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Regional flood-frequency reconstruction for Kullu district, Western Indian Himalayas

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Abstract

Floods are a major threat in many valleys of the Indian Himalayan Region (IHR). Yet, the lack of reliable data on past events renders the implementation of appropriate adaptation policies a difficult task, and therefore also hampers the mitigation of future disasters. In an attempt to overcome these shortcomings, we combine reconstructed paleoflood events based on tree-ring analyses with existing systematic records, so as to derive a regional flood frequency. Analysis was realized with tree-ring records and through the dating of growth disturbances in riparian trees of major rivers in Kullu district (Himachal Pradesh, Indian Himalayas). To this end, we combined field-based observations, tree-ring analyses, hydraulic modelling and statistical approaches. Results suggest that the occurrence of floods in Kullu district is recurrent, with a marked seasonality and a cyclic natural variability in flood frequency at multi-decadal scales, as well as distinct spatial representativeness. The inclusion of peak discharge data of past, previously ungauged, flood events derived from tree-ring records has a significant and positive impact on the flood frequency assessment. Flood hazards and associated risks have been clearly underestimated in the region and based on the systematic records alone. We also demonstrate that a regional flood frequency approach is suitable to optimize the information gathered from tree rings and that flood frequency can thus be analyzed for larger regions. The approach used in this paper can be implemented in the other, poorly gauged region and thus contribute to climate change adaptation policies in undocumented environments such as the Indian Himalayan Region.

Keywords: past food, flood frequency, hazard, tree rings, Kullu district, Indian Himalayas.

1 Introduction

Extreme floods represent the most frequent and widespread type of natural disaster in the Indian Himalayan Region (IHR) (Gardner, 2002; Gardner and Saczuk, 2004). Almost each year, flood disasters occur in its headwater catchments and thereby cause substantial economic losses and high death tolls in downstream valleys, thereby disrupting infrastructures and stressing the status quo of local communities. Recently, the occurrence of a series of very dramatic disasters has underlined the high vulnerability of the region. In August 2010, a heavy downpour and subsequent flash floods have killed more than 250 persons in Ladakh and damaged 71 villages (Hobley et al., 2012). The early onset of unusually intense monsoon rainfalls in June 2013 caused more than 6000 causalities at Kedarnath (Uttarakhand) (Allen et al.,in press). The most recent event on record occurred in Jammu and Kashmir when floods flooded major riverine cities (such as Srinagar) in September 2014 and March 2015 (Ballesteros-Cánovas et al., 2016), causing numerous fatalities and substantial economic losses.

Several studies have argued that ongoing climate change (GCC) was at the origin and the causative reason for the clustering of recent flood disasters, and therefore suggested an increase of situations favoring flood occurrences and exacerbation of flood severity over the next decades (Hirabayashi et al., 2013). Most often, changes in monsoon rainfall over India were held responsible for the recent peak in flood disasters and for those that might come in the future (Attri and Tyagi, 2010; Mathison et al., 2013; Turner, 2013). Besides, some authors have also pointed to the galloping economic development in the IHR and to the lack of preparedness and planning in most flood-prone areas, and have identified these socio-economic changes as the major and most significant amplifiers of flood impact (i.e. Gardner, 2002). While it is possible that the current flood situation could in fact deteriorate further over the next decades and as a result of GCC, it is also the extensive use of floodplains and the generalized lack of proper flood hazard zonation which renders the situation in the region critical, even in the absence of GCC.

The implementation of suitable adaptation policies, as part of a sustainable development process, requires therefore better knowledge of critical processes and a proper identification of the areas affected by floods (National Disaster Management Policy, 2009). Recently, the first Disaster Management Regulation has been implemented at the national level by the Government of India (i.e. Disaster Management Act, 2005), but the implementation of disaster preparedness strategies in the IHR has remained a very challenging process. As commonly recognized in the Hyogo Framework (UN, 2005), this challenge is very much related to the generalized lack of long-term flow records and the documentation of historical flood disasters, which is not only a problem in the IHR, but in most (mountain) regions of the World. For as long as such data are missing, rational flood hazard assessment and risk awareness of local citizens and authorities will, however, remain rather constrained.

