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REVIEW ARTICLE

# Tree-ring inferred natural hazards studies from western Himalaya, India: a review

Sadhana Vishwakarma[1,2] · Krishna G. Misra[1,3] · Vikram Singh[1,4] · Ravi S. Maurya[1,3] · Sandhya Misra[1] · Nandita Ghoshal[2]

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**Abstract**

Natural hazards increasingly threaten lives, settlements, and environments globally, with their frequency rising due to climate change driven by global warming and deforestation. High-altitude regions like the Himalayas face heightened risks of floods, droughts, and glacial lake outbursts. Observational records show reduction in rainy days but more intense precipitation events, alongside accelerated glacial retreat, driving rivers to dangerous levels. Tree-ring-based studies were conducted in the western Himalaya to comprehend the severity of past natural hazards and facilitate policy-making and community awareness. These studies utilized records of floods, snow avalanches, and glacial fluctuations. However, river flow reconstructions proved inadequate in identifying flash flood activities. Understanding natural hazards occurrence, frequency, and magnitude is crucial for effective hazard assessment and management. Tree rings, forming annually in trees, serve as invaluable records of historical environmental conditions. A high-resolution database from tree-ring analysis helps to understand historical events and suggests strategies to mitigate natural hazards. Analyzing tree-rings provides insights into the dynamics and recurrence of natural hazards. The review paper emphasizes the critical role of dendrogeomorphology and dendrochronology in reconstructing historical natural hazards and advancing scientific understanding, which can advise more effective risk mitigation and sustainable development strategies.

**Keywords** Dendrochronology · Drought · Flood · Sustainable development · Global warming · Deforestation

## Introduction

Tree-ring is an annual growth layer in the wood or xylem. In gymnosperms, this ring consists of an inner layer of larger, thin-walled earlywood cells and an outer layer of smaller, thick-walled latewood cells (Larson 1962). Dendrochronological techniques have been more widely applied in temperate regions than in the tropical areas where distinct tree rings are formed (Glock 1955). Tree growth is influenced by physical factors, such as soil type, and annual variations in climatic parameters like temperature and rainfall (Fritts 1976; Schweingruber 1996). Trees naturally respond to these conditions, and when they are sufficiently sensitive, their growth rings can record past environmental conditions (Speer 2010). By analyzing these rings, scientists can identify specific years when trees reacted to significant events such as insect infestations, volcanic eruptions, extreme cold, floods, and droughts (Schweingruber 1996). These growth patterns provide insights into tree adaptation over time and offer valuable information about historical climatic conditions (Fritts 1976). However, accurate interpretation requires understanding of the unusual changes or anomalies in tree rings. Intra-annual density fluctuations (IADFs) are distinctive layers of cells within a tree ring, characterized by unique shapes, sizes, and wall thickness (Kaennel and Schweingruber 1955). These formations are often referred to as false rings (Schulman 1938), multiple rings (Kozlowski 1971),

✉ Sadhana Vishwakarma
vishwakarmasadhana130@gmail.com

✉ Krishna G. Misra
kgmisrabsip@gmail.com

1 Birbal Sahni Institute of Palaeosciences, 53 University Road, Lucknow 226007, India

2 Department of Botany, Institute of Science, Banaras Hindu University, Varanasi 221005, India

3 Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India

4 B. D. Govt. P. G. College Jaiharikhal, Pauri Garhwal, Uttarakhand 246193, India

or intra-annual growth bands (IADFs, Fritts 1976). IADFs typically form within annual rings in response to short-term climatic changes during the growing season. They are sometimes linked to disruptions or reductions in photosynthesis caused by environmental stresses, such as extreme drought, frost, or defoliation due to fire or pathogen attacks (De Micco et al. 2007; Schweingruber 2007). Precipitation and temperature are the most frequently studied factors in IADF formation, as they are crucial for understanding the ecological significance of these fluctuations (De Micco et al. 2016). A recent study by Maurya et al. (2023) on IADFs in the Himalayan cedar tree-ring chronology from Kullu, Himachal Pradesh, western Himalaya, identified several occurrences of earlywood IADFs (IADF*e*) and latewood IADFs (IADF*l*). The years 1901, 1902, 1903, 1914, 1915, 1919, 1920, 1923, 1925, 1943, 1958, and 1959 were associated with short-term dry phases, while the years 1937, 1955, 1956, and 1988 corresponded to pluvial (wet) phases during the growing period.

Tree-ring analysis of climate variables in India has been practiced since the 1980s to understand long-term variability in climate records from different geographical regions (Pant et al. 1998). Recent advancements have expanded this field to include high-resolution reconstructions of temperature, precipitation, and drought patterns, utilizing a wider array of species and modern statistical techniques (Misra et al. 2021; Rastogi et al. 2023; Singh et al. 2021, 2022; Yadava et al. 2021). Natural hazard is a suddenly occurring phenomenon, which negatively impacts the growth of human society and lives. The natural hazards can be categorized into five sub-groups; climatological (extreme temperature, drought, and wildfires), hydrological (floods and flash floods), geophysical (earthquakes, volcanic activity, landslides, rock falls, avalanches, subsidence, and other mass movements), meteorological (tropical, extra-tropical, and local storms), and biological hazards (epidemics, insect infestation and animal stampede) (Rodriguez et al. 2009). Among them, the hydro-geomorphic processes, including droughts, floods, flash floods, snow avalanches, debris flows, landslides, glacier lake outburst floods (GLOF), and rock falls have devastating impacts in the Himalayan region due to its tectonically controlled fragile orography.

