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Navigating Climate-Related Financial Risks

Assessing the Vulnerability *of* Hydroelectric Power Plants in Uttarakhand

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About Us

Climate Risk Horizons
Climate Risk Horizons' (CRH) work highlights the systemic risks that disruptive climate change poses to investors, lenders and infrastructure investments. Through a data-driven, research-oriented approach that incorporates a holistic understanding of climate policy, energy infrastructure and regulatory processes, CRH provides advice on risk management strategies to minimise stranded, non-performing assets and economic disruption in the face of climate change.

Learn more about us at *climateriskhorizons.com*.

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Table *of* Contents

List *of* Figures

List *of* Tables

List *of* Abbreviations

AF	Adaptation Fund
AR6	Sixth Assessment Report
BIS	Bureau of Indian Standards
BMTPC	Building Materials and Technology Promotion Council
CEA	Central Electricity Authority
CRH	Climate Risk Horizons
DEMs	Digital Elevation Models
DFI	Development Finance Institution
DRA	Disaster Risk Assessment
GCF	Green Climate Fund
GIS	Geographical Information System
GLOFs	Glacial Lake Outburst Floods
HPP	Hydroelectric Power Plant
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
L&D	Loss and Damage
MDBs	Multilateral Development Banks
MHEWS	Multi-Hazard Early Warning Systems
MIGA	Multilateral Investment Guarantee Agency
NbS	Nature-based Solutions
PDNA	Post-Disaster Needs Assessment
PPPs	Public Private Partnerships
PRCP	Precipitation
R&D	Research and Development
SANDRP	South Asia Network on Dams, Rivers and People
SCADA	Supervisory Control and Data Acquisition
TMAX	Maximum Temperature
TMIN	Minimum Temperature
UNFCCC	United Nations Framework Convention on Climate Change
WB	World Bank

List *of* Images

1.0 Executive Summary

The state of Uttarakhand in India in the central Himalayas is on the frontlines of a changing climate and has been facing formidable challenges posed by natural hazards, including intense rainfall, landslides, flash floods, glacial lake outbursts floods (GLOFs), and droughts.[1] The state's mountainous terrain also hosts a number of hydroelectric power plants (HPPs) for electricity generation—these too are increasingly vulnerable to extreme climate events.[2] In addition to natural and climate-change related vulnerability, HPPs often face delayed project commissioning and rising insurance premiums, all of which contribute to mounting financial burdens on project owners/developers and governments. With the depletion of viable sites over the years, the dam construction industry has shifted its sites to higher risk, upstream areas. Such decisions are often based on outdated climate data, further amplifying the susceptibility of these projects to environmental and climate risks.

Climate Risk Horizons (CRH) conducted a comprehensive study to assess the existing climate-induced disaster risks to HPPs in Uttarakhand and the potential implications for financial stability and societal well-being. This study adopts a multi-faceted approach, integrating climate risk screening, identification of high-risk HPPs, and evaluation of potential losses to the state and national governments.

The climate risk screening involved the analysis of various climate impacts, stressors, and human and geophysical parameters across all river basins in Uttarakhand. Data sources included population disaggregation, climate scenarios from the Intergovernmental Panel on Climate Change (IPCC), and geographic information system (GIS) based assessments of climate risks. High-risk basins were identified based on their susceptibility to climate-related hazards, providing a foundation for further analysis on climate-related risks to HPPs.

Subsequently, high-risk HPPs were identified within these vulnerable basins, taking into account their geographical location, proximity to glacial lakes, and potential exposure to flash floods and GLOFs.

The study further conducted a detailed damage assessment for a climate disaster, using the rockfall and flash flood event that occurred near Joshimath town in Chamoli district in February 2021 as a case study. This assessment revealed the potential financial losses and climate-related risks associated with hydropower infrastructure in Uttarakhand, highlighting the urgent need for robust risk management strategies and climate-risk proofing of investments.

Key Findings

1. Climate-related extreme weather events have been increasing in the Himalayas. These events have the potential to completely destroy hydropower projects, as seen in the Chamoli (2021) and Teesta III (2023) instances, or at the very least set these projects back by several years, leading to significant cost escalations and financial implications for project proponents and insurers.

2. Estimates of the financial impact of such disasters vary widely. In the Chamoli example, some estimates put the financial impact of the disaster at approximately ₹1,625 crore. However, debris removal alone, based on standard costs for such work, is likely to cost over ₹3,400 crore. In addition, recovery costs for electro-mechanical components, repairs, maintenance, or loan amount escalation will further increase the bottom line. Each disaster has the potential to set the project back by several years, leading to significant cost escalations.

3. The hydropower industry is moving to higher risk locations as evidenced by the list of announced, pre-construction, and construction projects (see **Annexure 3**). There is a significant probability that some of these locations in the state will be hit by either seismic or climate-related events in the coming years. Cumulatively, at least 15 projects (totalling 10,678 MW) representing ₹70,150.30 crore of investment could be at high-risk locations in Uttarakhand.

4. Integrating adaptation measures into the planning, design and implementation stages of hydropower infrastructure projects can reduce vulnerability and enhance resilience. Judicious planning involves excluding high-risk sites and finding smart ways of combining financial instruments such as insurance and guarantees to mitigate the climate risk to hydropower infrastructure investments.

2.0 Background

Uttarakhand, nestled in the heart of the central Himalayas, stands as a testament to nature's awe-inspiring beauty and formidable power. This picturesque state faces a myriad of challenges as it grapples with a historic susceptibility to natural hazards, which is now aggravated by the unfolding climate crisis.[3] With its rugged terrain and fragile ecosystem, Uttarakhand is highly susceptible to extreme weather events including intense rainfall, landslides, fluvial floods, flash floods, glacial lake outbursts, and droughts. These phenomena, exacerbated by the changing climate, pose significant risks to the region's socio-economic fabric and environmental stability.

Due to its mountainous terrain, Uttarakhand is home to several HPPs built to meet the state's energy needs and to export power to the rest of India. Plans for several new HPPs are also in the pipeline. Per the CEA (**Annexure 2**), there are 81 large Hydro Power Projects in the pipeline (capacity above 25 MW). There are currently 18 HPPs operational in the state (see **Annexure 2**). However, the growing risks associated with extreme weather events have cast uncertainty over the future viability of these assets. Chamoli district in Uttarakhand, home to the Nanda Devi glaciers, gained prominence due to the 2021 floods triggered by glacial fragmentation. This disaster severely damaged four hydropower projects, including the under-construction Tapovan Vishnugad and the Rishiganga Hydro Project.[4] Similar disasters have previously impacted hydropower infrastructure in the region, notably during the 2013 floods when multiple projects, such as the Vishnuprayag hydropower plant, faced severe damage.[5] Further, delays in commissioning and operations, the risk of stranded assets due to weather events and mounting insurance premiums underscore the pressing need for a comprehensive assessment of climate risks to HPPs in Uttarakhand.

The Himalayan region's dynamic and evolving climatic conditions demand a nuanced understanding of the risks caused by and posed to hydropower infrastructure.[6] Outdated climate data and the spread of habitation and infrastructure into high-risk upstream areas have further heightened the vulnerability of HPPs to climate-induced disasters. Given the ambitious plans of the state and national governments to develop additional hydropower dams, a proactive and systematic approach is needed to address the ecological, social, and economic ramifications of such ventures.

In this context, the Post-Disaster Needs Assessment (PDNA) framework[7] is relevant as it systematically assesses disaster impacts on infrastructure, social services, and economic activities. While this report is not a PDNA study, it highlights the importance of such a framework in understanding the vulnerabilities of hydropower plants to climate-induced disasters. Implementing PDNA in Uttarakhand can aid in developing effective recovery strategies, identifying intervention areas, prioritising investments, and formulating policies to enhance the adaptive capacity of HPPs and local communities.

This report seeks to examine the existing climate risks faced by HPPs in Uttarakhand, with a focus on implications for financial stability, economic resilience, and human well-being. Through a comprehensive analysis of the interplay between climate variability, environmental risks and infrastructure expansion, the report seeks to offer valuable insights crucial for shaping policy frameworks, devising investment plans, and implementing effective risk management measures. This is essential to steer Uttarakhand towards a future characterised by sustainability and resilience in the face of evolving climate challenges.

3.0 Approach and Methodology

To understand the potential risks posed by climate change to hydropower infrastructure in Uttarakhand, this study followed a systematic methodology encompassing three sequential steps.

STEP 1: *Climate Risk Screening of River Basins in Uttarakhand*

A climate risk screening was initiated by delineating existing river basins in Uttarakhand, ranging from the micro to higher-order basins covering areas up to 6,000 sq. km. Eight major river basins were identified, with each basin corresponding to a major city within its boundaries. Indicators relevant to the study were selected, and data collection commenced using various sources.

» **Population Disaggregation:** Utilising WorldPop[8] datasets, raster data with a resolution of 100 m, demographic information was extracted, disaggregated by gender and age groups, and converted into usable formats for basin-level analysis. GIS and Remote Sensing tools facilitated the conversion of population density grids into estimates of population numbers per basin.

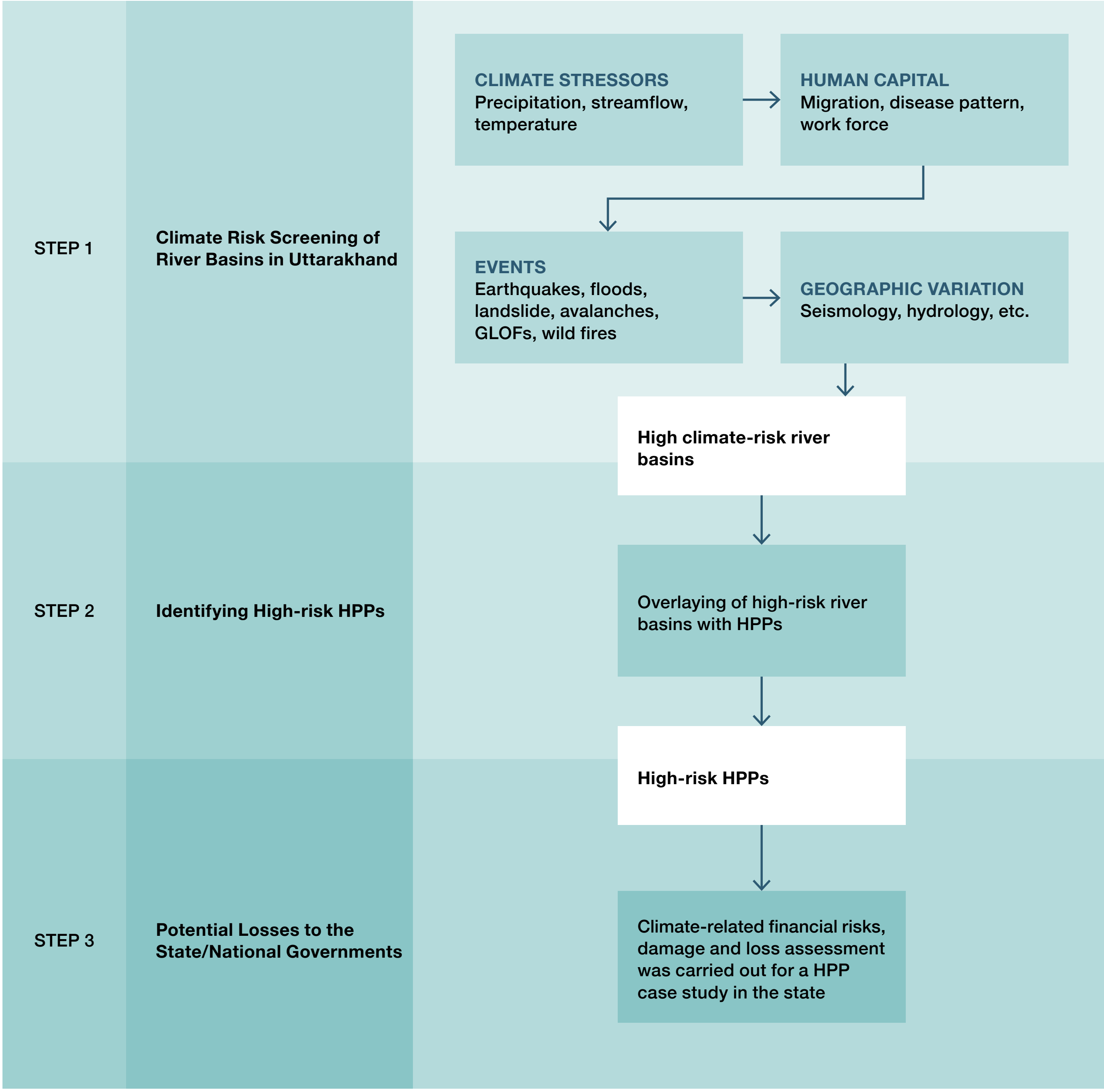
» **IPCC Climate Scenarios:** Climate scenarios from the IPCC were employed to understand potential climate impacts. Future climate analyses were carried out till 2100 considering data (in NetCDF format) from 1851 onwards from IPCC projections, CMIP6.

A GIS-based assessment using scoring methods assigned weights to different climate parameters, visualising river basins on a scale of “high risk” to “no risk”.

STEP 2 : *Identifying High-risk HPPs*

High-risk basins, as determined from the climate risk screening, were overlaid with the locations of existing HPPs and streams. Additionally, assessments of glacial lakes and their discharge patterns were conducted to evaluate potential risks from GLOFs. High-risk HPPs within these basins were then identified, considering IPCC’s Sixth Assessment Report (AR6) Working Group 2 (WG2) or Working Group 3 (WG3) projections of changing climate regimes and their impacts on HPP operations, particularly in light of recent flash flood events.

Figure 1 | Flow Chart of the Methodology



Source: Compiled by the authors.

