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Article

# Exposure to Climatic Variability and Associated Hydro-Meteorological Hazards in Beas River Basin of Western Himalaya, India

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**Abstract:** The factors contributing to vulnerability can significantly differ across different locations and time periods, as certain communities, age demographics, areas, landscapes, and countries are more at risk from climate change. As a result, comprehending the spatial and temporal trends of current climates and their dependable projections is essential for better preparing to tackle the consequences of climate change. Another critical element of climate change mitigation and adaptation involves creating strategies that are relevant to specific local contexts. Exposure was defined as the cumulative impact of various climate and hydro-meteorological hazards. This approach allowed us to establish a climate change exposure index that takes into account both historical and current conditions. The exposure index can amalgamate numerous factors representing climate variability and related hydro-meteorological threats to inform proactive decision-making. Consequently, several indicators have been consolidated into a unified index to assess the level of exposure to climate variability. A positive correlation has been identified between climate change, hydro-meteorological hazards, and exposure. Our analysis revealed that, out of fifteen districts, ten exhibit a high degree of exposure to rainfall variability, residents from eight districts might face the risks associated with landslides, six districts are vulnerable to wind damage, five are at risk of temperature variability, and five are exposed to flood events.

**Keywords:** climate change; exposure; vulnerability; hydrometeorological hazards

## 1. Introduction

The current knowledge in context of vulnerability to climate change, especially at basin scale seems to be very limited. There is ongoing concern about current and potential impacts of climate change on the vulnerable landscapes and communities of the Himalayan regions, as either is highly susceptible to such changes. The Indian Himalayan Region (IHR) and the Indo-Gangetic Plain Region (IGPR) are particularly sensitive to changes in the global climate from both physical and societal perspectives (IPCC, 2007, 2014, & 2018; Allen et al., 2016). Moreover, the IHR and IGPR are facing important challenges in view of coping with the adverse effects of climate change. Thus, understanding and anticipating the impacts of climate change on these regions and the services they provide to people are critical (Tewari et al., 2017). An important service provided by Himalaya to the downstream population of the Beas River basin is the year-round supply of fresh water. A consensus exists among the scientific community on the probability of likely impacts of climate change on the hydrology of the Himalayan basins (Tse-ring et al., 2010). Frequent occurrences of hazards such as landslides, snow avalanches, floods and other types of mass wasting are becoming common features of these regions (Prasad et al., 2016).

Exposure refers to the nature and degree to which various elements in an area are exposed to climatic variations and resultant hazard events. It could be defined as the presence of people, property, services, species, resources, infrastructure, and assets in areas which are likely to be adversely affected. Children, elderly people, disabled, women's, ethnic minorities, and socially deprived communities are often understood as highly exposed to climatic variability. These exposed groups are facing the impacts of climate change across the world, though their contribution to the climate crisis is least. Exposure, sensitivity and adaptive capacity, are the three components of vulnerability including both an internal and external dimension. Sensitivity and adaptive capacity represent the internal dimension related to the defence and security capacity – the capacity to anticipate, confront, resist and recover from a certain impact or damage. Several social, economic, cultural, political or environmental characteristics of a place determine sensitivity and adaptive capacity. While, exposure is the external dimension of vulnerability referring to the risk to a certain phenomenon or stressor.

Informative exposure assessment is essential for the development of quantitative estimates for vulnerability to climate change. Therefore, understanding and estimating exposure become fundamental to vulnerability assessment. Individuals, communities, and societies are known to have different exposures based on factors such as wealth, education, race, ethnicity, religion, gender, age, class, caste, disability, and health status (UNISDR, 2009; Cardona et al., 2012). Several rural societies still practicing traditional lifestyles are highly dependent on natural resources for their livelihoods all over the world. Such societies are projected to be directly exposed to both the projected climate change and an increase in disasters. This is particularly true for the already poor and marginalized communities living in the Himalayan region (ICIMOD, 2010). People living in the Himalayas are considered to be naturally exposed and vulnerable to climate change due to their geographical setting. Furthermore, altitude plays a dominating effect in deciding the levels of exposure. Researchers have noted that communities living at different elevations are differently exposed to climatic variability as the altitude changes sharply at small distances. Perhaps all the people living in the Himalayan region are found to have a low capacity to cope, yet those who live in the middle altitudes of the Himalaya are the most vulnerable to climate change (Chauhan et al., 2020).

## *Study Area*

Chorley et al. (1985) advocated the drainage basin as a basic erosional landscape element due to its topographic and hydrological unity. It is considered as a basic hydro-geomorphic unit for systematic analysis of input-processing-output. In the present research investigation, the area drained by the river Beas was taken to quantify the exposure to ongoing climate change and associated hydro-meteorological hazards. Beas River Basin (BRB), the study area lies between 31°09'16"-32°32'59" North Latitudes and 74°58'31"-77°54'08" East Longitudes covering an area about 19097 sq. km (Figure 1). The Beas is an eastern tributary of the Indus River and is the second smallest in length among all other tributaries of the Indus drainage system. The name of the river 'Beas' is known to have originated from its Sanskrit name 'Vipasha'.

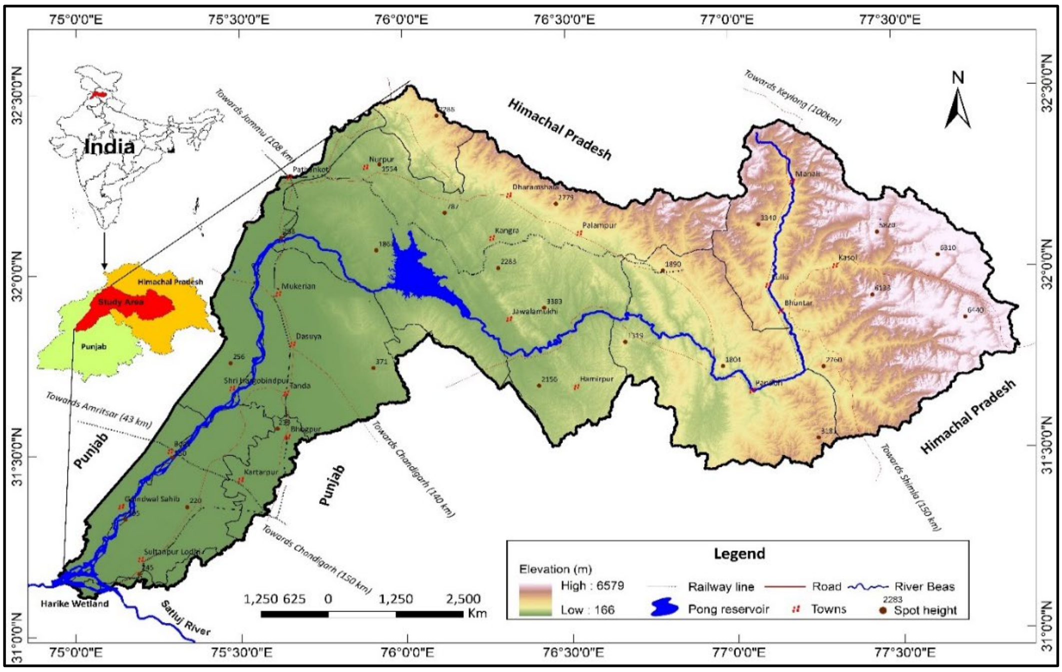



*Figure 1.* Location map of the study area-the Beas River basin.