The Himalayan Mountain system is unique in the world due to its young and dynamic geology. Rugged and dissected Himalayan topography due to folded, faulted, and thrusted rock sequences make it more vulnerable to natural hazards (Pathak 2016). The active plate movement of the Indian subcontinent and the large-scale climate variability on a spatio-temporal scale leads to an increase in natural hazard activity along the Himalayan Mountain belts. Climate variables such as precipitation and temperature are important factors that trigger natural hazards over the Himalaya and influence socio-economic lives (Thapliyal et al. 2024). Available studies indicate linkages of natural hazards with extreme climate events and such activities may be enhanced in the future due to rapid changes in the global climate (Bhattacharyya et al. 2017). The varied mountain ranges and complex atmospheric processes in the Himalayas create distinct climatic regimes influenced by the dominance of the Indian Summer Monsoon (ISM) and Western Disturbances (WD). During the active phase of ISM, high precipitation caused floods on several occasions in the Indian subcontinent, whereas WD became responsible for heavy snowfall and snow avalanches in the western Himalayan region. Similarly, increasing global temperature seriously impacts glacier boundaries, resulting in significant loss of glaciers in the Himalaya (Bolch et al. 2012; Kulkarni and Karyakarte 2014). The excessive precipitation and/or rapid melting of glaciers accelerate the water flow rate in the river channels and create havoc in the western Himalaya. Some examples of recent floods are; Leh-Ladakh (2010), Himachal Pradesh (2012), Kedarnath (2013), Jammu–Kashmir (2014 and 2017), and Rishiganga flood (2021) etc. The immense loss of infrastructure, agricultural land, forest, natural resources, along with thousands of lives, occurred in the Himalayan region due to such hazardous events (Chauhan and Sharma 2012; Mueller et al. 2019; Malik and Hashmi. 2021; Rao et al. 2014). Figure 1 demonstrating the significant impact of natural hazards on natural resources and socioeconomic conditions. Under the current global warming scenarios, the risk of such hazardous events is expected to increase soon, posing grave danger to life and property. Therefore, to mitigate the impact of such events, long-term information on the occurrence and severity of such hazardous events is essential (IPCC 2023). However, limited observational data hinder our understanding of the long-term occurrence of such events, but high-resolution, annually resolved tree-ring data can help to understand the climatic events and extend these records beyond the period of instrumental observations. Tree-rings capture high-resolution annual scale environmental changes and proved its utility as a potential proxy for investigating such events. However, no such attempt was made earlier to collect such randomly dispersed information to provide a database of natural hazards. Therefore, in the present attempt, we tried to summarize the tree-ring-based studies which include natural hazards over the western Himalaya. We illustrated results from climate reconstructions and dendro-geomorphological investigations of natural hazards with significance on hydrological (floods, droughts, and debris flows) and mass-movement processes (snow avalanche and landslide). Most of the studies conducted over the western Himalaya primarily focused on climate reconstruction (Misra 2010; Misra et al. 2021; Singh et al. 2009, 2017, 2021, 2022; Yadav 2007, 2011, 2013, 2015; Yadava et al. 2016, 2021) and only patchy/scanty information is so far available on dendro-geomorphic studies focusing on the natural hazards (Ballesteros-Cánovas et al. 2017; Bhattacharyya et al. 2017). Therefore, we aimed to integrate climate reconstruction with natural hazard factors and

