# Dendrogeomorphic potential of the Himalaya – case studies of process dating of natural hazards in Kullu valley, Himachal Pradesh

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**Trees impacted by the forces of natural processes such as flash floods, snow avalanches, landslides, rockfalls or earthquakes, record these events and exhibit growth disturbances in their growth-ring series. As a consequence, these disturbances provide an excellent signal for the spatio-temporal reconstruction of past natural hazard activity and a means to date and document past disasters. In the context of the Indian Himalayas Climate Change Adaptation Programme (IHCAP; http://www.ihcap.in/), a field trip was carried out in May 2014 to define suitable sites for dendrogeomorphic research in Kullu valley, Himachal Pradesh. Several tree species and sites where recent and past process activity can be reconstructed were inventoried, namely flash floods in the Beas and Sainj rivers as well as snow avalanches in Solang valley. Through this exploratory analysis, we ascertain that tree-ring techniques have wide applicability in the analysis of natural hazards, not only in the Kullu region but also in other geographical contexts of the Himalayas.**

**Keywords:** Dendrogeomorphology, flash flood, Himachal Pradesh, snow avalanche, tree-ring.

IN the Himalayan region, natural hazards and related human disasters are widespread due to neo-tectonic mountain-building processes and the occurrence of intense downpours, especially during the monsoon season. Among the more common hydrogeomorphic processes, one might think of (flash) floods, snow avalanches, debris flows, landslides, rockfalls or glacier lake outburst floods (GLOF). These processes are related to extreme climate events and changes thereof; hence future changes in their activity appear as a response to global climate change[1,2]. At the same time, evidence exists that human activity may transform natural processes into man-made disasters[3]. Drawing on this evidence, the occurrence of future natural hazards is likely to stress economic development by leading to adverse effects on ecosystems, human lives and livelihoods.

In recent example of a devastating and extreme climatic event that occurred in Kedarnath and elsewhere in Uttrakhand during June 2013, severe cloudbursts resulted in huge floods that were responsible for the large-scale destruction of property and loss of human lives[3,4]. Similar extreme disasters were reported for other regions in the Himalayas prior to 2013 (ref. 5). Some of these events might have potentially been favoured by extensive deforestation of inhabited valleys[6].

Natural hazards affect the status quo of the communities, stress the future welfare of the populations living in hazard-prone areas and hamper proper economic development, which in many cases is based on incipient tourism. To mitigate future loss of lives and properties as well as to assure proper performance of critical civil infrastructures, a better understanding of drivers and processes underlying natural disasters is needed. One such pre-requisite for improved understanding of the natural variability and mechanisms of such devastating processes is contained in the records of past events[7–9]. Such long-term instrumental or observational records also help in the modelling of disasters with physically-based models[10,11], in order to define recurrence intervals and magnitudes of natural processes as well as to understand the climatic, physical or anthropogenic mechanisms behind these processes[12]. This information is essential for delineating hazardous sites, carrying out risk assessment and designing strategies that reduce potential losses and improve the reliability of infrastructures. However, in most mountainous regions of the world, including the Himalayas, such records are largely lacking both in temporal and spatial terms.

One of the most accurate records of past natural disaster activity in unmonitored mountainous environments is contained in trees and their growth-ring records. A tree records internal factors (related to genetics or age) and local (or external) environmental conditions such as climate, stream flow or drought in its annual growth

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rings[13]. At the same time, it also keeps track of past natural disasters, which is obtained by removing the non-geomorphic factors (e.g. climate, stand dynamics, insect outbreaks) from the records[14]. The science combining tree growth with geomorphology is called dendrogeomorphology and aims at documenting anomalies in growth related to the occurrence of past geomorphic events[9]. During geomorphic process activities, such as rock falls, debris flows, floods, snow avalanches or erosion process, the material transported by the process can wound trees, tilt their stems, break their crown or branches, partially bury their bases or expose roots and others. These mechanical disturbances are recorded in the tree-ring series (Figure 1), allowing the dating of past geomorphic events with annual or even sub-seasonal precision[15]. Since the 1960s, tree-ring records have been widely used in diverse mountainous regions, but only used a little in the Himalayan environments. The records provide an understanding of long-term variability of geomorphic events in relation to large inter annual and longer climatic variations[16].