The headwaters of the river are at 'Beas Kund' at an altitude of 4361 meters above sea level (m asl). Beas Kund is located on the southern face of Rohtang Pass, near the southern end of the Pir Panjal range, from where the river Beas flows south through the famous "Kullu" valley, supplemented by various snow-fed tributaries. It is fairly steep in the upper valley and the steepness keeps on declining in the lower valley. The river-flow in summers mainly consists of monsoonal runoff combined with snowmelt discharge. It drains through various districts of Himachal Pradesh and Punjab states in northern India. The study area is divided into two major divisions: the upper Beas River basin (UBRB) and the lower Beas River basin (LBRB). The UBRB occupy parts of 8 districts, namely Chamba, Hamirpur, Kangra, Kinnaur, Kullu, Lahaul & Spiti, Mandi, and Shimla. While, seven districts, namely, Una, Gurdaspur, Amritsar, Hoshiarpur, Jalandhar, Kapurthala, and Firozpur are covered fully or partially in the LBRB. Some important upper bank settlements on the banks of the Beas are Manali, Manikaran, Kullu, Mandi, Bajaura, Pandoh, Sujanpur, Tihar, Nadaun, and Dehra-Gopipur. In Punjab, Mukerian, Dasua, Sri Hargobindpur, Dhilwan, Sri Goindwal Sahib, Kapurthala, and Sultanpur Lodhi are situated on the lower banks.

There are eight major land use/land cover classes such as built-up, cropland, dense forest, open forest, wastelands, sandbars, snow cover, and waterbodies mapped in the basin (Figure 2). The dense and open forests occupy maximum share accounting to 54.3% area of the basin. These forests are extensively distributed with dense forests primarily restricted to the higher hills and interior valleys. Moreover, in addition to the forests, the eastern part of the upper basin was dominated by snow cover and wasteland. Contrary, the lower basin is least forested because it is more accessible and the forests have been cleared to make room for cultivation and settlement. The croplands and built-up areas make up the majority accounting for approximately 19% and 7.1% respectively. Sandbars and wastelands cover approximately 11.6% while, waterbodies occupy 2.7% of the study area, with Pong reservoir being the largest. In addition, there are many other smaller dam reservoirs, including Pandoh and Larji and a large number of moraine-dammed lakes in the upper basin.

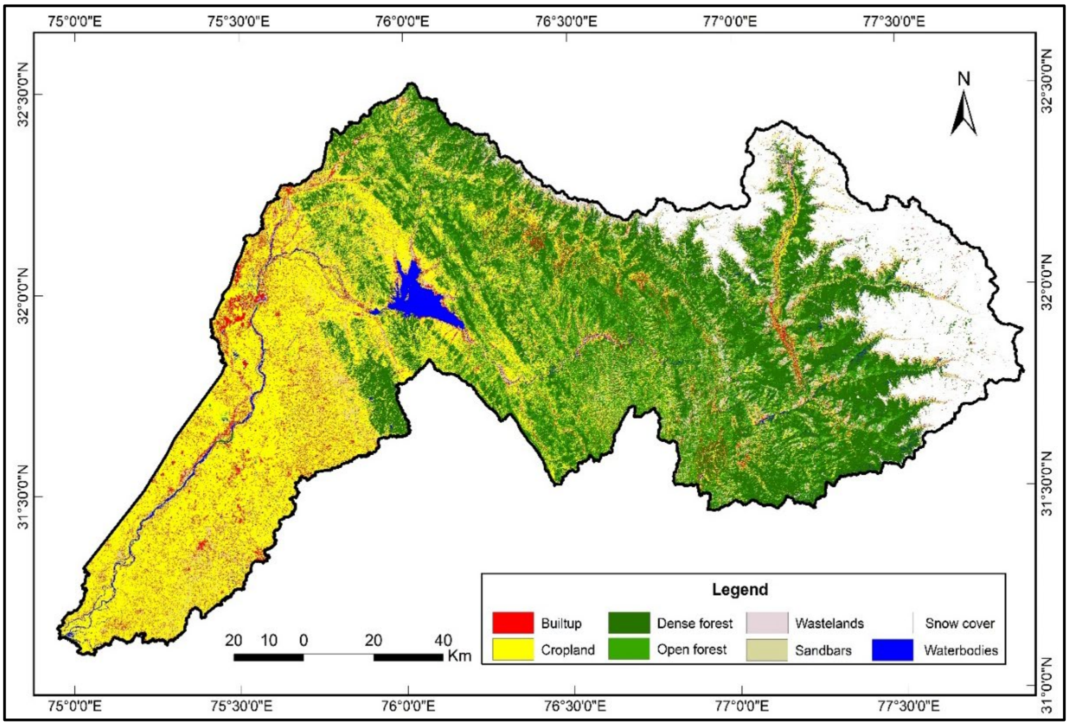



***Figure 2.*** Land use and land cover of Beas River Basin.

## 2. Methods and Materials

The climate change exposure index (CCEI) is a tool that can be applied to identify and measure the levels of risk due to climatic variability. It has the potential to integrate exposure to different climatic elements and hazards into a single parameter. It could be taken as an initial step in the process of adaptation planning and preventive decision-making (Sullivan and Meigh, 2005; Ravindranath et al., 2011; Pandey and Jha, 2012; Edmonds et al., 2020). An indicator-based approach was employed to capture the spatial variations in climate change exposure across the study area. To assess the exposure to climate change and hydro-meteorological hazards, a large amount of data was processed pertaining to the selected indicators representing the climatological aspects of the study area including the current state of the climatic variability and trends in the past. By integrating these diverse datasets, the research sought to offer a detailed insight into the impact of climatic factors on various regions, thereby enabling specific adaptation and mitigation approaches.

The study area was delineated with the help of Survey of India (SOI) Open Series Map (OSM) toposheets on 1:50,000 scale and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)-Global Digital Elevation Model (GDEM). The ASTER-GDEM was obtained from the website https://earthexplorer.usgs.gov. The land use and land cover (LULC) in the study area was derived using Google Earth Engine (GEE) with the help of Landsat OLI (30 m resolution) images for the year 2017. Satellite images of March 19, 2017 and April 17, 2017 with less than 5% cloud cover were used to delineate different LULC categories for the study area. A specific LULC code was generated to perform pixel-based supervised classification with 40 signature points for each LULC category.

Monthly rainfall and temperature data was obtained from the Climate Research Unit, University of East Angelia (CRU-UEA). The analysis was carried out using the collected data for the period of 1901 to 2017. The long-term average (LTA) of 117 years of temperature and rainfall was considered as the normal values and the trends were evaluated by using linear trend analysis. The spatial database was created for generating maps using ArcGIS 10.6.1 software. Microsoft Excel (2016) software was used for calculating statistical measures, tabulation, and analysis. XLSTAT (2021.3.1) software was used for performing the Mann-Kendal trend test and Sen's slope estimation. The methodology and workflow adopted for assessment of CCEI in the Beas River basin is as given in Figure 3.

**Scoping of exposure assessment:** The Beas River Basin (BRB) exhibits significant heterogeneity across its physical, economic, social, demographic, and institutional dimensions. This diversity manifests in varying topographies, from the high-altitude Himalayan regions to the low-lying plains, and encompasses a range of climatic conditions, land-use patterns, and socio-economic activities. Such disparities influence the degree and nature of exposure to climate change impacts across different districts within the basin.

Recognizing this complexity, our assessment aimed to rank districts based on their level of exposure to climate change. This approach facilitates the identification of areas most at risk, enabling the prioritization of adaptation strategies tailored to local conditions. By focusing on district-level analysis, we align with national efforts, such as the Climate Vulnerability Index (CVI) developed by the Council on Energy, Environment and Water (CEEW), which emphasizes the importance of localized assessments in understanding and addressing climate risks.

The district-level ranking serves as a critical tool for policymakers and stakeholders, guiding the formulation of locally relevant and effective adaptation plans. It ensures that resources are allocated efficiently, and interventions are designed to address the specific vulnerabilities and capacities of each district.