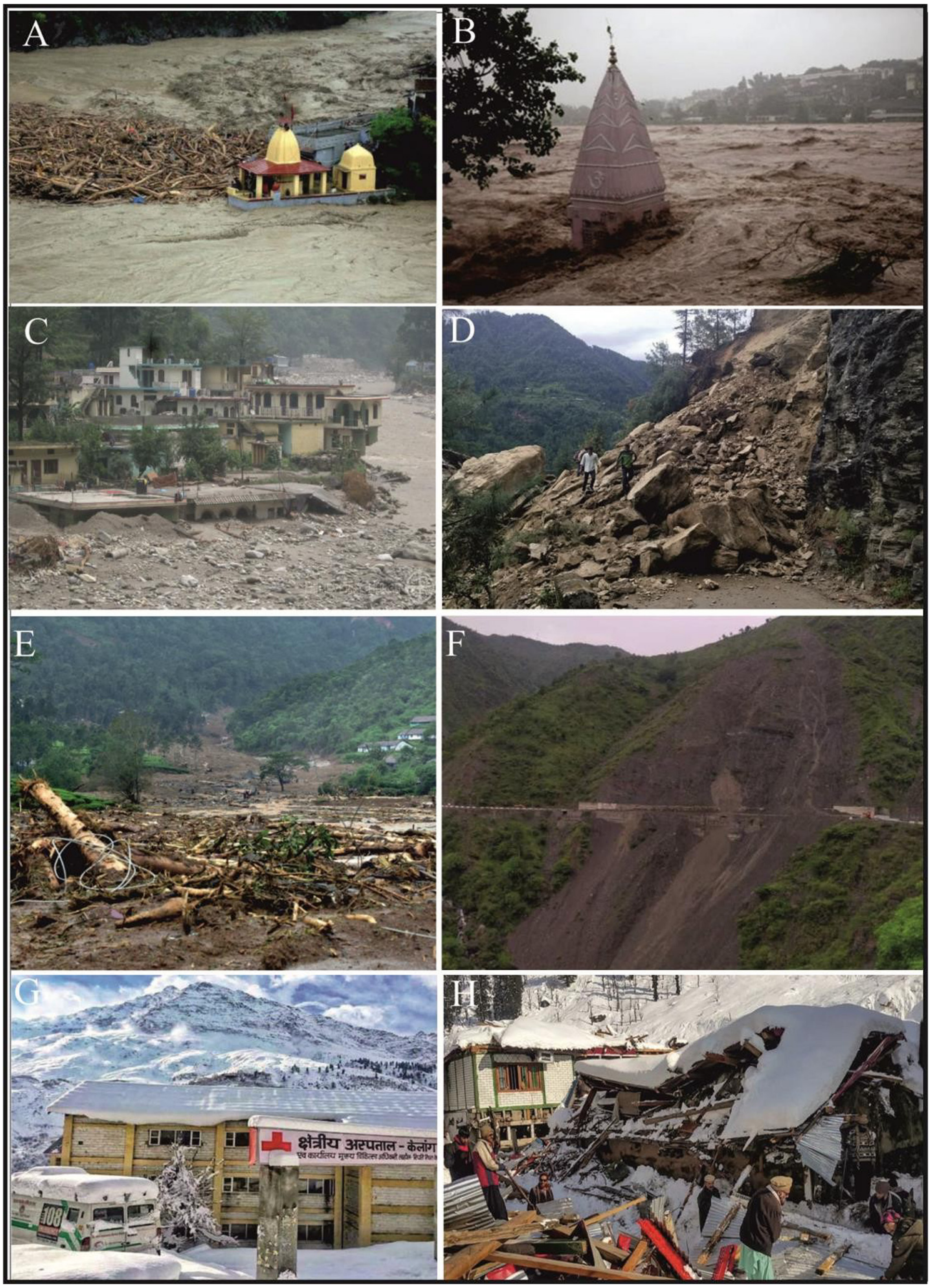


**Fig. 1** Figures are representing different kinds of natural hazards and their impacts over western Himalaya **A** flood in Kedarnath, Uttarakhand during 2013, **B** flash flood in Uttarakhand during 2021, **C** Jammu and Kashmir flood during 2014, **D** excessive precipitation caused landslide in Himachal Pradesh, **E** flash flood caused massive landslide and debris flow in Himachal Pradesh, **F** rock failures resulted in a huge landslide over Kinnaur, Himachal Pradesh, **G** snowstorm at Keylong, Lahaul–Spiti, Himachal Pradesh and **H** snow avalanche caused damages of houses at Jammu and Kashmir. *Source* from Google

dendro-geomorphic studies (Fig. 2) to understand the connections between floods, glacial movements, and snow avalanches in the occurrence of natural hazards in the western Himalaya.

## Materials and methods

The review of scientific articles focused on the natural hazards based on tree-ring studies from western Himalaya was conducted using Internet search engines such as Web of Science, Science Direct, Semantic Scholar, CORE and Scopus. Several keywords, including tree-ring, natural hazards, droughts, floods, glacier lake outburst floods, landslide, avalanche, and precipitation, were used in the literature search. For this study, we collected and assessed scientific articles published in national and international journals. Only publications linking tree rings to natural hazards and climate reconstruction were included, while those focused-on tree-ring chronologies or grey literature (such as theses, conference proceedings, and technical reports) were excluded.

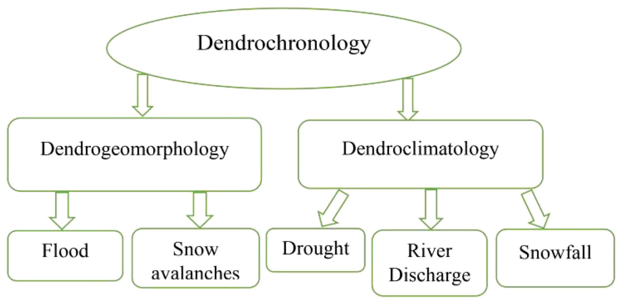


**Fig. 2** The parameter taken for the review of natural hazards over the western Himalaya are described through the flow chart

## The western Himalaya: an overview

The Himalaya means "adobe of snow" itself denotes the significance and impact of the glaciers and is known as the "Third Pole" of the planet (Immerzeel et al. 2010). The geographical area of the Indian Western Himalayas (IWH) covers 1.69% of the country's total land area and 10.54% of the entire Himalayan landmass. This region is home to a significant population, with approximately 29.49 million people residing there (Census of India 2011). The region encompasses three physiographic provenances namely Jammu–Kashmir Himalaya, Himachal Himalaya, and Uttarakhand Himalaya. Jammu and Kashmir is a northwestern Indian state, that cover an area of 222,236 km$^2$, and its high elevation regions are mostly covered by snow and glacier above 3600 m asl (Romshoo et al. 2020). Similarly, Himachal Pradesh covers a geographical area of 55,673 km$^2$ (Ramachandra et al. 2012). The mountain ranges of the state have been extensively deconstructed, interspersed with deep gorges and valleys. The climate in the region is diverse, ranging from sub-tropical conditions in the lower hills to cold, alpine conditions in the cold desert regions of Spiti and Kinnaur, with elevation ranges from 350 to 6975 m asl. On the other hand, Uttarakhand with its scenic beauty extends in an area of 53,484 km$^2$ (Kumar 2010). Figure 3 represents the western Himalaya along with the locations of tree-ring-based studies considered for the present study.

## Climate setting of the western Himalaya

The climate of the western Himalaya varies from cold-alpine to sub-tropical and is mainly controlled by its complex orographic setting (Dimri et al. 2015). Due to the altitudinal differences of mountains and valleys, large-scale spatial variability exists in climate within a very short distance (Yadav 2011). In the high-altitude northern-most Himalaya, the climate is generally alpine type, where precipitation occurs in the form of snow. The middle altitude region is a temperate zone where the climate is generally mild with cold winters and short summers. In this zone, precipitation occurs in both forms; snow as well as rain. However, in the lower altitude regions towards the south, the climate is generally sub-tropical type. In this zone, winters are moderate, summers are relatively hot, and maximum precipitation occurs during monsoon periods.

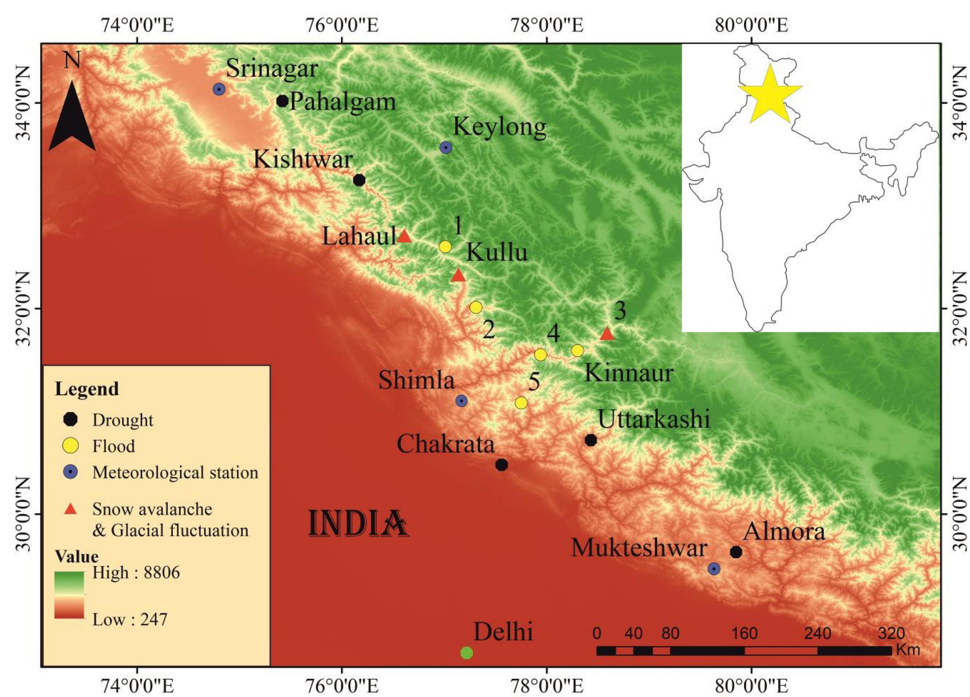


**Fig. 3** The map is showing the locations of climatic/natural hazards records from western Himalaya used in the present review work. In the map index high and low values indicate elevation levels