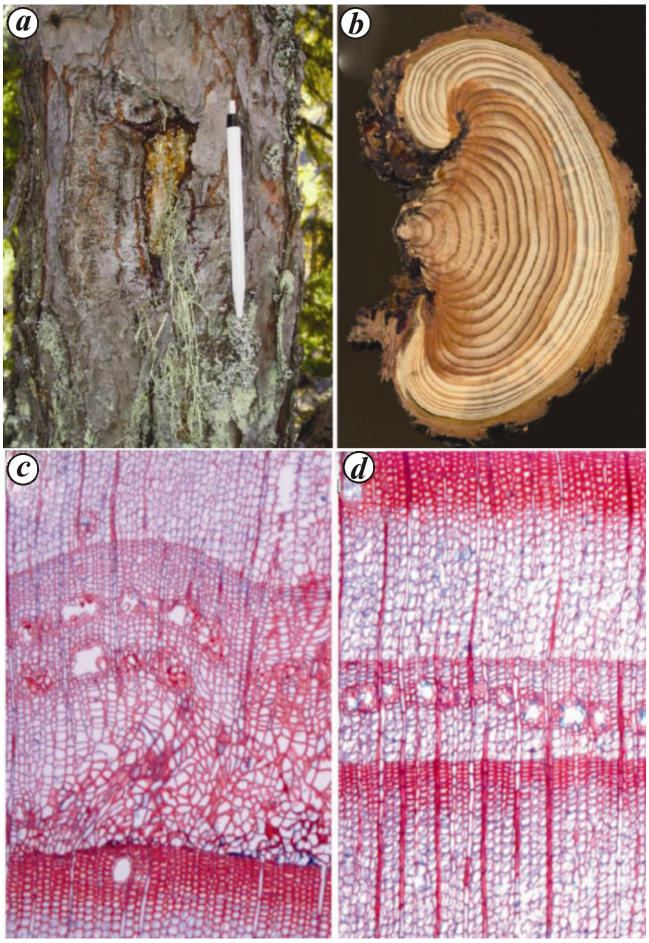


**Figure 1.** ***a***, Stem injuries induced by hydrogeomorphic processes. ***b***, Cross-section showing overgrowing wound wood. ***c***, Callus tissue formed next to the injury is a characteristic reaction to wounding. ***d***, Tangential row of traumatic resin ducts following wounding in European larch (*Larix decidua* Mill.) (Source: Stoffel and Bollschweiler, 2008).

In this paper, we review tree-ring studies carried out in the region in relation to climate-related events and provide exploratory results from the samples collected from our field study during 2014 in the context of Indian Himalayas Climate Change Adaptation Programme (IHCAP; www.ihcap.in) and the Indo-Swiss initiative with a field component in Kullu district (Himachal Pradesh). One of the aims was to define the suitability of tree-ring techniques to improve our understanding of geomorphic processes and related hazards and risks. Specifically, we (i) assess the potential of dendrogeomorphic assessments in improving process understanding in the Himalayan region, and (ii) explore suitable tree species and areas for the analysis of flash flood and snow avalanche activity at study sites in Dhundi, Solang valley and Sainj River from the Kullu Himalaya.

## Basis of tree-ring application in natural hazards assessment

Applications of dendrogeomorphology in dating natural hazards are recognized since the mid-20th century[17,18]. Some common signatures of the disturbances on tree in response to geomorphic processes are: wounds on trunks, stem tilting, sudden growth suppression, etc. (Figure 1). The basic principle of dendrogeomorphology in dating of these features is described in the seminal papers[19,20]. Wounds are caused by sediments transported during geomorphic events that partially remove the bark and consequently damage the meristematic tissues. Trees react upon this damage with anatomical and chemical changes so as to minimize decay and assure transportation of water and nutrients. Dating of the resulting scar takes advantage of anomalous wound-induced anatomical features such as callus tissue, cell size changes and/or tangential rows of traumatic resin ducts[15]; the latter occur only in certain conifer species. It has been demonstrated that these features can be used to date hidden scars, and consequently, also track past events that are no longer visible on the stem surface or in the trunk geometry[9]. Stem tilting is another disturbance feature that is formed by unidirectional pressure on stems induced by a geomorphic event (i.e. deposition of material due to a debris-flow or snow avalanche event) or the partial destabilization of the root-plate system of tree through landslide activity or erosion. To compensate the negative effects of tilting, trees form reaction wood which is characterized by chemical changes at the cell level. At the macroscopic level, reaction wood is recognized via eccentric growth and formation of compression wood (in the case of conifer trees) or tension wood (broad leaved trees). Another common feature such as sudden growth suppression, is observed in trees that have lost their crown. This decrease is due to the sudden decrease in photosynthetic activity, and consequently in the growth rate. The same suppression is observed in trees with trunks buried in sediment, as the material hampers water and nutrient supply to the roots. Roots exposed as a result of sudden or continuous erosion processes will also result in reduced growth rates. At the same time the roots will also experience noticeable changes in wood anatomy, in the form of eccentric growth and clearer transitions between the early- and late-wood portions of growth rings[21]. Moreover, survivor trees may benefit from less competition, more light, nutrients and water availability, which may favour increased growth for some years after an event. At the same time, new trees will germinate on new, yet bare surfaces, which in turn offer opportunities to determine minimum ages of new landforms.