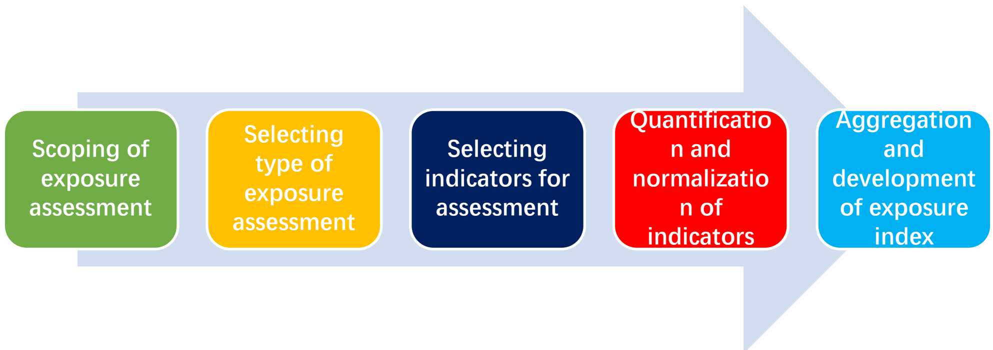



***Figure 3.*** Workflow for Calculating Climate Change Exposure Index.

**Selection of type of exposure assessment:** Exposure in any region can be assessed using multiple criteria based on the set of input indicators. If indicators are specific to biophysical environment, it can be called biophysical exposure assessment. On the other hand, if assessment is confined to certain socio-economic phenomenon, it is a socio-economic exposure assessment. Exposure can also be calculated using hazard-specific indicators. The most comprehensive among others is the integrated assessment (Alessa et al., 2008; Sullivan and Meigh, 2005). For the present study, indicators capable to expose the extent of climate change and hydro-meteorological hazards are integrated into exposure assessment.

**Identification and selection of indicators:** Identification of appropriate input indicators is one of the most critical steps as the outcome and effectiveness of the assessment depend on the choice of indicators. In order to accomplish greater validity and cross-comparison, we selected most of the indicators based on previous studies and expert knowledge in review discussions. To find out the spatial patterns of exposure to climate change and various hydro-meteorological hazards, 8 indicators were taken into account. The indicators of exposure explain how and to what extent the study area is exposed to climate change and allied hazard events. The description of exposure indicators and their functional relationship to exposure is presented in Table 1.

***Table 1.*** Details of exposure indicators for measuring climate change exposure index.

| **Category** | **Indicator** | **Unit of measurement** | **Functional relation** |
|---|---|---|---|
| CLIMATIC | Changes in average annual temperature (AAT) | Degrees Celsius | Positive |
| | Changes in diurnal temperature range (DTR) | Degrees Celsius | Positive |
| | Changes in average annual rainfall (AAR) | Millimetre | Positive |
| | Changes in monsoon season rainfall (MSR) | Millimetre | Positive |
| HAZARD | Area prone to floods (APF) | Percentage | Positive |
| | Population prone to landslides (PPLS) | Percentage | Positive |
| | Area with slope greater than 25 degrees (ASD) | Percentage | Positive |
| | Area prone high to very high wind damage (APWD) | Percentage | Positive |

**Quantification and normalization of indicators:** The required data was collected from multiple sources in quantifiable units to apply mathematical operations over it. Different indicators are measured in different units (e.g., average annual temperature in degrees Celsius, average annual rainfall in millimetres, etc.). As the CCEI is about ranking and prioritization the selected indicators have to be brought into common units of measurement. Therefore, in order to make the indicators unit-free, the normalization technique was used for each indicator.
Following equation is used for the purpose.

$$\text{normalized value} = \frac{\text{actual indicator value} - \text{minimum indicator value}}{\text{maximum indicator value} - \text{minimum indicator value}}$$

In developing the exposure index, we utilized min-max normalization to standardize all indicators within a range of 0 to 1. This method enhances comparability among different units and magnitudes while maintaining the relative distribution of the original data, which is essential for accurately depicting spatial differences in exposure levels. The choice of min-max normalization was influenced by its ease of use and efficiency, as it is commonly employed in vulnerability assessments due to its simple application and clarity.

**Assigning weights, composite index and development of CCEI:** Following the normalization of indicators, the subsequent step involved assigning weights reflecting their level of impact on exposure and consolidating indicators into a composite index. We applied an equal weights approach in which equal weights are assigned to each indicator to determine the exposure. The equal weights approach for assessing exposure offers several practical and methodological advantages, particularly when combining multiple indicators into a composite index. It offers a straightforward, clear, and impartial approach to developing exposure indices, particularly in cases where there is no solid theoretical or empirical rationale for attributing varied significance to indicators. By treating all variables equally, it guarantees a balanced representation of the multi-faceted nature of climate exposure, minimizes the risk of distortion, and improves comparability across different regions or time frames. The normalized values of individual indicators were then aggregated to obtain the overall exposure index for each district of the basin. The overall values of exposure were then labelled low (<0.4), moderate (0.4-0.6) and high (>0.6) and each district was placed into respective category to visualize the spatial distribution of exposure

## 3. Results and Discussion

### *3.1. Climatic Indicators*

3.1.1. Changes in Average Annual Temperature (AAT)

Climate change is often manifested as changes in temperature. The greater the fluctuations in temperature, greater will be the uncertainty. Average annual temperature significantly influences a region's exposure to climate change by intensifying both acute and chronic hazards. Elevated temperatures increase the frequency and severity of heatwaves, leading to heightened risks of heat-related illnesses and mortality, particularly among vulnerable populations such as the elderly and those with pre-existing health conditions.

The increasing temperature is affecting the availability of water, biodiversity, ecosystem boundaries, distribution and duration of rainfall and content of carbon in the soil (Ives, 2005; Xu et al., 2009; Kotlia and Joshi, 2013; Liang et al., 2013; Kohler et al., 2014). To find out the spatial pattern of exposure to temperature variability, the actual change in average annual temperature (AAT) for a period of 117 years from 1901 to 2017 using the annual temperature records was calculated (Figure 4). Huge variability is recorded in temperature over BRB in space and time. The AAT was noted maximum 22.6°C during 2016, followed by 22.5°C (2002), and 22.4°C (1999). Whereas, the minimum was observed 20°C in 1917, preceded by 20.3°C (1912), and 20.4°C (1913). Overall, it was noted that BRB has experienced relatively warmer temperatures after the first half of the 20th century.

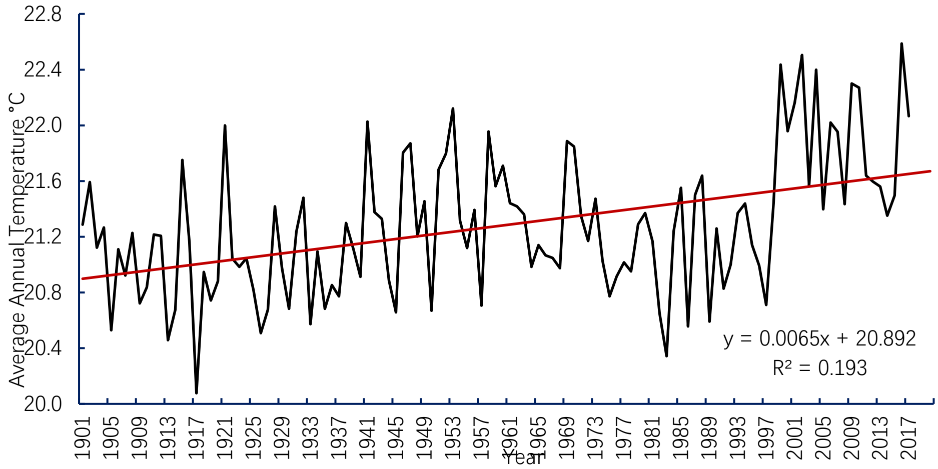



***Figure 4.*** Trends in average annual temperature over Beas River basin (1901-2017).

Spatially, higher temperatures were observed in the LBRB and the UBRB owing to its higher altitudes experience comparatively lower temperatures throughout the year. During the study period, the Firozpur district had the highest temperature with an LTA temperature of 25.4°C, followed by Jalandhar (24.8°C) and Amritsar (24.8°C). In addition, all other areas with high temperatures were part of LBRB, whereas all of the low temperature areas, including Lahaul and Spiti (9°C), Kinnaur (12.7°C) and Kullu (17.5°C) were part of UBRB. A range of 16.4°C was noted between the highest (Firozpur) and lowest (Lahaul & Spiti) temperature districts located at the southern and northern ends of the basin, respectively. The LTA temperature for the entire study area was calculated as 21.2 °C.