In high mountain regions, lacking baseline data of past extreme events is a common and widespread problem (Ballesteros-Canovas et al., 2015; Bodoque et al., 2015; Stoffel et al., 2010). Although not readily available for administration, policy, and decision makers in the form of reports or statistics on flood quantiles, data on past disasters and the gauging of ungauged catchments would indeed be possible in many mountain regions of the world, including the IHR. In fact, field-based geomorphic, botanical, or historical records are often readily available in these regions and can be used to describe and document the hydrodynamics of past flood in ungauged catchments with up to seasonal precision and over multi-centennial timescale (Baker, 2008). More specifically, tree rings have been used repeatedly in mountain environments to document past disasters (Stoffel et al., 2010), and have been demonstrated to have several advantages over other approaches when it comes to flood reconstructions in mountain streams (Ballesteros-Canovas et al., 2015a). The approach is based on the concept that trees affected by hydrogeomorphic processes will conserve information on the event in their growth-ring records (Shroder, 1978; Stoffel and Corona, 2014; Stoffel and Wilford, 2012), and that the analysis of tree-ring series of riparian vegetation can thus be used to infer the frequency and magnitude of individual floods (Ballesteros-Canovas et al., 2015a). The applicability of tree-ring records for Disaster Risk Reduction (DRR) has been tested in several mountain streams worldwide with the aim to document past flood activity and to decipher flood-climate linkages at the catchment (Ballesteros-Cánovas et al., 2015; Ballesteros et al., 2011; Ballesteros Cánovas et al., 2011; Ballesteros et al., 2010ab; Corriell, 2002; McCord, 1990; Ruiz-Villanueva et al., 2013; St. George and Nielsen, 2003; Therrell and Bialecki, 2015; Yanosky and Jarret, 2002; Zielonka et al., 2008) or regional (e.g., Ballesteros-Cánovas et al., 2015b, c; Rodriguez-Morata et al., 2016; Šilhán, 2015) scales.

In analogy to geological and historical flood records (Gaál et al., 2010; Gaume et al., 2010; O'Connell, 2005; O'Connor et al., 1994), tree-ring based flood reconstructions can contribute to important changes in the flood frequency distributions and thus can help to improve existing flood records and to reduce uncertainties related to flood processes (in terms of both frequency and magnitude) in a substantial manner (Ballesteros-Cánovas et al., 2013; Ballesteros-Cánovas et al., 2015c). Information derived from tree rings has also been used to analyze the non-stationary behavior of flood-prone catchments and to address its implications in terms of flood hazard zonation (Brooks and St George, 2015), with major impacts on future flood risk assessments. However, all of these experiences have focused at the catchment scale, and have, at best, assessed hazards in the same sub-system. Yet, the potential of an incorporation of tree-ring-based peak flood reconstruction into flood frequency assessments at the regional scale has remained unexplored.

Accordingly, this paper aims at dating past flood activity in Kullu district (Himachal Pradesh, Indian Himalayas) at the regional scale and at virtually extending the network of existing flow gauge network across the region. We combine flood reconstructions from sub-catchments of the Beas river for a regional flood frequency assessment comprising the entire Kullu district. To this end, tree-ring analyses have been combined with field-based recognition, hydraulic approaches, and Bayesian statistical procedures. In this paper, we present a regional flood frequency estimation for the Kullu region and compare results with data derived from instrumental records in terms of flood quantiles and uncertainties in the estimates. Our results can be used as a basis for the definition of policies aimed at climate change adaptation to natural disaster in the study region or at the scale of larger regions within the IHR.

2 Physical setting: Kullu District, Himachal Pradesh, India

The rivers chosen for the regional flood reconstruction are located in Kullu district (~5.5×10^3 km^2), in the state of Himachal Pradesh, where population is in the order of >4×10^5. The study region is located close to the Great Himalayan National Park at around ~ 32° N and 77°2' E (Fig. 1) and also includes the tourist mecca of Manali. This part of the IHR is characterized by a main valley running in north-south direction, formed by the Beas River; as well as by a series of tributary valleys shaped, among others, by the action of the Parvati, Sainj, and Thirtan Rivers. The river valleys are generally characterized by wide bottom floodplains occupying large parts of the U-shaped valley floors. The valley floors also are hotspots of population and transportation. The tributary rivers are characterized by narrow side valleys, forcing inhabitants to live on the steeper slopes or on the limited, yet often flood-prone, flatter surfaces in the valley bottoms.

