

Article

Flood Management Issues in Hilly Regions of Uttarakhand (India) under Changing Climatic Conditions

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Abstract: Uttarakhand, an Indian Himalayan state in India, is famous for its natural environment, health rejuvenation, adventure, and a pilgrimage centre for various religions. It is categorised into two major regions, i.e., the Garhwal and the Kumaon, and geographically, the Bhabar and the Terai. Floods, cloudbursts, glacier lake outbursts, and landslides are the major natural hazards that cause the highest number of mortalities and property damage in this state. After becoming a full 27th state of India in 2000, the developmental activities have increased many folds, which has added to such calamities. This study briefly summarises the major incidents of flood damage, describes the fragile geology of this Himalayan state, and identifies the natural as well as the anthropogenic causes of the flood as a disaster. It also highlights the issue of climate change in the state and its adverse impact in the form of extreme precipitation. Besides these, it reviews the challenges involved in flood management and highlights the effective flood risk management plan that may be adopted to alleviate its adverse impacts.

Keywords: flood management issues; natural disasters; climate change; government policies



Citation: Kansal, M.L.; Singh, S. Flood Management Issues in Hilly Regions of Uttarakhand (India) under Changing Climatic Conditions. *Water* **2022**, *14*, 1879. <https://doi.org/10.3390/w14121879>

Academic Editors: Slobodan P. Simonovic, Subhankar Karmakar and Zhang Cheng

Received: 11 February 2022

Accepted: 7 June 2022

Published: 10 June 2022

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1. Introduction

The occurrence of natural disasters and climate change are the two complex and most challenging issues which have long-term impacts on any country's environmental, economic, and social well-being. Researchers have focused on forecasting extreme hydro-meteorological events, such as cloudbursts and extreme precipitation, and their increased intensity and frequency, especially in the mountainous regions [1]. The mountainous region's characteristics such as fragile geology and restricted or marginal accessibility further escalate such hazards into a disaster [2]. Flash flood, along with the landslides in mountainous regions, is the most catastrophic natural disaster that causes the loss of lives and damage to infrastructure and other economic activities [3]. In the last 30 years, flood alone has contributed to about 50% of the total affected 80 million people due to natural disasters. On the economic front, flood damage is worth more than USD 11 million around the world [4]. It is feared that precipitation extremes and the ensuing flooding are expected to become even more frequent in most parts of Asia, Africa, and South and Southeast Asia in the next decades due to climate change. Moreover, these countries face significant difficulty acquiring land use, topography, and hydro-meteorological information, contributing to major uncertainty in flood management studies [5]. Among Asian nations, India has the most flood-related fatalities and is highly exposed to disaster risks. In India, planning and enacting a climate response strategy is even more difficult as the country has vast geographic heterogeneity [6]. India ranks 31st out of 191 countries in the INFORM Risk Index (Index for Risk Management), 2020 [7]. In 2021, India ranked 121st out of 182 countries under the Notre Dame Global Adaptation Initiative (ND-GAIN) Index [8], representing the vulnerability to climate change.

The Indian Himalayan Region (IHR), with diverse demographic, economic, social, environmental, and political systems, plays an important role in the country's nexus of

water, energy, and food. It has an inimitable topographical and climatic setting, making it prone to numerous hydro-meteorological disasters such as floods, cloudbursts, glacier lake outbursts, and landslides [9,10]. In the last 30–40 years, the frequency and severity of natural hazards have risen due to various anthropogenic and changing climatic conditions [11]. The anthropogenic activities such as the construction of dams, roads, deforestation, etc., have further aggravated the disasters which have disrupted the Himalayan ecosystem in the various states such as Uttarakhand [12]. The climate change in the Himalayas has resulted in irregular precipitation, temperature rise, drying up of perennial rivers, depletion of natural resources, and an increase in the frequency and intensity of flash floods [13]. Uttarakhand, an important state in the IHR, has undergone a considerable expanse of flood disasters. The major natural disasters in Uttarakhand include the disasters of 1970, 1986, 1991, 1998, 2001, 2002, 2004, 2005, 2008, 2009, 2010, 2012, 2013, 2016, 2017, 2019, 2020, and 2021 [14,15]. It may be noticed that the severity and frequency of flood incidents have increased in recent years.

Flood risk management is crucial as it provides optimal utilisation and exploitation of land and water resources that bring prosperity and sustainable development to a nation [16]. In India, flood risk management in plains has been emphasised, and policies have been framed to mitigate its ill effects. However, flood risk management in hilly regions is still in the infancy stage, particularly due to complex and tough terrain with limited accessibility and a low level of monitoring [17,18]. Experience with the last few decadal floods has shown that the structural measures alone could not ensure adequate security against such disasters. Therefore, an effective flood management strategy to safeguard these disasters is essential. This study briefly summarises the major flood damage incidents in the state and identifies its natural and anthropogenic causes. Further, the study reviews the challenges involved in flood management and highlights the flood risk management plan that may be adopted to alleviate its adverse impacts.

2. Material and Methods

2.1. Study Area Physiography

The IHR is one of the world's youngest mountain ranges and is characterised by fragile and sensitive ecosystems concerning geological hazards, geodynamics, topography, biodiversity, and water resources status [19]. It spreads over 11 states and 2 union territories and covers 500,000 sq. km. It stretches approximately 2500 km from the Hindu Kush in the north-west to Myanmar in the south-east [20].

The state of Uttarakhand, a part of IHR, is located between latitudes 28.44° and 31.28° north and longitudes 77.35° and 81.01° east. Uttarakhand was created out of northern Uttar Pradesh in the year 2000. Uttarakhand is well-known for its thriving spiritual and religious tourism industry, ecological diversity and richness, and a cultural ethos rooted in traditions. The state hosts numerous pilgrimage sites, namely Panch Kedar for Hindus, Piran Kaliyar for Muslims, Hemkund Sahib for Sikhs, Digambar Jain temple for Jains, and Christ Church for Christians, the hotspot of tourism activities. The state is divided into two regions, Garhwal (the western region) and Kumaun (the eastern region), as shown in Figure 1, having 95 development blocks in 13 districts.

Many perennial Indian rivers originate in Uttarakhand. There are six major river basins in the states, namely, Alaknanda, Bhagirathi, Ganga, Kali, Ramganga, and Yamuna, as shown in Figure 2. The major basins of Garhwal region are Alaknanda, Bhagirathi, Yamuna, and Ganga and major tributaries are Bhilangna, Dhauliganga-Garhwal, Mandakini, and Tons. The major basins of Kumaon region are Kali and Ramganga and major tributaries are Saryu, Gori Ganga, and Pindar. Some basic characteristics of the major river basin of Uttarakhand estimated from geographic information system (GIS) analysis are given in Table 1.

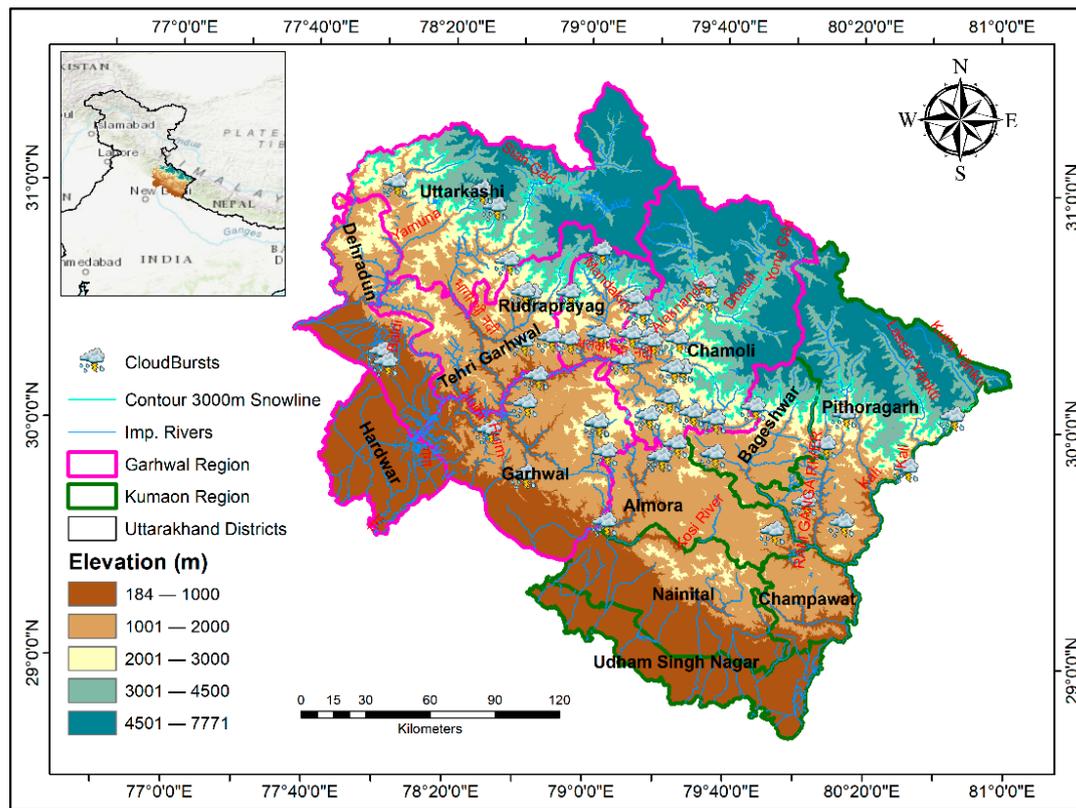


Figure 1. Map of Uttarakhand showing district, regions, and locations of cloudbursts.