***Table 2.*** Differences of average annual temperature in the study area during 1901 and 2017.

| **Basin** | **District** | **1901** | **2017** | **Change** | **Sub basin** | **District** | **1901** | **2017** | **Change** |
|---|---|---|---|---|---|---|---|---|---|
| UBRB | Chamba | 19.28 | 20.37 | 1.09 (+) | LBRB | Una | 24.1 | 24.17 | 0.07 (+) |
| | Hamirpur | 23.29 | 24.36 | 1.07 (+) | | Amritsar | 24.97 | 25.06 | 0.09 (+) |
| | Kangra | 22.39 | 23.49 | 1.10 (+) | | Firozpur | 25.74 | 25.78 | 0.04 (+) |
| | Kinnaur | 12.75 | 13.98 | 1.23 (+) | | Gurdaspur | 23.79 | 25.06 | 1.27 (+) |
| | Kullu | 17.42 | 18.66 | 1.24 (+) | | Hoshiarpur | 24.19 | 24.56 | 0.37 (+) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Lahaul & Spiti | 8.87 | 10.15 | 1.28 (+) | | Jalandhar | 24.95 | 25.42 | 0.47 (+) |
| | Mandi | 22.09 | 23.27 | 1.18 (+) | | Kapurthala | 24.94 | 24.92 | 0.02 (-) |
| | Shimla | 20.57 | 21.76 | 1.19 (+) | | | | | |

During the study period of 117 years, a total of 62 years had an AAT of less than LTA and 48 years were recorded with temperatures warmer than LTA. Although the number of years with an AAT less than LTA temperature was more, the overall linear trend indicated an increasing temperature. Annual departures of temperature in the basin from the LTA vary between 1.3°C (2016) and-1.1 °C (1917). A huge range of 2.6°C was observed in the AAT between the warmest and the coldest years. The spatial distribution of AAT for the years 1901 and 2017 is presented in Table 2. It was noted that warming is more pronounced in the UBRB. The UBRB was 1.05°C warmer in 2017 as compared to 1901, while the LBRB was 0.37°C warmer than in 1901. The comparative analysis of the beginning year (1901) and the end year (2017) has revealed an increase in the mean temperature of all the districts for calculation of exposure index. It is asserted that, higher the normalised value, greater the exposure to climate change. Hence, the highest values were assigned to the districts with high exposure and vice versa.

3.1.2. Changes in diurnal temperature range (DTR)

The diurnal temperature range (DTR) is another important indicator used in assessing climate change because it provides a more detailed description of the complicated variations in daily maximum and minimum temperatures than the mean surface temperature (Braganza et al., 2004; Qu et al., 2014). A narrowing DTR, frequently caused by higher nighttime temperatures, can interfere with ecological processes like plant growth and soil respiration, which may change species distributions and ecosystem interactions. On the other hand, an expanding DTR, defined by larger temperature variations throughout a single day, has been associated with greater health risks, including more hospitalizations for cardiovascular and cerebrovascular illnesses. These fluctuations in temperature can increase stress on at-risk populations, especially in areas where healthcare resources are insufficient. DTR was obtained by subtracting the minimum temperature from the maximum temperature. The lesser the fluctuations in DTR, the smaller the probability of getting affected from climatic variability. Therefore, high values were assigned to the districts with the highest exposure to diurnal temperature change. It was observed that DTR was declining during the study period. Along with maximum temperatures, the minimum temperatures also increased throughout the study area.

The range of temperature over the study area increased from north to south, i.e., the UBRB witnessed less temperature variability than the LBRB. Temporal fluctuations in DTR are presented in Figure 5. Maximum DTR was noted in 1970 with complete spatial unity as all parts of the basin were noted with maximum DTR in the same year. DTR has shown a sudden decline during 1951–1960 and a considerable increase in the following decade. A detailed description of spatio-temporal variations in DTR is presented in Table 3. Although the lowest DTR was noted in 1962, huge variations were observed spatially (Figure 6). DTR fell the most in the upper basin, including Lahaul and Spiti (-0.22°C), Chamba (-0.21°C), and Kullu (-0.20C°) districts in Himachal Pradesh, and the least in the lower basin, including Firozpur (-0.06°C), Kapurthala (-0.09°C), and Jalandhar (-0.09°C) districts in Punjab. To be taken into consideration is that the upper basin is experiencing temperature increases with much more intensity as compared to the lower basin. The DTR for the entire basin kept on increasing for the first five decades of the twentieth century, and for the second half it had an undulating behaviour. The diurnal temperature range has decreased from 12.5°C in 1901 to 12.4°C in 2000.

***Table 3.*** Spatio-temporal distribution of minimum and maximum diurnal temperature range.

| Basin | District | DTR of minimum temperature | | DTR of maximum temperature | |
|---|---|---|---|---|---|
| | | Year | Range | Year | Range |
| UBRB | Chamba | 1962 | 11.83 | 1970 | 13.31 |
| | Hamirpur | 1961 | 12.47 | 1970 | 14.10 |
| | Kangra | 1962 | 12.38 | 1970 | 13.87 |
| | Kinnaur | 1961 | 8.18 | 1970 | 10.55 |

| | | | | | |
|---|---|---|---|---|---|
| | Kullu | 1961 | 9.92 | 1970 | 11.87 |
| | Lahaul & Spiti | 1960 | 10.59 | 1970 | 11.72 |
| | Mandi | 1961 | 11.81 | 1970 | 13.64 |
| | Shimla | 1961 | 10.72 | 1970 | 12.84 |
| LBRB | Una | 1961 | 12.82 | 1970 | 14.34 |
| | Amritsar | 1982 | 13.08 | 1970 | 14.19 |
| | Firozpur | 1982 | 13.65 | 1970 | 14.66 |
| | Gurdaspur | 1982 | 12.87 | 1970 | 14.07 |
| | Hoshiarpur | 1962 | 12.90 | 1970 | 14.27 |
| | Jalandhar | 1961 | 13.07 | 1970 | 14.37 |
| | Kapurthala | 1962 | 13.11 | 1970 | 14.31 |