STEP 3: *Assessing Potential Losses to the State/National Governments*

A damage assessment exercise was undertaken in this study, focusing on a HPP case study based on the Chamoli flash floods of February 2021. The damages and losses suffered by the NTPC Tapovan Vishnugad HPP[9] served as a baseline for estimating potential losses due to future flash floods or GLOF events. Financial losses and climate-related financial risks to hydropower infrastructure in Uttarakhand were quantified, providing insights into potential economic impacts.

Data Collection and Analysis

Data collection involved gathering information on climate stressors, damages from past and anticipated future events, demography, geophysical variations, glacial lakes, HPP locations, economic data, and climate projections from various sources. Data analysis was conducted using ArcGIS, analysing river basin stretches and overlaying HPP locations with high-risk basins to identify vulnerable HPPs. Data analysis had more aspects than just the identification of high-risk basins. Impending physical and financial losses were estimated, and corrective recommendations were formulated based on the analysis.

This systematic approach facilitates a holistic understanding of climate-related risks to hydropower infrastructure in Uttarakhand, aiding in the formulation of targeted mitigation and adaptation strategies to enhance resilience of hydropower infrastructure in the face of climate change impacts.

4.0 Climate-induced Disaster Risk Screening

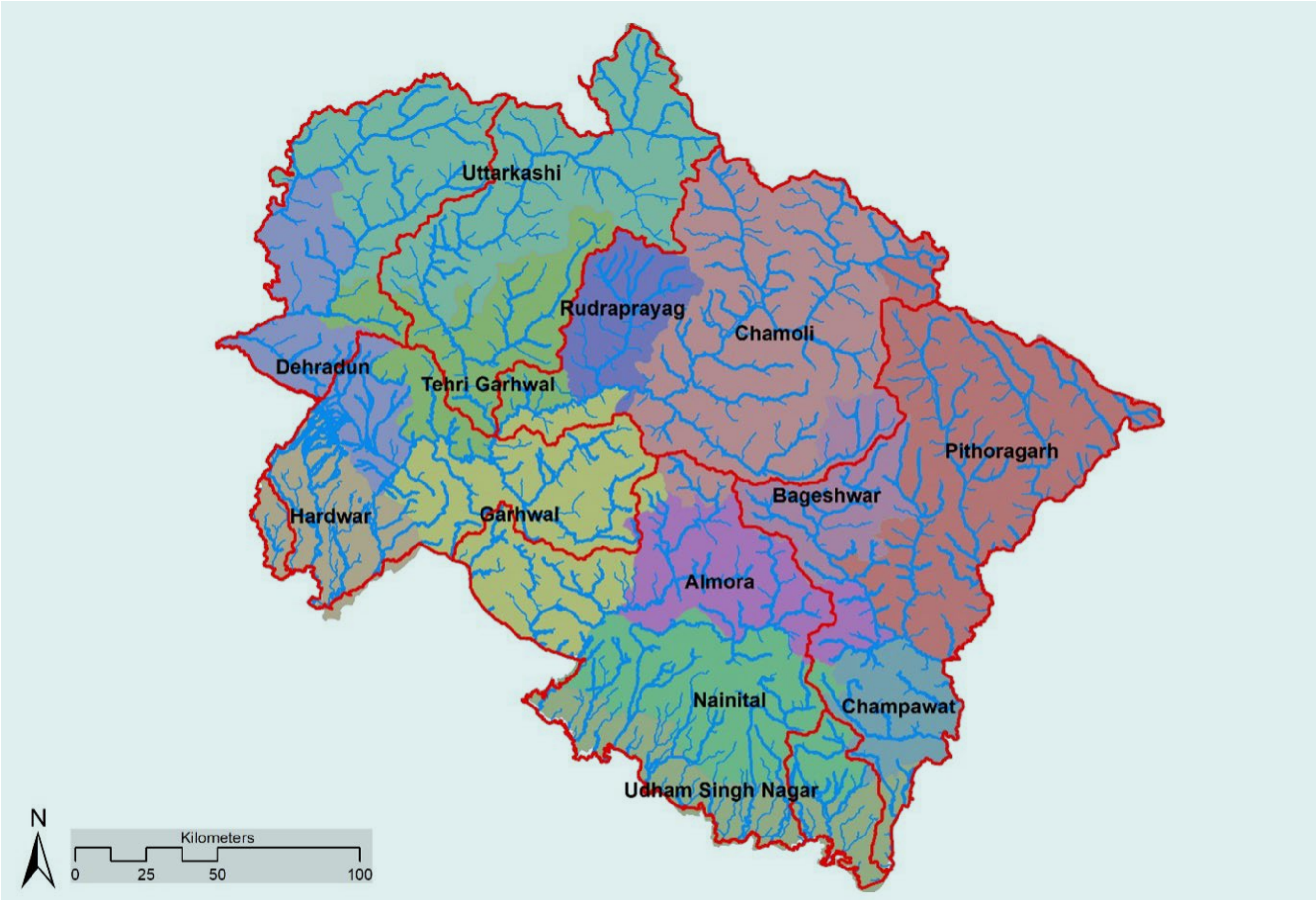
This chapter is a comprehensive examination of the vulnerability of river basins to climate-induced disasters. It employs a multi-faceted approach to delineate and identify vulnerable basins, integrating geographical, socio-economic, and climatic factors. The presence of HPPs is scrutinised as a critical factor, alongside the examination of glaciers and glacial lakes within these basins. The chapter unfolds through distinct steps, systematically outlined to ensure a thorough understanding of the potential risks associated with climate-induced disasters. It also considers past disasters and anticipated future risks, forming a holistic framework for comprehensive understanding and proactive management of climate-induced disaster risks.

Delineation of River Basins

The delineation of river basins is the process of defining the geographical boundaries of a river basin or watershed. This process is crucial for understanding and managing water resources, environmental conservation, and land-use planning. The state of Uttarakhand has six river systems flowing through it. Glaciers are the main sources of these rivers, which subsequently accumulates other runoff culminating in Ganges.

Eight major river basins in Uttarakhand were identified, with each basin corresponding to a major city within its boundaries. Detailed river basins were derived from high-resolution digital elevation models (DEMs). The most detailed resolution of the watershed/basins covers very small areas and is difficult to process, presenting a computational challenge. Conversely, as the watershed/basin size increases, the granularity of the data is lost. To address this trade-off, a consensus in the literature suggests that a resolution of approximately >5000 sq. km. serves as a pragmatic basis for a basin. Further, detailed streams are delineated for each of the river systems as shown in the basin maps below.

Figure 2 | Uttarakhand River Basins and Districts



Source: Authors' analysis using GIS.

Indicators Used for Identifying Vulnerable Basins

The identification of vulnerable basins was conducted through a comprehensive analysis of multiple indicators, encompassing geography, demography, socio-economic indicators, glaciers, glacial lakes, climate-induced vulnerability, past disasters, and future hazard settings. District-level data for each of the indicators was collected and subsequently aggregated to the basin-level using pro-rata spatial extent conversion techniques and GIS methodologies.

1. Geography

The state's geographical characteristics were considered to discern the locations of HPPs. The study encompassed river basin attributes, including area, population density, river networks, existing dams, reservoirs, and HPP locations.

2. Socio-economic Factors

Population demographics and socio-economic conditions were scrutinised due to their pivotal role in HPP operations in Uttarakhand. Factors such as per capita income, gross domestic product (GDP) of the region, job creation, in-migration of labour, out-migration of local youth, and health indicators, including morbidity and mortality data, were examined.

a. Demography

Demography, focusing on population size, structure, and development, serves as a fundamental indicator of geographical growth. In this context, population is studied for its intrinsic vulnerability, considering attributes such as:

i. Population

Uttarakhand, also known as Uttaranchal, comprises two divisions, Garhwal and Kumaon, with 13 districts. As per the 2011 Census, Uttarakhand's population is 1,00,86,292, with 69.77% residing in rural areas. The gender ratio is 963 females per 1,000 males. The crude birth rate in the state is 18.6 with the total fertility rate being 2.3. The state has a mortality rate of 43, a maternal mortality rate of 188 and a crude death rate of 6.6. Uttarakhand is a multi-ethnic population spread across the two divisions. The population density, growth rates, and district-wise populations are detailed in **Table 1**.

ii. Disabled Persons

The basin-wise percentage of disabled persons was assessed, emphasising the vulnerabilities of individuals, especially with disabilities. Ponta-Vikasnagar basin exhibited the highest percentage, followed by Joshimath-Srinagar.

iii. Life Expectancy

Life expectancy, a crucial indicator of long-term health improvements, varied across basins. The Pithoragarh-Bageshwar basin demonstrated the highest life expectancy at 72.1 years.

iv. Multidimensional Poverty Index (MPI)

Basin-wise MPI scores were calculated to assess poverty considering deprivations in education, health, and living standards. Tehri-Uttarkashi and Ponta-Vikasnagar basins exhibited higher deprivation.

Table 1 | Socio-economic Factors of Uttarakhand

	Name of the basin	Area (sq. km.)	Population (no.)	Density (persons/ sq.km.)	% of disability persons	Life expectancy	MPI score
1	**Pithoragarh-Bageshwar**	10,940.21	13,71,376	125	1.90	72.1	0.06
2	**Khatima**	1,321.04	48,538	37	1.69	71	0.10
3	**Nainital-Ranikhet**	10,025.87	31,21,905	311	1.69	71.9	0.10
4	**Haridwar-Roorkee**	6,868.57	23,03,877	335	1.67	67.7	0.05
5	**Tehri-Uttarkashi**	7,304.26	3,70,556	51	2.14	68.7	0.11
6	**Joshimath-Srinagar**	11,061.31	9,59,397	87	2.23	71.7	0.07
7	**Ponta-Vikasnagar**	5,476.04	5,58,918	102	3.91	70.5	0.11
8	**Manglaur**	305.41	7,860	26	1.67	67.7	0.10

Source: Institute for Human Development (2018). *Human Development Report of the State of Uttarakhand.*

b. **Gross Domestic Product (GDP):** Economic indicators, including basin-wise GDP, were analysed to understand economic development. Manglaur, Ponta-Vikasnagar, and Khatima basins exhibited substantial contributions to the state GDP.

Table 2 | Basin-wise GDP of Uttarakhand

	Name of the basin	GDP (₹ thousand crore)
1	**Pithoragarh-Bageshwar**	4.92
2	**Khatima**	32.07
3	**Nainital-Ranikhet**	11.16
4	**Haridwar-Roorkee**	6.72
5	**Tehri-Uttarkashi**	2.93
6	**Joshimath-Srinagar**	4.67
7	**Ponta-Vikasnagar**	32.91
8	**Manglaur**	49.66

Source: Institute for Human Development (2018). *Human Development Report of the State of Uttarakhand.*

c. **Per Capita Income:** Per capita income varied significantly among basins, with Manglaur exhibiting the highest at ₹2.54 lakh.

Table 3 | Basin-wise Per Capita Income of Uttarakhand

	Name of the basin	GDP (₹ lakh)
1	**Pithoragarh-Bageshwar**	1.02
2	**Khatima**	1.87
3	**Nainital-Ranikhet**	1.15
4	**Haridwar-Roorkee**	1.10
5	**Tehri-Uttarkashi**	0.89
6	**Joshimath-Srinagar**	1.18
7	**Ponta-Vikasnagar**	1.96
8	**Manglaur**	2.54

Source: Institute for Human Development (2018). *Human Development Report of the State of Uttarakhand.*

Image 1: Ichari Dam, Tons River, Uttarakhand. **Source:** Vaibhav78545–Own work, CC BY-SA 4.0, *https://commons.wikimedia.org/w/index.php?curid=100201649*

3. HPPs in the Basin

The vulnerability assessment of river basins incorporates the evaluation of HPPs, considering both their current number and installed/proposed capacities. The rationale posits that basins with a higher concentration of HPPs may exhibit heightened vulnerability to anthropogenic and other hazards. The basin-wise number of HPPs, both existing and planned, along with its capacity is given below:

Table 4 | Number of HPPs Per Basin in Uttarakhand

	Name of the basin	Number of HPPs	Capacity of the HPPs (MW)
1	**Pithoragarh-Bageshwar**	25	487.7
2	**Khatima**	0	0
3	**Nainital-Ranikhet**	4	198
4	**Haridwar-Roorkee**	4	173.7
5	**Tehri-Uttarkashi**	11	2,237.5
6	**Joshimath-Srinagar**	21	913
7	**Ponta-Vikasnagar**	9	140.85
8	**Manglaur**	0	0

Source: Authors' analysis.

4. Glaciers and Glacial Lakes

The assessment of vulnerable basins incorporates the quantification of glaciers and glacial lakes as a key criterion because higher count of glaciers within a basin is indicative of increased vulnerability. Uttarakhand, with its notable glaciers, such as the Nanda Devi group in the Nanda Devi Sanctuary, underpins the significance of this criterion. The Chamoli district in Uttarakhand, where the Nanda Devi glaciers are located, gained prominence due to the 2021 Uttarakhand floods triggered by glacier fragmentation.

The Gangotri Glacier, situated in the Garhwal Himalayas, Uttarkashi district, is a prominent glacier and the primary source of the Ganges, India's largest river. Additional glaciers in the Kumaon region, including Kafini, Maikoti, Milam, Namik, Pindari, Ralam, and Sundherdurga, contribute to Uttarakhand's glacial landscape. The Garhwal region features glaciers such as Bander Paunch, Chorbari, Dokriani, Doonagiri, Khatling, Satopanth, and Bhagirath-Kharak, alongside the renowned Gangotri and Nanda Devi glaciers. A basin-wise compilation of glaciers is provided in **Table 5**, with the Joshimath-Srinagar basin hosting the highest count of glaciers and glacial lake area.

