused on gender discrimination. Gender inequality is very high in male-dominated regions. Women have less social roles in society. Particular attention should be paid to improvements in the rights of women and girls in rural areas (Dhungana, 2022).

5 Conclusion and Discussion

Among the human-induced effects that increase climate change are factors such as the use of fossil fuels, cutting of forests and animal husbandry. For a sustainable future, global warming must be stopped. Therefore, it is essential to control the influence of human-induced factors (European Commission, n.d.). The climate crisis, the effects of which became visible in the twenty-first century, threatens the ecosystem in the HKH region. Policies should be developed urgently for the protection of biodiversity and the continuity of the ecosystem in the Himalayas. In particular, strategies on resilience need to be established (Kattel, 2022). Panwar (2020) determined the importance of preventing global warming and climate change effects on the Himalayas immediately. Unsustainable human-based activities will destroy the biodiversity and ecosystem in the Himalayas in the short term.

The most important risk of the Himalayan region is the melting of glaciers as a result of temperature increases due to climate change. The primary risk is thought to be melting glaciers. Because the melting of glaciers affects fresh water resources and negatively affects life by causing floods and overflows in the region. People living in the region first have to deal with natural disasters such as floods. On the other hand, the changing climate affects agricultural activities. Sustainable agriculture does not seem possible. Deforestation for agricultural purposes will affect the population living in the region in the long term as drought and erosion. In fact, stable work for 2030SDGs is required for the salvation of the region in the face of global warming and rising temperatures. The resilience of this region is important for the future of the whole world. If the Himalayan region falls, so will the Asian region. In other words, the world is not and can never be ready for the great wave of immigration that will start from Asia. It is estimated that Asia, which hosts a large part of the world's population, will not be able to host climate refugees in other regions due to climate change-related problems. As a result, in order not to lose the Himalayas region, it is necessary to urgently reduce the activities that cause carbon emissions among the human-induced activities and to prevent temperature increases. Deforestation for agricultural land in the Himalayas region should be prevented and it is recommended to continue on existing agricultural areas. In order for the region to be self-sufficient, improvements in the 2030 SDGs should be made, but it is recommended that activities that have accelerating effects on climate change should be eliminated with alternative solutions, even if they have positive outputs. For example, farming is an important area in gender equality. However, each new agricultural area enters the ecosystem as less forest. As suggested by Goal-17, the Himalayas region should be made resilient through global cooperation and regional cooperation.

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