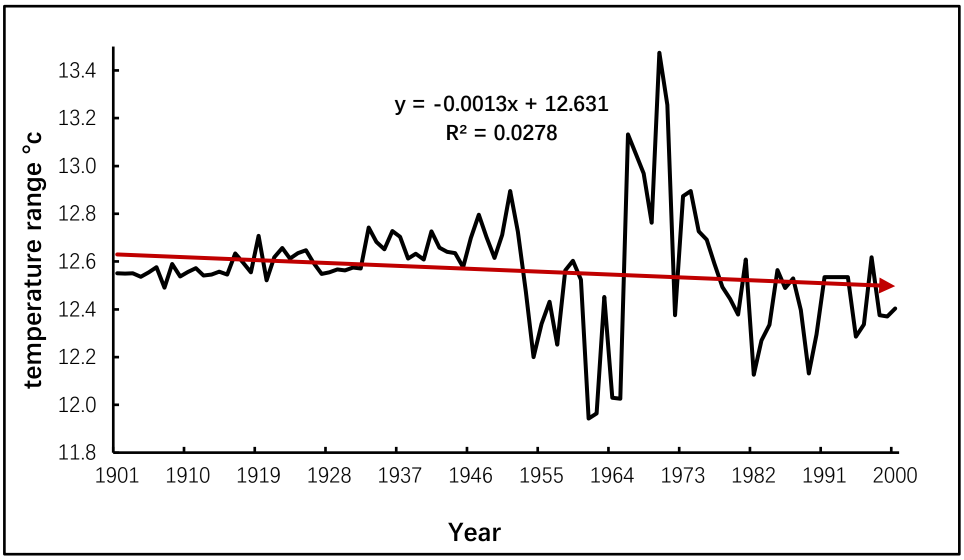



***Figure 5.*** Fluctuations in Diurnal Temperature Range over Beas River Basin.

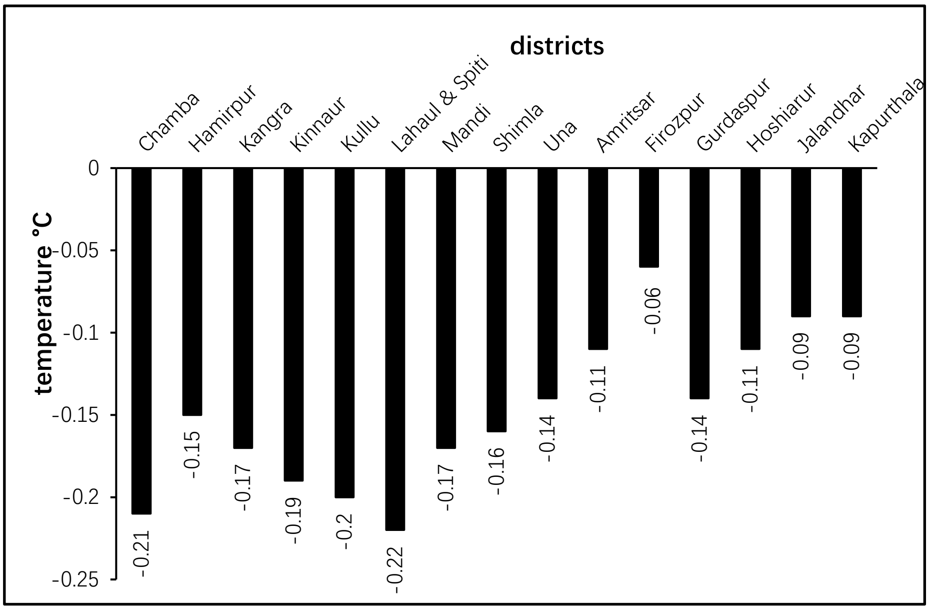
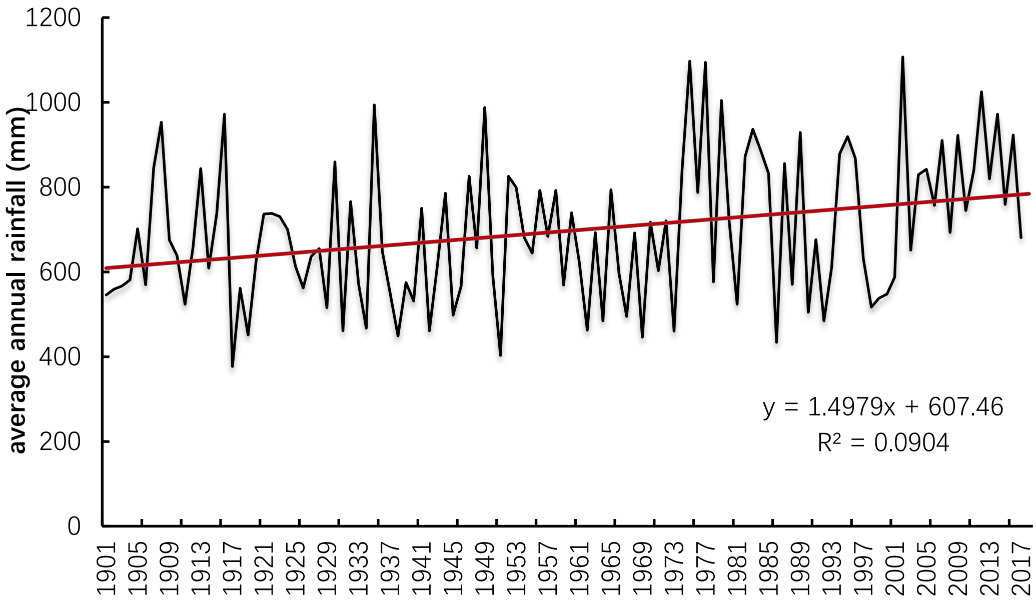



***Figure 6.*** Spatial distribution of change in Diurnal Temperature Range (DTR).

The analysis has revealed that Kinnaur (9.3°C), Lahaul & Spiti (10.6°C) and Kullu (10.7°C) had the minimum diurnal temperature range (DTR) in 1901. During the year 2000, DTR was found to be the lowest again in Kinnaur (9.2°C), Lahaul & Spiti (10.3°C) and Kullu (10.5°C) districts. However, the DTR in these districts was relatively lesser than 1901. On the other side, in 1901, the maximum DTR was recorded in Firozpur (14 °C), Jalandhar (13.5°C), and Kapurthala (13.5°C) and the DTR decreased to 13.9°C in Firozpur, 13.4°C in Jalandhar, and 13.4°C in Kapurthala during 2000. The highlight was that, the maximum fall in DTR has been noted in the areas of upper basin including Lahaul & Spiti (-0.22), Chamba (-0.21), and Kullu (-0.20) districts of Himachal Pradesh and minimum fall has been noted in the lower basin in Firozpur (-0.06), Kapurthala (-0.09) and Jalandhar (-0.09) districts of Punjab.

3.1.3. Changes in Average Annual Rainfall

Another manifestation of climate change is the pattern of quantum and the distribution of rainfall. Rainfall is also one of the main indicators in the studies of climate change impacts that influence the hydrologic system and agriculture of a region. An analysis of the distribution of rainfall over a region, both temporally and spatially, provides a better understanding of climatic variability. The average annual rainfall (AAR) for a period of 117 years (1901–2017) recorded in the entire Beas River basin is presented in Figure 7. **The long-term average annual rainfall (LTA) noted was 743.4 mm.** The analysis of the AAR revealed that the minimum rainfall was 400.7 mm during the year 1918, preceded by 428 mm (1952), and 461.3 mm (1987). On the other hand, maximum rainfall was 1166.4 mm in 1976, followed by 1163.9 mm (1978), and 1125 mm.




**During the study period of 117 years, a total of 66 years received rainfall less than the long-term average, whereas 51 years were observed with more rainfall than the LTA.** Although the number of years with lesser rainfall than LTA was greater than those received more rainfall than LTA, the overall linear trend in rainfall was upward. Annual rainfall departures from the LTA in the basin range from -346.9 mm in 1918 to 419.1 mm in 1976. During 1901-1950, a total of 35 years received rainfall less than LTA, as compared to the second half, that received lesser rainfall only in 27 years. A considerable increase in rainfall was observed during latter half in the $20^{th}$ century. Moreover, it is also noted that the first quarter of the twenty-first century has experienced a comparatively higher amount of downpour than the first quarter of the twentieth century.

Spatially, Kullu district of UBRB has received the maximum amount of rainfall during last 117 years with an LTA rainfall of 966.4 mm, followed by Shimla (938.9 mm) and Kinnaur (918.6 mm). In addition, all other high rainfall districts were part of UBRB. whereas all of the low rainfall receiving districts, including Firozpur (303.2 mm), Amritsar (475.2 mm) and Kapurthala (504.4 mm) were part of the LBRB. A range of 663.1 mm was noted between the highest (Kullu) and lowest (Firozpur) rainfall receiving districts located at the northern and southern ends of the basin, respectively. Further, it was observed that northern, north-eastern, and south-eastern parts of the study area receive much rainfall, whereas the north-western, southern, and south-western parts receive a comparatively lesser amount of rainfall. The maximum variation in annual rainfall was observed in lower parts of the basin. The average annual rainfall increased during the second half in all the districts except Kinnaur. Maximum increase was observed in the low-lying areas of Punjab and the rainfall increase kept on decreasing towards the north and the hilly parts of the UBRB (Kumar and Rao, 2021).

#### 3.1.4. Changes in Monsoon Season Rainfall

The Indian summer monsoon rainfall is controlled mainly by the south-west monsoon. It occurs from June to September every year and plays an important role in the agricultural production in India. The study and prediction of monsoon rainfall variability has been a matter of great importance to both society and the scientific community because a deficit or excess in summer monsoon rainfall in a year leads to drought or flood disasters respectively, causing great impacts on the agriculture and economic activities of the region (Webster et al., 1998). Similarly, the maximum amount of rainfall in the study area is received during the south-west monsoon season. Hence, the monsoon season rainfall has been taken into consideration in addition to the average annual rainfall.