## Tree-rings and natural hazards in a Himalayan context

Tree rings have been used widely to document, study and understand natural hazards and risks in a multitude of natural settings around the globe[9,14,18,19,22–25]. Though a large number of tree ring studies were pursued from India, these primarily focused on the reconstruction of climate. As a consequence, with the exception of some papers and several stray reports, our review reveals that dendrogeomorphic approaches in dating natural hazards have not been applied significantly[26,27]. These few dendrogeomorhic studies in the Himalayan region include dating of avalanche events, glacial movements and dating of earthquake events. An exploratory study undertaken in the Lahaul Himalaya of Himachal Pradesh[28] revealed four snow avalanche events dated in a single track for the past twenty years (1985, 1997, 2000 and 2004). This study, despite the rather limited number of disturbed trees reported, clearly evidences the suitability of tree ring data of *Cedrus deodara* for reconstructing past snow avalanches activity. In the past tree ring data of several tree species have been shown to be good proxies for reconstructing glacier extensions with significant correlations between tree growth, climate and/or glacier activity[29–34]. Tree-ring data of *Pinus wallichiana* growing in the sub-alpine region of Kinnaur, exhibited low growth during years with positive glacial mass balance and with glacial advances reported during the recent past in the Himalayan region[29]. Similar growth patterns were noted for *Abies pindrow* trees at the snout of Dokriani Bamak Glacier[30] as well as for *Cedrus deodara*[31] and *Pinus wallichiana*[32] growing close to Gangotri Glacier. *Betula utilis* growing along moraines around Bhojbasa, close to the snout of Gangotri Glacier, formed larger tree rings due to rapid glacier retreat[33]. In another study[34] November–April snow water equivalents (SWE) reconstruction was made with tree-ring records of *Cedrus deodara* which date back to AD 1460. While these reconstructions do not allow any conclusions on mass-movement activity, the information quite clearly indicates that trees growing at high-elevation sites of the Himalayas seem to be sensitive recorders of environmental changes. For dating the palaeoseismic activity, tree rings have been demonstrated to be a good proxy. The focus here was on the examination of growth patterns in trees following earthquake-induced damages, such as severing of roots, tilting and sometimes even complete destruction. Trees surviving such shocks record the event in their annual growth rings in the form of narrow rings (growth suppression), growth eccentricity (reaction wood), tree death as well as structural and morphological changes in internal wood structures[35]. Tree ring data of *Abies densa* analysed from the NE Himalayan region show evidence of strong earthquakes in the form of reduced tree growth in the years of strong earthquakes. The study clearly indicates that tree-ring sequence is a promising tool to date palaeoseismicity in NE Himalayas[36]. In Agora, Uttarkashi Western Himalaya, tree-ring data from *Pinus wallichiana* were studied to evaluate the effect of the 1991 earthquake on tree growth. Since the shocks occurred outside the growing season (dormancy), its effect in the form of narrow rings was recorded only in 1992 in most of the trees studied. Most of these trees were tilted and exhibited eccentric growth[37]. Few of these exploratory studies also clearly testify the prospect of tree-ring data in dating palaeoseismic events in the Himalayan region[36,37]. Through preferred selection of trees along fault zones, it is expected that dendrogeomorphology could contribute considerably to an improved understanding of seismicity in the Himalayas. In contrast, dendrogeomorphic applications in dating flood events in periglacial environments are lacking as of now. Sporadic glacial lake outbursts (GLOF) have the potential to drain in the form of powerful floods. GLOFs are thus considered one of the most important natural hazards in terms of direct damage potential in the Himalayan context[38]. Glacier lakes typically form close to glacier snouts during the retreat of glaciers, and are expected to form even more frequently and at enhanced speed in a warming climate[11].