Table 5 | Basin-wise Glaciers in Uttarakhand

	Name of the basin	Number of glaciers	Area of glacial lakes (sq.m.)
1	**Pithoragarh-Bageshwar**	211	1,401,045.36
2	**Khatima**	0	0
3	**Nainital-Ranikhet**	0	0
4	**Haridwar-Roorkee**	0	0
5	**Tehri-Uttarkashi**	323	2,040,460.50
6	**Joshimath-Srinagar**	662	3,833,342.42
7	**Ponta-Vikasnagar**	65	314,923.50
8	**Manglaur**	0	0

Source: ISRO, 2021.[10]

Additionally, **Table 6** presents a state-wise overview of glacial lakes, specifying dangerous lakes that have historically posed threats. It is notable that this 2006 overview did not envisage either the Kedarnath flash flood (2013) or Chamoli rock-ice avalanche (2021).

Table 6 | State-wise Overview of Glacial Lakes

State	Glacial lakes		
	Number	Area (sq.km.)	Dangerous lakes
Himachal Pradesh	156	385.22	16
Uttarakhand	127	2.49	0
Sikkim (Teesta River)	266	20.20	14

Source: Bajracharya et al., 2006.[11] **Note:** This overview did not envisage either the 2013 or 2021 events in Uttarakhand.

This comprehensive evaluation elucidates the critical role of glaciers and glacial lakes in determining vulnerability within Uttarakhand's distinct river basins.

5. Climate Variables

The present investigation delves into regional climate variability by scrutinising precipitation and temperature patterns spanning the preceding four decades and extending until the year 2100. The study acknowledges the impact of climate change on precipitation characteristics, wherein alterations in the intensity and frequency of precipitation are anticipated. The observed rise in global temperatures is identified as a prominent manifestation of climate change.[12]

5.1. Temperature

The following table provides a summary of average temperature data recorded across various basins in Uttarakhand. The temperatures indicate notable variations among the basins. The highest temperatures were recorded in Manglaur basin followed by Joshimath-Srinagar.

Table 7 | Basin-wise Temperature in Uttarakhand

	Name of the basin	Max temperature (in deg C)
1	**Pithoragarh-Bageshwar**	21.23
2	**Khatima**	20.96
3	**Nainital-Ranikhet**	21.29
4	**Haridwar-Roorkee**	16.15
5	**Tehri-Uttarkashi**	12.67
6	**Joshimath-Srinagar**	24.66
7	**Ponta-Vikasnagar**	13.31
8	**Manglaur**	35.40

Source: Author's analysis.

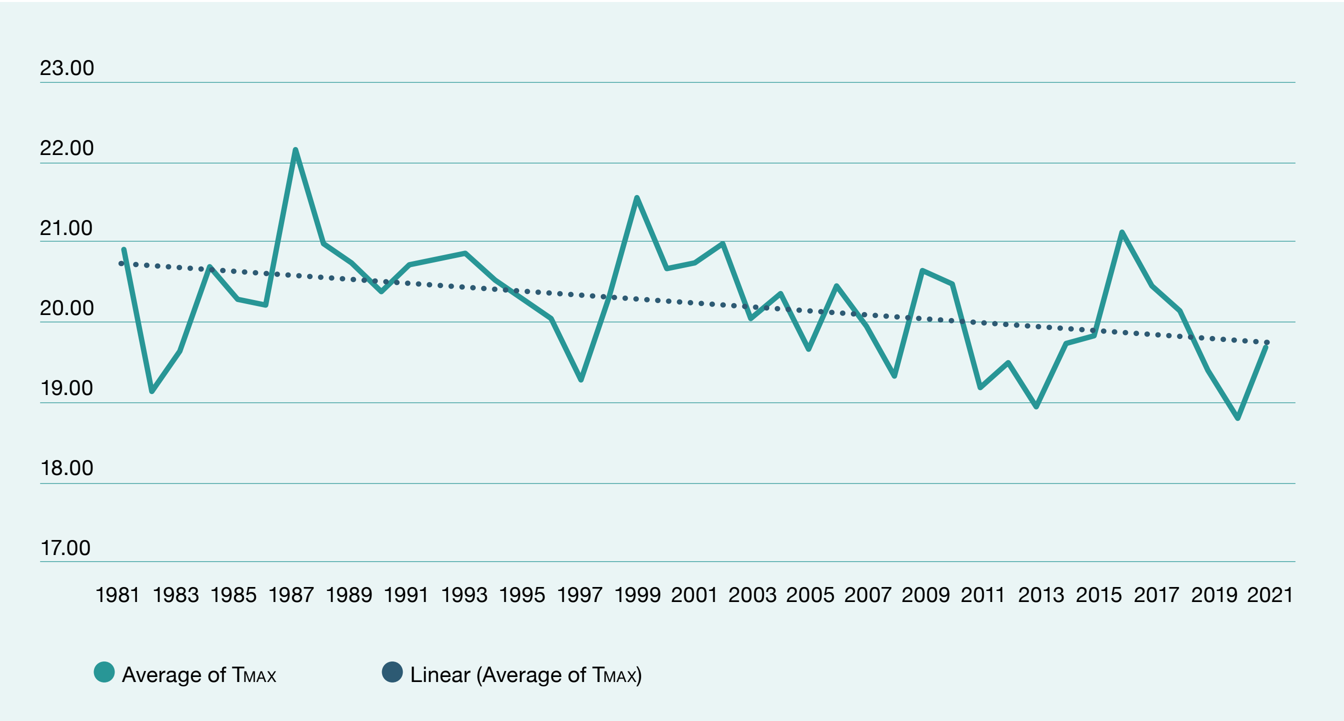
Further, the investigation focused on temporal variations in minimum and maximum temperatures across distinct seasons and spatially distributed grid points. The minimum temperature within a specified temporal interval, exhibits a discernible increasing trend in summer, monsoon, and post-monsoon seasons. This upward trajectory in minimum temperatures during the aforementioned seasons is notably pronounced over the years. However, in the winter season, increments in minimum temperatures are observed across the temporal spectrum.

Figure 3 | Average of Minimum Temperatures (in Deg C) in Uttarakhand

Source: Author's analysis based on data obtained from the NASA Langley Research Center (LaRC) POWER Project.

Conversely, the maximum temperature, representing the highest recorded temperature within the designated time frame, manifests a decreasing trend across all seasons. Particularly noteworthy is the discernible decline in maximum temperatures during the monsoon season, with an approximate reduction of 1.5 degree Celsius. These findings collectively underscore the intricate dynamics governing temperature fluctuations, elucidating both upward and downward trends in minimum and maximum temperatures, respectively, across diverse seasons and spatial grids.

Figure 4 | Average of Maximum Temperatures (in Deg C) in Uttarakhand



Source: Author's analysis based on data obtained from the NASA Langley Research Center (LaRC) POWER Project.

Hence, the spatial distribution of maximum and minimum temperature was systematically examined across the comprehensive grid encompassing the entire region. The graphical representation reveals a consistent rise in minimum temperatures over the temporal span across all regions. This increment is observed to be relatively modest in the northwest and northern sectors of the region. In tandem, the maximum temperatures exhibit a discernible reduction throughout the region over the four-decade period. Remarkably, the southeastern region experiences comparatively minor alterations in maximum temperatures, indicating a region-specific variability in the observed trends.

These spatial variations further contribute to the nuanced understanding of the dynamic interplay between climatic variables and geographic locales within the studied region.

5.2. Precipitation

Table 8 provides a detailed account of average precipitation levels across various basins in Uttarakhand. The highest precipitation was recorded in Haridwar-Roorkee basin followed by Khatima.

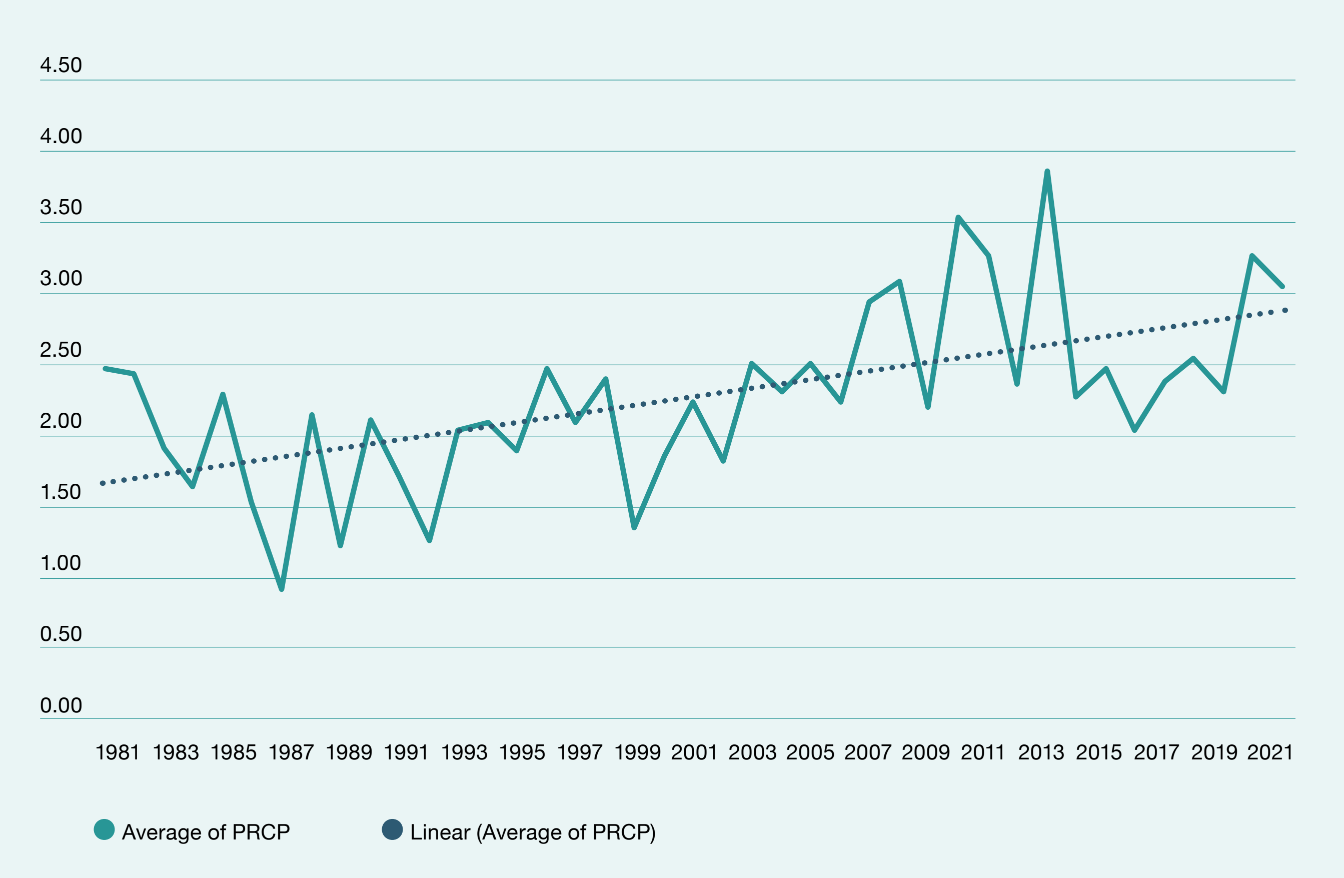
Table 8 | Basin-wise Precipitation (in mm) in Uttarakhand

	Name of the basin	Precipitation (in mm)
1	**Pithoragarh-Bageshwar**	2.04
2	**Khatima**	2.96
3	**Nainital-Ranikhet**	2.93
4	**Haridwar-Roorkee**	3.08
5	**Tehri-Uttarkashi**	1.94
6	**Joshimath-Srinagar**	2.02
7	**Ponta-Vikasnagar**	2.71
8	**Manglaur**	2.92

Source: Author's analysis based on data obtained from the NASA Langley Research Center (LaRC) POWER Project.

The annual average rainfall patterns span a 40-year duration, considering variations across seasons and spatial distribution within the region's grid. An upward trend in precipitation was observed over the specified timeframe, particularly evident in the monsoon, summer, and winter seasons. However, the increment in precipitation during the post-monsoon period was observed to be marginal.

Figure 5 | Average Precipitation (in mm) in Uttarakhand



Source: Author's analysis based on data obtained from the NASA Langley Research Center (LaRC) POWER Project.

The climatic parameters, specifically rainfall and temperature, were systematically gathered from a network of 42 strategically chosen locations spanning the entirety of Uttarakhand, as shown in **Figure 6**. The comprehensive analysis of these 42 locations yields a repetitive depiction of the climate variability prevalent across the entire state, incorporating certain buffer areas situated beyond its geographic boundaries. The holistic insights derived from this extensive dataset are visually encapsulated in **Figure 6** (basin-wise location of climate data), which serves as a compelling testament to the inclusivity of these selected locations in capturing the climatic dynamics of Uttarakhand and its surrounding regions.

Furthermore, a detailed regional analysis revealed a pronounced increasing trend in precipitation within the northeast region of Uttarakhand. Conversely, the northwest region exhibited a modest elevation in precipitation levels only, suggesting a spatial variability in the observed trends. These findings contribute valuable insights into the temporal and spatial dynamics of precipitation patterns, offering a nuanced understanding of the climatic changes occurring within the region over the studied time period (40 years).