During monsoon season, Amritsar, Firozpur, Jalandhar, and Kapurthala districts were noted with significant increases in rainfall at a rate of 1.2, 1, and 0.8 mm/year respectively. In addition, Chamba, Hamirpur, Kangra, Una, Gurdaspur, and Hoshiarpur districts were also observed with increasing trends, but the trends were not statistically significant. Moreover, negative trends were also observed at some locations during the monsoon season. Although Kinnaur, Kullu, Lahaul & Spiti, Mandi, and Una districts had negative trends in rainfall, these trends were not statistically significant. Overall, huge spatial variability was noted during the monsoon season. The southern and south-western parts of BRB have shown a statistically significant increase in rainfall during 1901–2017.

### *3.2. Hazard Specific Indicators*

#### 3.2.1. Area Prone to Floods

The hazard event is not the sole driver of risk because the severity of the impacts depends strongly on the level of exposure of societies and socio-ecological systems to such events (Alford, 1992; UNISDR, 2004; Birkmann, 2006). Frequent occurrences of hazards such as floods are becoming common features in the mountainous and plain regions of northern India. Furthermore, the growing population and the expansion of human activities on fragile land trigger disasters in the lower Himalayan region. The larger the area prone to flood events, the greater the exposure. The occurrence of floods is limited to the rainy season when almost 80% of the annual rainfall is received. It was noted that, the exposure to flood events in BRB is primarily restricted to lower regions and the upper regions does not face extensive flooding. Although, the amount of annual rainfall received by UBRB is more than double the amount received by LBRB, the mountainous relief and steep slopes provide suitable topographic conditions for rapid runoff. The analysis of spatial distribution of floods in the LBRB highlighted that Jalandhar district has the highest percentage of area prone to floods followed by Amritsar and Hoshiarpur. All these three districts have more than 80% area prone to floods.

#### 3.2.2. Area Prone to Landslides

Landslides cause a large-scale disruption of natural resources, economic valuables, and human lives. With particular reference to the Himalaya, a large number of landslides occur every year, causing extensive damage to human lives, properties, and natural resources (ADB, 2010; Prasad et al., 2016). The Himalayan ranges are formed of tectonically active younger geological formations and the exposure of these juvenile and not so stable steep slopes in various Himalayan ranges, has increased at a rapid rate recently due to activities like deforestation, road cutting, terracing, etc. Another hazard in the basin is the occurrences of landslides, however, the incidences of damages caused due to landslide events are limited only to UBRB.

The classification of intensity of landslide and levels of risk is adopted from the BMTPC vulnerability atlas. The classification has four levels of risk such as severe to very high, high, moderate to low and Unlikely (Figure 8). For calculation of exposure index, the first two levels of risk i.e., severe to very high and high are taken into account. The hilly and mountainous relief of Himachal Pradesh is liable to suffer landslides during south-west monsoon season. Moreover, such events can also occur due to high intensity earthquakes. It was noted that the high-altitude districts with steep slopes are more prone and exposed to landslides, particularly during the rainy season. The maximum area prone to landslides lie in the districts of Lahaul and Spiti, Chamba and Kinnaur. Whereas, the highest percentage of the total population prone to landslides resides in the districts of Kangra, Shimla and Mandi (Table 4). Around 13% population in Kangra district is prone to landslides. While the population in the lower basin does not face landslide hazard events.

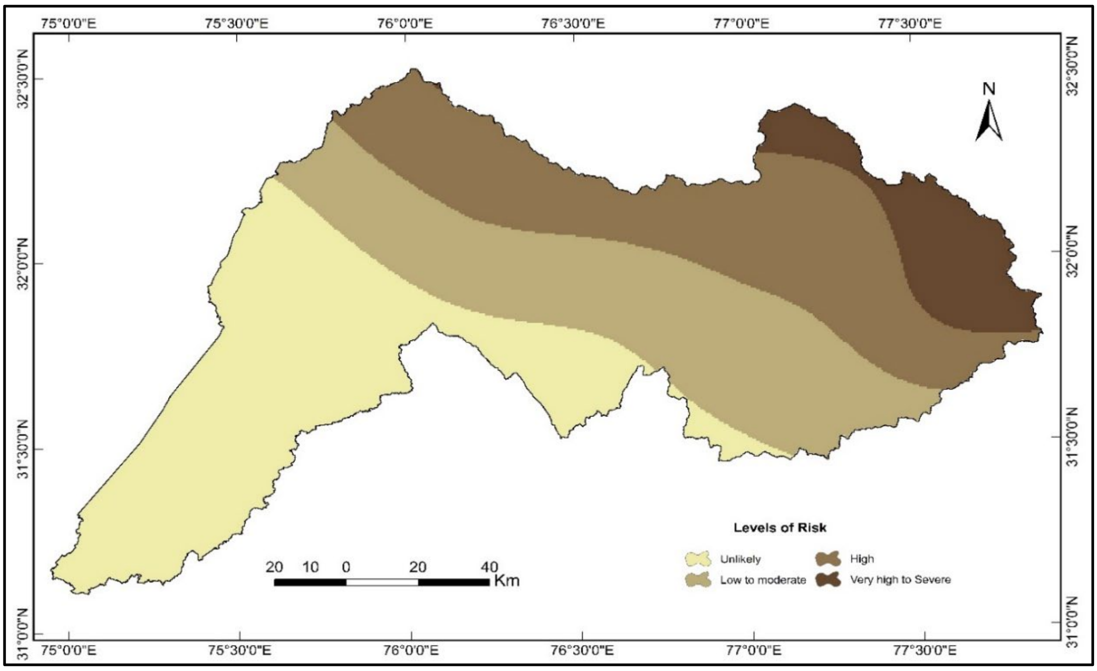



*Figure 8.* Spatial distribution of risk due to landslides in Beas River basin.

3.2.3. Area with Slope Greater than 25 Degrees

Slope is a hazard-specific indicator that determines the sensitivity of a region. Various climate-dependent parameters affecting the sub-surface hydrology led to slope instability, which may result in landslide activity (Dehn et al., 2000). Therefore, slope stability is one of the vital indicators primarily in the hilly and mountainous regions for assessing the exposure to hydro-meteorological hazards (Dijkstra and Dixon, 2010). Steep topographical features imply lack of availability of flat land, instability, and inaccessibility. These areas are more susceptible of being adversely affected due to changes in the climate. Hypsometric analysis was carried out to measure the topographic area-elevation relationship and slope distribution in the study area. Advanced Land Observing Satellite (ALOS) Global Digital Surface Model-2018 (ALOS World 3D-30m (AW3D30) Version 2.1) was used to generate contours and derive slope. The slope in degrees was divided into six categories (Figure 9) such as very gentle (less than 5), gentle (5-10), moderate (10-15), moderately steep (15-25), steep (25-35) and very steep (above 35).

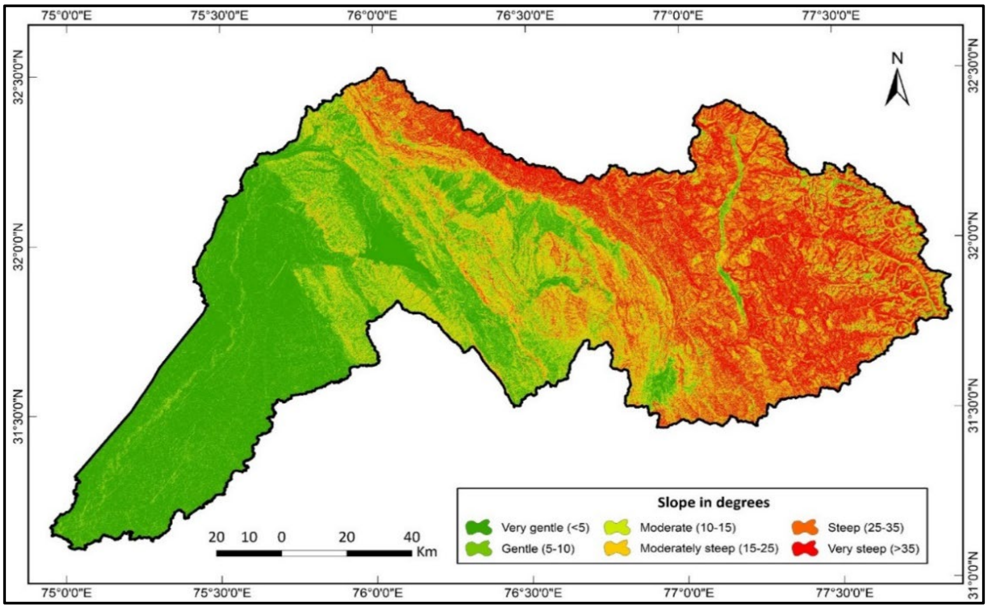



*Figure 9.* Distribution of slope in Beas River basin.