The two sources are mainly responsible for the precipitation over the Indian Himalaya, ISM and WD. The ISM is active in the Indian subcontinent from June to September and mostly affects the low-lying areas of Himalaya. The high mountain peaks towards the north create a barrier for ISM and do not allow the monsoon winds to cross them (Dimri et al. 2015, 2021). Therefore, in the high-altitude mountainous region, a monsoon shadow zone develops where precipitation mainly occurs in the winter and spring seasons from October to May due to the mid-latitude westerlies. The westerlies originate from the Mediterranean Sea and Atlantic Ocean and brought precipitation towards the high-altitude Himalayan regions along their way through Pakistan and Afghanistan. All three states (Jammu and Kashmir, Himachal Pradesh, and Uttarakhand) receive precipitation through westerlies or WD in its active phase. However, the foothills of the Himalaya and low-lying areas of Jammu and Kashmir, Himachal Pradesh, and Uttarakhand also receive precipitation during monsoon season. Whereas, high-altitude western Himalayan regions get negligible amount of precipitation during the summer monsoon, except Uttarakhand, where monsoon precipitation is the dominant source (Das et al. 2002).

## Tree-ring: a proxy to analyse past environment

Trees can survive for hundreds or even thousands of years in diversified geographic and climatic conditions. During their life, they experience dry, cold, hot, and wet years, sometimes getting injured through early forest fires and other natural phenomena under varied climatic and human-induced changes. The tree wood grows in different stages at different times of the year and represents precise information about the climate of each year of a tree's life (Fritts 1976). For example, the light-coloured ring represents the wood that grows in the spring and early summer, while the darker rings denote wood that grows in the late summer and fall season (Fig. 4). Tree's 1-year growth is defined by the combination of one light colour and one dark colour band (Camarero et al. 1998; Fritts 1967; Rigling et al. 2002; Stoffel et al. 2005). Trees are highly sensitive to the environment in which they grow and can disclose the local climatic conditions, such as precipitation and temperature, which significantly influence their growth. In wet and warmer year tree rings are usually wider, and the narrow rings are met in dry and cold years. Similarly, when tree faces stressful conditions, viz., drought or heavy snowfall events, the tree hardly forms annual rings in such conditions. By measuring the ring-width of trees from a site, ring-width sequences could be developed up to the age of trees of that region. The measured tree-ring sequences can infer an accurate year of their formation if cross-dated precisely. The cross-dated pattern of trees from a specific site can be used further to develop the ring-width chronology of the region. These annually resolved tree-ring chronologies provide a source to analyze the past climate through climatic reconstruction.

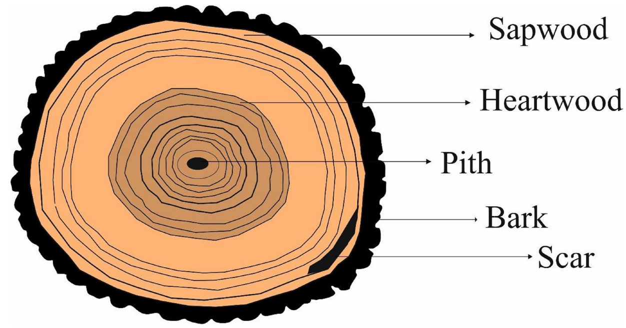


**Fig. 4** A sketch of a wood stem to show the pattern of growth-ring sequences that develops in a tree

Similarly, trees preserve evidence of past events, such as geomorphic process. Shroder (1978) gave a concept related to such events known as process-event-response, which is based on dendro-geomorphological investigation. The theory suggested that any geomorphic agent is considered as a "process" while geography event is a manifestation of the effect of a geomorphic process on a tree upon disturbances. The tree reacted to such events and responded in the form of wounding, scars, and resin ducts on the heated portion of the plant. Because of this, tree physiology got disrupted and resulted in callus formation (Larson 1994; Sachs 1991). The dating technique of these features and the basics of dendrogeomorphology have been described by Shroder (1978). According to Shroder (1978), when a tree is affected by any process that might be in the form of natural hazards, its impact on the tree discloses about its event and in response to that plant modifies its anatomical structure and shows different structure such as tilting of the tree, reduced growth, etc. (Fig. 5). This happens because trees meristematic tissue got disrupted by such injuries, which is the main factor of plant growth. Although, trees also started to produce some chemicals in response to any foreign attack or such injuries on the plant known as secondary metabolites such as an alkaloid, resin etc. (Luchi et al. 2005; McKay et al. 2003; Ruel et al. 1998). After getting injured, the tree started to form callus, which is the undifferentiated tissue and in result the tree shows eccentric growth (Fig. 5). The clear presence of eccentric growth due to tilting events makes it possible to date the disturbing incidence with precision. It is possible to observe compression wood (in the case of conifers trees) and tension wood (in the case of broad-leaved trees) on the trunk side. Trees may similarly respond to tilting by reducing their growth in addition to different kind of reaction wood (Bollschweiller 2007). Physical damage caused by debris during floods can create scars, which are healed