Figure 6 | Basin-wise Location of Climate Data

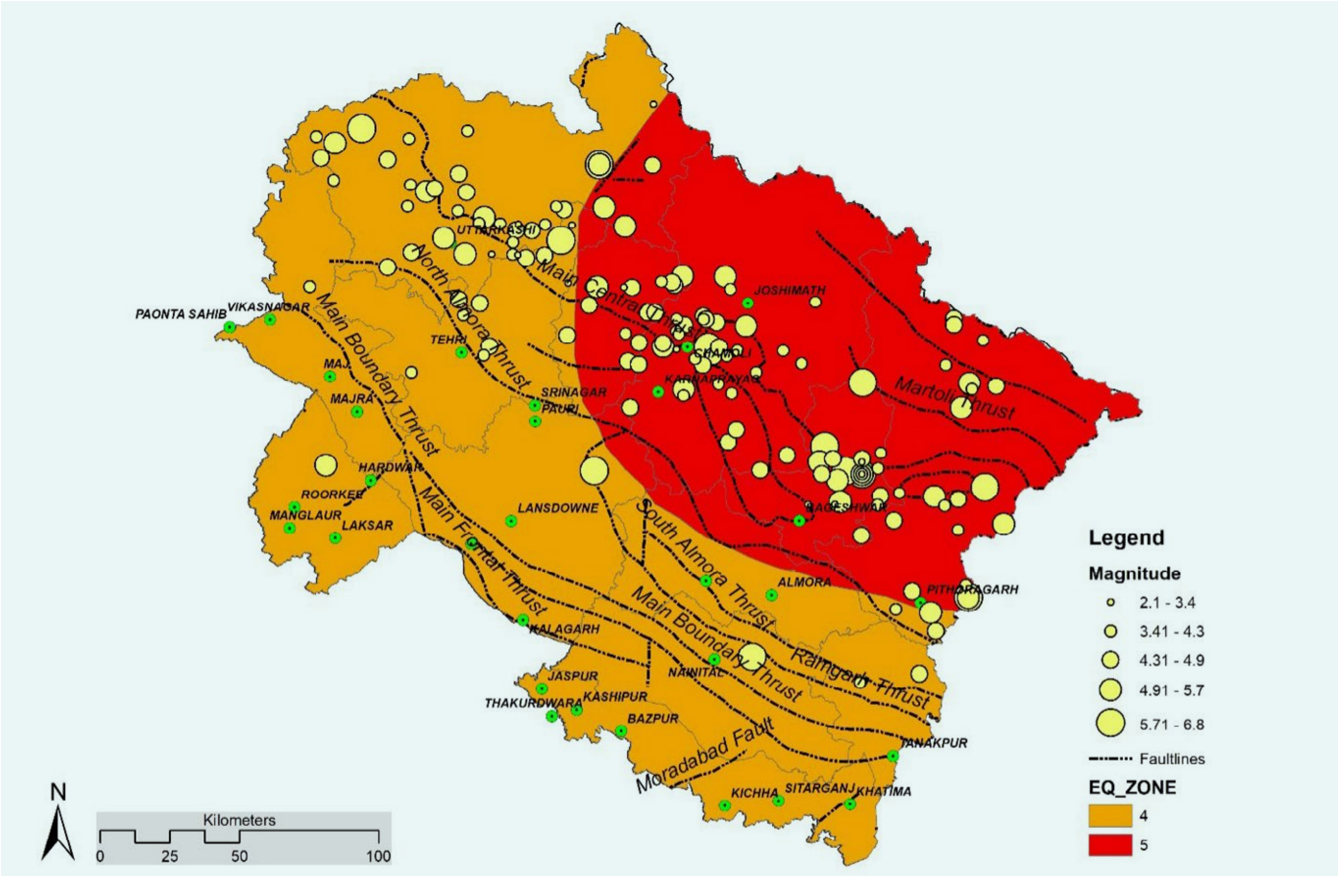
Source: Author's analysis.

6. Past Disasters

6.1. Earthquakes

The state is vulnerable to recurrent seismic activities owing to its geographical location along the Himalayan region. Positioned within seismic zones IV and V, as delineated by the Bureau of Indian Standards (BIS) code[13], the state occupies areas characterised as one of the most seismically active zones in the country. The frequent occurrence of earthquakes in this region underscores the imperative for robust seismic risk assessment and mitigation strategies to enhance the resilience of infrastructure and communities in face of seismic events. **Figure 7** depicts 155 historical earthquakes in the state.

Figure 7 | Uttarakhand's Seismic Setting



Source: Vulnerability Atlas of India, BMTPC, 2016.[14]

Table 9 provides a comprehensive overview of earthquake occurrences and their corresponding magnitudes across various districts in the region. This table enumerates seismic events within each district with their recorded magnitudes ranging from 2.1 to 6.8 on the Richter scale, indicating a diverse seismic profile across the districts. Notably, certain districts such as Nainital, Garhwal, and Haridwar have experienced earthquakes with magnitudes of 6 or higher, emphasising the seismic vulnerability of these regions. This data is instrumental in understanding the seismic landscape of the area and contributes to the ongoing efforts in seismic risk assessment and preparedness.

Table 9 | District-wise Earthquakes and Their Magnitudes Recorded in the State of Uttarakhand as of August 2024

District	Magnitude of earthquakes experienced within the district
Bageshwar	4, 4.2, 4.3, 4.4, 4.6, 4.7, 4.8, 5, 5.1, 6, 6.3, 6.5
Pithoragarh	2.4, 2.9, 3.1, 3.3, 3.6, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9, 5, 5.1, 5.2, 5.4, 5.6, 5.7, 5.8
Chamoli	4, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9, 5, 5.1, 5.5, 6.8
Joshimath	2.1, 3.3
Rudraprayag	4.1, 4.4, 4.5, 4.6, 4.7, 4.9, 5, 5.5
Champawat	4.3, 4.5
Nainital	6
Tehri Garhwal	4, 4.1, 4.5, 4.6, 4.7, 4.8, 6.6
Uttarkashi	2.5, 2.6, 2.8, 3.2, 3.4, 4, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9, 5, 5.1, 5.2, 5.5, 5.6, 5.9, 6, 6.8
Dehradun	4, 4.3
Garhwal	6
Haridwar	5.5

Source: Compiled by authors using multiple sources.

The state has a historical record of enduring significant seismic events for centuries, with the notable instances of the Kumar earthquake of 1720, Garhwal earthquake of 1803, Kangra earthquake of 1905, Uttarkashi earthquake of 1991, and the Chamoli earthquake of 1999. This protracted history underscores the region's susceptibility to high-intensity earthquakes and seismic activity, attributable to its location along the Himalayan belt.

Moreover, the state has been subject to both substantial earthquakes and minor tremors, indicative of the dynamic geological processes in the Himalayan region. A noteworthy observation is the seismic gap exceeding two decades in this area, a period during which significant tectonic stress may accumulate. The potential release of such accumulated stress could result in an earthquake of considerable magnitude, surpassing 6 on the Richter scale. These insights indicate the significance of seismic monitoring and preparedness efforts to mitigate the potential impact of future seismic events in the region.

Table 10 delineates a comprehensive analysis of major earthquakes within the state, categorised according to their respective river basins. It reveals varying seismic activity across different basins, with notable concentrations in the Pithoragarh-Bageshwar (49 earthquakes), Tehri-Uttarkashi (37 earthquakes), and Joshimath-Srinagar (51 earthquakes) basins.

Table 10 | Basin-wise Earthquakes Recorded in the State of Uttarakhand as of August 2024

	River basin	Number of Earthquakes recorded
1	**Pithoragarh-Bageshwar**	49
2	**Khatima**	0
3	**Nainital-Ranikhet**	1
4	**Haridwar-Roorkee**	3
5	**Tehri-Uttarkashi**	37
6	**Joshimath-Srinagar**	51
7	**Ponta-Vikasnagar**	14
8	**Manglaur**	0

Source: Author's analysis based on the BMTPC, 2016.

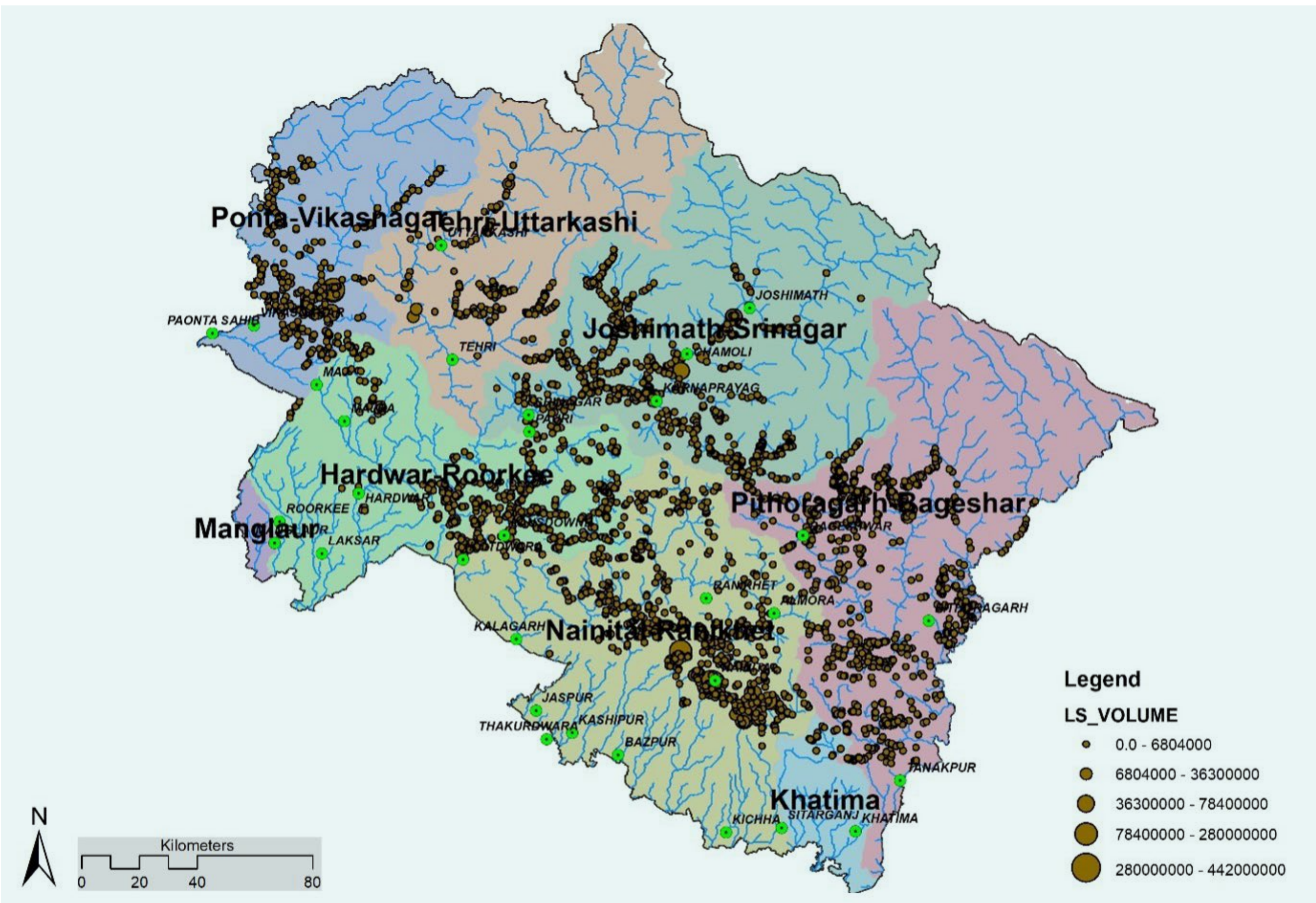
The observed correlation between seismic activity and river basins implies differing seismic risks across the regions. Notably, basins with higher earthquake counts, such as Joshimath-Srinagar, Pithoragarh-Bageshwar, and Tehri-Uttarkashi, pose elevated risks, particularly concerning the potential impact on HPPs. Given the seismic vulnerability associated with increased earthquake occurrences in specific basins, it is imperative to prioritise seismic risk assessment and implement robust mitigation strategies to safeguard critical infrastructure and enhance overall resilience in the face of future seismic events.

6.2. Landslides

The state of Uttarakhand is highly susceptible to landslides, and recent significant events underscore the severity of the associated risks. Two major incidents stand out in recent memory, beginning with the cloudburst event of 2013 in Kedarnath, which evolved into one of India's most devastating disasters since the 2004 Tsunami. Resulting in over 6,000 fatalities and numerous missing individuals, this event had a profound impact on the region. Subsequently, the flash flood triggered by an avalanche in the Nanda Devi glacier on the Rishiganga valley in 2021 in Chamoli led to another calamity, causing over 75 deaths and leaving many more missing.

The state has also experienced numerous small landslides, often attributed to anthropogenic activities such as slope cutting for roads and highways, deforestation for agricultural purposes, and urban development. **Figure 8** illustrates the scars of historical landslides in these river basins, including the associated volume of debris flow.

Figure 8 | Uttarakhand's Historic Landslides and Volume of Debris (cubic metres)



Source: Author's analysis from GSI National Landslide Susceptibility Mapping (NLSM), 2016

The Geological Survey of India (GSI) has documented over 3,500 landslides in the state, with basin-wise occurrences outlined in **Table 11**. Notably, the Pithoragarh-Bageshwar, Nainital-Ranikhet, and Joshimath-Srinagar basins exhibit significant landslide occurrences, indicating the diverse geographical areas affected by this natural hazard. Urgent attention to landslide-prone regions and sustainable land use practices is essential to mitigate the risks posed by landslides and safeguard the vulnerable populations and infrastructure in Uttarakhand.

Table 11 | Basin-wise Landslides

	River basin	Number of Landslides
1	**Pithoragarh-Bageshwar**	847
2	**Khatima**	18
3	**Nainital-Ranikhet**	771
4	**Haridwar-Roorkee**	530
5	**Tehri-Uttarkashi**	221
6	**Joshimath-Srinagar**	795
7	**Ponta-Vikasnagar**	341
8	**Manglaur**	0

Source: National Landslide Susceptibility Mapping (NLSM), 2016.

7.0 Future Risks

The Uttarakhand region is inherently susceptible to disasters, making it imperative to assess future disaster risks comprehensively. The future disaster risk is based on a ranking from the Uttarakhand State Disaster Management Authority (USDMA)'s Disaster Risk Assessment (DRA) Report of Uttarakhand, 2019.[15]

7.1 Earthquakes

Earthquake risk is evaluated based on economic and human vulnerabilities within these basins. Dehradun and Haridwar, which are significant contributors to the state's economy with several residential buildings and tourist attractions, are identified as the highest-risk areas. The Manglaur and Haridwar-Roorkee basins are ranked the highest for earthquake disaster risk, as indicated in the **Table 12**.