Forest cover represents more than 35% in the study region and comprises both broadleaved and conifer taxa, with the latter being more prominent at higher elevations. Forests of *Alnus nitida* associated with *Ulmus* sp. and *Populus* sp. are common in new floodplains whereas *Cedrus deodara* and *Pinus wallichina* are prevailing on older flood deposits. In terms of climate, the area is influenced by both westerlies and the south-western influence of the monsoon. Climate in the region ranges from alpine, cold temperate, warm temperate to subtropical, as do forest types as per the classification of Champion and Seth (1968). At the level of the settlement of Kullu, average air temperatures range from -4° to 20°C in winter and up to 35°C in summer. During the monsoon period, monthly rainfall typically exceeds 150 mm, which is beneficial for local agriculture/horticulture representing the single-most important sector in Kullu district (74% of the GDP). In recent years, however, tourism (both national and international) has gained momentum and increased significantly in the area (Sah and Mazari, 2007).

Existing hydro-meteorological records at Kullu district consist of two rain gauge stations and twelve flow gauge stations. However, flow gauge records are highly fragmented, and multi-decadal records are exclusively available for Beas River; this series exists since the late 1960s (see Supplementary Information for details)

3 Material and Methods

3.1 Tree-ring based flood dating

This study started with a field survey and aerial picture recognition to detect the most suitable river reaches for tree-ring reconstructions. Analyses focused on six river reaches in the Upper Beas, Paravati, Thiertan, and Sainj river catchments and included the collection of eye-witness data (i.e., pictures and videos) on recent floods events as well as interviews with the local population, forest, and village authorities. This initial contact was essential for the engagement of the local population in the study and greatly facilitated further analyses and interpretations. At each of the river reaches assessed in this study, we applied classical tree-ring sampling of trees affected by floods and recprded their position along the channel and in the floodplain (Ballesteros-Canovas et al., 2015a). In addition, we also included samples taken from trees growing in undisturbed forest stands so as to build reference chronologies representing local, yet undisturbed growth conditions. Increment borers and hand saws were used to obtain increment cores and wedges from disturbed trees. We preferentially sampled trees with visible abrasion scars induced by debris transported during past floods (Ballesteros et al., 2011; Ballesteros Cánovas et al., 2011), as these are considered the most reliable signal for flood reconstructions (Ballesteros-Canovas et al., 2015a; St. George, 2010). To detect hidden scars, older trees growing close to the channel in exposed locations with respect to the flow were sampled as well, as hidden scars can often be dated indirectly (Arbellay et al., 2010; 2012a,b; Ballesteros et al., 2010ab; Schneuwly et al., 2009; Stoffel and Perret, 2006). Additional information, such as the geographical location and graphical information of the tree and the channel reach as well as river cross-sectional topography and the maximum height of the scars (i.e. paleostage indicator, PSI), were recorded as well and by using a GPS, camera, laser distometer (TruePulse 3600B, precision: 30 cm), tape measure, and clinometer. A total of 256 increment cores and 27 cross-sections and wedges were sampled from 177 disturbed *Pinus wallichina*, *Alnus nitida*, *Ulmus* sp., and *Populus* sp. trees at six different study reaches. In addition, we sampled 35 undisturbed samples of *Abies pindrow* and 55 cores from *Cedrus deodara* to build two reference chronologies and to separate climate signals from flood imacts in the affected trees.

In the lab, we sanded all samples and counted their rings before the growth series were cross-dated using skeleton plots. During this step, we used extremely narrow rings from two reference chronologies as benchmark years for the cross-dating. Using a stereomicroscope, we then identified growth disturbances (GD) related to floods, namely scars and injuries, callus tissue and reaction wood (Stoffel and Corona, 2014). Definition of past flood events was based on the weighted index value (W_{it}; see Kogelnig-Mayer et al., 2011), which considers the number, intensity, and typology of GDs within each tree-ring series and the total number of trees available for the reconstruction at any moment of the past (thus taking account of reduced sample availability as one goes farther back in time). We only accepted flood-event in those years for which we observed GDs in more than two trees and for which the Wit was >0.8 (Ballesteros-Cánovas et al., 2014).