## Potential outputs from tree ring analysis related with natural processes in Kullu

In the framework of the IHCAP, a joint field expedition was organized from 5 to 30 May 2014 to identify suitable sites and tree species for dendrogeomorphic studies in Kullu district, Himachal Pradesh. This area is considered highly susceptible to natural hazards as a result of its physiographic (rugged topography with high relief and complex geological features), climatic (SW monsoon and W disturbances) and anthropogenic[39] factors (e.g. multifarious human activity especially deforestation). The area under study (Figure 2) is cradled by the Pir Panjal

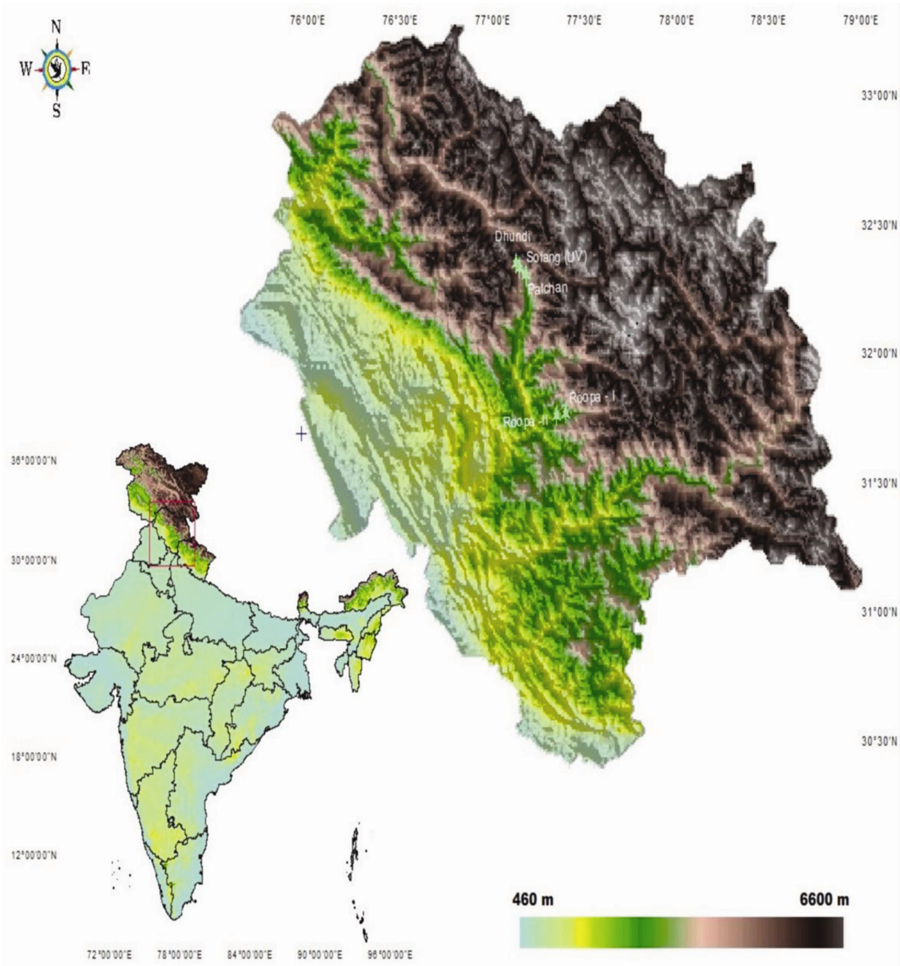


**Figure 2.** SRTM map showing sites surveyed for dendrogeomporhological study from the Kullu Himalaya.

to the North, the Parvati Range to the East, and the Barabhangal Range to the West.