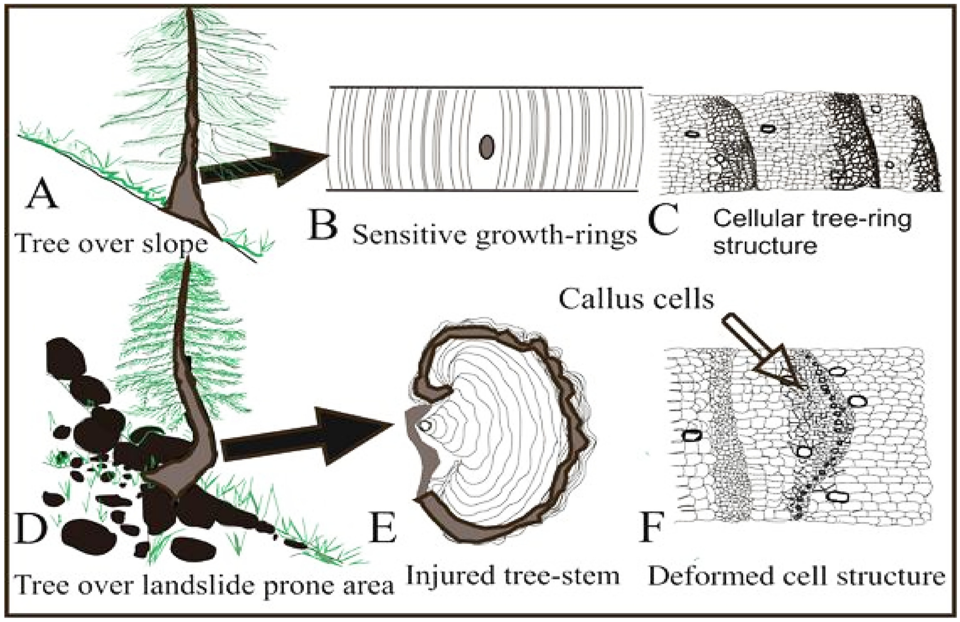


**Fig. 5** A graphical representation of the trees and their growth-ring sequences in **A** normal climatic stressed conditions—when tree-rings can be used to develop the climatic records, **B**, **C** represents the sensitive growth ring patterns and cell size in annual growth rings, respectively, **D** represents when trees grow in landslide-prone regions—such trees form the callus tissues and they can be used to date directly the natural hazards activity, **E** represents the injured tree-stem due to the physical damages through rockfalls, and **F** shows the formation of callus tissues or deformed cell structure

by the formation of wound tissue or callus growth (Stoffel et al. 2010). In extreme drought conditions, water stress may lead to some trees skipping ring formation altogether, resulting in missing rings in the growth record (Schweingruber 1996). Intense heat from wildfires can leave scars on tree trunks, with subsequent rings often displaying patterns of healing or growth suppression (Baisan and Swetnam 1990). To understand the fire history, Fulé et al. (2021) developed the *Pinus roxburghii* tree-ring chronology using fire-scarred samples from both dead and living trees from Uttarakhand, spanning from 1900 to 2017. Fires were recorded regularly from the 1920s onwards, with an increasing number of fire-scarred trees from the 1970s onward. A total of 31 fire years occurred out of 43 years between 1975 and 2017. The trees in such a way reflect their past condition and helps to know the climate variability and different kind of events that occurred in the past.

## The natural hazards studies over the western Himalaya

The western Himalayan region has been the subject of very few studies focusing on natural hazards such as floods, avalanches, and glacial movements, and their adverse impacts on the local environment and communities (Ballesteros-Cánovas et al. 2017; Bhattacharyya et al. 2017; Das and Mehar 2019; Gardner 2002; Negi et al. 2012; Smith and Bookhagen 2020). These studies have provided valuable insights into the region's vulnerability to floods and lake outbursts, which disrupt the landscape dynamics and create hardships for the local population.

To better understand the climatic factors contributing to these societal calamities, high-resolution tree-ring studies have been conducted in the western Himalaya region (Ballesteros-Cánovas et al. 2017, 2020; Bhattacharyya et al. 2017; Fulé et al. 2021; Laxton and Smith 2008). These studies utilize annually resolved tree-ring data to reconstruct past climate conditions and investigate the relationship between climatic phenomena and natural hazards. By examining tree growth patterns, researchers have gained insights into historical flood events, glacial movements, and avalanches, enabling a more comprehensive understanding of the region's hazard-prone nature. A summary of these high-resolution tree-ring studies highlighting the specific climatic phenomena and associated natural hazards investigated in the western Himalaya region (Table 1). These studies have significantly contributed to our understanding of the region's susceptibility to various natural hazards and have implications for disaster preparedness, land-use planning, and community resilience in such events.

### Floods

Floods are one of the most frequent and extensively occurring hydrological disasters worldwide, resulting in significant socio-economic losses, particularly in low-lying areas (Arnell and Gosling 2014; Hirabayashi et al. 2013). However, in high-altitude mountainous regions, floods can be caused by long-lasting rainfall and cloudbursts, leading to glacier lake outburst floods (GLOFs) or landslide lake outburst floods (LLOFs; Arnell and Gosling 2014; Hirabayashi et al. 2013). River discharge plays a vital role in flood occurrences, as floods are primarily caused by stream discharges

**Table 1** Details of the studies; including study area, tree-species, reconstruction length and contributing authors, used to compile present review work