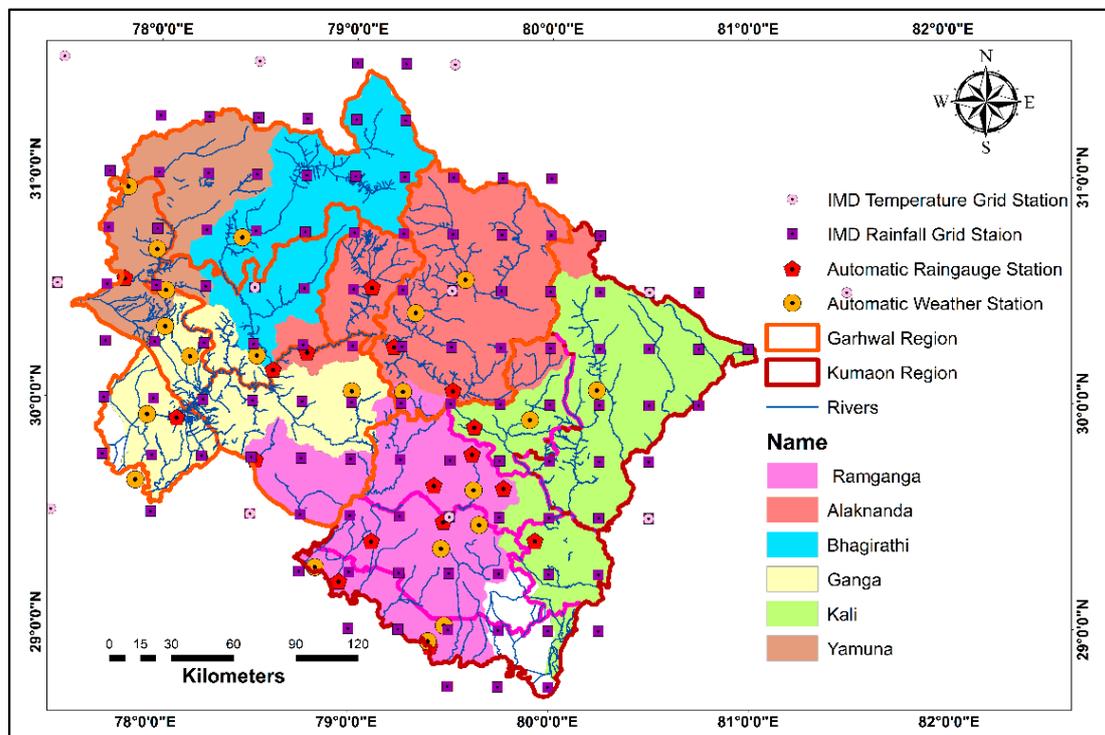


Figure 2. The spatial distribution of IMD-ARG and IMD-AWG along with the major river basins in the state of Uttarakhand.

Table 1. The basic characteristics of major rivers of Uttarakhand estimated from GIS analysis.

S. No.	Name	Area (sq. km.)	Mean Annual Rainfall (mm)	Mean Slope (Degrees)	Mean Elevation (m)	Elevation Range (m)	River Length (km)
1	Alaknanda	11,083	1035	28	3402	459–7785	195
2	Bhagirathi	7323	1011	27	3451	459–7054	190
3	Yamuna	5462	1175	24	2182	360–6278	170
4	Ganga	7282	1240	14	936	217–3076	125
5	Ramganga	11,319	1354	13	939	190–3089	185
6	Kali	11,014	1193	26	2552	185–7070	252

The state is divided into five transverse zones: (a) To the south of the Himalayan Frontal Fault (HFF)—the Terai. (b) Between the Shivalik (Outer Himalayan) range and the Main Boundary Fault (MBF)—the Doons. (c) Between the Main Central Thrust (MCT) and the MBF, along with the ridges up to around 3000 m high—the Middle Himalaya. (d) The area north of the MCT, which includes the perennially snow-covered peaks at heights of up to 8000 m—Inner Himalaya. (e) To the north of the snow-covered hills—the Trans Himalaya. Uttarakhand is a geological part of the Western Himalayas that can be classified into five morphological regions of varying physiographical and geological features. The regions from South to North comprise the Outer (sub-Himalayas), then the Lower Himalayas (Lesser Himalayas), followed by the Greater Himalayas, the Tethys (Tibet), and the Trans Himalaya [21].

2.2. Climatic Characteristics

The climate in the state ranges widely from the Terai region's sub-tropical humid atmosphere to the tundra-like atmosphere in the Greater Himalayas. The climate and landscape vary greatly with altitude (186–7619 m), from the largest glaciers in the higher elevation to the subtropical forests in the lowest elevation. Substantial annual precipitation falls as snow and feeds the Himalayans at high altitudes (>3000 m) [22].

The lowlands along the border of Uttar Pradesh are covered by the drier Terai-Savanna grasslands, the moist deciduous forest of the Upper Gangetic Plains, and form the Bhabhar belt. However, due to the extensive agricultural practices, most of these lowland forests have been cleared [21]. Snow and bare ice occupy the highest altitudes.

This mountainous state occupies 53,483 sq. km., i.e., 1.63% of India's total land area. Out of the 13 districts, Uttarkashi occupies the maximum area of 8039 sq. km. (15%), while Champawat covers the minimum area of 1634 sq. km. (3%). Uttarakhand experiences four types of seasons, namely, Monsoon from June to September (JJAS), Post-monsoon from October to November (ON), Cold weather from December to February (DJF), and Pre-monsoon (Hot Weather) from March to May (MAM). The estimated normal annual precipitation in the state is 1446 mm. Rain usually starts at the end of April and lasts until September. The monsoon rainfall amounts to 78% of annual rainfall, making this state prone to flood incidents during monsoon. Bageshwar receives the maximum normal annual rainfall (1872 mm), out of which 81% falls in the monsoon season. Haridwar receives the minimum normal annual rainfall (1107 mm) of all.

Further, due to differences in elevation, position, slope, and other topographical features throughout the state, the state's temperatures vary widely. During March and April, temperatures rise until they peak in May and June, when the mean maximum temperature in the southern and valley regions of the state is between 34 and 38 °C, and the mean minimum temperature is between 20 and 24 °C. Temperatures can reach 42 °C in the valleys and southern half of the state and 30 °C in two-kilometre-high elevations on some days. Day and night temperatures begin to dip around the end of September and reach the lowest in January and early February. January is the coldest month, with an average maximum

temperature of around 20 °C and an average lowest temperature of approximately 6 °C in the southern section and river valleys. The mean maximum and mean minimum temperatures range from 10 to 12 °C at altitudes of 2 km [23]. Table 2 summarises the district-wise details of the area, rainfall, temperature, and elevation characteristics in the various seasons. Figure 3 shows the state’s district-wise climatic characteristics regarding normal rainfall and temperature.

Table 2. The district-wise climatic characteristics and topography of the state.

District	Area (sq. km.)	Temperature (°C)						Normal Rainfall (mm)					Elevation (m)	
		Min. Temp.			Max. Temp.			ON	DJF	MAM	JJAS	Annual	Min.	Max.
		Min.	Max.	Mean	Min.	Max.	Mean							
Almora	3088	1.9	19.2	11.0	13.7	26.7	21.6	32	118	188	1238	1576	519	2619
Bageshwar	2267	−4.8	14.5	4.9	6.4	20.3	14.8	37	128	192	1515	1872	714	6513
Chamoli	7821	−13.3	8.5	−2.8	−3.0	15.1	7.1	40	150	229	1286	1705	714	7619
Champawat	1634	4.2	20.5	12.9	15.5	28.1	23.1	28	92	116	1114	1351	268	2199
Dehradun	3055	2.1	20.9	12.0	14.6	29.6	23.4	25	127	170	931	1253	283	2962
Garhwal	5444	4.4	22.0	14.0	16.3	31.3	24.9	29	107	156	1070	1361	254	3049
Hardwar	2372	6.6	25.6	17.0	19.0	36.8	28.8	19	93	91	904	1107	214	874
Nainital	4124	5.0	22.0	14.3	16.5	31.2	24.9	31	101	124	1099	1355	212	2522
Pithoragarh	7228	−4.2	8.6	3.0	−2.9	15.1	7.1	27	122	134	1184	1467	428	6985
Rudraprayag	1821	−7.8	12.8	2.2	3.9	18.8	12.6	44	144	262	1400	1851	584	6869
Tehri Garhwal	3854	−0.6	18.4	9.2	11.7	25.7	20.2	30	131	204	1031	1396	339	6392
Udham Singh Nagar	2737	7.3	24.8	17.2	19.1	35.6	28.3	32	78	81	1209	1400	186	421
Uttarkashi	8039	−7.0	8.6	−4.0	−3.5	15.9	7.3	30	144	203	875	1252	711	6990
Overall	53,483	−	−	−	−	−	−	31	123	172	1120	1446	186	7619

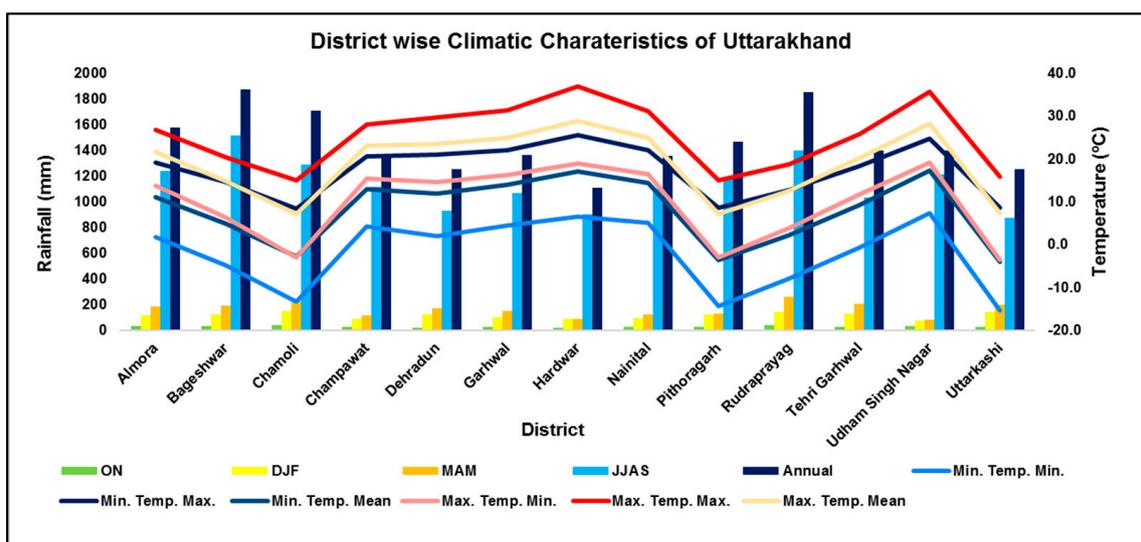


Figure 3. The climatic characteristics of various districts in Uttarakhand.

2.3. Flash-Flood Incidents

Hydro-meteorological disasters have increased rapidly over the last 20 years [24], as displayed in Table 3. Chamoli, Pithoragarh, Rudraprayag, and Uttarkashi are the most affected districts. Therefore, to alleviate the future occurrences of such disasters and suggest probable mitigation strategies, it is necessary to identify various issues and challenges faced during flood management.

Table 3. The list of major flash-flood locations in the state of Uttarakhand.