Table 12 | Basin-wise Earthquake Risk Ranking

	Name of the basin	Earthquake risk ranking
1	**Pithoragarh-Bageshwar**	11
2	**Khatima**	4
3	**Nainital-Ranikhet**	6
4	**Haridwar-Roorkee**	4
5	**Tehri-Uttarkashi**	7
6	**Joshimath-Srinagar**	9
7	**Ponta-Vikasnagar**	5
8	**Manglaur**	2

Source: USDMA, 2019. **Note:** Lower the rank value, higher the risk.

7.2. Fluvial Floods

The distribution of people, assets, and production systems exposed to flooding varies across Uttarakhand. Focusing on fluvial floods, Manglaur basin emerges with the highest risk, followed by the Ponta-Vikasnagar basin, as indicated in **Table 13**.

Table 13 | Basin-wise Fluvial Flood Risk Ranking

	Name of the basin	Fluvial flood risk ranking
1	**Pithoragarh-Bageshwar**	11
2	**Khatima**	6
3	**Nainital-Ranikhet**	7
4	**Haridwar-Roorkee**	4
5	**Tehri-Uttarkashi**	4
6	**Joshimath-Srinagar**	11
7	**Ponta-Vikasnagar**	3
8	**Manglaur**	1

Source: USDMA, 2019. **Note:** Lower the rank value, higher the risk.

7.3. Landslides

Landslide susceptibility is evaluated based on terrain conditions, predicting areas where landslides are more likely to occur. The Pithoragarh-Bageshwar basin is identified as the highest-risk area for landslides, as per **Table 14**.

Table 14 | Basin-wise Landslide Risk Ranking

	Name of the basin	Landslide risk ranking
1	**Pithoragarh-Bageshwar**	4
2	**Khatima**	11
3	**Nainital-Ranikhet**	9
4	**Haridwar-Roorkee**	7
5	**Tehri-Uttarkashi**	7
6	**Joshimath-Srinagar**	5
7	**Ponta-Vikasnagar**	11
8	**Manglaur**	12

Source: USDMA, 2019. **Note:** Lower the rank value, higher the risk.

5.0 Identification of High-risk Basins and Hydroelectric Power Plants

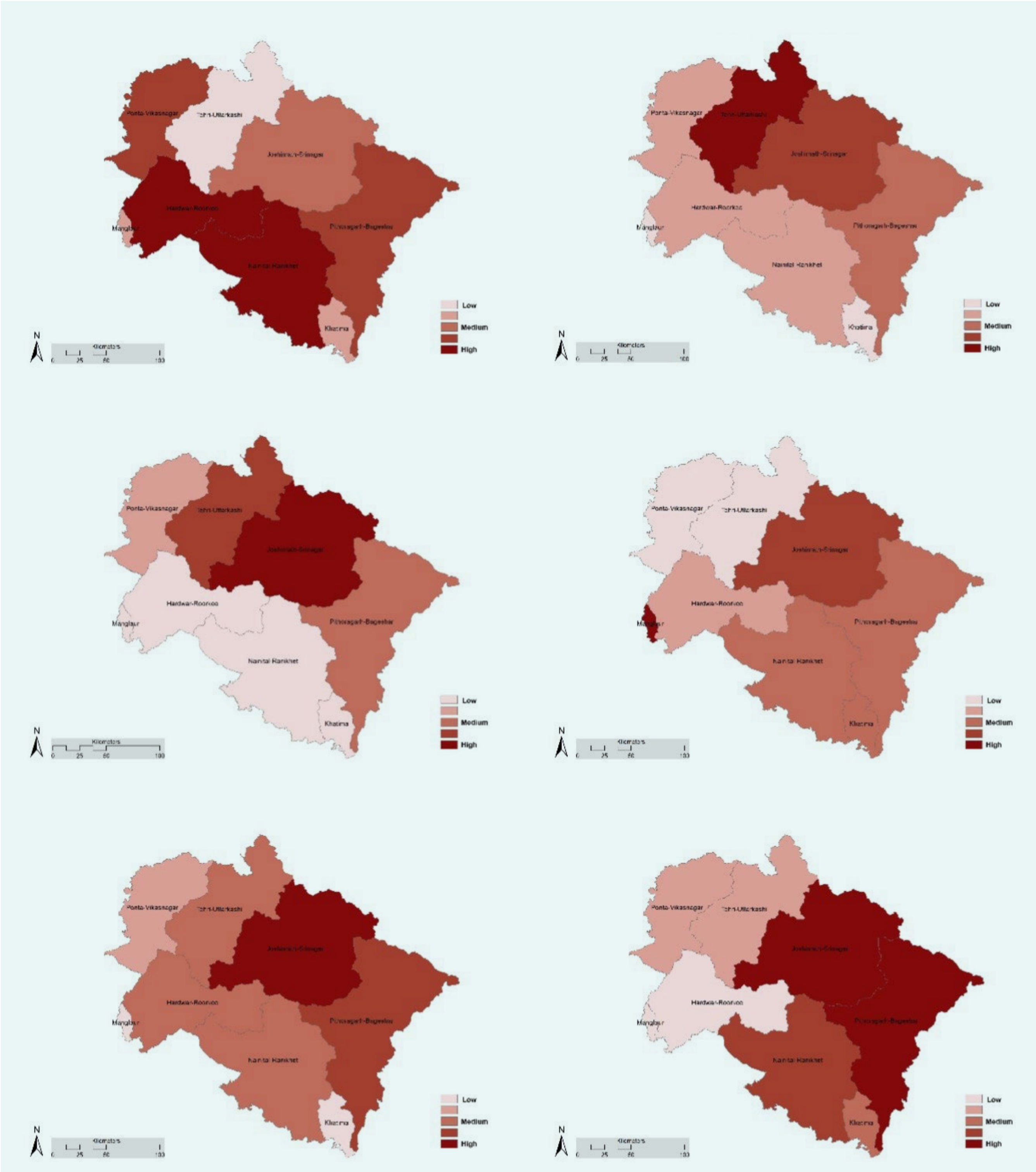
Based on this data processing and analysis, a multi-criteria evaluation methodology was formulated to ascertain the most vulnerable basin amongst the eight basins under consideration. Weightages were assigned to six different indicators based on how they influence the vulnerability of HPPs. Ranks were assigned based on the individual values of each of these indicators. The results, depicted in **Figure 10**, provide a visual representation of the vulnerability index across the eight basins, highlighting the most and least vulnerable areas. **Table 15** shows the individual values assigned to each of the indicators and the overall ranks of each basin.

Table 15 | Ranks for Individual Indicators

	Basin name	Socio-economic	HPPs	Glaciers	Climate variables	Past disasters	Future disaster risks	Overall
1	**Pithoragarh-Bageshwar**	1.5	0.5	0.7	0.8	2.5	1.2	1.31
2	**Khatima**	1.0	0.0	0.0	0.8	0.0	1.0	0.54
3	**Nainital-Ranikhet**	2.9	0.2	0.0	0.8	1.9	1.1	1.255
4	**Haridwar-Roorkee**	3.0	0.2	0.0	0.7	1.3	0.7	1.115
5	**Tehri-Uttarkashi**	0.9	2.2	1.0	0.5	1.3	0.8	1.295
6	**Joshimath-Srinagar**	1.2	0.9	1.9	0.9	3.5	1.2	1.81
7	**Ponta-Vikasnagar**	1.5	0.1	0.2	0.6	1.0	0.8	0.78
8	**Manglaur**	1.1	0.0	0.0	1.3	0.0	0.7	0.68

Source: Author's analysis. **Note:** Red represent higher vulnerability, orange represent medium vulnerability, and green represent lower vulnerability.

Figure 9 | Basin-wise Maps for Each Indicator



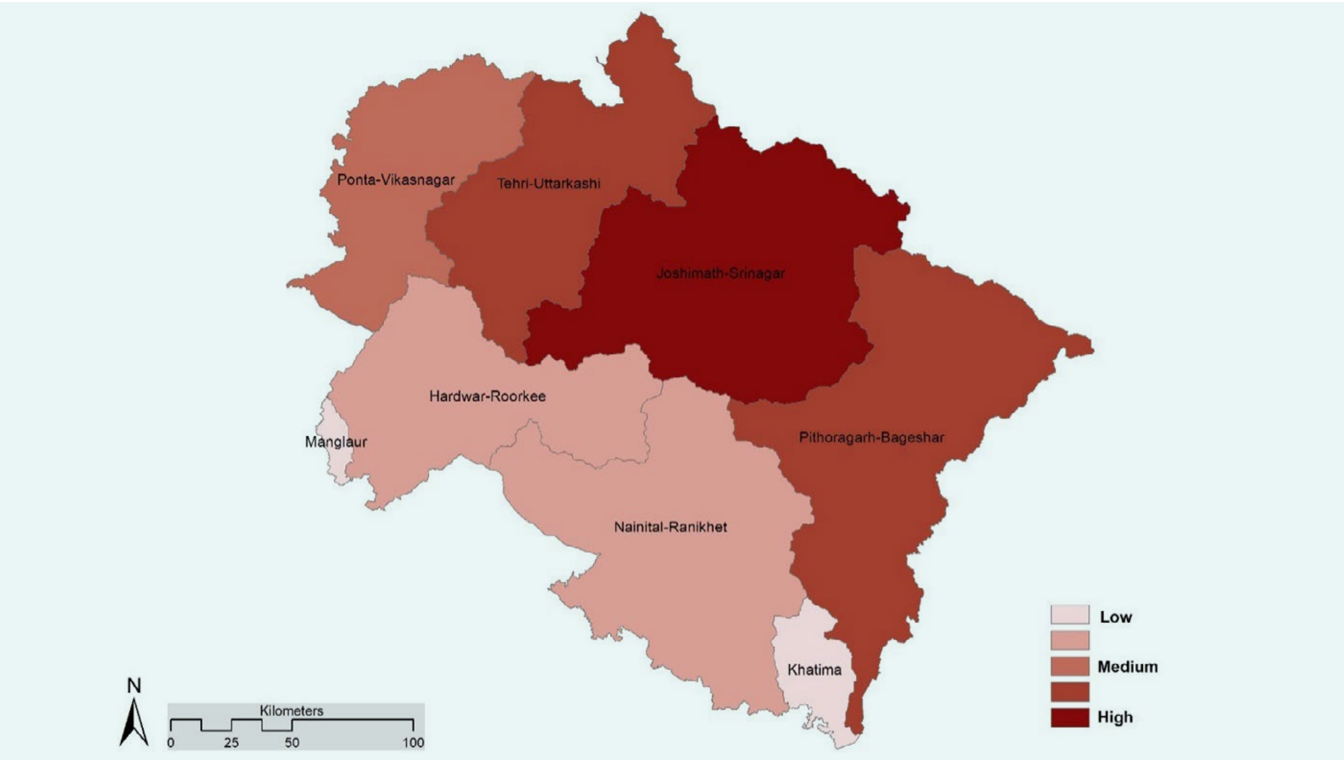
Source: Author's analysis.

Ranking and Weighting

The graphical representation in **Figure 9** illustrates how each of the eight basins fares in terms of the six pertinent indicators described in the previous chapter. A directional scoring methodology was employed to assess the eight basins based on these indicators. The amalgamation of the six district indicator maps resulted in the generation of a comprehensive vulnerability ranking assigned to each basin, as delineated in **Figure 10**. This final vulnerability ranking serves as a synthesised assessment of the potential susceptibility of these basins to various natural hazards, particularly in the context of HPPs.

Ranks were assigned to each indicator based on their significance in determining basin vulnerability, considering expert opinions and literature review. Based on the ranks, weights were assigned, and a final vulnerability index was calculated. Weights were assigned to each parameter to reflect their relative importance in influencing vulnerability. Weightages were determined from multiple experts based on the Delphi method[16]. Each basin was ranked based on their vulnerability index scores, with higher scores indicating higher vulnerability. The basin with the highest vulnerability index score was identified as the most vulnerable basin amongst the eight basins. The **Figure 10** shows the most vulnerable of the basins as assessed from this process.

Figure 10 | Basin-wise Vulnerability Ranking



Source: Author's analysis.

Image 2: Tehri Dam, Bhagirathi River, Uttarakhand. **Source:** Arvind Iyer, Mumbai, India–Tehri Dam, CC BY-SA 2.0, *https://commons.wikimedia.org/w/index.php?curid=4159690*

The Joshimath-Srinagar river basin has been identified as the most vulnerable among the considered river basins, particularly in the context of HPPs. Tehri-Uttarkashi and Pithoragarh-Bageshwar basins were also identified as highly vulnerable. **Annexure 3** of this report shows Uttarakhand's hydropower projects at various stages of development, excluding the ones in operation. As of April 2024, there are a total of 15 HPPs planned, announced and under construction in these three most vulnerable basins, according to the Global Hydropower Tracker.[17] Overall, these 15 projects have a project cost of ₹70,150.30 crore and have total capacity of 10,678 MW—refer **Annexure 3**.

The elevated vulnerability score of these regions is primarily attributed to past disasters and presence of glaciers within the basin. Additionally, socio-economic factors and climatic variables have further substantiated the high vulnerability ranking.

Moving forward, this outcome will serve as a foundational basis for subsequent analyses, which shall focus on evaluating the vulnerability of specific river stretches and existing HPPs in the next phase of study. This strategic progression aims to refine the understanding of vulnerabilities and facilitate targeted interventions to enhance resilience in the face of potential natural hazards.