| SN | Study area | Tree species | Period of chronology/reconstruction | Study parameter | References |
|---|---|---|---|---|---|
| 1 | Chakrata, Uttarakhand | *Cedrus deodara* | 1773–2016 | Drought | Yadava et al. (2021) |
| 2 | Gangotri Glacier, Central Himalaya | *Betula utilis* and *Pinus wallichiana* | 1646–2016<br>1863–2016<br>1643–2016 | Glacier fluctuation | Singh et al. (2020) |
| 3 | Sainj and Beas Valley Kullu, Himachal Pradesh | *Picea smithiana* and *Abies pindrow* | | Flood | Bhattacharyya et al. (2017) |
| 4 | Kullu, Himachal Pradesh | *Pinus wallichiana, Ulmus* and *Populus* | | Flood | Ballesteros-Cánovas et al. (2017) |
| 5 | Kishtwar, Jammu and Kashmir | *Cedrus deodara* | 1740–2014 | Drought | Singh et al. (2017) |
| 6 | Padder Valley, Kishtwar, Jammu and Kashmir | *Cedrus deodara* and *Pinus gerardiana* | 1439–2014 | Glacial fluctuation | Yadav et al. (2017) |
| 7 | Uttarkashi | *Pinus roxburghii* | 1767–2013 | Drought | Shekhar et al. (2017) |
| 8 | Gangolihat and Jageshwar, Uttarakhand | *Cedrus deodara* | 1720–2012 | Drought | Yadav et al. (2015) |
| 9 | Kinnaur, Himachal Pradesh | *Cedrus deodara* | 1660–2004 | River Flow | Misra et al. (2015) |
| 10 | Jageshwar and Gangolihat, Uttarakhand | *Cedrus deodara* | 1730–2012 | Precipitation | Yadav et al. (2015) |
| 11 | Lahaul (Himachal Pradesh) | *Cedrus deodara* | 1460–2008 | Snowfall | Yadav and Bhutiyani (2013) |
| 12 | Kullu, Himachal Pradesh | *Cedrus deodara* | 1834–1984 | River Flow | Shah et al. (2013) |
| 13 | Kinnaur, Himachal Pradesh | *Pinus gerardiana* and *Cedrus deodara* | 1295–2005 | River Flow | Singh and Yadav (2013) |
| 14 | Lahaul, Himachal Pradesh | *Cedrus deodara*, and *Pinus wallichiana* | | Snow avalanche | Laxton and Smith (2008) |
| 15 | Satluj River basin, Himachal Pradesh | *Cedrus deodara* | 1980–2005 | River discharge | Singh and Yadav (2012) |
| 16 | Kashmir Valley | *Pinus wallichiana* | 635 CE–Present | Flood | Ballesteros-Cánovas et al. (2020) |
| 17 | Pahalgam Srinagar | *Picea smithiana*, and *Abies pindrow* | 1820–1981 | Drought | Ram (2012) |
| 18 | Yoche Valley, Lahaul–Spiti, Himachal Pradesh | *Betula utilis* | 1752–2014 | Drought | Singh et al. (2022) |
| 19 | Kumaun–Gharwal (Uttarakhand) Himalaya (KGH) | *Abies spectabilis*, *Cedrus deodara* and *Picea smithiana* | 1508–2015 | Drought | Shah et al. (2023) |
| 20 | Kashmir | *Abies pindrow* | 1643–2016 | Drought | Chinthala et al. (2023) |

that exceed the capacity of the normal stream channel. Excessive precipitation in high-altitude regions increases the level of river discharge, which can result in floods. For example, the Kedarnath flood in the Uttarakhand Himalayas in June 2013 was triggered by excessive precipitation and a subsequent lake outburst in Chorabari above the Kedarnath temple, leading to a devastating flood in the Kedarnath area and nearby low-lying regions (Arnell and Gosling 2014; Hirabayashi et al. 2013).

Tree-ring data has been utilized in flood frequency analysis (FFA) to improve the reliability of flood measurements, particularly in areas with limited data. Tree rings, which grow along mountain streams, can provide valuable information about flood events due to their longevity and the high number of flood-affected trees (Bodoque and Ballesteros-Cánovas 2020). A very few studies have documented the discharge history through tree rings in the western Himalaya, demonstrating the potential of tree-ring chronologies to reconstruct long-term river discharge (Misra et al. 2015; Singh and Yadav 2013; Shah et al. 2013). For intense, using tree-ring chronologies of *Cedrus deodara* and *Pinus gerardiana*, Singh and Yadav (2013) reconstructed the Satluj River discharge back to AD 1295, identifying high discharge years such as 1953 and 1954. During these consecutive years, excessive rainfall was reported in the Chamba district of Himachal Pradesh (Anonymous 2017). Across the entire state, precipitation levels were notably high in both years, with 1953 receiving nearly twice the precipitation of 1952 (Randhawa et al. 2015).

Updating the work of Singh and Yadav (2013), Misra et al. (2015) strengthened the reconstruction back to AD 1660 by incorporating a network of tree-ring chronologies from seven moisture-stressed *C. deodara* sites in the Satluj River basin at Kinnaur. Their findings revealed significant variability in river flow, with 1957 recording the highest discharge during the period from October to June.

Similarly, the Beas River flow was reconstructed using tree-ring width chronologies of Himalayan cedar from Kasol, Kullu Valley, showing the highest stream flow period in the year 1973 (Shah et al. 2013). In the same year, a devastating flood occurred in Himachal Pradesh and the formation of a lake resulting from the blockage of the Satluj River due to the Nathpa rock fall led to significant damage to the Sanj Powerhouse, with an estimated loss of approximately Rs. 45 million (Sah and Mazari 1998; Sah and Bist 1988; Paul et al. 2000).

Ballesteros-Cánovas et al. (2017) employed dendrogeomorphological techniques to reconstruct past floods in Kullu, Himachal Pradesh to complement tree-ring analysis. Their research identified numerous flood events since the early twentieth century, including ungauged floods in 1977, 1988, 1995, 1997, 2001, 2003, 2005, 2006, 2009, 2010, and 2011. Floods caused the maximum damage in 1988 along with 2001, 2005. In a related study, Bhattacharyya et al. (2017) focused on palaeofloods and snow avalanches in the Sainj and Beas Valleys. They discovered evidence of catastrophic flood events in recent history, such as in 1980, 2003, 2005, 2006, 2008, 2009, 2010, and 2012.