S. No.	Date	Region	District	Damage	Reference
1	7 February 2021	Tapovan	Chamoli	More than 200 people were killed or missing, and several hydel plants suffered	[25,26]
2	18 August 2019	Makudi	Uttarkashi	17 people died	https://sandrp.in/ (accessed on 25 January 2022)
3	16 July 2018	Tharali	Chamoli	55 houses, 10 vehicles, 2 ropeways, 1 road bridge washed, 2 cattle died, mini-hydro projects affected	https://sandrp.in/ (accessed on 25 January 2022)
4	14 August 2017	Dharchula	Pithoragarh	16 people	https://www.skymetweather.com (accessed on 25 January 2022)
5	28 May 2016	Kemra	Tehri	120 houses, 100 animals	Millennium post, 28 May 2016
6	15 August 2014	Purala	Pauri Gharwal	16 people reported dead	[13]
7	16 June 2013	Kedarnath	Rudraprayag	10,000 people, 365 houses	[27,28]
8	13 September 2012	Ukhimath	Chamoli	66 people	[15]
9	3 August 2012	Pandrasu ridge	Uttarkashi	35 people, 436 livestock lost, 591 houses	[29]
10	11 August 2001	Phata	Rudraprayag	27 people, 64 animals, 22 houses	[30]

2.4. Hydroclimatic and Topographic Dataset

The daily gridded IMD precipitation datasets at 0.25° resolution and maximum temperature datasets at 1° resolution from 1990 to 2019 were used in this study. Both datasets were obtained from <https://www.imdpune.gov.in/> (accessed on 25 January 2022). Around 103 rainfall and 13 temperature grid points were utilised to cover the entire state, as shown in Figure 2. The daily rainfall and temperature datasets of the fifth generation “European Centre for Medium-Range Weather Forecasts (ECMWF) Atmospheric Reanalysis (ERA5) [31]” for the period 1990–2019 from Google Earth Engine [32] were also utilised.

The elevation map was prepared from Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) acquired from <https://portal.opentopography.org> (accessed on 25 January 2022) at 30 m resolution. The locations of the India Meteorological Department’s (IMD) Automatic Weather Station (AWS) and Automatic Rain Gauges (ARG) were obtained from <http://aws.imd.gov.in:8091> (accessed on 25 January 2022). The satellite imageries of the flood events were acquired from Google Earth Pro. The climatic characteristics of the state were also obtained from the IMD annual report, and State Disaster Management Action plan on climate change [6,33,34].

2.5. The Proposed Methodology for Flood Risk Management

The methodology adopted in this study is divided into three parts, A, B and C, as shown in Figure 4. Part A summarises the primary causes of the disasters in the state and analyses the climatic variation by incorporating rainfall and temperature datasets. This part also discusses the topographic influences causing the two major disasters in the state.

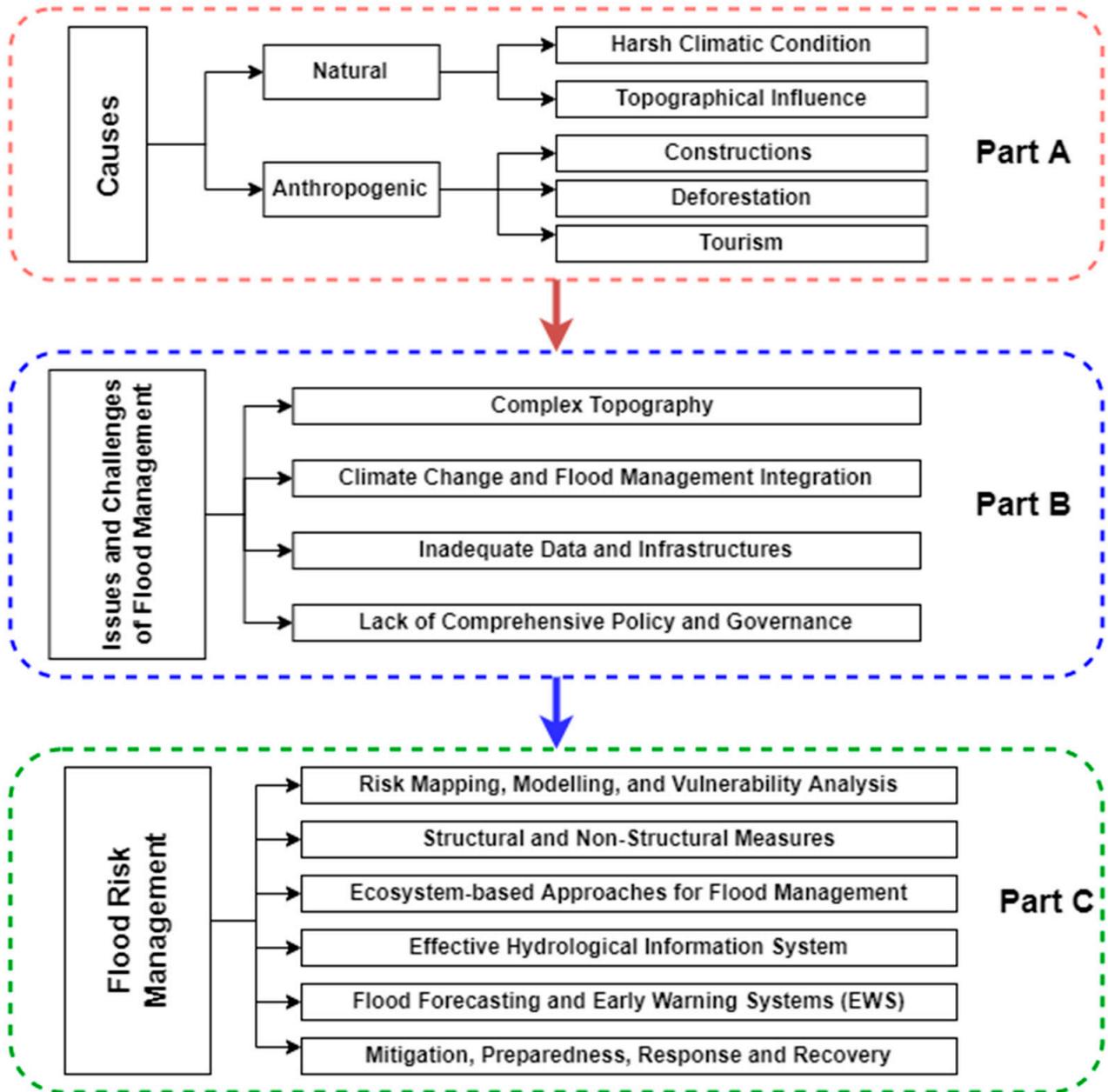


Figure 4. The proposed methodology for flood risk management.

Part B reviews the issues and challenges involved in the flood management of the region. Part C provides the basic approach for flood risk management in the Himalayan state to reduce the likelihood of flood incidents for people living in flood-prone areas.

2.6. Methodology for Climatic Variation Assessment

The methodology for climatic (rainfall and temperature) assessment is shown in Figure 5. The daily rainfall datasets are aggregated into seasonal datasets to assess the rainfall trends and variations. Then, the histogram of the rainfall value is plotted to

assess the distribution. Furthermore, the Mann–Kendall and Theil–Sen slope method (Equations (1)–(5)) is utilised to estimate each district’s trend. Non-parametric tests, such as the Mann–Kendall (MK) [34,35] test, are frequently used to identify patterns in time series of hydrological changes. For instance, Y_i ranked from $i = 1, 2, \dots, N - 1$, and Y_j ranked from $j = i + 1, 2, \dots, N$. Each data point Y_i is used as a reference point and is compared with all other data points Y_j such that,

$$\text{Sgn} (Y_j - Y_i) = \begin{cases} +1, > (Y_j - Y_i) \\ 0, = (Y_j - Y_i) \\ -1, < (Y_j - Y_i) \end{cases} \quad (1)$$

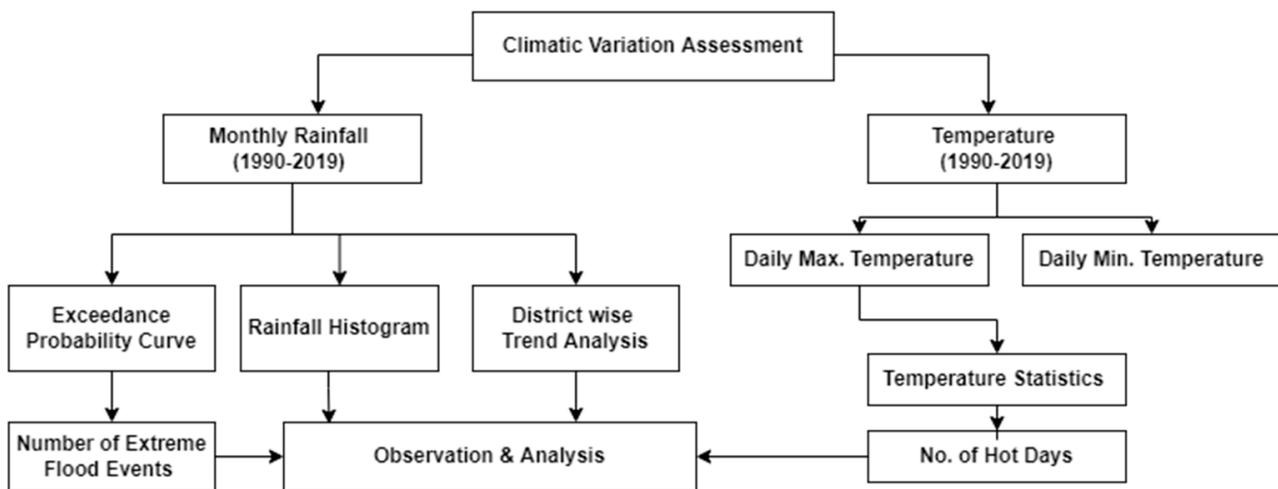


Figure 5. Methodology for climatic variation assessment.

The Kendall statistic S is estimated as

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^N \text{Sgn}(Y_j - Y_i) \quad (2)$$

The variance of the statistic S is defined by

$$\text{Var}(S) = \frac{N(N-1)(2N+5) - \sum_{i=1}^N t_i(i-1)(2i+5)}{18} \quad (3)$$

In which t_i denotes the number of ties up to sample i . The test statistic Z_c is estimated as

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, & S < 0 \end{cases} \quad (4)$$

and follows a standard normal distribution. If Z_c is positive, the trend is upward; the negative Z_c shows a downward trend. A statistical significance of 95%, i.e., p -value of less than 0.05, is considered for the trend to exist. Additionally, for the determination of slope when there is a linear trend, Sen’s slope method is used. Moreover, the magnitude of a time series trend was evaluated by a simple non-parametric procedure developed by Sen [35]. The trend is calculated by

$$\beta = \text{Median} \left(\frac{Y_j - Y_i}{j - i} \right), j > i \quad (5)$$

where β is Sen’s slope estimate. $\beta > 0$ indicates an upward trend in a time series and vice versa.