The BRB is lowest in the 'Bet' areas of the alluvial plains and highest near its headwaters with elevations ranging between 166 m in the plains to more than 6500 m in the Great Himalayan range highlighting the great heterogeneity in physiographical characteristics. Around 55% of the basin is occupied by areas with elevation less than 1000 m. As far as slope is concerned, BRB has huge slope variations ranging from very gentle to very steep. The steep to very steep slopes is the chief characteristic feature of the UBRB, while the LBRB has very gentle to gentle slopes. It is noted that, the slope gradient in the study area keeps on declining as one moves from north-east to north-west. Moreover, the percent area under slope more than 25° is greater in the districts of UBRB. In Lahaul & Spiti and Kullu more than 50% of district area has slope greater than 25°. For the analysis we have taken into account the district area under steep and very steep slopes only. The steep topographic environment and monsoon climate combine to produce landslide problems in the Himalaya. Therefore, areas with more than 25-degree slope were considered highly sensitive regions to climate change.

***Table 4.*** Spatial distribution of risk from floods, landslides and wind disasters.

| **Basin** | **District** | **Level of Risk (area in %)** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **Flood Prone Area** | **Landslide** | | | **Wind Velocity m/s** | | |
| | | | **Very High** | **High** | **Total** | **Very High** | **High** | **Total** |
| UBRB | Chamba | 0.00 | 33.27 | 60.08 | 93.35 | 0.00 | 0.00 | 0.00 |
| | Hamirpur | 0.00 | 0.00 | 77.36 | 77.36 | 0.00 | 0.00 | 0.00 |
| | Kangra | 0.00 | 2.19 | 65.91 | 68.10 | 0.00 | 0.00 | 0.00 |
| | Kinnaur | 0.00 | 13.72 | 78.31 | 92.03 | 0.00 | 0.00 | 0.00 |
| | Kullu | 0.00 | 33.69 | 65.00 | 98.69 | 0.00 | 0.00 | 0.00 |
| | Lahaul & Spiti | 0.00 | 0.93 | 85.55 | 86.48 | 1.9 | 0.00 | 1.9 |
| | Mandi | 0.00 | 25.00 | 51.08 | 76.08 | 0.00 | 0.00 | 0.00 |
| | Shimla | 0.00 | 17.81 | 66.70 | 84.51 | 0.00 | 0.00 | 0.00 |
| LBRB | Una | 0.00 | 0.13 | 44.97 | 45.10 | 12.7 | 0.00 | 12.7 |
| | Amritsar | 84.4 | 0.00 | 0.00 | 0.00 | 100 | 0.00 | 100 |
| | Firozpur | 51.4 | 0.00 | 0.00 | 0.00 | 16.8 | 83.2 | 100 |
| | Gurdaspur | 67.2 | 0.00 | 0.00 | 0.00 | 71.5 | 0.00 | 71.5 |
| | Hoshiarpur | 81.7 | 0.00 | 0.00 | 0.00 | 79.6 | 0.00 | 79.6 |
| | Jalandhar | 86.4 | 0.00 | 0.00 | 0.00 | 100 | 0.00 | 100 |
| | Kapurthala | 65.5 | 0.00 | 0.00 | 0.00 | 100 | 0.00 | 100 |

Source: BMTPC, vulnerability atlas of India.

3.2.4. Area prone to wind damage

High wind is a component of weather that can pose many threats to life and property (Adelekan, 2012). Wind speed and turbulence intensity over mountainous terrain with different topographical characteristics, such as escarpments, cliffs, ridges, and hills, are quite different from those over flat terrain. The IPCC's assessment highlighted the likely increase in the frequency and intensity of extreme weather events related to temperature, wind, and rain, consequent to global climate change. The occurrence of more extreme weather events, together with rapid and unplanned growth, poor environmental management, and poor socioeconomic conditions, has been largely responsible for the increasing vulnerability of societies to natural disasters.

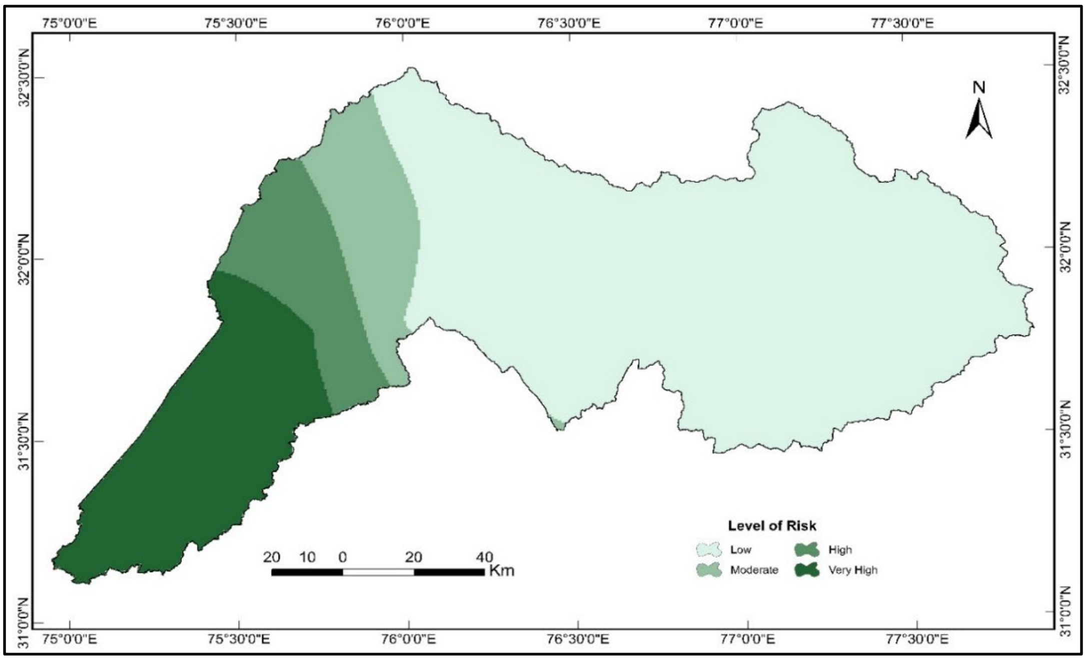



***Figure 10.*** Distribution of risk due to wind damage in Beas River basin.

The classification of wind speed and levels of risk is adopted from the BMTPC vulnerability atlas (Figure 10). The classification has four levels of damage risk such as low, moderate, high and very high damage risk zones depending upon the nature of material used for construction of the buildings. For calculation of exposure index, we have taken into account the first two levels of risk i.e., very high damage risk zone (wind speed 50 m/s) and high damage risk zone (wind speed 47 m/s). In the study area, the UBRB has low exposure to wind-specific hazards while, most of the LBRB lies in the high to very high damage risk zone. Districts like Amritsar, Jalandhar and Kapurthala fall entirely in the very high wind damage risk zone while, other districts of Firozpur, Gurdaspur and Hoshiarpur also has considerably large area of the district in the category of high to very high damage risk zones.