In a next analytical step, we combined flood occurrence data from all catchments, i.e. the reconstructed (tree-ring based) floods and the flow records of existing gauge stations, to derive a regional flood activity index (RFAI) as follows:

$$RFAI = \frac{\sum_{i}^{t}(F_{tree}+F_{gauge})}{\sum_{1}^{t} Rc}$$

where F_{tree} represents dated floods in year t in the four catchment (i.e. Beas, Parvati, Sainj, and Thiertan); F_{gauge} indicates the number of measured flows (>90th of flow record) at the gauge station for each catchment in year *t*; and where *Rc* represents the number of catchments reacting in year *t*. The index we use is similar to the one used for snow avalanche reconstructions (Germain et al., 2009), and aims at limiting possible bias in the composite analysis associated to dissimilar sample depths and at reflecting a homogeneous regional flood activity in the study region.

3.2 Peak discharge reconstruction

Due to the lack of detailed topographic information (e.g., high-resolution Digital Elevation Model or LiDAR data), which are needed to run hydraulic models (Ballesteros Cánovas et al., 2011), we used Manning's equation to transform the height of dated scars on trees (Fig. 2) into peak flow discharge at each of the cross-sections surveyed in the field (Jarrett and England, 2002). At each surveyed cross-section, we measured the slope of the main channel and the maximum scar height at each position where a tree was sampled. We are well aware that this procedure is strongly biased by the initial hydraulic assumption (Jarret, 1985). as Manning's equation assumes uniform flow, in which the water-surface and energy gradient are parallel to the channel slope; and the area and hydraulic radius remain constant along the reach river (Jarret, 1985). Moreover, we are also aware of the uncertainties related to the calibration of roughness parameters, which can stem from the mixture of water and sediment in the rivers analyzed (Bodoque et al., 2015), as well as to the assumed invariability of channel geometry (Ballesteros et al., 2011). For this reason, analysis has been restricted to uniform river reaches for which bedrock or stable floodplain situations should have prevailed over longer periods of the past, so as to avoid uncertainties in peak discharge reconstruction due to vertical (and horizontal) changes in channel topography. Thus, uncertainties in peak discharge have been incorporated by varying the specific roughness as a uniform distribution (±25%) with respect to the initial set of values gathered in the field and in line with the typology of river reaches as provided by Chow

(1964) (i.e. n= 0.06). The resolution of the equation and estimated parameters are provided in the Supplementary Information.

Figure 2

3.3 Regional flood-frequency analysis

Reconstructed peak discharge values and related uncertainty were incorporated as a range of values into the systematic record of the flood frequency analysis. We applied a regional flood frequency analysis approach based on Bayesian Markov Monte Carlo Chain algorithms (Gaume et al., 2010). In addition, a Generalized Extreme Value distribution (GEV) has been used to derive flood quantiles. Homogeneity of the existing systematic flow series has then been tested using the Hosking and Wallis (1987) algorithm, which compares the variation between-site in samples Lcv (coefficient of L-variation) for the analyzed sites. The regional flood frequency analysis therefore allows inclusion of flood quantile estimations at different catchment locations by flow-index regionalization. This approach is based on the distribution of a flow discharge from different catchments of a homogenous region. Analysis was performed by using the R package nsRFA (Viglione et al., 2014). The robustness of this method has been tested previously in other hydrological contexts (Gaume et al., 2010). A depth theoretical and practical description of the procedure followed in this paper can be found in Gaál et al. (2010). Finally, we compared the impact which the addition of tree-ring based records to systematic series has on flood quantiles and uncertainties at each of the study catchments.