Now, the rainfall events of the monsoon season (JJAS) are considered to estimate the number of extreme monthly flood events. The probability of exceedance, i.e., the Weibull method [36], is applied to estimate the suitable threshold. For this estimation, it is necessary to sort all the rainfall data in decreasing order and assign a serial order number ranging from 1 to n . The formula is given by,

$$\text{Probability of exceedance (PE)} = \frac{m}{(n + 1)} \quad (6)$$

where m = rank order and n = number of events.

The probability of exceedance value of 5% is selected as a threshold to estimate the number of extreme flood events. It is assumed that a high amount of rainfall would indicate a flood event. Moreover, the daily maximum temperature statistics of 30 years are utilised to analyse the number of hot days every year. Mean plus one Standard Deviation is selected as a threshold for hot days count for the analysis.

2.7. Methodology for Topographic Influence Estimation

For the analysis of topographic influence, the visual image interpretation technique was employed [37]. The information of area, shape, texture, tone, size, pattern, and association of the incidents was taken as the image interpretation elements. Moreover, the analysis used Google Earth imagery of pre and post incidents information gleaned from literature and the DEM of the region to estimate the basic physiography of the affected watersheds. Two case studies were investigated. The first case study examined the Kedarnath flood incident of 2013 [38–41]. The second case study assessed the Chamoli flash flood of 2021 [26,42].

3. Results and Discussion

3.1. Part A—Causes of the Flood Disasters in the State

The Himalayan's young, fragile, steep gradients are vulnerable to climate change [19]. In addition, these mountain areas' ecological and social-economic systems are becoming increasingly susceptible due to swelling human density. Moreover, the disasters disrupt society's functioning and adversely damage infrastructure, properties, life, and the environment. Furthermore, they aggravate other distress such as social conflict, financial crisis, environmental degradation, and diseases. Both natural and anthropogenic causes trigger these disasters in the mountain ecosystem.

3.1.1. Natural Causes

The two major natural causes of disaster in the state are the harsh climatic conditions causing extreme rainfall and the complex undulating topography causing rapid flood characteristics. During the southwest monsoon season, the Uttarakhand area experiences significant to extremely heavy rainfall.

The following are the primary meteorological conditions that contribute to high rainfall in the area:

- (1) From the Bay of Bengal, the low-pressure areas rise and migrate through the central part of India and then recurve northwards and north-eastwards and cause high rainfall in the Uttarakhand's foothill. Furthermore, depressions from the Arabian sea cross north Maharashtra and south Gujarat coasts, reach the Kumaun-Garhwal region and cause severe cloudbursts, flash floods, and landslides.
- (2) Flooding due to heavy rainfall occurs in the central and eastern Himalayas when the monsoon's axis shifts to the Himalayan foothills from the Northern Indian plains in July and August (the setting in the 'break situation').
- (3) Western/Extra-tropical disturbances, originating from Caspian and the Mediterranean Sea in the far west and moving towards north India through Afghanistan, Iran, and Pakistan, cause snow and rain during the winter season over the western Himalayas.

This rainfall from Western disturbances occurs four to five times per month during monsoon and six to seven times during the winters.

Results for Climatic Variation Assessment

A detailed seasonal rainfall trend analysis (Equations (1)–(5)) for each district is carried out to study the temporal variation in rainfall, and the results are displayed in Table 4. The increasing trend is represented by ‘+ve’, decreasing trend by ‘-ve’, and the no-trend by ‘0’. The observations made are as follows,

- (1) In the monsoon season (JJAS), 9 out of 13 districts, namely, Almora, Bageshwar, Chamoli, Champawat, Dehradun, Garhwal, Hardwar, Rudraprayag, and Tehri Garhwal, show an increasing rainfall trend.
- (2) In post-monsoon (ON), no significant trend is observed.
- (3) In the cold season (DJF), an increasing trend is observed for Chamoli, Pithoragarh, and Rudraprayag districts, while in the other districts, no trend is observed.
- (4) In the hot weather season (MAM), all the districts except Uttarkashi show an increasing rainfall trend.
- (5) Out of 13 districts, 8 districts, namely Almora, Bageshwar, Chamoli, Champawat, Hardwar, Pithoragarh, Rudraprayag, and Tehri Garhwal, exhibit an increasing annual rainfall trend.

Table 4. The trend analysis of seasonal and annual rainfall for each district.

District	Season				Annual
	JJAS	ON	DJF	MAM	
Trend, <i>p</i> -Value, <i>z</i> Value					
Almora	+ve, 0.003, 2.98	0, 0.652, 0.45	0, 0.733, 0.34	+ve, 0.004, 2.85	+ve, 0.09, 1.7
Bageshwar	+ve, 0.01, 2.57	0, 0.084, 1.73	0, 0.266, 1.11	+ve, 0.001, 3.23	+ve, 0.048, 1.97
Chamoli	+ve, 0.021, 2.31	0, 0.077, 1.77	+ve, 0.01, 2.59	+ve, 0, 4.13	+ve, 0.049, 1.97
Champawat	+ve, 0.011, 2.53	0, 1, 0	0, 0.967, 0.04	+ve, 0.008, 2.67	+ve, 0.001, 3.18
Dehradun	+ve, 0.021, 2.31	0, 0.363, 0.91	0, 0.119, 1.56	+ve, 0, 3.6	0, 0.034, 2.12
Garhwal	+ve, 0.01, 2.57	0, 0.375, 0.89	0, 0.586, 0.55	+ve, 0.007, 2.72	0, 0.055, 1.92
Hardwar	+ve, 0.049, 1.97	0, 0.719, −0.36	0, 0.182, 1.34	+ve, 0.004, 2.85	+ve, 0.119, 1.56
Nainital	0, 0.058, 1.89	0, 1, 0	0, 0.965, −0.04	+ve, 0.021, 2.3	0, 0.043, 2.02
Pithoragarh	0, 0.075, 1.78	0, 0.132, 1.51	+ve, 0.046, 2	+ve, 0.027, 2.21	+ve, 0.048, 1.98
Rudraprayag	+ve, 0.011, 2.53	0, 0.076, 1.77	+ve, 0.038, 2.08	+ve, 0, 3.83	+ve, 0.033, 2.13
Tehri Garhwal	+ve, 0.011, 2.53	0, 0.163, 1.39	0, 0.125, 1.53	+ve, 0.001, 3.3	+ve, 0.013, 2.49
Udham Singh Nagar	0, 0.095, 1.67	0, 0.824, 0.22	0, 1, 0	+ve, 0.003, 2.99	0, 0.002, 3.09
Uttarkashi	0, 0.058, 1.89	0, 0.103, 1.63	0, 0.08, 1.75	0, 0.091, 1.69	0, 0.067, 1.83

Overall, it is observed that the rainfall trend is mostly increasing in the pre-monsoon and monsoon seasons. Chamoli and Rudraprayag districts show the maximum increasing rainfall trend. This increasing rainfall trend during the monsoon season results in frequent flash floods and cloudbursts in the state. The results obtained are consistent with the state IMD’s annual report [34].

The rainfall histogram (Figure 6a) prepared from 103 grid points for 30 years, considering months from June to September, at 100 mm bin size, shows that the majority (24.6%) of the monthly rainfall falls in the range 100–200 mm. Around 20% of monthly rainfall lies in the range of 0–100 mm, 19.6 % lies in the range 200–300 mm, 14.1% lies in the range 300–400 mm, 9.8% lies in the range 400–500 mm, and only 11.8% has rainfall >500 mm.

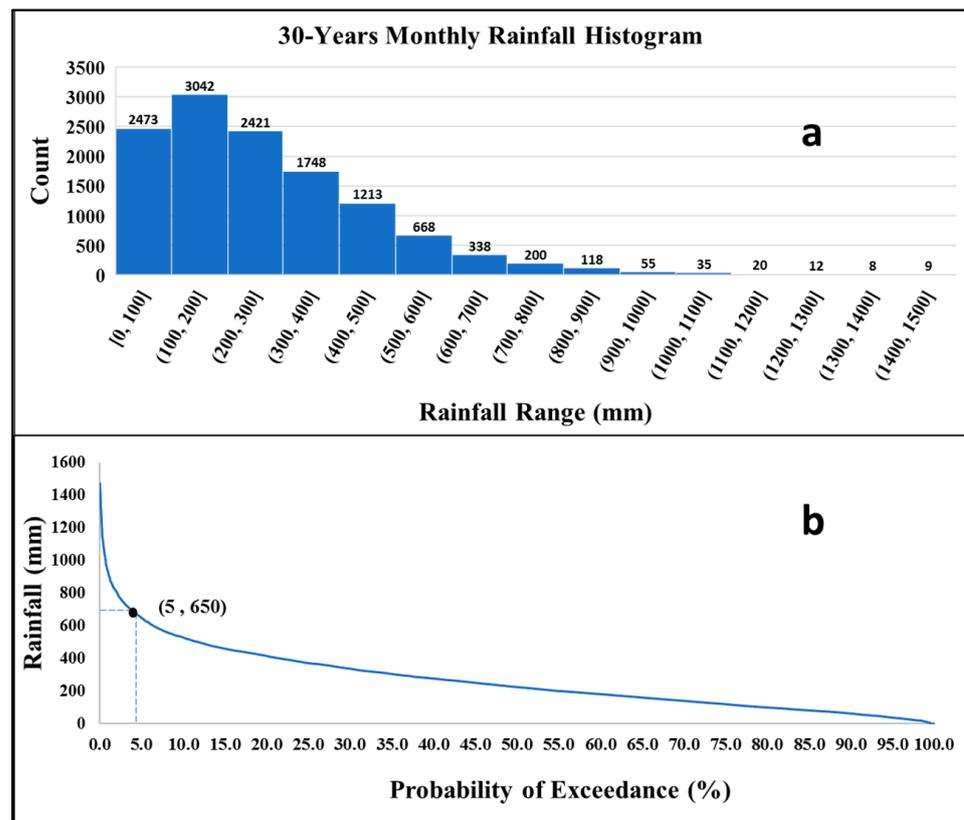


Figure 6. (a) The histogram and (b) the probability of exceedance curve of the monthly rainfall (June to September) obtained for the years 1990–2019.

The probability of exceedance curve (Figure 6b) was prepared using Equation (6), and considering the value of 5%, the value of rainfall depth threshold was estimated to be 650 mm. Therefore, all the monthly rainfall of more than 650 mm is considered an extreme flood. The result shows that the maximum number (288) of total extreme flood events is in July, 242 in August, 51 in September, and 34 in June in the past 30 years. This also demonstrates that the region is highly vulnerable in July and August. To understand the trend of the flood incidents, the Mann–Kendall test was carried out. It is observed that there is no statistically significant trend in the monsoon season (June to September) (Figure 7). However, a very small increasing trend in July and August and a small decreasing trend in June and September may be due to random fluctuating components in the time series.