## Sites, materials and methods

In the context of the exploratory field mission, a limited number of tree-ring samples were initially analysed from promising study sites covering a large area of the Kullu Himalaya located between 31°96′–32°21′N and 77°1′–77°13′E (Figure 2). To understand the past flood and snow avalanche activity, several sites in both the Sainj and Beas valleys (Roopa, Kullu, Manali, Solang) were visited. In addition, locations were identified to reconstruct baseline data for stream flow and snowpack. Detailed collection of the samples that include location, altitude of the site along with name of trees, number of samples collected from each site are shown in Table 1. In Sainj Valley, sediment transport during monsoon or cloud burst floods left a multitude of scars (Figure 3) in the riparian trees, viz. *Alnus*, *Populus*, *Juglans*, *Acer*, *Aesculus* and also *Pinus roxburghii* growing along the banks of Sainj River. Using increment borer samples in the form of increment cores were collected from more than sixty disturbed trees showing scars in their trunks. Samples were taken close to the wound in order to date the related growth disturbance[9]. Additionally, a reference sample from the side opposite to the scar was also collected from each tree. In some cases, supplement samples, i.e. wedges from scarred trees and cross-section from injured branches and roots were also collected. We also recorded the position and height of scars on the trunk of trees as well as the river cross section. By using hydraulic models, we could reconstruct the peak discharge by dating the floods generated tree scar which in turn complemented existing flood records and improved the frequency-magnitude records needed for risk assessments[18].

At the upper Beas river valley, Palchan, a critical area, a heavy flood in 2012 caused large-scale destruction of the primary school and bridge and also the partial demolition of the hydroelectric power generation grid. We noted that scars exist in surviving trees in the upstream of Palchan (Figure 4 *a*). We took topographic measurements (river cross-sections) and also gathered historical information regarding this flood (event description, pictures and videos), courtesy the headmaster of the school. For

**Table 1.** Detail of sampling sites showing location, altitude along with the name and number of trees sampled from each site

| Catchment site | Location | Objective | Name of tree | Number of trees |
|---|---|---|---|---|
| Beas at Palchan | Lat: 32°30′<br>Long: 77°17′ | Flood magnitude<br>Risk assessment | *Alnus* sp.<br>*Abies spectabilis* | 30 |
| Parvati at Shat | Lat: 31°97′<br>Long: 77°21′ | Flood chronology | *Morus* sp.<br>Alnus sp. | 50 |
| Sainj at Ropa | Lat: 31°76′<br>Long: 77°35′ | Flood chronology<br>Flood magnitude | *Alnus* sp., *Juglans* sp.<br>*Acer* sp., *Pinus roxburghii* | 60 |
| Thiertan at Nagini | Lat: 31°64′<br>Long: 77°39′ | Flood chronology<br>Flood magnitude<br>Risk assessment | *Pinus roxburghii* | 30 |
| Thiertan at Gushaini | Lat: 31°63′<br>Long: 77°43′ | Flood chronology<br>Risk assessment | *Alnus* sp.<br>*Pinus roxburghii* | 30 |
| Thiertan at Bathad | Lat: 31°60′<br>Long: 77°48′ | Flood chronology | *Alnus* sp. | 30 |
| Solang Valley at Dundi | Lat: 32°33′<br>Long: 77°13′ | Avalanche chronology | *Juglans* sp., *Acer* sp.<br>*Abies spectabilis*, *Picea smithiana*<br>*Cedrus deodara* | 50 |

**Figure 3.** Scar marks on the tree, indicating past flood events along the bank of Sainj river.

hydro-climatic reconstruction, we collected tree ring cores from old conifers (*Cedrus deodara* and *Pinus roxburghii*), from trees growing on steep and rocky slopes above Roopa (e.g. Skati, Delcha) and from *Abies pindrow* and *Picea smithiana* growing above Palchan. This long record helped to build the relationship of dated flood events with the extreme events of river discharge and precipitation of this region.

In the Solang-Dundhi area, upstream of Manali, we observed both conifer and broadleaved trees growing within known snow avalanche tracks. These trees show clear evidence of damage induced by past snow avalanches (i.e. impact scars, stem tilting and/or branch and crown losses). More than 50 disturbed trees were sampled according to the nature of disturbance[9]. Samples of the scarred trees (Figure 4 *b*) were collected similar to the samples collected for the flood scarred trees mentioned earlier. However, in tilted trees, samples were collected at the position of maximum trunk curvature to date the occurrence of reaction wood. Trees with crown or branch losses were systematically sampled at 1.30 m approximately.