In 1977, the Chamba region experienced severe flooding due to excessive rainfall, recording 268.3 cm over the last 50 years (1953–1994), which was 198% of the normal rainfall (Anonymous 2017). In 1988 a flash flood was occurred due to cloud burst in Soldang Khad. The devastating flood in Soldang village caused heavy loss of life and property, including the destruction of the Bhabanagar water works (Bhandari 1988). In September 1995, flash flood with landslide along Beas River in Kullu Valley causes 65 people killed and damage of many properties, road, and bridges a worth of US$ 182 million. In the Pabbar Valley, flash flood in the August 1997, killed 124 people, 456 cattle (Sah et al. 1996a, b). Besides this, in same year a total loss of 672.9 million was reported along Satluj River (Pandey et al. 2015). In the month of July 2001 cloudburst with flash flood triggered, a heavy loss of infrastructures, human as well as cattle life was reported from Kullu, Mandi, Kangra, and Shimla district of Himachal Pradesh (Bhan et al. 2004). Following the 2003 downpour, monsoonal rainfall badly impacted Gharsa Valley and the Solang region, and caused the loss of 51 people's lives. However, the 2005 flood was very disastrous, over 150 people died, 200 head of cattle perished, and property worth over 1000 crore was destroyed by flash flood in the Satluj River (Chandel 2014). The successive years of 2009 and 2010 high rainfall damaged many properties and washed away several roads along with loss of lives from Dharampur, Mandi and Kharahal valleys (Revenue Department, Government of Himachal Pradesh 2015). A massive flood in 2011 damaged crops worth 417.390 crore, and a 0.608 million population was affected in Himachal Pradesh (Anonymous 2017). The 1977 Chamba flood, the 1988 cloudburst in Solden Khad, and the floods in Kullu Valley (1995), Pabbar Valley (1997), and multiple regions, including Kullu, Mandi, Kangra, and Shimla (2001), align with flood records identified in dendrogeomorphic studies by Ballesteros-Cánovas et al. (2017) and Bhattacharyya et al. (2017). Similarly, the 2003 Solang flood and the 2005 Satluj River flood further support these findings, demonstrating consistency with tree-ring-based flood reconstructions in the Kullu region.

The collective findings of these studies highlight the recurrent nature of floods in the western Himalaya region and the importance of utilizing various methodologies and historical records to understand their occurrence and impacts. The interconnectedness of the studies helps to build a comprehensive picture of the flood history in the region and provides valuable insights for future research and mitigation efforts.

## Drought

Drought, a deficiency of precipitation over an extended period, poses significant challenges to societies and the environment (UNICEF 2015–2016). Wilhite (2000) defines drought as a climatic phenomenon lasting several years and affecting more people than many other natural hazards. The National Commission on Agriculture (GOI 1976) categorizes drought into meteorological, agricultural, and hydrological types in India. Each year, a large part of India experiences the detrimental effects of drought, necessitating a deeper understanding of its causes and mechanisms due to increasing temperatures and reduced precipitation.

The Monsoon Asia Drought Atlas (MADA) by Cook et al. (2010) provides the first comprehensive drought record in the region. It explores the potential of tree-ring data networks for drought analysis in high Asia. Using tree-ring chronologies of *Abies pindrow* and *Picea smithiana* from Pahalgam, Jammu and Kashmir, Ram (2012) reconstructs the Palmer Drought Severity Index (PDSI), revealing multiple dry periods. Yadav (2013) worked on this aspect by developing a seven-century drought record in Himachal Pradesh, identifying severe droughts during 1677–1678 and 1815–1816, which persisted for longer durations. Yadav et al. (2015) investigated drought variability in the Kumaun Himalaya, identifying 1816 as the driest year in three centuries due to the effect of 1815 Tambora eruption. The study links drought to Rabi crop failure, affecting regional productivity. Severe food shortages during the droughts of 1890, 1892, 1896, and 1897 led to Rabi crop failures in Kumaun. The consecutive droughts of 1896–1897 caused famine-like conditions, impacting 307,000 miles$^2$ (800,000 km$^2$) and 69.5 million people in central and southern India (Oxford at the Clarendon Press 1907).

Singh et al. (2017) reconstructed drought records from Kishtwar, Jammu and Kashmir, revealing distinct dry phases since 1740, with the 1780s being the driest period. The relationship between the Standardized Precipitation Index (SPI8-May) and the Palmer Drought Severity Index (JJA-PDSI) suggests that droughts in the north western Himalayan regions are influenced by precipitation during the winter and spring seasons. Also, from the western Nepal region Himalayan hemlock (*Tsuga dumosa*) tree-ring-based spring temperature reconstruction showed that the year 1740 was the warmer period (Aryal et al. 2020).

In another study, Yadav et al. (2017) reconstructed the April–May SPI (SPI2-May) from Kishtwar, revealing severe droughts during the fifteenth to early seventeenth centuries. The 1970–1971 droughts, causing significant stress on the socio-economy of the region, affected not only India but also neighbouring countries (Chandrasekara et al. 2021). Shekhar et al. (2017) investigated Uttarkashi, western Himalaya, and identified 32 drought years, with 1772, 1802, 1813, 1815, 1820, 1837, 1848, 1854, 1873, 1895, and 1972 CE being extreme drought years. The reconstructed Standardized Precipitation Evapotranspiration Index (SPEI) aligns with major drought events in India and demonstrates a negative correlation between Chir pine growth and November–March SPEI. This indicates a link between winter droughts and November–March SPEI in the region. During the nineteenth century, India experienced a series of devastating droughts, resulting in widespread crop failures, food shortages, and famines. The impact of these droughts varied across different regions of the country. However, the year 1873 is often highlighted as a particularly severe drought year. The drought of 1873 had severe consequences for agricultural production and food availability, leading to widespread famine and loss of life in many parts of India.

Yadava et al. (2021) expanded their research to the Chakrata region of the Garhwal Himalaya, where they reconstructed the SPEI4-May record and identified severe droughts linked to famines and crop failures. They found that 1774 was the driest year (SPEI-3.11), along with several other notable dry periods. The consistency of reconstructed drought records with agricultural production failures underscores the significant role of droughts in disrupting socio-economic systems. Yadav (2007) also mentions that 1774 was hot and dry year in three basins: Alaknanda, Bhagirathi, Tons, Satluj and Chandrabhaga River basin of western Himalaya.

Singh et al. (2022) observes an increasing occurrence of droughts over the Himalayas since the latter part of the Little Ice Age (LIA) through the reconstruction of SPI12-May records in Jammu and Kashmir. The study highlights 1626 as the driest year and reveals a strong resemblance between SPI12-May precipitation and river flow records in the western Himalayas. From the Karakoram region the year 1626 was the one of the driest years of the seventeenth century in which precipitation was below $< 293$ mm (Khan et al. 2019).