The daily maximum temperature statistics revealed that the region has a normal maximum temperature of 30.1 °C and a standard deviation of 6.2 °C. Therefore, considering the threshold temperature as 36.3 °C (mean + one std. dev.), the values of no. of hot days obtained are shown in Figure 8. It is observed that the years 1999, 2002, 2009, 2010, 2012, 2014, and 2019 experienced more than 70 hot days in a year. To understand the trend, the Mann–Kendall test was performed. It is observed that statistically, there is no significant trend in the number of hot days during the last three decades. The very small increasing trend may be due to natural random fluctuating components in the time series. These increasing hot day events contribute to the glaciers’ mass loss, permafrost degradation, and increased snowmelt in the Himalayas.

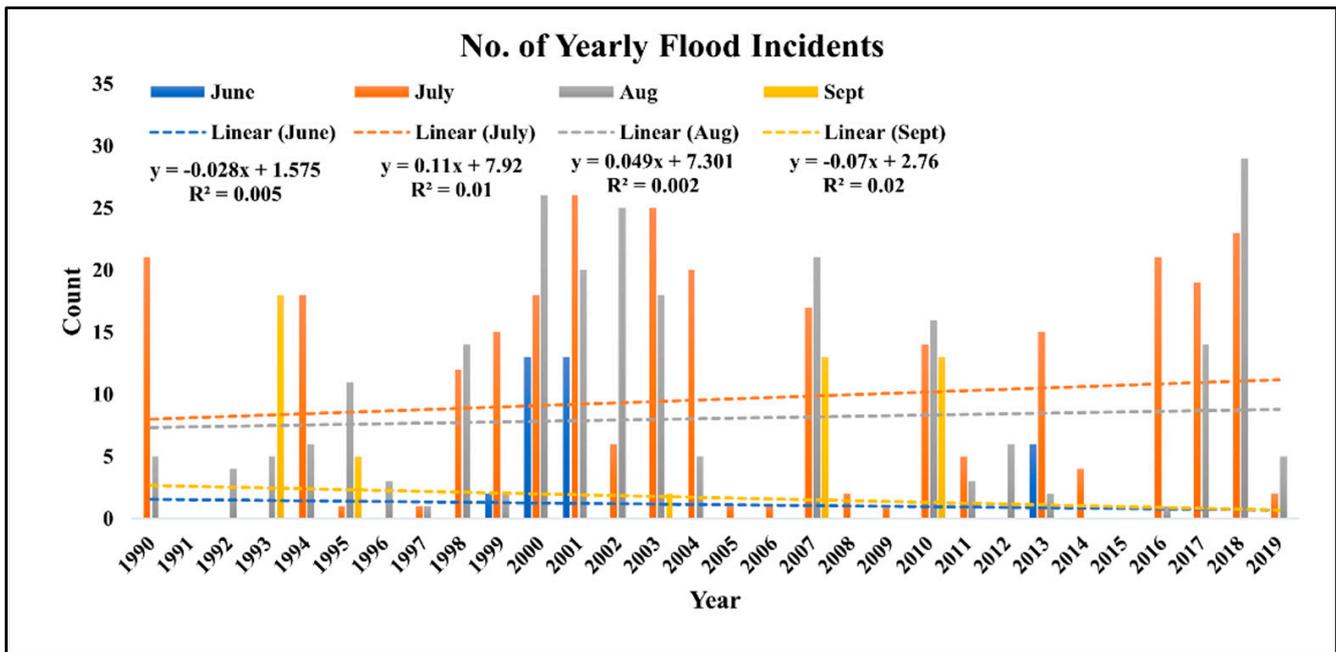


Figure 7. The time series of the number of flood incidents.

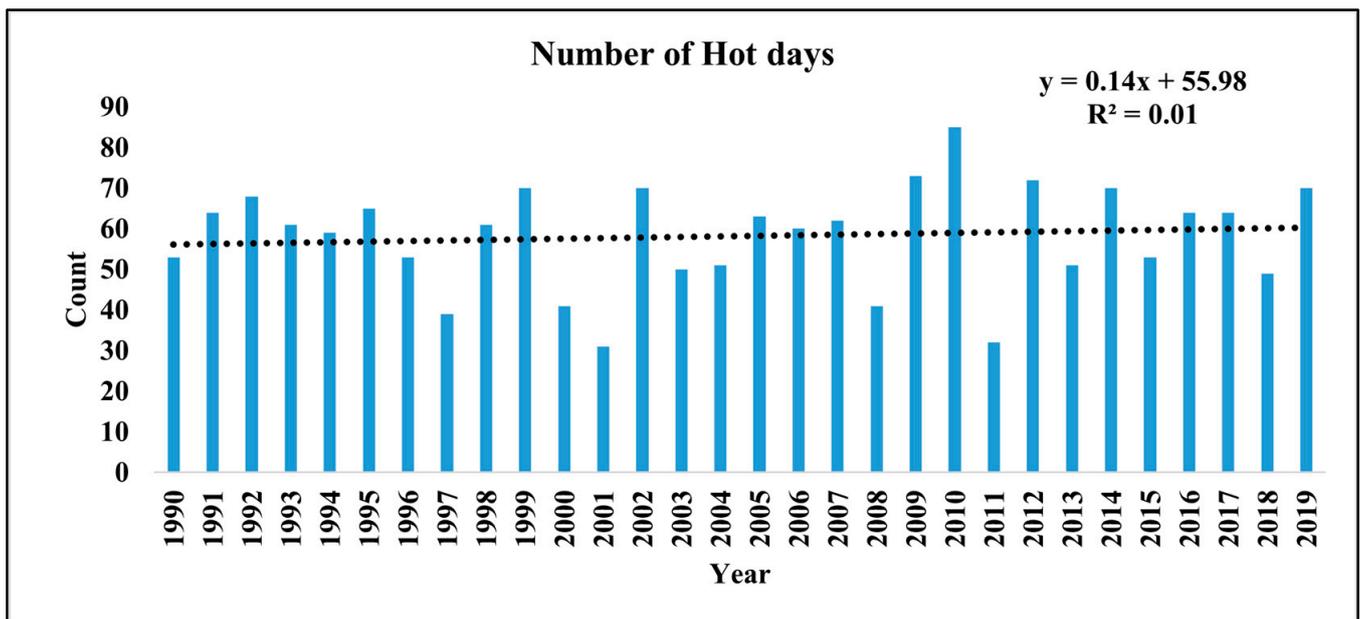


Figure 8. The time series of the number of hot days.

Results for Topographic Influence Assessment

The floods developed in a mountainous region differ from those generated in flood plains lying in low elevation zones. In hilly regions of Uttarakhand, floods are sudden and often termed flash floods. These flash floods are usually generated by extreme events such as heavy rainfall, cloudbursts, glacial lake outbursts, and dams created due to the blockage of rivers [43]. Such incidents are localised, occur with little to no warning, and pose significant damage in downstream areas. A wide range of variables, including hydrological characteristics, such as high-intensity rainfall and huge flow velocity, high frequency of occurrence, high peak flood, and basic characteristics such as the steepness of slope,

elevation, and shape of the area, the degree to which the water carries sediments, and the vulnerability of the populations to the flowing floods, can further stimulate their impact.

In 2013, an extreme event in the form of a cloudburst combined with flash floods and landslides occurred in the Mandakini River basin. More than 10,000 people were presumed dead as a result of this catastrophe. Over 135 highways, 150 bridges, and 2000 houses/buildings were affected [39,40]. The basin length of Mandakini is about 66 km and covers 1982 sq. km. The relative relief ranges from 177 to 1416 m, in which 53% of the relief ranges from 500 to 750 m (moderate-high). Additionally, around 68% of the region has a slope of 25–35° [44]. Such topographical conditions of the basin make it prone to flash floods. The pre- and post-flash-flood scenario near the Kedarnath temple depicting the debris deposition and damage to the roads is shown in Figure 9.

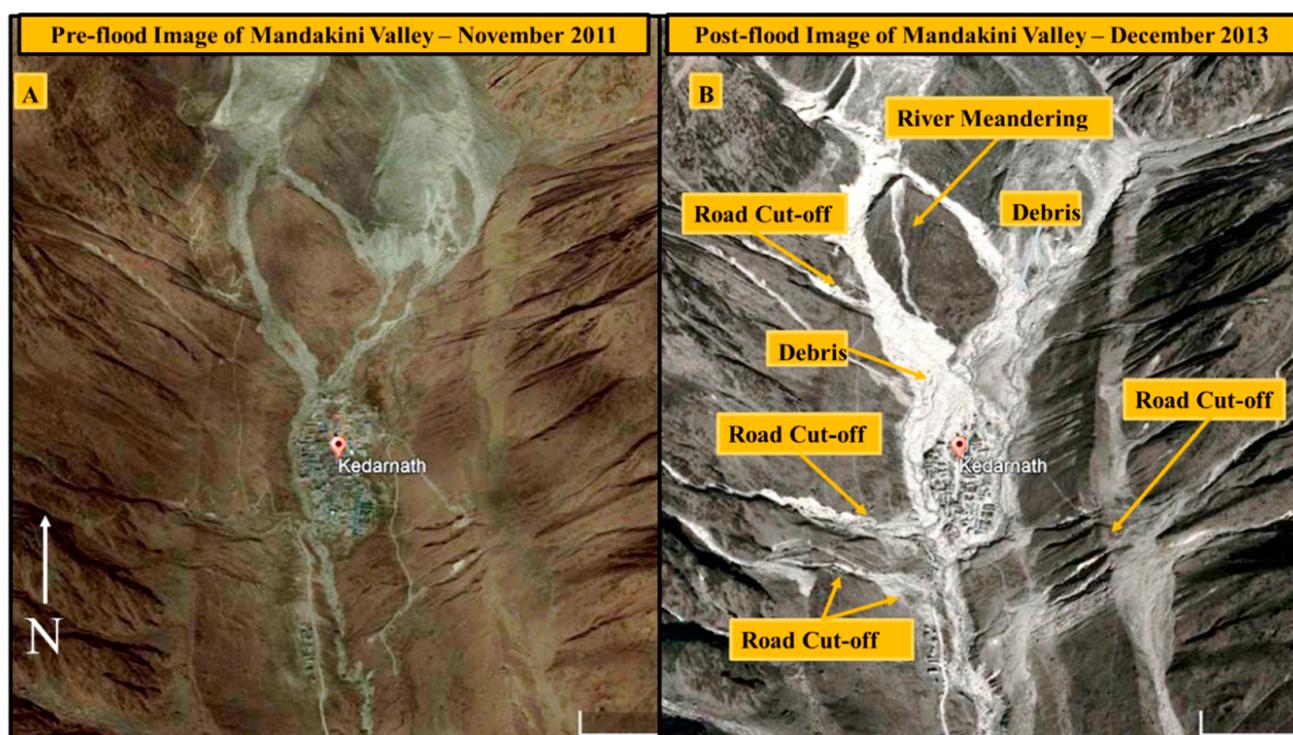


Figure 9. The Google Earth images showing, (A) Pre-flood (November 2011), (B) Post flood (December 2013) impact of the extreme flash-flood event in the Kedarnath region of the Mandakini river basin.