4 Results

4.1 Temporal flood reconstruction at Kullu district

Dating of the tree-ring sequences from both the increment cores and (partial) cross-sections of trees affected by floods allowed identification of 33 past floods in Kullu district since the early 20th century. Most of the dated floods were restricted to the period 1960-2014, this is because older trees were not readily available in the floodplains, either as a result of their frequent removal by floods, or due to human pressure and use. Based on the ten available flow gauge records, we identify 42 years during which flow exceeded the 90th percentile for the length of the record. Figures 3 and 4 show the temporal reconstruction of floods in the different catchments analyzed at Kullu district. By considering only those floods which were either recorded by one of the flow gauge stations or reconstructed in the tree-rig records in one of the six river reaches in the four catchments analyzed, we identify at least 56 flood incidents since 1965, defining an average occurrence rate of floods of almost 1.1 events year^{-1}.

Sainj river exhibits the largest number of reconstructed floods based on tree-ring records, with 11 ungauged events since 1977 (sample size = 51 trees). Years with ample evidence of floods include 1977, 1988, 1995, 1997, 2001, 2003, 2005, 2006, 2009, 2010, and 2011. By contrast, the smallest number of reconstructed events was found at Beas River, with 5 reconstructed flood events during the last decade (sample size = 30 trees: 2005, 2006, 2010, 2011, and 2012. The limited amount of evidence found at this catchment is related to the young age of vegetation which is in turn also reflects high flood activity in the fluvial domain. In the Thiertan river, 9 ungauged flood events have been reconstructed over the course of the 20th century and based on evidence found in 53 trees, namely in 1910, 1919, 1971, 1974, 1980, 2002, 2005, 2008, and 2010. At Parvati river, we reconstructed 8 floods based on evidence found in 43 disturbed trees, namely in 1993, 2003, 2005, 2008, 2010, 2011, 2013, and 2014.

The spatial inter-catchment comparison of floods reveals that events at Kullu district operate at both regional and catchment-specific scales, and point to the presence of two major local-to-larger scale triggering mechanisms, i.e. high-intensity, but short-lived rainfalls (i.e. mostly cloudbursts) and longer duration, but less intense rainfall events (i.e. monsoon rains). A total of 56% of all flood years can be observed in more than two catchments, and in 15% of the cases, flood signals are discernible in more than four catchments. By contrast, and for the remaining 44% of flood years, reactions were exclusively found in one specific catchment. The RFAI index also suggests dissimilar flood activity over the past few decades, with distinct phases which were rich or poor in floods. Periods with high activity can be fund between 1977-1981, 1988-1995, and 2003-2014, whereas low flood activity is observed between 1981-1987 and 1996-2001.

Figure 3

Figure 4

Table 1

4.2 Ungauged floods and regional flood frequency analysis

A total of eight intense, yet ungauged flood events have been reconstructed at the river reaches of Kullu district (Table 2). At Sainj valley, trees growing in the river reach located next to the settlement of Ropa (drainage area of ca. 470 km^2) showed evidence of 7 major floods during which reconstructed peak discharges ranged from 233 to 824 m^3/s. The ungauged events in this catchment took place in 1978 (655 ± 169 m^3/s), 1997 (244 ± 88 m^3/s), 2003 (494 ± 127 m^3/s), 2005 (719 ± 185 m^3/s), 2006 (639 ± 164 m^3/s), 2009 (191 ± 49 m^3/s), and 2011 (181 ± 46 m^3/s). In the Thiertan valley, we reconstructed a major flood in 2005 with a reconstructed peak discharge of 1869 ± 482 m^3/s. All measurements at each of the cross sections are provided in the Supplementary Information.

The Hosking and Wallis test was applied on ten flow gauge records covering the period 1964 to 2010 and contributing catchment areas ranging from 22 and 3836 km^2; it yielded a H1 value of -0.05, therefore indicating that the dataset used in this study can be assumed homogeneous for as long as H1≤1 (see Supplementary Information). Figure 5 provides an example of differences in flood quartiles, including uncertainties at the 90% interval confidence level, between the regional flood frequency obtained in this study and extrapolated estmates based on the flow gauge data from the Telara dam in Sainj valley alone. Quantitative comparison between the flood frequency data using only the existing flow gauge records and the regional approach combining tree-ring and flow gauge records exhibits major differences for e.g., the 100-year flood quartiles with average differences between the series of up to +76±81%. In a similar way, mean differences in the uncertainties are in the order of –41 ± 59% (Table 3). We therefore demonstrate that flood hazards in Kullu district have been systematically underestimated so far and by using exclusively the available set of fairly short and incomplete systematic records.