6.0 Estimating Potential Losses Based on Case Study

In this chapter, we focus on the case study of the rockfall and flash flood event in Chamoli during February 2021 and the financial implications it has had for the NTPC Tapovan Vishnugad HPP project. This case study acts as a lens through which conceivable losses can be gauged, in order to help formulate effective risk management and mitigation strategies. While the focus is on an individual project, the findings have overarching implications for the financial viability of large-scale infrastructure development in the region.

In February 2021, Chamoli district in Uttarakhand experienced a catastrophic flash flood that inflicted extensive damage upon the NTPC Tapovan Vishnugad HPP. This calamity ensued from a glacial burst in the Rishiganga River, resulting in widespread flooding within the vicinity. The aftermath witnessed substantial destruction and severe impairment to various components of the NTPC Tapovan Vishnugad HPP, encompassing tunnels, bridges, and powerhouses.

Various research and news reports indicated that the damage incurred to the NTPC Tapovan Vishnugad HPP, as a consequence of the flash floods, was notable.[18] Numerous structures vital to the project's functionality, including tunnels, bridges, and powerhouses were severely damaged.[19] Before the Chamoli disaster, the project cost had escalated from an initial ₹2,978.5 crore to ₹13,500 crore, with a scheduled operational date of 2023. The aggregate financial ramifications of this calamitous event were estimated by the South Asia Network on Dams, Rivers and People (SANDRP) at approximately ₹1,625 crore.[20] However, our analysis suggests that this estimation errs on the conservative side, particularly when considering the computation of debris removal costs, as enumerated below.

Estimating Dredging Cost

An estimate of dredging costs following the flash flood event in the Chamoli district involves a consideration of the sediment deposition in various locations, notably the river/reservoir and associated civil structures of the NTPC Tapovan Vishnugad HPP. Based on satellite data analysis, we find that a debris layer of approximately 10–15 metres was deposited along the river/reservoir and civil structures. The reservoir, extending 2.7 km upstream of the NTPC Tapovan Vishnugad HPP, spans a length of 3 km and a width of 150 metres.[21] In the event that a decision is taken/has been taken to forego debris removal from the riverbed/reservoir, the viability of the project would need to be re-examined as the site characteristics would have undergone drastic changes, resulting in vastly reduced water impoundment/levels.

In addition to the reservoir, various subterranean civil structures of the HPP experienced sediment deposition. The volumetric estimates for debris accumulation in these structures are detailed in **Table 16**. The locations include the Machine Hall, Powerhouse, Head Race Tunnel (HRT), Cofferdam, Barrage sediment, Desilting tank, Diversion tunnel, Barrage, Pressure shafts, Tail Race Tunnel, Intake tanks, Sedimentation Tank, Penstock, and Head Regulator. The cumulative volume of debris in these civil structures is calculated to be approximately 1,74,58,547.24 cubic metres. These estimations serve as a foundational basis for comprehending potential dredging requirements and associated costs pertinent to the post-disaster restoration and rehabilitation efforts.

Image 3: Tapovan Vishnugad Hydropower Plant of NTPC, in Joshimath, Tuesday, Jan. 17, 2023. **Source:** PTI

Table 16 | HPP Components and Their Volume

Location of the debris	Volume of debris (in cubic metres)
Reservoir debris	67,50,000.00
Machine hall	51,93,619.60
Powerhouse	40,29,925.90
Head race tunnel–1	3,41,635.14
Cofferdam	3,30,000.00
Head race tunnel–2	2,10,634.21
Barrage sediment	2,08,824.00
Desilting tank	1,96,000.00
Diversion tunnel	1,01,660.00
Barrage	53,328.00
Pressure shafts (2 nos.)	11,925.90
Tail race tunnel	11,025.33
Intake tanks	9,800.00
Sedimentation tank	8,640.00
Penstock	793.16
Head regulator	736.00
Total volume	**1,74,58,547.24**

Source: USDMA, 2019.

Estimating Debris Removal Cost

The total volume of debris is estimated at 1,74,58,547.24 cubic metres of debris, which is equivalent to 4,30,35,319 tonnes.[22]

The actual costs for debris removal may vary significantly based on factors such as debris distribution and disposal site characteristics. Here, we use the example of the Noida twin building demolition,[23] where it took 90 days to remove 80,000 tonnes of debris. However, debris removal from an urban, contained building site is vastly different from a dispersed river valley. The HPP site presents significantly more complex challenges due to the vast and rugged terrain, the dispersed nature of the debris, exponentially larger volumes involved, and the presence of varying materials with accessibility challenges for machinery.

If we directly apply the Noida removal rate, it suggests that removing 1,74,58,547.24 cubic metres of debris would take 48,415 days (~133 years). The project proponent would want to restore the already delayed HPP in a much shorter time frame, say two years. This timeline can be met by scaling up resources, including equipment and labour.

The calculation integrates the following cost[24] components with specific assumptions:

1. Equipment Cost

Assumed to involve a combination of:

- Bulldozers (5 units, each clear about 200 m^3 of debris per hour)
- Excavators (8 units, each clear about 150 m^3 per hour)
- 3-tonne Loaders (10 units, each clear about 80 m^3 per hour)
- Backhoe Loader (JCB) (5 units, each clear about 100 m^3 per hour)

Combining the monthly capacities of all the equipment, a total of 7,28,000 m^3 of debris is piled up each month, based on an 8-hour daily operation over 26 working days. (For simplicity, this calculation assumes that the volume of debris removed by each type of equipment is mutually exclusive and thus can be considered cumulatively in the total, though in actuality this would not be the case. As a result, this is a conservative estimate.) To transport 7,28,000 m^3 of debris per month within two years would require 2,800 dump trucks, each with a carrying capacity of 10 m^3 and making a single round trip of 80 km per day.

Based on the respective monthly rates of equipment and quantities, and using the formula for equipment cost:

Total Equipment Cost = ∑(Number of Equipment × Monthly Rate × 24 months) + fuel costs

The total equipment cost is estimated at ₹712.11 crore.

2. Labour Cost

Assuming the requirement of 2,500 workers for manual labour, each remunerated at ₹550 per day for 730 days (24 months), the total labour cost amounts to ₹100.38 crore.

3. Dumping Fees

Contingent on the location, an assumed dumping fee of ₹1,500 per m^3 for disposing 1,74,58,547.24 m^3 debris lead to a total cost of ₹2,618,78 crore.

Consequently, the overall cost for debris removal is estimated to be ₹3,431.27 crore.

Table 17 | Overall Cost of Debris Removal

	Item	Estimated cost (in ₹ crore)
1	Equipment cost	712.11
2	Labour cost	100.38
3	Dumping fees	2,618.78
4	**Total estimated cost**	**3,431.27**

Source: Authors' analysis.

It is imperative to note that this estimate does not encompass additional recovery costs, including electro-mechanical costs, repairs and maintenance, acquisition and procurement expenses, loan amount escalation over time, etc. The overall impact of the disaster on the HPP is emphasised by the observation that each disaster sets back the project by at least five years, optimistically assuming high resource deployment during debris clearance. An initial project cost of ₹2,978.5 crore[25] has thus more than doubled due to various cost escalations.

Other Costs Incurred Due to Flood

The recurrent inundation events affecting the HPP inevitably induce an escalation in the project development costs, encompassing diverse facets such as financial debt servicing, rehabilitation of plant systems, reinstatement of power generation, and restoration of power distribution systems. The rehabilitation process entails the intricate restoration of electrical and mechanical components, including turbines, transformers, distribution lines, generators, Supervisory Control and Data Acquisition (SCADA) systems, control panels, switch yards, cables, and transmission lines, among others, as shown in **Table 18** below.

Image 4: Aftermath of flash floods, Pithoragarh District, Uttarakhand. **Source:** Ramwik, CC BY-SA 3.0, *https://commons.wikimedia.org/w/index.php?curid=49775510*.

Table 18 | Details of HPP Components

Main group of structures	Details
Intake structure	This is where water from the river or stream is diverted into the power plant through a canal, pipeline or other conduit.
Forebay	The water flows into a forebay or reservoir which acts as a buffer to regulate the flow of water to the turbine.
Penstock	A large pipe or tunnel that carries water from the forebay to the turbine.
Turbine	The water passes through the turbine, which converts the energy of the falling water into mechanical energy.
Generator	The turbine drives a generator, which converts the mechanical energy into electrical energy.
Transformer	The electricity generated by the generator is transmitted to a transformer, which steps up the voltage to a level suitable for transmission to the grid.
Transmission lines	The electricity is transmitted from the transformer to the grid through transmission lines.
Tailrace	The water leaving the turbine flows through a tailrace and is discharged back into the river or stream.

The quantification of these items adds supplementary dimensions to the previously estimated costs. Moreover, the delineated costs pertain exclusively to HPP-related aspects and do not incorporate the broader spectrum of socio-economic restoration and rehabilitation efforts.

Within the framework of post-disaster recovery initiatives, a meticulous PDNA is crucial for addressing the socio-economic reconstruction, rehabilitation, and recovery costs specific to HPPs affected by disasters. The PDNA also extends to broader domains, encompassing the overall impact on infrastructure, communities, and the economy. While this report primarily focuses on the vulnerability of HPPs to climate-induced disasters, the need for a thorough PDNA is emphasised to ensure effective and holistic recovery planning.

7.0 Findings

1. Himalayan Hydro Projects are Ignoring Financial Risks Due to Climate Events

Climate-related disasters pose significant financial risks to infrastructure projects in a fragile region such as the Himalayas. However, sufficient financial provision is not being made to manage these risks, as seen in the Chamoli case study, to the potential detriment of insurers, lenders and the local community.

2. High-Risk Basins and HPPs

The Joshimath-Srinagar basin was identified as the most vulnerable among the considered river basins, with Tehri-Uttarkashi and Pithoragarh-Bageshwar basins also showing high vulnerability. This elevated vulnerability is attributed to past and potential future disasters, the presence of glaciers, and socio-economic factors.

There are at least 15 HPPs at various stages of development in these three basins, with a total project cost of ₹70,150.30 crore. Further studies should delve into specific river stretches and existing HPPs to refine vulnerability assessment and suggest targeted interventions to mitigating and enhancing resilience against potential natural hazards. This study has provided a foundational basis for refining understanding and implementing focused strategies for disaster risk reduction.

3. Potential Losses to the State/National Governments and Investors and Insurers

The financial impact of the Chamoli disaster as estimated by SANDRP was approximately ₹1,625 crore. However, a detailed examination of the likely cost for debris removal post-flash flood gives us a conservative estimate of ₹3,431.27 crore. This estimate includes factors such as debris distribution, disposal site characteristics, and the extensive resources and equipment needed, covering costs for equipment, labour, and dumping fees.

This estimate does not encompass recovery costs for electro-mechanical components, repairs, maintenance, or loan amount escalation. Each disaster sets back the project by at least five years, leading to significant cost escalations. The initial project cost of ₹2,978.5 crore has thus more than doubled due to these factors, emphasising the need for proactive site selection screening and the consideration of abatement costs within the initial project budget for any project in the region.

The flash flood also induced an escalation in project costs, with repair and restoration costs exclusive to HPP-related aspects (that is, not socio-economic restoration efforts). This process involves intricate restoration of electrical and mechanical components, including the intake structure, forebay, penstock, turbine, generator, transformer, transmission lines, and tailrace.

Given the recurrence of such disasters, and the large number of HPPs in the region, the cumulative financial impacts to project proponents (particularly state and central governments) is significant. The likelihood of such impacts must be factored into financial projections of planned projects and the investment return calculations that determine financial viability.

PDNA is crucial for post-disaster recovery initiatives, covering socio-economic reconstruction, rehabilitation, and recovery costs. The recovery process can extend over years or even decades, highlighting the prolonged and intricate nature of restoration and reconstruction efforts.

Image 5: Tehri Dam, Bhagirathi River, Uttarakhand. **Source:** Gaurav Arora–Tehri Dam, CC BY 2.0, *https://commons.wikimedia.org/w/index.php?curid=4089090*.

8.0 Recommendations

To enhance the resilience and sustainability of hydropower projects in the face of climate-induced disaster risks, it is crucial to adopt holistic risk management approaches. The recommendations are categorised based on the following broad categories of comprehensive risk management approaches:

1. Assessing Risk

- Integrated risk assessment framework for HPPs that considers the complex interplay of geographical, socio-economic, and climate factors; and integrating climate-induced disaster risk screening into the early stage of HPP siting, planning and design HPPs.
- Conduct PDNA to evaluate the impacts of disasters and inform future planning.
- Adopt a multi-hazard planning approach that considers the interconnectedness of various climate-induced risks to HPP and evaluate their resilience against multiple hazards, addressing cascading effects.

2. Reducing Risk

- Avoid new HPPs in high-risk areas to minimise exposure to potential climate-induced disasters.
- Implement multi-hazard early warning systems (MHEWS) to provide timely alerts for impending climate-induced disasters, enabling proactive responses and strengthening monitoring systems for climate variables, glacial movements, and other indicators of potential disasters.
- Enforce and enhance climate-resilient HPP design standards, considering potential risks such as flash floods, landslides, and glacial bursts. Regularly update design codes based on the latest climate science and disaster risk assessments. Implement robust engineering solutions and innovative technologies to enhance the structural integrity of HPP components.

Image 6: 2021 Avalanche Rescue Operations in Uttarakhand. **Source:** Press Information Bureau, India, CC0, *https://commons.wikimedia.org/w/index.php?curid=99694449*.

3. Retaining Risk

- Conduct regular capacity-building programmes for local communities, government officials, and HPP operators on disaster preparedness, response, and recovery.

- Develop comprehensive disaster recovery planning including disaster relief funds that encompass not only debris removal; but also restoration of electrical and mechanical works, transmission lines, and other critical components. Include provisions for financial debt servicing and resumption of power generation in recovery plans.

4. Social Protection

- Incorporate community-centric approach including traditional knowledge in the location, planning and design of HPPs. Implement community-based adaptation strategies that enhance local resilience and empower communities to cope with climate-induced disasters. Conduct social impact assessments to identify and mitigate potential adverse effects on vulnerable populations.