Apart from extreme weather-induced disasters, the region also suffers from landslides and avalanches. In 2021, the Chamoli region experienced a flash-flood event resulting from an avalanche near the Ronti Glacier (Figure 10) at an elevation of 4064 m. At the confluence of the Rishi and Dhauliganga rivers, the height is 1908 m, while Nanda Devi, at 7817 m, is the highest point in the region. The floods, while travelling downstream, demolished the bridge near Raini village, damaged the Rishiganga and the National Thermal Power Corporation (NTPC) Tapovan Hydel plant, and killed over 200 people [45]. The velocity and flood discharge at 89 m upstream of the Rishiganga Dam is estimated to be 24 m/s and 12,448 cumecs. The length of the rockslide surface is about 1182 m, having a maximum width of 755 m and a mean slope of 62° [46].

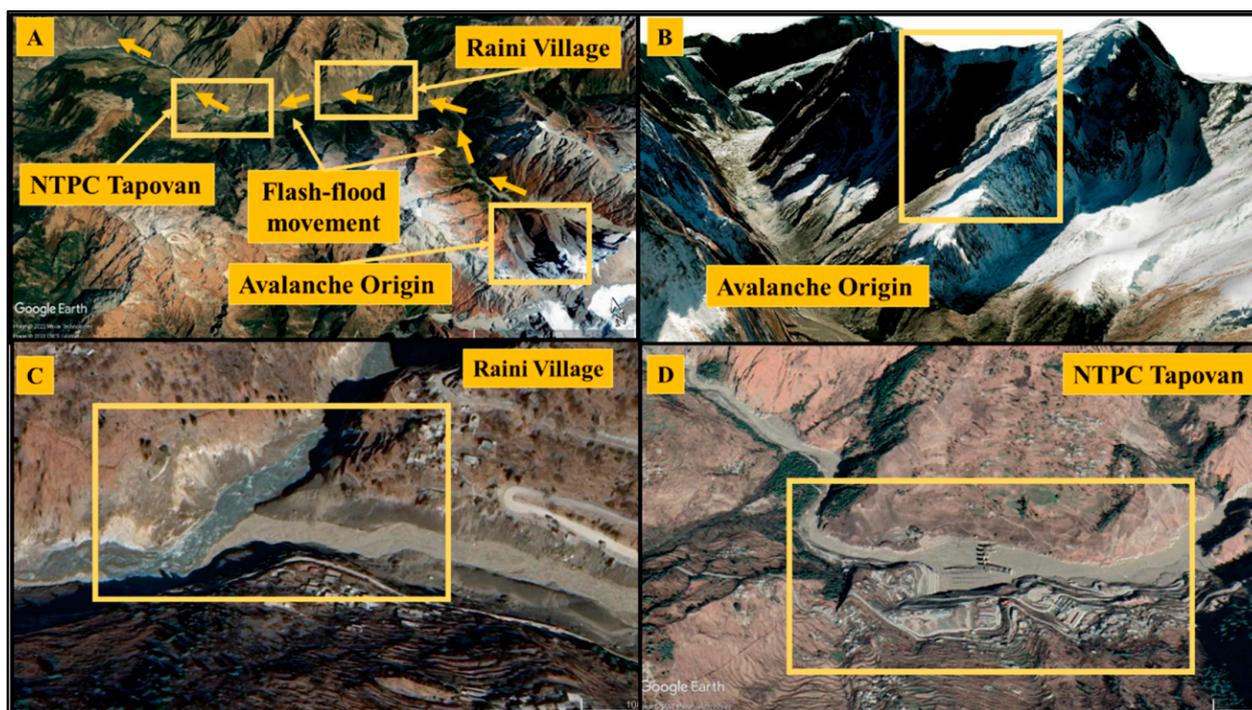


Figure 10. The Google Earth imagery shows, (A) An overall view of the incident, (B) The actual location of the avalanche near Ronti Glacier, (C) The confluence of Dhauliganga and Rishiganga, near Raini village, and (D) The inundated NTPC Tapovan sites.

3.1.2. Anthropogenic Causes

The increasing population growth in these mountain regions hampers the ecological and socio-economic systems. Numerous anthropogenic activities, such as the construction of roads, buildings, hydropower projects, abundant tourism, forest encroachment, etc., pose a serious threat to the climate and mountain ecosystem [40]. Blasting and massive cutting of the rocks, which generates high-intensity vibrations, is the primary method of clearing mountains for development. New roads are continually being developed, and old highways are being expanded and maintained in the Indian Himalayas. Such activities cause steepening of the hill slopes and further lead to slope instability. The unplanned development over the riverbed has essentially replaced the agricultural land, allowing the river habitat to decline.

The elimination of natural vegetation, and the expansion of impervious areas, lead to a reduced water storage capacity and, as a result, a higher flood peak and a shorter time to peak [47]. Certain anthropogenic ritual activities such as cremation ceremonies cause heavy pressure on the forest ecosystem as they result in deforestation and lead to air and water pollution. Morbidity among agricultural workers is exacerbated by these developments, which have a greater impact on the economy [48].

Greenhouse gas (GHG) emissions in the valley have increased significantly due to uncontrolled human activities such as tourism and vehicle traffic. The AR6 IPCC reports that solar radiation is absorbed by anthropogenic aerosols such as black carbon, which increases moist static energy, warms the lower troposphere, and further increases convection inhibition, suppressing light rainfall [49]. Aerosols intensify convection in the Himalayan foothills during the pre-monsoon season, resulting in regional convergence; this phenomenon is known as the ‘Elevated-Heat-Pump’ mechanism [50]. Intense monsoon rainfall in northern India and western Nepal in 2013, which caused landslides and one of the worst floods in history, has been further linked to increased GHG and aerosols [38]. A direct association between an increase in tourism and the landslide’s frequency has also

been observed [51]. The major anthropogenic activities in the state of Uttarakhand has been discussed [52] and are shown in Figure 11.

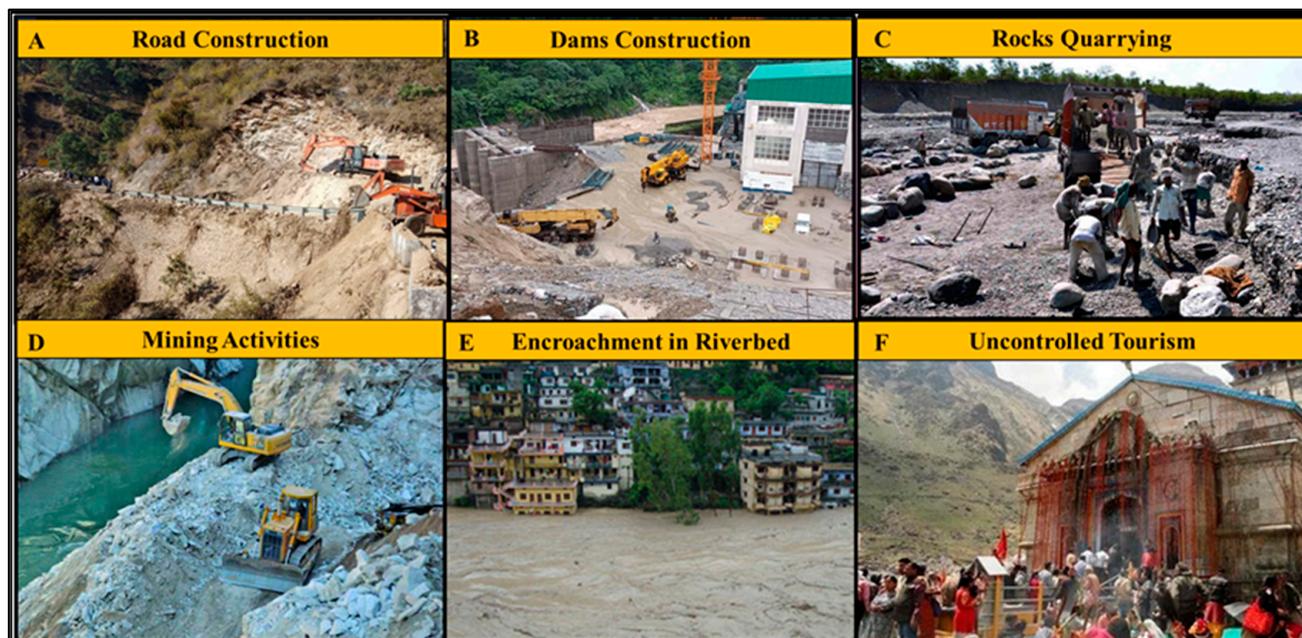


Figure 11. The impact of anthropogenic activities on the degradation of river ecosystem in Uttarakhand. (A) (Source: <https://sandrp.in/2020/02/24/uttarakhand-road-widening-work-in-almora-damages-traditional-water-sources/> (accessed on 6 June 2022)), (B) (Source: <https://sandrp.in/2021/09/17/uttarakhand-cloud-bursts-around-vyasi-hep/> (accessed on 6 June 2022)), (C) (Source: <https://news.euttaranchal.com/uttarakhand-bans-quarrying-ganga-tributaries-following-ngt-order> (accessed on 6 June 2022)), (D) (Source: <https://news.euttaranchal.com/no-mining-within-10-km-national-parks-uttarakhand-high-court> (accessed on 6 June 2022)), (E) (Source: <https://www.downtoearth.org.in/news/urbanisation/undone-by-rampant-mining-illegal-buildings-41450> (accessed on 6 June 2022)), (F) (Source: <https://www.hindustantimes.com/cities/dehradun-news/uttarakhand-char-dham-yatra-to-kedarnath-halted-amid-heavy-rain-imd-warns-of-thunderstorms-101653301156476.html> (accessed on 6 June 2022)).