For snow pack analysis, using increment borer, we collected samples from *Abies webbina* (Figure 4 *c*) and *Picea smithiana* growing on the upper part of the Beas valley close to Dhundi. These trees were considered to be sensitive to changes in winter snowpack changes and thus used for a reconstruction of temperature, precipitation and snow pack parameter. At the same place, we recorded old *Cedrus deodara* trees growing on steep slopes. We hypothesize that these trees would be suitable for snowpack reconstruction as well.

## Data analysis

### *Flood history*

All samples collected from flood scarred trees were processed following standard dendrogeomorphologic procedures[9]. We counted and dated tree rings of these trees considering the date of last ring as 2013, since the ring formation in 2014, i.e. the year of sample collection had not started in most trees. Moreover, evidences of scar marks in a large number of trees in same year's tree ring also suggest that there is coherence in ring feature, indicating that these rings are annual in nature. Preliminary observations suggest that flood scars provide information of at least several intense flood events in the region that occurred in the recent past, i.e. during 1980, 2003, 2005, 2006, 2008, 2009 and 2010 (Figure 5). These results are


**Figure 4.** ***a***, Palaeoflood observation, i.e. scars marks on riparian trees growing along the bank of river at Palchen. ***b***, Avalanche events causing multiple scars marks on a tree growing along the avalanche track at Solang. ***c***, *Abies spectabilis* trees at the upper part of SASE Dundi station indicating winter-snowpack sensitive trees.

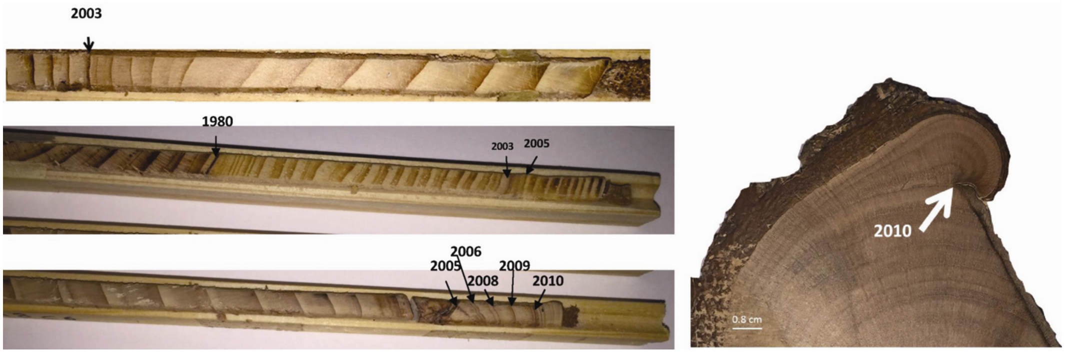


**Figure 5.** Polished surface of the increment cores and cross sections of trunk from trees at Sainj valley showing dated flood scar mark 1980, 2003, 2005, 2006, 2008, 2009 and 2010.


**Figure 6.** Polished surface of the increment cores and tree trunk sections from trees at Pulchan showing dated flood scar mark at 2012.

particularly in agreement with the observation made by the Flood and Irrigation Department, Kullu (HP) regarding the intense flash floods that took place in this site. The results also confirm the potential of dendrogeomorphology for extending flash flood series in this valley, and presumably in the region. Therefore, it is expected that the dating of scars would yield a local and multi-decadal chronology of past floods, which could then be employed to assess potential triggers of past disasters. Detailed analysis of flood history with spatial scale, covering entire time span of the tree ring chronology is under progress.

In the Beas river valley at Palchan we dated the tree rings for the evidence of scars (Figure 4 *a*) that exist in surviving trees from the devastating flood of 2012. We observed occurrence of several floods, not only in 2012 (Figure 6) but also in 2006 and 2011. These three major flood events have also been corroborated by the documents collected from local authorities. Moreover, data collected on topographic measurements (river cross-sections) along with historic information (event description, pictures and videos) were used to reconstruct the magnitude of the 2012 disaster, to put this event into a longer-term context and to understand its driving mechanisms.