- Consider community benefit sharing mechanisms such as a mix of revenue sharing, equity sharing, community development funds, and preferential employment and procurement schemes to ensure that the local communities benefit directly from the project. Ensuring the needs and priorities of the community are addressed through a meaningful participation and empowerment in decision-making process.

- Ensure gender equality, disability, and social inclusion (GEDSI) strategies in all aspects of HPP planning and implementation. Develop specific programmes to address the needs of women, people with disabilities, tribal and other groups affected by HPP projects.

5. Transferring Risk

- Develop and implement comprehensive disaster risk financing strategies that include a mix of financial instruments such as insurance, catastrophe bonds, and contingency funds. Explore the creation of a dedicated disaster risk financing pool to collectively manage risks and share financial burdens among multiple stakeholders.

- Develop Public Private Partnerships (PPPs) where the risks are shared between government and private sector investors to enhance the resilience and sustainability of HPPs.

6. Enabling Environment

- Create and enforce policies and regulations that promote climate-resilient infrastructure investments. Allocate resources for ongoing research and development to understand evolving climate patterns and their potential impacts on vulnerable regions. Foster collaboration with regional/national research institutions, government agencies, and the private sector to advance knowledge and technological solutions.

- Structure PPPs to attract private sector investment in hydropower projects by offering regulatory support and incentives in climate resilience.

7. Transformational Approaches

- Invest in technologies for enhancing climate resilience of hydropower infrastructure. Provide funding for research and development (R&D) on advanced materials and technologies for hydropower projects.

- Implement integrated water resource management practices that support sustainable hydropower operations by developing comprehensive water resource management plans that align hydropower development with broader environmental and social goals.

Climate Risk-proofing of Hydropower Infrastructure Investments

Climate risk-proofing involves integrating adaptation measures into planning, design and implementation of hydropower infrastructure projects to reduce vulnerability and enhance resilience. It encompasses processes such as site selection, risk assessment, design, planning, implementation, and monitoring and evaluation. This approach ensures that investment and infrastructure development projects are resilient to the impacts of climate change by accounting for future climate conditions and mitigating potential risks. This chapter provides a detailed framework for climate-risk proofing hydropower infrastructure investments, linking each risk management approach to appropriate financial instruments and sources of finance.

Table 19 is an illustrative list of financial instruments against the risk management approaches. Finding smart ways of combining financial instruments is crucial for addressing the risks for hydropower infrastructure investments.

Table 19 | Illustrative List of Financial Instruments Against Risk Management Approaches

Risk management approach	Risk assessment	Risk reduction	Risk retention	Social protection	Risk transfer	Sources of finance
Grants	✓	✓	✓	✓	✓	UNFCCC Funds (GCF, AF, L&D), Bilateral Aid, Philanthropic
Bonds		✓	✓		✓	MDBs, Sovereign Green Bonds, Corporate Green Bonds
Contingency financing		✓	✓		✓	MDBs, IMF, WB Contingent Financing
Insurance				✓	✓	Insurance Companies, Multilateral Risk Pools, WB, Private Sector
Concessional loans		✓	✓			Multilateral Development Banks (MDBs)
Non-concessional loans		✓	✓			Commercial Banks, IFC, Regional Development Banks
Equity investments		✓	✓			Private investors, Venture Capital Funds, DFIs
Guarantees			✓		✓	WB (e.g., MIGA), DFIs, Bilateral Aid Agencies

Source: Authors' analysis.

It is important to examine instruments not in isolation but in complementarity and combination across financial instruments and policies—no single financial instrument can optimise channel financing to cover a full spectrum of impacts. Multiple sources of finance are available for each stage:

- Grants are versatile, covering all aspects from risk assessment to social protection and risk transfer.
- Bonds are useful for risk reduction, retention, and transfer, with support from multilateral development banks (MDBs) and green bond markets.
- Contingency financing provides flexibility for risk reduction, retention, and transfer, backed by MDBs and international financial institutions.
- Insurance focuses on risk retention and transfer, offered by insurance companies and multilateral risk pools.
- Concessional loans and non-concessional loans support risk assessment and reduction, provided by development banks and commercial banks.
- Equity investments aid in risk assessment and reduction, driven by private investors and venture capital funds.
- Guarantees facilitate risk retention and transfer, supported by entities like the World Bank and bilateral aid agencies, and national government agencies.

By strategically combining these financial instruments, stakeholders can effectively manage and mitigate the risks associated with hydropower infrastructure investments, ensuring long-term resilience and sustainability in the face of climate change.

Moreover, stakeholders can address additional fundings gaps and enhance support by using catalytic investments from various sources, including private investors, development finance institutions (DFIs), and philanthropic organisations. Key aspects of catalytic investments include accepting disproportionate risk or concessionary returns, filling financial gaps, blended finance, demonstrating viability, and mobilising additional capital. These strategies are crucial for climate risk-proofing hydropower projects, fostering the development of resilient infrastructure development.

Similarly, by integrating mountain-specific nature-based solutions (NbS) into hydropower planning and implementation, stakeholders can further enhance the resilience and sustainability of infrastructure investments. Examples include reforestation, sustainable land management practices, and the restoration of natural water systems, etc., NbS in mountainous regions not only support hydropower projects by reducing the risks of landslides, floods, and soil erosion; but also promote biodiversity and support local communities, ensuring they are better equipped to handle the impacts of climate change.

9.0 Conclusion

This report emphasises the urgent need to address the escalating climate-related risks facing HPPs in Uttarakhand. The state's geographical, socio-economic and climatic factors place both existing and proposed hydropower projects at significant risk from natural hazards and climate change impacts.

The analysis identified the Joshimath-Srinagar basin as the most vulnerable to climate-induced disasters, primarily due to its high incidences of past disasters, significant glacial presence, and socio-economic challenges. Over the past four decades, there has been a noticeable increase in minimum temperatures and fluctuating precipitation patterns. These climatic changes heighten the risk of GLOFs and flash floods, further endangering hydropower infrastructure.

Uttarakhand's history of earthquakes, landslides, and floods, along with projections of future climatic events, underscores the critical need for robust disaster risk management and climate adaptation strategies. By mapping high-risk basins and HPP locations, the study pinpointed the most vulnerable installations. This approach facilitates targeted risk assessments and the development of specific mitigation strategies to protect these essential assets.

The case study of the Chamoli flash flood in February 2021, which caused extensive damage to the NTPC Tapovan Vishnugad HPP, highlights the severe financial risks associated with such disasters. Estimated costs for debris removal and infrastructure rehabilitation underscore the necessity for pre-emptive risk management and budget allocations for potential climate impacts. More recent events in Sikkim (GLOF of October 2023 and landslides in August 2024) further illustrate the dire consequences of ignoring these risks. The GLOF caused catastrophic damage to the Teesta III Hydroelectric Power Project, demonstrating the vulnerability of HPPs to such events. The flood destroyed infrastructure, displaced communities, and disrupted power supplies, leading to significant economic and social impacts. This incident is a stark reminder of the urgent need for robust climate resilience measures in hydropower development.

Image 7: An aerial view of flood-ravaged Rudraprayag, Uttarakhand. **Source:** Ministry of Defence (GODL-India), GODL-India, *https://commons.wikimedia.org/w/index.php?curid=71889561*.

To address these risks effectively, climate risk-proofing measures must be integrated into the planning, design, and implementation of hydropower infrastructure projects. This involves a comprehensive process of risk assessment, site selection, adaptive design, planning, implementation and monitoring to reduce vulnerability and enhance the resilience of HPPs. By accounting for future climate conditions and mitigating potential risks, climate risk-proofing ensures that hydropower investments are sustainable and secure. The framework presented in this report links each risk management approach to appropriate financial instruments, allowing stakeholders to align with global best practices in resilience-building and climate adaptation.

Addressing the climate-related risks to HPPs in Uttarakhand is critical for safeguarding financial stability, ensuring societal resilience, and fostering sustainable development. Investing in climate risk-proofing measures or disaster prevention not only saves lives and infrastructure; such investments also make financial sense: the cost of climate risk-proofing/prevention is almost always less than the cost of restoration and recovery.