Shah et al. (2023) report a decline in precipitation across the Kumaun–Garhwal Himalaya (KGH), attributed to shifts in the Indian Summer Monsoon (ISM). Their 508-year tree-ring reconstruction reveals a rising trend in drought severity, particularly in recent decades, as indicated by the weakening June–July–August (JJA) PDSI. The study identifies six major drought years: 1877, 1883, 1905, 1907, 1918, and 1941. Additionally, the prolonged dry spell of 1782–1784 CE aligns with the Chalisa famine (1783–1784 CE), which was associated with anomalous El Niño events. Similarly, Chinthala et al. (2023) developed a 373-year (1643–2016 CE) scPDSI reconstruction from the Kashmir region, identifying two distinct moisture phases: a wetter period (1657–1816 CE) with a mean scPDSI of $+0.58$, followed by a drier period (1817–2016 CE) with a mean scPDSI of $-0.11$. Severe dry conditions ($-3$ to $-4$) were recorded in 1645, 1646, and 1999 CE, emphasizing significant periods of moisture stress.

## Glacial lake outburst flood, snow avalanches, snowfall and glacial fluctuations

Tree rings have been extensively used to study the relationship between past climate and natural hazards such as glacial lake outburst floods (GLOFs), snow avalanches, snowfall, and glacial fluctuations. The implications of tree ring analysis in these areas have been highlighted in previous studies (Bhargava 1995; Clague and Evans 2000; Malone 2010). Earlier studies have shown that GLOFs have had severe impacts on both the Himalayan region and other parts of the world (Bhargava 1995; Clague and Evans 2000). The potential risks associated with GLOFs because of climate change have gained increased attention (Malone 2010).

The consequences of mass wasting events and avalanches have direct impacts on human habitation and the ecosystem throughout the Himalayan region (Brundl et al. 2004). In the cold-arid Lahaul Himalaya, Laxton and Smith (2008) observed four avalanche events between 1972 and 2006, with tree scars indicating avalanches in 1985, 1997, 2001, and 2004. Another study by Ballesteros-Cánovas et al. (2018) shed light on snow avalanches in the Hindu-Kush Himalaya. They reconstructed the largest avalanche history using tree rings, revealing 521 growth anomalies caused by snow avalanches since 1855. They observed variations in avalanche activity, with high activity between 1970 and 1977 and from 1989 to 2003. Tree-ring width chronologies have been utilized to analyze past glacial behaviour in the Himalayan regions. Bhattacharyya and Yadav (1996) found that low tree growth rates coincided with glacial advances during years of positive mass balance. Similarly, Singh et al. (2020) documented the recession of the Gangotri Glacier and projected accelerated recession in the twenty-first century due to warming. In the Lahaul–Spiti region, tree-ring samples have also been used to develop records of Snow Water Equivalent (SWE). Yadav and Bhutiyani (2013) found that low SWE values indicated severe droughts in the 1780s and 1480s, while pluvial conditions were observed in 1948–1958 and 1986–1996. Overall, these studies highlight the valuable insights provided by tree-ring analyses into the occurrence and impacts of natural hazards in the western Himalaya region. The findings from Bhargava (1995), Clague and Evans (2000), Malone (2010), Brundl et al. (2004), Laxton and Smith (2008), Ballesteros-Cánovas et al. (2018), Bhattacharyya and Yadav (1996), Singh et al. (2020), and Yadav and Bhutiyani (2013) collectively contribute to a better understanding of past events could be used for future preparedness.

## Future prospectives

- Tree-ring studies focusing on natural hazards from the western Himalaya are limited, resulting in a critical gap in our understanding of natural hazard variability and extreme events within the region.
- Tree-ring data offers annual-resolution records of environmental fluctuations, providing valuable insights into historical climatic events and the occurrence of natural hazards.
- The high-resolution tree-ring data to understand natural hazards is essential for advancing future preparedness and policymaking, contributing to effective climate adaptation strategies and risk mitigation efforts in changing climate scenarios.

## Conclusions

This paper highlights the urgent need to address the growing risks posed by natural hazards in the western Himalaya region. Tree-ring reconstructions serve as a vital tool for understanding past environmental conditions, enabling the establishment of long-term records of floods, landslides, and avalanches. By analyzing tree-ring patterns, researchers can explain the frequency and magnitude of these hazards across centuries. Based on dendrogeomorphic and dendrochronological records, several catastrophic flood events, and years of high river discharge in Kullu and Kinnaur regions of Himachal Pradesh have been identified. These include 1953, 1954, 1957, 1977, 1980, 1988, 1995, 1997, 2001, 2003, 2005, 2006, 2008, 2009, 2010, 2011, and 2012. From the Lahaul–Spiti region tree-ring based snow water equivalent (SWE) study recorded decadal scale of dry during 1480s and 1780s; as well as wet period from 1948s–1958 and 1986–1996. Several severe drought years have been identified: 1626, 1740, and the 1780s in Kishtwar, Jammu and Kashmir; 1774, 1816 and 1897 in Kumaun; and 1772, 1802, 1813, 1815 and 1972 in Uttarkashi. Besides this several snow avalanche years such as 1985, 1997, 2001 and 2004 in Lahaul–Spiti region and increased avalanche incident within the periods such as 1970–1977 and 1989–2003 have been identified in Hindu-Kush Himalayan region.

The reconstructed records of floods, droughts, and snow avalanches highlight the variability of natural hazards in the western Himalayan region. These events underscore the importance of understanding past climate extremes to improve regional hazard preparedness and resilience in the face of future climatic and geomorphic challenges. To mitigate these impacts, comprehensive records of natural hazard occurrences and severity are essential. While observational data are limited, tree-ring data provide unique insights that extend beyond instrumental records, revealing links between river discharge, droughts, snowfall, and related disasters. However, challenges remain in fully reconstructing past flood events, necessitating advancements in methodologies.

This paper advocates for integrating tree-ring-based insights into disaster management and land-use planning to enhance resilience. By adopting proactive measures and leveraging interdisciplinary approaches, policymakers can strengthen disaster preparedness, develop sustainable infrastructure, and protect vital resources. Addressing the increasing frequency and intensity of natural hazards under global warming scenarios is critical for ensuring the sustainable development of the western Himalaya region and safeguarding future generations.

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## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

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