3.2. Part B—Issues and Challenges of Flood Management in the State of Uttarakhand

Flood hazards in Himalayan Rivers are diverse, necessitating a multi-faceted and multi-scaled approach to preparedness. It is necessary to monitor, forecast, and disseminate information about these processes and phenomena. These initiatives must cross traditional disciplinary boundaries and involve scientists, policymakers, and members of civil society working together at all levels of government and administration to be effective. The four major challenges of flood management in Uttarakhand are: (1) complex and steep topography that controls the flow path and velocity, (2) lack of comprehensive policy and governance, which is essential for effective risk governance, (3) inadequate data and infrastructure, that is necessary for estimation and evaluation of flood-generating mechanisms, and (4) climate change and flood management integration, which is required for a long-term solution to flooding risks and hazards.

3.2.1. Complex Topography of the Mountainous Terrain

The complex and steep topography of the hilly regions of Uttarakhand links to their unusual sharp atmospheric changes (i.e., moisture, precipitation, radiation, temperature, pressure), soil, vegetation, and hydrological conditions over short distances. These sharp gradients throughout the terrain control the form of precipitation, intensity and frequency, groundwater interactions, biodiversity, and soil moisture, which sequentially lead to high

rates of flood variability over short distances [17,53,54]. The main impact in hilly terrain is undercutting check dams, river damming by debris, riverbanks collapse and erosion, debris flows and deposits, channel displacement, clogging bridges, scour, and inundations of low-lying areas. Floods associated with geophysical flows, such as glacial dam burst floods, river avulsions, and glacial lake outburst floods (GLOF), are often extremely disruptive and lack enough evidence and models for understanding and controlling them in mountain regions [55,56]. When combined with limited hydro-meteorological statistics, such complexities lead to partial knowledge of the flood generation process, particularly with localised extreme events such as cloudbursts and glacier lake outbursts, landslides, and other convective storms. In the Himalayas, the cloudbursts are the least understood weather patterns [15,28]. The terms thunderstorms and cloudbursts have been used for decades interchangeably. However, the cloudbursts are hard to track as they are scattered and mostly occur on remote mountain slopes with limited rain gauges [24]; they are often only reported if lives are lost [57]. Given the degree to which the infrastructure and human resources are harmed, it is crucial to underline the processes that produce cloudbursts and establish a model for proper predictions.

3.2.2. Lack of Comprehensive Policy and Governance on Flood Mitigation

The key gaps in current policy are the lack of rigidity of the legislative framework, the inability to follow a legal strategy, the question of authorisation of power, and the local government's role in policy processes. In the Disaster Mitigation, Management and Prevention Act (2005), the separation of responsibilities and the functions of local authorities was remarkably integrated but not implemented as a legislative framework [10]. Land management policies and preparation may better mitigate floods by reducing risk and hazard exposure. Such laws include construction codes, land use laws, environmental protection acts, emergency management legislation, and water policy, which govern human actions and practices focused on environmental and ecological conservation, flood prevention, and control measures. Building law, for example, specifies the safe distance of houses from the rivers, construction size, and floor height to reduce waterlogging and flood damage. In flood control, institutional aspects and effective governance play a critical role. Policy planning alone is not adequate to handle the flood without enough preparation.

Furthermore, for local-level planning and proper land use management, the participation of the community is also required. There is also a requirement for strong coordination among the institutes and flood management boards for effective risk governance. A strong rehabilitation and resettlement policy for re-establishing the socio-economic stability of the vulnerable communities is much needed in the state.

3.2.3. Inadequate Data and Infrastructure

The Himalayan regions' basic climate and hydrological data are scarce, which greatly disrupts the prediction, estimation, and evaluation of devastating flood-generating climate events, flood warnings, and other life-saving management systems [17]. Due to the remoteness, lack of connectivity, inadequate communication networks, and other infrastructure, it is challenging to develop response systems and instrumentation in hilly mountain areas. Primary data collection issues include transportation logistics to the gauging sites, loss of facilities during extreme flood events, and the expense of installation and maintenance of gauges. In addition, in river basins with steep valley walls, wireless coverage, and radio telemetry are frequently inaccessible with highly restricted choices for transmitting long-term hydrographic data and early warning systems. Remote sensing systems can address the difficulties of in situ measurements. However, mountainous places might have significant constraints (e.g., resource-intensive processing of data through remote sensing, limited data documentation, the cloud cover impacts, or other data biases) and complex topography, including insufficient spatial and temporal resolutions [58–60]. Due to the difficulties in data gathering and the insufficiency of information, the hydrology of hilly mountain areas is still not understood fully.

In Uttarakhand, the flood forecasting (FF) and early-warning system (EWS) are expanding. The district offices do have sirens but have a small range of 2 km, which is a significant shortcoming considering the geographic area that would be addressed. Data, however, is transmitted with the help of different media, such as televisions, mobiles, radio, and newspapers. With the speed of urbanisation and development witnessed in the villages, various patterns were observed in the individuals. Many people used radio, and those who had television did not wish to watch weather reports. Rather, many people, despite having TV access, did not have the set-up boxes that made them work. As per the India Water Resources Information System portal, the state of Uttarakhand has 85 flood forecasting sites of the Central Water Commission, as shown in Figure 12, along various rivers of Uttarakhand. However, most rivers in this region come under the category of “Classified river”; thus, the information about their flood discharge, velocities, and related warning is unknown to the public. Furthermore, due to a limited number of communication towers in remote locations and the unavailability of good quality real-time data, the whole set-up of the warning system fails during heavy rainfall and cloudbursts, which leads to a huge loss of lives and properties.

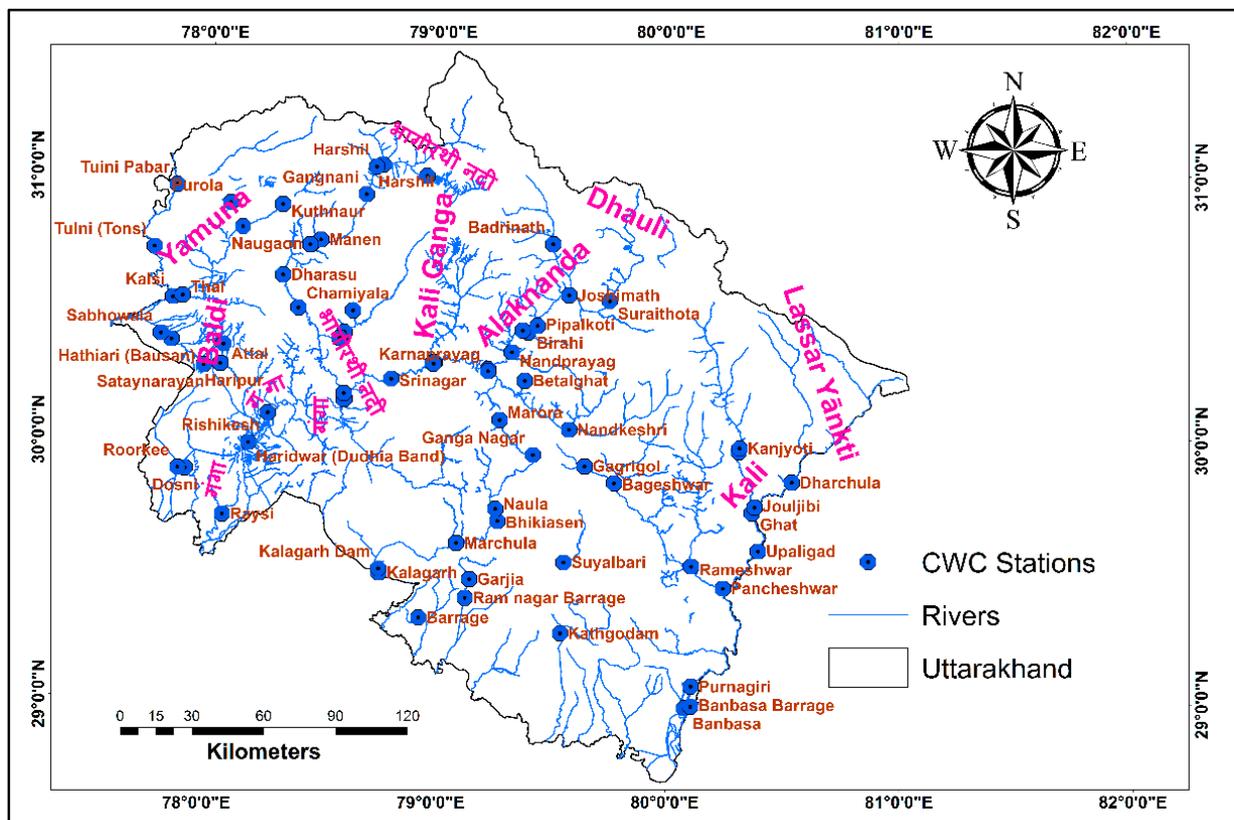


Figure 12. The locations of various river monitoring stations of the Central Water Commission.

3.2.4. Climate Change and Flood Management Integration

The Himalayan glaciers are the source of several river systems in India, but they are affected by human-caused global warming and climate change. The AR6, IPCC 2021, states that significant changes in temperature and precipitation have occurred in the Himalayas since the 1960s, including glacier mass loss, permafrost degradation, snowmelt, and increased glacier runoff [61]. Moreover, studies show that the glaciers in the Himalayan regions have unpredictable retreat and volume change rates due to microclimate and physiography variations [62]. Out of over 5000 glaciers, only 11 glaciers in the Indian Himalayas are being examined for their mass balance. Nearly 100 glaciers are regularly tracked for glacier snout shifts [48]. Decreasing glacier area and magnitude can briefly raise runoff

before the glacier has retreated to such a degree that it no longer leads to runoff, temporarily raising flood levels and eventually causing landslides, GLOFs, and other geophysical flows. Due to the rapid response of landscapes, ecosystems, vegetation, water, snow and glaciers, and soil to environmental change, mountain areas are exclusively vulnerable to climate change [63–65]. Thus, incorporating climate change into flood management could be an effective long-term solution to flooding risks and hazards.

Furthermore, the land erosion in the state is likely due to a combination of excessive rainfall and prolonged drought periods. The vulnerability of mountain areas against climate change indicates that mountain populations become highly susceptible because snowpack, glacial cover, and weather cycles shift and increase the severity and intensity of several mountain flood processes. Future flood management strategies must integrate glacier shifts, monsoonal rains, and snowfall patterns.