Figure 5

Table 2

Table 3

5 Discussion

5.1 Flood occurrences at Kullu district

In this paper, we have shown how tree-ring records can be used to inform authorities and the population about the frequency and magnitude of flood events in a selection of poorly gauged catchments of the IHR. In addition, we have provided examples of how regional flood frequency information can be obtained. Based on the analysis of 177 disturbed trees from the four main river catchments of Kullu district, we have added 33 ungauged floods since 1910 to the archival record. In combination with the short (and sometimes incomplete) flow records gathered from ten gauge stations, we also analyzed spatio-temporal patterns of floods at Kullu district and provide insights into cyclic flood variability and high spatial representativeness of the records provided here. Besides, the reconstructed peak discharges of eight intense floods have been merged with data from instrumental flow series to produce a new, regional flood frequency assessment. We therefore probed whether the inclusion of extreme ungauged flood events into the regional flood frequency would indeed result in substantial changes of flood quartiles and the related range of uncertainty.

Our results provide clear evidence that flood incidents at Kullu district occurred more than once per year since at least the 1960s (1.1 event $year^{-1}$), i.e. for the time for which we have reliable data. Our approach considered both tree-ring and instrumental flow records (for which we only considered exceedances of the 90^{th} percentile). In addition, we realize that the reliability of the flood reconstruction is well-supported by historical and flow gauge records from the valleys, at least for those events which occurred during the last four decades (i.e., 1971, 1978, 1988, 1989, 1995, 2005, and 2013). These events have been recorded in the EM-DAT (www.emdat.be) and DFO (www.dartmouth.edu) databases and are well presented in our reconstructions. Our results also match with data from earlier work (Parthasarathy et al., 1987), where the occurrence of several droughts and floods have been reported based on substantial departures from normal rainfall conditions over the period 1871-1984. In this study, the 1970s are shown as a decade with intense flood conditions, which also coincides with a reported shift in monsoon behavior (Terray and Dominiak, 2005; Yim et al., 2014). At the same time, however, the tree-ring based approach also points to the occurrence of twenty additional flood events which have not been documented for Kullu district so far. This outcome suggests that historical datasets clearly underrepresent flood activity in the study region – as is the case also in other mountain regions of the world. Consequently, relying exclusively on systematic datasets will represent a limitation, with potentially major impacts on Disaster Risk Management (DRM) and on the design of mitigation and adaptation plans.

The regional flood index weights the impact of the dissimilar availability of gauge station data and/or tree rings to record floods and provides a homogeneous dataset of flood occurrence in the four catchments investigated. Even though the nature of available data sources, heterogeneous over time, does not allow deriving robust long-term trends from our flood chronologies, the index suggests frequent flood occurrences in Kullu district since the late 1960s, however with marked and cyclic flood variability over time. In fact, several studies postulate a causal linkage between monsoon variability and the El Niño Southern Oscillation (ENSO; Kripalani and Kulkarni, 1997; Rajeevan et al., 2008; Ranatunge et al., 2003). However, unlike other parts of the globe, on the Indian subcontinent, ENSO can so far only be held responsible for its influence on monsoon rainfall patterns and to the extent of its year-to-year variability and linkage with occurrences. A positive trend in flood occurrences was recognized by DST (2012) at multi-decadal timescales for Himachal Pradesh, but are partially in disagreement with monsoon rainfall observations, for which trends have been shown to decrease recently (Kumar et al., 2005).

Moreover, Chase et al. (2003) and Duan et al. (2006) suggested that monsoon activity would have decreased over the Himalayas since the mid-20th century.