10.0 Annexures

Annexure 1

Figure 11 | Season-wise Daily Average Minimum Temperatures

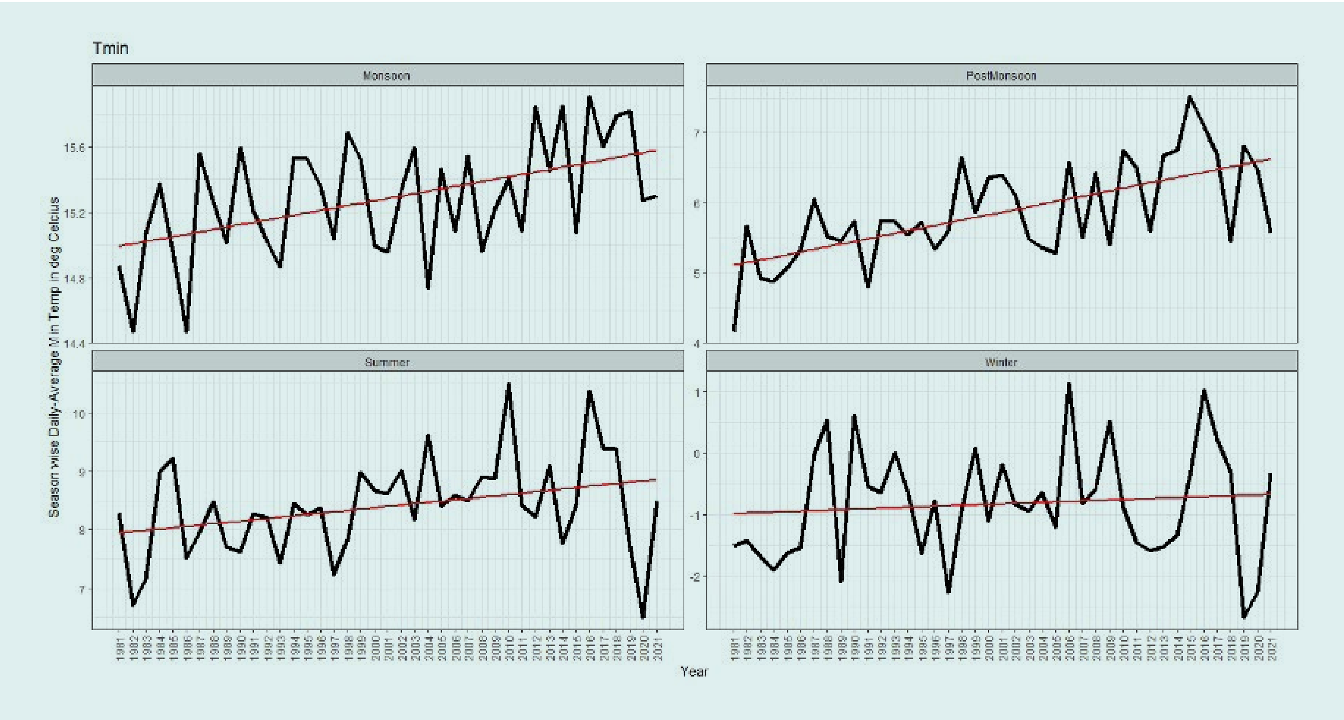


Figure 12 | Season-wise Daily Average Maximum Temperature

Figure 13 | Season-wise Average Rainfall

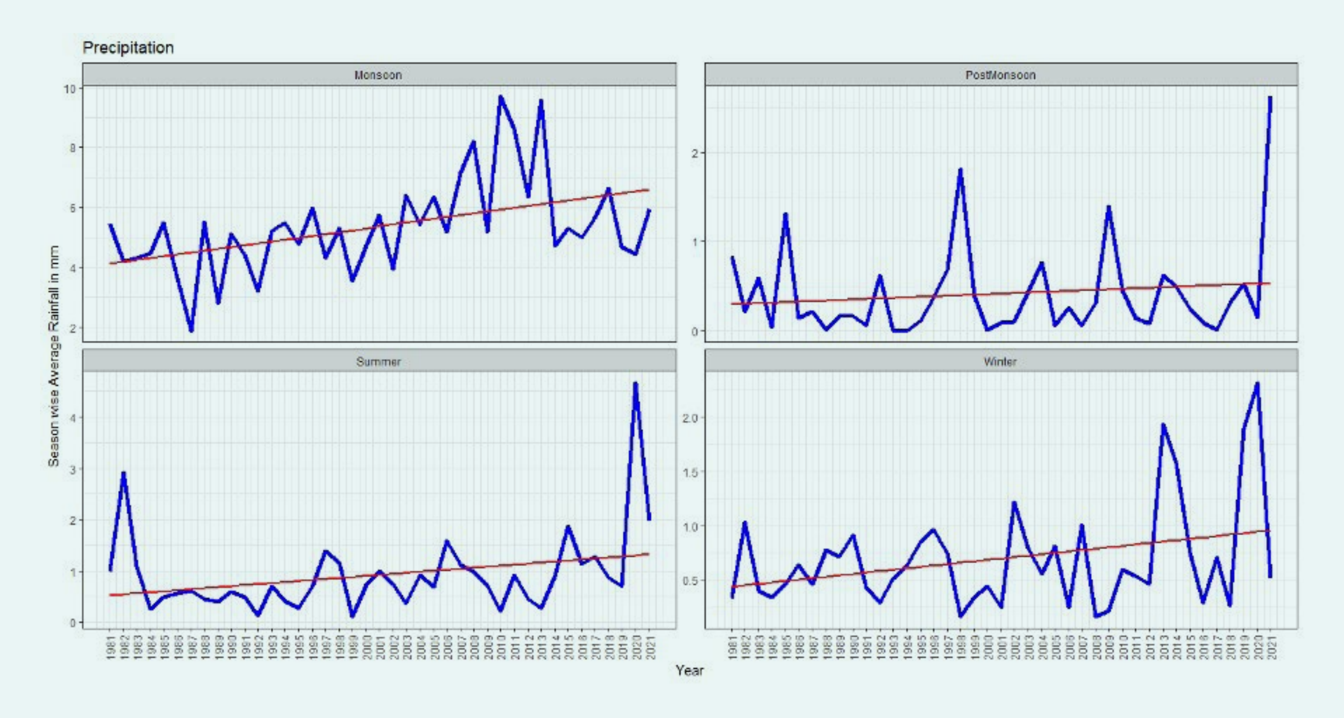


Figure 14 | Location-wise Variation in Tmin

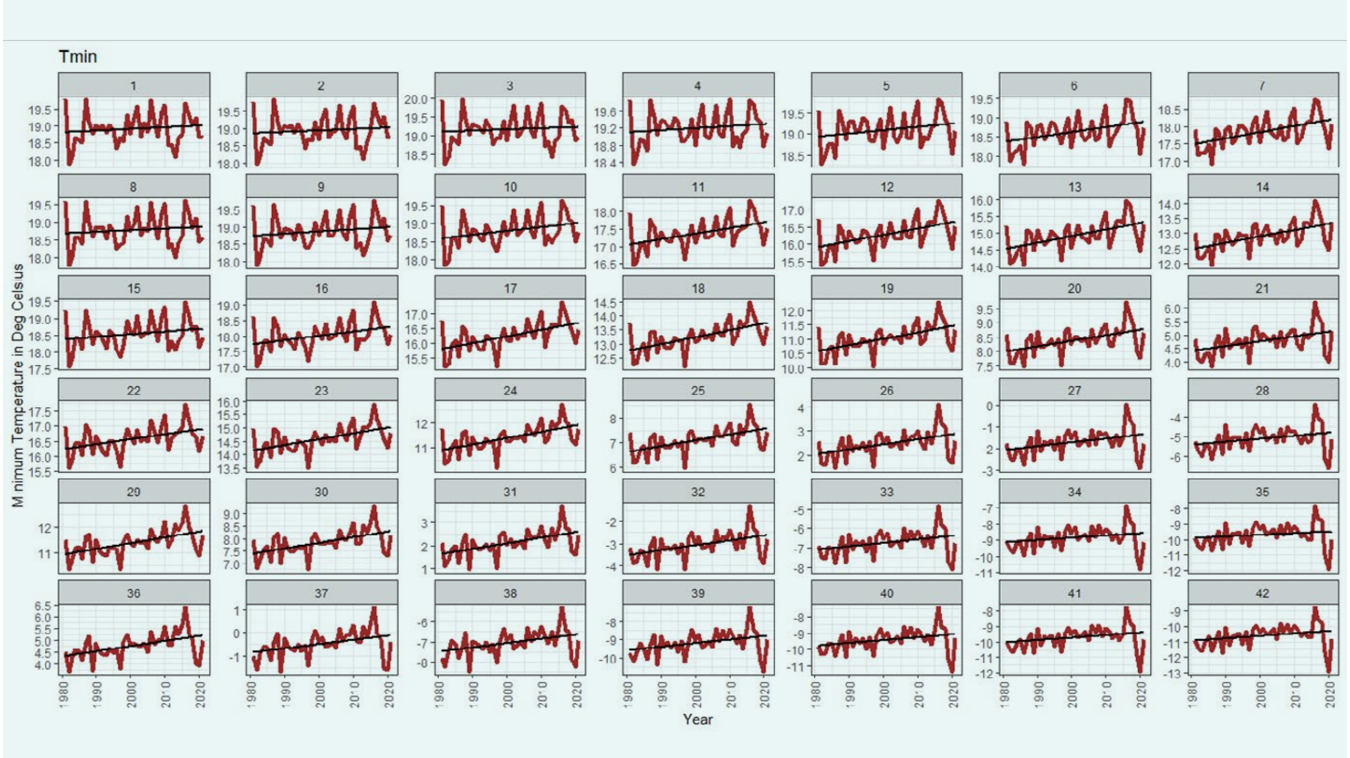


Figure 15 | Location-wise Variation in Tmax

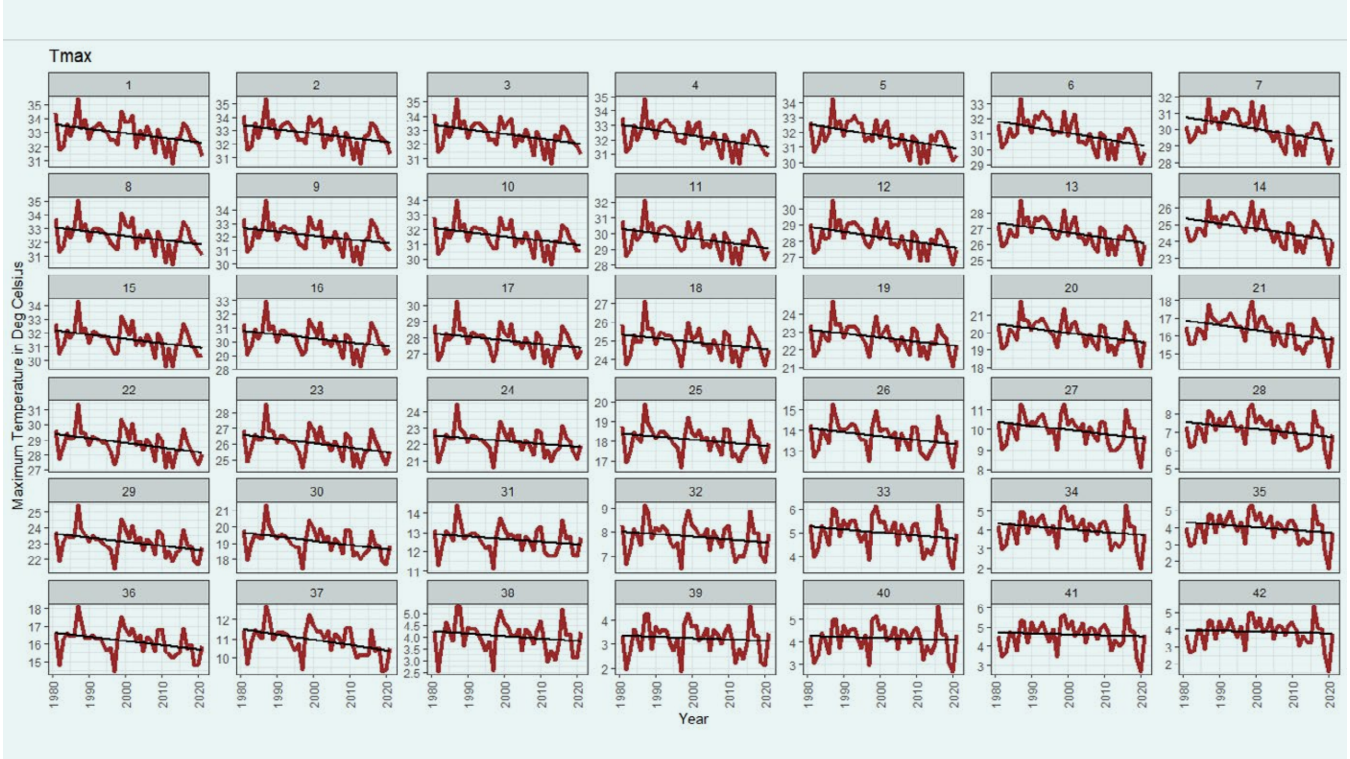
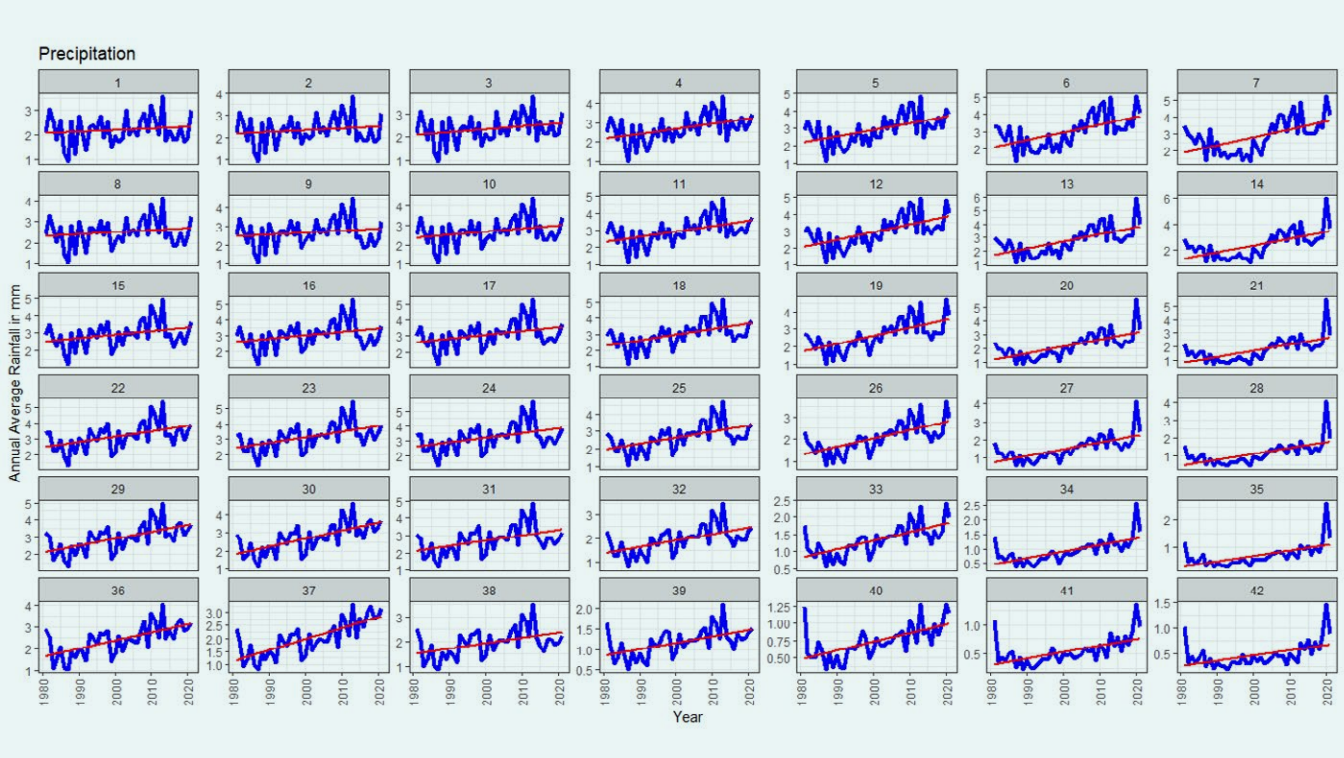


Figure 16 | Location-wise Variation in Precipitation



Source: Analysis by author based on data obtained from the NASA Langley Research Center (LaRC) POWER Project.

Annexure 2

According to the Central Electricity Authority (CEA), the status of large hydropower development in Uttarakhand as of January 11, 2023,[26] is given below:

		Nos.	Capacity (MW)
Total identified Large Hydro Power Projects potential (capacity above 25 MW)		81	17,356.75
Projects in operation		18	3,975.35
Projects under active construction		3	1,024
Projects on which construction is held up		2	247
Projects allotted by State for development			
(i)	**Projects yet to be taken up for construction**	3	815
(ii)	**Projects returned to project authorities**	6	789
(iii)	**Multi-Purpose Projects (International Projects) under examination by India and Nepal**	2	2,400
(iv)	**Multi-Purpose Projects**	2	960
(v)	**Projects under Survey & Investigation (S&I)**	3	434
(vi)	**Projects on which S&I is held up**	15	2,366
Projects dropped/stuck due to basin studies/other reasons		7	2,457
Projects yet to be allotted by the State for development		22	3,028

Annexure 3

The table below, derived from the Global Hydropower Tracker—April 2024, displays the hydropower projects at various stages of development in Uttarakhand. These projects are mapped against the different basins in the region.

Basin Name	Hydropower plant	Capacity (MW)	Project cost (in ₹ crore)	Price level	Status
Tehri-Uttarkashi	Arakot Tiuni	81	583.65	2008	Announced
Pithoragarh-Bageshwar	Bokang Bailing	165	449.2	2019	Announced
Joshimath-Srinagar	Bowala Nand Praya	300	2226.56	2015	Announced
Pithoragarh-Bageshwar	Garba Tawaghat	630	5389.46	2022	Announced
Pithoragarh-Bageshwar	Kalika Dantu	230	1935.43	Not available	Announced
Joshimath-Srinagar	Nand Prayag	100	1140	2010	Announced
Pithoragarh-Bageshwar	Sela Urthing	230	696.73	2023	Announced
Pithoragarh-Bageshwar	Pancheshwar	6480	34971.94	2015	Pre-construction
Joshimath-Srinagar	Devsari	194	1387.37	2019	Pre-construction
Joshimath-Srinagar	Jhelum Tamak	108	1290.25	2013	Pre-construction
Nainital-Ranikhet	Kotli Bhel I A	195	1298.49	2011	Pre-construction
Nainital-Ranikhet	Kotli Bhel I B	320	1911.33	2011	Pre-construction
Haridwar-Roorkee	Lakhwar Multipurpose	300	1388.28	2012	Pre-construction
Joshimath-Srinagar	Sirkari Bhyol	120	7949.26	2024	Pre-construction
Joshimath-Srinagar	Phata Byung	76	466	2023	Construction
Joshimath-Srinagar	Tapovan Vishnugad	520	2978.5	2006	Construction
Tehri-Uttarkashi	Tehri Pumped Storage	1000	4825.6	2019	Construction
Joshimath-Srinagar	Vishnugad Pipalkoti	444	3860.35	2019	Construction

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