3.3. Part C—Flood Risk Management Plan

Flood risk management aims to reduce the likelihood of flood incidents for people living in flood-prone areas. It involves “the development of policies and strategies and plans for implementation and associated means of review”. The hilly regions of Uttarakhand are mostly affected by the flash-floods situation because of steep slopes and high drainage density. Thus, implementing flood reduction measures requires a holistic approach throughout the pre-flood, post-flood, and post-flood stages [66,67]. During the pre-flood stage, the recommendations are as follows: implementation of disaster contingency planning and flood risk management for all causes of flood, preventing inapt development within the flood plains, constructing physical flood defence infrastructure, implementation of proper warning and forecast systems, proper land use planning and public communications. Then, at the ‘during-flood’ stage, the following measures could be followed: issuing a warning to the appropriate authorities, forecasting the future river flow conditions, and identifying the probability of flood-forming zones. At the ‘post-flood’ stage, measures adopted are as follows: reconstruction and restoration of damaged infrastructure, providing relief to the affected, regeneration and retrieval of the economic activities, and improving and reviewing the flood management activities for future occurrences. Thus, for effective flood management, coordinated development and management of flood plains for maximising the benefits in a balanced manner could be ensured via the following approach:

3.3.1. Risk Mapping, Modelling, and Vulnerability Analysis

Mapping the specific hazards, locating important facilities, mobilising resources during and after an event, and mapping the physical constraints of an incident site to mitigate the risks of possible hazardous occurrences would help in hazard zoning, vulnerability assessment, and identifying the risk areas. Furthermore, involving local knowledge, perceptions, and socio-cultural values would help develop know-how, resources, and self-help capacities.

3.3.2. Structural and Non-Structural Measures

A combined approach of structural and non-structural measures should be adopted to control flash-flood hazards effectively, as shown in Figure 13. The structural measures generally include the catchment interventions and water control works, such as embankment protection, channel modifications and improvements and diversions, and river training works such as Check dams and the Gabion wall. The non-structural measure is divided into two classes: risk acceptance and risk reduction. The risk acceptance class adopts certain strategies for flash-flood insurance and emergency response systems. In the risk reduction approach, the prevention and mitigation strategies are adopted.

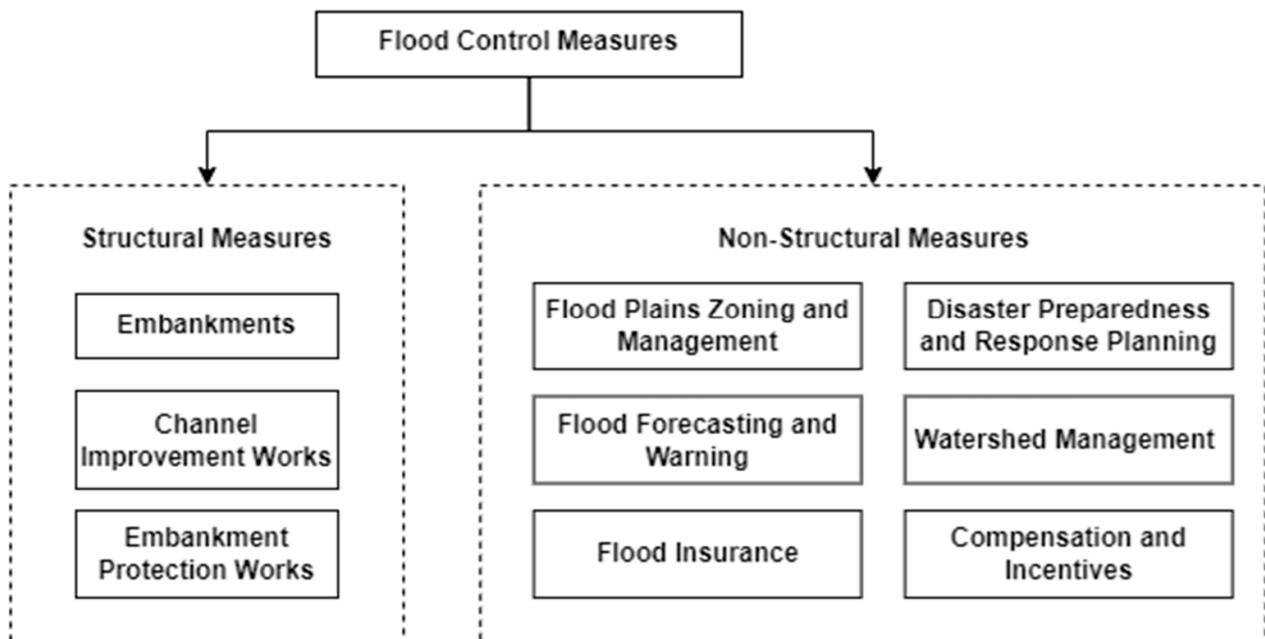


Figure 13. The flood control measures.

3.3.3. Ecosystem-Based Approaches for Flood Management

Researchers and practitioners have recommended that Nature-Based Solution (NBS), a novel approach toward catastrophe risk reduction, water security, and climate change resilience, is more effective and sustainable than traditional strategies [68]. Both urban and rural areas can benefit from ecosystem flood management services. The ecosystem services can lower the hazard caused by heavy precipitation. The wetlands can prevent floods by storing and temporarily slowing them down. Additionally, the roots of the wetland vegetations stabilise the riverbanks and hill slopes by holding the soils. The runoff fraction reduces the vegetated buffer zones, and other natural processes such as infiltration, evapotranspiration, water storage in aquifers, etc., reduce the runoff fraction [69,70]. Thus, a large-scale NBS is ideal in extreme events due to its ability to make more space for water, hence reducing the risk through retention, slowdown, and infiltration [71].

3.3.4. Effective Hydrological Information System

The management of flood data and related information necessitates the implementation of an effective Hydrological Information System. It could be done by maintaining the hydrometric networks and utilising its datasets for hydrological and hydrodynamic modelling, which would help generate flood scenarios and forecast floods during extreme events. Additionally, the interaction of land use land cover with climate change and hydrology should be adopted in the research [72–74]. Furthermore, increasing inter-sectoral communication through enhancing human and institutional capacities must be promoted. Moreover, the development of shared information portals and platforms for facilitating knowledge exchange between stakeholders should be espoused.

3.3.5. Flood Forecasting and Early Warning Systems (EWS)

For effective flood control, accurate and timely flood forecasts and early warnings are continually improved and upgraded [75]. An early warning system employs a flood sensor coupled to a transmitter to detect increasing water levels in local water basins (rivers, lakes) or flood defence structures such as dams and embankments. When the water reaches a crucial level, a signal is wirelessly relayed to the receiver. The flood warning is subsequently communicated to concerned agencies and vulnerable people through mobile phones [76,77]. By incorporating local participation, the critical flood levels could be determined. IMD

and CWC are developing observation sites, weather stations, computational simulation tools, computer infrastructure, and communication networks to improve the forecasting framework to deliver more reliable data that can produce greater socio-economic benefits. The spatial distribution of IMD–AWS and ARG in Uttarakhand is already shown in Figure 2. The locations of the flood forecast station of the CWC are shown in Figure 12. For example, approximately 11 CWC gauging sites in the Alaknanda river basin can be viewed at <https://ffs.tamcnhp.com/main/site> (last accessed on 10 April 2022). In an extreme rainfall event, real-time flood level information upstream and downstream of the Alaknanda river could aid in formulating appropriate disaster response and management strategies.

3.3.6. Mitigation, Preparedness, Response, and Recovery

The whole system is broken into four steps for effective flood management: Mitigation, Preparedness, Response, and Recovery [33].

Mitigation aims to reduce or remove the risk of flooding substantially before its occurrence by developing a strategy to minimise the effects of disaster on a community, facility, or organisation through raising public knowledge of disaster risk management. The main components of the mitigation strategy, therefore, are,

- Land-use planning and management.
- Retrofitting of the existing structures.
- Risk assessment and vulnerability analysis.
- Performance and conceptual design of the structures.
- Building bylaws and codes.

Preparedness activities are structured to create a sense of readiness for an emergency disaster. The key initiative for disaster preparedness is community participation in contributing to the response process by being involved in the training and capacity building process. The effective flood management response involves providing immediate emergency relief and search and rescue assistance. The actual work of this process depends on the characteristics of the community, but the primary goal is to meet citizens' basic needs before the rehabilitation begins. In the hilly regions, the response phase forms an important criterion for successfully preventing the adverse impact of natural hazards, as the warning durations are less. In this regard, incident management systems and tools for analysing the consequences of disasters built on geographic information systems (GIS) may substantially aid rapid response and emergency management. A useful application of geospatial technology during a disaster may be a map showing public access to emergency services (such as electricity and transportation). The final stage, known as the recovery phase, includes assessing the damage, rebuilding, and helping the afflicted. Restoring normalcy to disaster-affected areas is the overall objective of this stage. Conducting a quick damage assessment forms a top objective to expedite the rescue effort. Rapid damage assessment and relief operations can be supplemented by measures such as coordinating the spatial inventory of damage, assuaging and educating the public, and averting reoccurrence.

4. Conclusions

The Indian Himalayan Regions are the home of the major Indian population and create an important nexus among water, energy, and food for society, biodiversity, and life, but they are often subject to catastrophic natural disasters, especially floods. The study highlights the natural causes, such as harsh climatic conditions and topographical influence and anthropogenic causes, such as construction activities, deforestation, and tourism that have aggravated the extreme flood conditions. Further, the study identifies the challenges of flood management, viz., complex topography, weak policy and governance, lack of adequate data and infrastructure, and the need for climate change and flood management integration. The study suggests adopting an effective flood risk management plan to assess the multi-institutional, land use planning, mitigation policy execution, and mitigation strategies in pre-, during-, and post-flood scenarios with a special focus on the districts, viz., Chamoli, Pithoragarh, Rudrapur, and Uttarkashi.

Furthermore, adopting nature-based solutions, such as wetlands, is proposed to counter extreme flood events. Additionally, a combined structural and non-structural measures approach is recommended to manage flash floods effectively. Furthermore, the study commends a need for collaborative governance between local, state, and central policymakers and an integrated communication network for improved flood control in hilly regions. Additionally, the work recommends installing and upgrading flood forecasts and early warning systems for the region's accurate and timely flood forecasts. Adopting an effective flood management system in hilly regions requires an infrastructural and technical contribution to long-term monitoring and assessment. Moreover, comprehensive model-based studies of climate changes and environmental effects and process-based hydrology studies in altitudinal and mountainous gradients should be espoused.

Author Contributions: Conceptualisation—M.L.K. and S.S.; formal analysis and writing—S.S.; supervision and guidance—M.L.K. All authors have read and agreed to the published version of the manuscript.

Funding: The second author is thankful to the Ministry of Education, Government of India, for the fellowship grant for carrying out the research at the Department of Water Resources Development & Management at IIT Roorkee. The APC is waived-off.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are thankful to the Ministry of Education, Government of India for the financial support provided through the Indian Institute of Technology, Roorkee, for carrying out this research.

Conflicts of Interest: The authors declare no conflict of interest.

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