We explain this apparent mismatch between monsoon rainfall and flood trends by the dissimilar triggering mechanisms involved in the occurrence of floods at Kullu district. Indeed, spatial analysis of past flood occurrences at Kullu district suggests that an important number of past events would have been limited to individual catchments. The lack of widespread flooding response would in fact point to localized cloudbursts as a trigger of extreme floods, and less so (but also) to monsoon rainfalls, which is consistent with other studies realized in the state of Himachal Pradesh (Sah and Mazari, 1998, 2007). In addition, and in the context of the recent Kedarnath disaster in Uttarakhand, Allen et al., (in press) suggested that rather localized, extreme rainfall events, in combination with other hydro-geomorphic processes (such as the temporary formation and subsequent failure of landslide dams; Ruiz-Villanueva et al., 2016) can indeed trigger larger and more severe events in smaller-scale catchments than would monsoon rainfalls (alone) in the same environments. The fact that only five flood events occurred in all four catchments during the same year points to very extreme and localized rainfall precipitation event as the major, and presumably the most important, triggering mechanism of floods at Kullu district. Yet, the annual-to-seasonal resolution of tree-ring proxies does only allow dating of events to the month at best (e.g., Stoffel, 2008; Stoffel and Wilford, 2012), but does not allow confirmation of a simultaneous (i.e. daily resolution) occurrence of floods in the different catchments. In fact, the highly localized nature of extreme rainfall events in headwater catchment of the IHR is such that a monitoring of these events is difficult, even today, due to the generalized lack of rain-gauge stations in the region or the impossibility to access existing time series of rainfall. Despite the generalized absence of evidence, which would be needed for an attribution of reconstructed floods to specific rainfall events, the high frequency of flood events in the headwater catchments is in line with the rising trend observed in the frequency of heavy rainfall events in the region since the 1950s (Goswami and Xavier, 2005).

5.2 Impact of tree-ring based flood reconstruction on regional flood frequency assessments

The inclusion of peak discharge reconstructions into the regional flood frequency analyses has important consequences on flood quartiles. If one compares the 100-year quartile of the systematic record with the series including both systematic and reconstructed peak discharge values, substantial changes become apparent in both expected discharge values and in terms of a reduction of uncertainties. Similar changes in flood quartiles have been obtained elsewhere and by comparing systematic data with conventional historical records (Gaál et al., 2010; Gaume et al., 2010), sediment-based reconstruction (Benito et al., 2003; Kjeldsen et al., 2014; Stedinger, 2001) or tree-ring-based reconstructions (Ballesteros-Cánovas et al., 2013; Ballesteros-Cánovas et al., 2015). Therefore, our results are supporting the previously stated drawbacks of flood hazard assessments based on short-flow gauge series, as they tend to underreport extreme events (Baker, 2008).

Rather than focusing at the catchment scale, this paper has illustrated how tree-ring reconstructions can be used to inform managers dealing with regional flood frequency analyses in poorly gauged, but highly vulnerable regions such as the IHR. The methodology used in this study in fact overcomes the usual limitations related to the spatial distribution of trees (or any other paleoflood proxy) suitable for reconstruction and its comparability with systematic rain-gauge records located elsewhere in the system. We are convinced that the approach presented here has major methodological advantages over more conventional work, since the reconstruction of past floods can indeed be realized at the most suitable river reaches (i.e. stable bedrock, existence of evidence, and critical flow conditions; Ballesteros-Canovas et al., 2015; Ballesteros Cánovas et al., 2011; Benito, 2004; Bodoque et al., 2015; Jarrett and England, 2002) for which uncertainties in paleoflood reconstructions can be minimized. As these conditions can only rarely be found at the location of the gauge station, direct flow comparison has so far been limited due to the increase/decrease of catchment area between the sites. Here, we overcome this limitation by showing that ungauged floods reconstructed with tree-ring records in the headwater catchment, and consequently at some distance of the gauge station, indeed are a very useful and valuable proxy for flood-frequency analyses.

This approach is especially interesting in the geographical context of the IHR (Kullu district is part of this region), where the inaccessibility and/or lack of highly-accurate topographic data generally hampers the reconstruction of flood magnitude data in appropriate river reaches. Therefore, field-based surveys and sampling used to be extremely difficult here, due to the very high stream power of the surveyed catchments which limited the use of two dimensional models or the critical-depth method to minimize uncertainties related to the calibration of roughness parameter. These constrains resulted in only a handful of suitable river reaches for which an adequate estimation and representation of channel cross-sections was possible. Remaining uncertainties can indeed be addressed with a Bayesian approach as used in this study so as to considerthe ungauged flood extreme as a range of values provided by the resolution of Manning’s equation and by varying the roughness parameter by ±25% with respect to the initial set of values. Yet, we are well aware that the estimation of peak flow may represent a source of uncertainties (i.e. up to 30%) due to the initial hydraulic assumption (i.e. uniform flow) related to