## Avalanche history

Trees growing in the Solang-Dundhi area show clear evidence of damage induced by past snow avalanches (i.e. impact scars, stem tilting and/or branch and crown losses). Preliminary results obtained from the tree-ring analyses focusing on dating of growth disturbances, suggest a very high activity of snow avalanches. We were able to date more than 20 snow avalanches since 1970, with a major event in 1974. We plan to extend the snow avalanche reconstruction by including the analysis of new disturbed trees and to use an approach in which the outcome of tree-ring analysis (in terms of frequency, lateral spread and down slope reach of avalanches) is used to calibrate and validate a two-dimensional, numerical snow avalanche model. Results are not only valuable in terms of our understanding of climate variables driving avalanching, but also in view of the design of future mitigation structures. Despite ample dendrogeomorphic evidence of important avalanche activity in the Solang valley, a paucity of documents exists on past frequency, magnitude and climatic drivers of snow avalanching in the region[40]. Potential sites for detailed snow avalanche reconstructions are found along many portions of the road connecting Solang and Dhundi. An additional component of the fieldwork included an assessment of ecological and successional composition[41] of vegetation in and adjacent to the avalanche track and an analysis of its morphology to enable identification of slope characteristics associated with changes in avalanche activity.

## Conclusions

Trees are natural archives of a large bandwidth of environmental processes including natural hazards, as they record the impact of past disturbances in their tree-ring series. Over the past few years, the application of tree rings to mass-movement processes (dendrogeomorphology) and related fields has evolved from a pure dating tool to a broad range of applications[16,21]. Besides the tree ring sequence of the oldest trees growing on geomorphic forms and/or the construction of pure event frequencies, tree rings allow, if coupled with spatial positioning systems, the assessment of spread, run-out distance, breakout locations or preferred flow paths. Similarly, the wide field of applications includes the identification of magnitudes and triggers of past disasters if meteorological data is included[42]. The May 2014 Indo-Swiss field mission to Kullu and exploratory tree ring analysis in dendrogeomorphic aspect provided a first glimpse of the various processes and sites in the region that can be analysed in detailed to enhance the overall understanding of natural hazards in the area. It is anticipated that the outcome of this project will definitely be of great help to manage natural hazards and to conduct risk assessments in the valley. The generated data will form a vital source of baseline data which is crucially needed for the prediction of future events and for the planning of mitigation measures. In the future, and if applied systematically, dendrogeomorphic techniques could provide the information basis for local planners to quantify slope failure hazards in forested areas throughout the Western Himalayas[28], in addition to improving frequency–magnitude plots of floods in the many ungauged river basins in the region. If coupled with pollen data (palynological data) from glacial lake, the work planned in Kullu will also extend and complement the climatic records and provide information regarding vegetation succession after large-scale devastation.

Future missions should also include trees growing in flood plains farther down the river valley where transported materials have inflicted wounds on tree stems. These injuries stem from outburst or monsoon floods. During the 2014 mission, we saw such scar marks in riparian trees. Detailed data on past events help in the understanding of possible future hazards and risks induced by extreme events, even if the ongoing climatic warming may likely favour disasters without historical parallels. The coupling of tree-ring data with pollen records from lacustrine sediments is an excellent proxy to understand the interactions and interdependencies of climatic changes and glacial fluctuations at timescales ranging from annual to millennial. Palaeoclimatic records from the Kullu Valley and adjacent Lahaul-Spiti and Kinnaur valley are expected to become key datasets for understanding the impacts of climatic changes in the region. Glacio-geomorphic evidence from the Himalayan region points to several sub-recent phases of glacier advances and retreats, but the timing of these fluctuations is yet unclear. Organic matter deposited in moraines and in sediments of glacial lakes appears to be an ideal source for dating (radiocarbon) and can be combined with pollen data. Besides, trees growing on moraines provide minimum ages of these deposits, as they need to have at least the age of the trees that they support. Moreover dendroclimatic analysis of trees and shrubs growing close to existing glaciers provide information on climatic changes in the region during the recent past. In addition to enhancing our understanding of recent climatic changes in glaciated environments, data is also used for glacier mass balance and run-off modelling. More data is also crucially needed to analyse tree growth-climate modelling in various geographic contexts of the Himachal Himalaya to understand relationships between the temporal variability of precipitation brought by both monsoons and the western disturbance and glacial advance and retreat in the region. This information also provides a solid baseline for an effective appraisal and management of water resources.


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