3.2.5. Exposure Index (EI)

The normalized values for individual exposure indicators and the cumulative exposure for all the indicators are given in Table 5. It is noted that the districts of the UBRB, including Chamba, Kangra, Kullu, Kinnaur, and Lahaul & Spiti, were highly exposed to variability of temperature. While the districts of LBRB such as Amritsar, Firozpur, Hoshiarpur, Jalandhar, and Kapurthala were least exposed. Other districts, namely Hamirpur, Mandi, Shimla, Gurdaspur, and Una, were moderately exposed to temperature variability. Both maximum and minimum temperatures increased during the study period as a result the diurnal temperature range decreased from 12.54°C in 1901 to 12.40°C in 2017.

***Table 5.*** Normalized values of exposure indicators.

| BASIN | DISTRICT | AAT | DTR | AAR | MSR | APF | APLS | SL25 | APWD | CCEI | BASIN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| UBRB | Chamba | 1.00 | **1.00** | **0.69** | **0.47** | **0.00** | **0.95** | **0.64** | **0.00** | **0.59** | **0.43** |
| | Hamirpur | 0.52 | **0.56** | **0.61** | **0.63** | **0.00** | **0.78** | **0.06** | **0.00** | **0.40** | |
| | Kangra | 0.72 | **0.72** | **0.69** | **0.63** | **0.00** | **0.69** | **0.25** | **0.00** | **0.46** | |
| | Kinnaur | 0.79 | **0.39** | **0.00** | **0.00** | **0.00** | **0.93** | **0.20** | **0.00** | **0.29** | |
| | Kullu | 0.67 | **0.58** | **0.30** | **0.22** | **0.00** | **1.00** | **0.93** | **0.00** | **0.46** | |
| | Lahaul & Spiti | 0.81 | **0.81** | **0.38** | **0.19** | **0.00** | **0.88** | **1.00** | **0.02** | **0.51** | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mandi | 0.56 | **0.50** | **0.44** | **0.45** | **0.00** | **0.77** | **0.56** | **0.00** | **0.41** | |
| | Shimla | 0.57 | **0.22** | **0.21** | **0.54** | **0.00** | **0.86** | **0.01** | **0.00** | **0.30** | |
| LBRB | Una | 0.36 | **0.53** | **0.74** | **0.79** | **0.00** | **0.46** | **0.02** | **0.13** | **0.38** | **0.50** |
| | Amritsar | 0.00 | **0.47** | **1.00** | **1.00** | **0.98** | **0.00** | **0.00** | **1.00** | **0.56** | |
| | Firozpur | 0.21 | **0.00** | **0.64** | **0.74** | **0.59** | **0.00** | **0.00** | **1.00** | **0.40** | |
| | Gurdaspur | 0.42 | **0.69** | **0.98** | **0.97** | **0.78** | **0.00** | **0.01** | **0.72** | **0.57** | |
| | Hoshiarpur | 0.26 | **0.47** | **0.85** | **0.90** | **0.95** | **0.00** | **0.00** | **0.80** | **0.53** | |
| | Jalandhar | 0.20 | **0.28** | **0.87** | **0.97** | **1.00** | **0.00** | **0.00** | **1.00** | **0.54** | |
| | Kapurthala | 0.10 | **0.27** | **0.87** | **1.00** | **0.76** | **0.00** | **0.00** | **1.00** | **0.50** | |
| **BRB** | | **0.47** | **0.50** | **0.61** | **0.64** | **0.33** | **0.49** | **0.24** | **0.37** | **0.46** | **0.46** |

| | | | |
|---|---|---|---|
| **Levels of Exposure** | **High (>60)** | **Moderate (40-60)** | **Low (<40)** |

A positive relationship was established between DTR and exposure to climate change. Districts of Chamba, Kangra, Lahaul & Spiti, and Gurdaspur recorded higher variations in DTR and, hence, were highly exposed. On the other hand, Kinnaur, Shimla, Jalandhar, Kapurthala, and Firozpur districts were least exposed to changes in DTR. In context to annual and monsoon rainfall, the spatial distribution of exposure is ironic to temperature as high exposure was noted in the districts of LBRB including Amritsar, Kapurthala, Gurdaspur, Hoshiarpur, Jalandhar, Una and Firozpur.

A positive relationship was established among various hydro-meteorological hazards and exposure because more the exposure to hazard events, greater the loss to life and property. Earthquakes, landslides, cloudbursts, avalanches, flash floods, and other natural disasters are common in UBRB. On the other hand, LBRB is particularly exposed to annual flood events, winds and dust storms. The normalized values for flood exposure were highest in Amritsar, Gurdaspur, Hoshiarpur, Jalandhar, and Kapurthala, while UBRB has no exposure to such events. Similarly, damage due to wind hazards was limited to the southern parts of the basin. Amritsar, Firozpur, Gurdaspur, Hoshiarpur, and Jalandhar were highly exposed to wind hazards. Whereas, the mountainous and hilly regions of UBRB were found to be completely devoid of any damage due to furious winds because the mountainous landscape does not allow the free movement of winds.

All the indicators were assigned equal weights to derive the cumulative values of exposure using normalized values of different indicators using a simple arithmetic mean equation. High exposure was recorded in the UBRB for the indicators of change in average annual temperature and change in the diurnal temperature range. While, the indicators of change in average annual rainfall, change in monsoon season rainfall, and percentage of people at risk of landslides showed moderate exposure. Furthermore, due to steep slopes and high altitudes, UBRB had very little to no exposure to annual flood events and wind damage. Overall, minimum and maximum exposure to climate change and hydrometeorological hazard evets were recorded in the districts of Kinnaur and Chamba respectively.

The lower basin is highly exposed to changes in average annual rainfall, changes in monsoon season rainfall, areas prone to flood hazards, and district areas prone to high wind hazards. It is interesting to know that, despite being highly exposed to individual indicators, no district has high exposure in cumulative climate change exposure index. The districts were either moderate or low exposure. Moderate exposure was noted in the districts of Chamba, Kangra, Kullu, Lahaul & Spiti, Mandi, Amritsar, Gurdaspur, Hoshiarpur, Jalandhar and Kapurthala. Low exposure was observed in Hamirpur, Kinnaur, Shimla, Una, and Firozpur districts of the study area.

## 4. Conclusion

Our research indicates a concerning pattern regarding climate change exposure in the Beas River Basin. Among the fifteen districts examined, ten demonstrate a high level of vulnerability to fluctuations in rainfall, implying that these regions may face considerable disruptions in agricultural production, water supply, and an increased likelihood of flooding. Moreover, residents in eight districts are at an elevated risk of landslides, a danger intensified by heavy rainfall and unstable slopes, particularly in hilly areas. Six districts are especially at risk for wind damage, which could endanger infrastructure and raise the potential for injuries and economic losses. In addition, five districts are markedly at risk from temperature fluctuations, which may result in various health issues and impact crop yields. Likewise, five districts are considerably prone to flooding events, posing threats to lives, livelihoods, and essential infrastructure.

The implications of these findings for demographics are significant. As populations expand in areas with high exposure risks, the number of individuals vulnerable to these risks is expected to rise. In light of future climate change scenarios, millions may encounter extreme weather phenomena like never before, resulting in critical water shortages, an increase in diseases spread by vectors and contaminated water, and intensified strain on healthcare and emergency services. These transformations are likely to threaten food and livelihood security, particularly for those communities that depend on climate-sensitive industries such as agriculture and forestry.

Additionally, there remains a significant knowledge gap concerning the vulnerability of diverse ecosystems—particularly in mountainous regions—to climate change. These ecosystems are highly responsive; even slight rises in temperature can hasten the melting of glaciers, alter snow-laden terrains, and quickly transform climatic zones. Consequently, mountainous regions may experience serious ecological impacts, such as loss of biodiversity, soil deterioration, reduced plant cover, less availability of water, and lower agricultural yields.

In this context, it becomes imperative to integrate climate change considerations into development and planning processes. Recognizing exposure is a vital initial step in evaluating vulnerability. Charting the geographic distribution of exposure aids in pinpointing the populations and ecosystems most at risk, as well as guiding tailored and region-specific adaptation approaches. This understanding is vital for enhancing climate resilience and lessening the lasting effects of a shifting climate on both human and natural systems.

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**Competing of interests**

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