Manning's equation (Jarret and England, 2002). Nevertheless, the values obtained are very reasonable and still present the only viable solution to overcome the notorious lack of data in poorly gauged IHR valleys. Therefore, this study has shown quite clearly that the coupled paleoflood-regional flood frequency approach indeed opens a large set of possibilities for a more useful integration of past flood reconstructions into systematic records over large homogeneous regions. In fact, the information provided by the regional flood frequency allows an upscaling of hydrological information to conduct regional flood hazard assessments, and can thus contribute to the design and succesful implementation of adaptation policies to reduce advers impacts of climate change in the IHR region.

6 Conclusions

Tree-ring based flood reconstructions have been successfully applied in the Indian Himalayan region (IHR), demonstrating their potential for flood hazard analyses. We have also illustrated the value of a coupled paleoflood record (derived from tree-ring series) with flood regional frequency approaches and have shown that the coupling of the two datasets enables maximization of the gathered information, improvement of peak discharge estimates for specific return periods and a reduction of uncertainties. Besides the fact that we provide the first flood frequency estimation for the region, the second key factor for flood risk evolution is the built environment and the ever increasing population density in the floodplains of the IHR, which will in fact have an impact on losses during future flood situations. In view of thesignificantly increased (and ever increasing) exposure level of populations and their goods in floodplains (Gardner, 2002; Gardner et al., 2002), future flood disasters must be expected in the IHR region. Our flood reconstruction supplements the lack of long-term data and therefore can improve the basic knowledge on flood processes, as demanded in Disaster Management Plans. As such this study can contribute to the adaption to climate change in the region.

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Captions

Figure 1. Study sites at Kullu district, Himachal Pradesh (Indian Himalayan Region).

Figure 2. Examples of scars used as paleostage indicators (PSI) of past floods. These trees are growing in the floodplain of a tributary stream (A) and in the main channel (B) of the Thiertan River in the valley of the same name. For details see Figure 1.

Figure 3. Temporal occurrence of floods at Kullu district as a combination of dated floods at each of the catchments studied (black vertical lines), and years with flow measurement values exceeding the 90th percentile of gauge station records (grey vertical lines).

Figure 4. Composite flood occurrence at Kullu district based on tree-ring and flow gauge station records. Sample depth indicates the decreasing number of trees with scars available for analysis as one goes back in time.

Figure 5. Example of the regional (upper panel) and site-specific (lower panel) flood frequency assessment for Thiertan, Sainj, and Beas Rivers. The inclusion of tree-ring records provides an improved estimate of discharge values for specific return periods and reduces uncertainty in discharge estimates for events with large return periods.

Table 1. Flood events per catchment, including those dated with tree rings (years given in bold) and those with extreme runoff recorded in the flow series (the word "extreme" here refers to the exceedance of the 90th percentile of runoff values).

N° of catchments	Flood years
1	**1910**, **1919**, 1967, 1968, **1971**, 1972, 1973, **1974**, 1975, **1981**, 1994, 2002, 2009, **2013**, **2014**
2	1989, 1992, **1997**, 1999, **2001**, **2003**, **2006**, 2008, **2012**
3	**1978**, **1988**, **1995**, **2011**
4	**1993**, **2005**, **2010**

647 **Table 2:** Reconstructed peak discharge for past flood events at Kullu district

Site	Catchment area (in km^2)	Year	T_{100} (m^3/s)	STDEV (m^3/s)	Limit $_{low}$ (m^3/s)	Limit $_{upp}$ (m^3/s)
Sainj river	470	2005	719	185	533	904
Sainj river	470	2009	191	49	142	240
Sainj river	470	2003	494	127	366	621
Sainj river	470	2006	639	164	474	804
Sainj river	470	1997	244	88	155	333
Sainj river	470	2011	181	46	135	227
Sainj river	470	1978	655	169	486	824
Thiertan river	112	2005	1869	482	1387	2351

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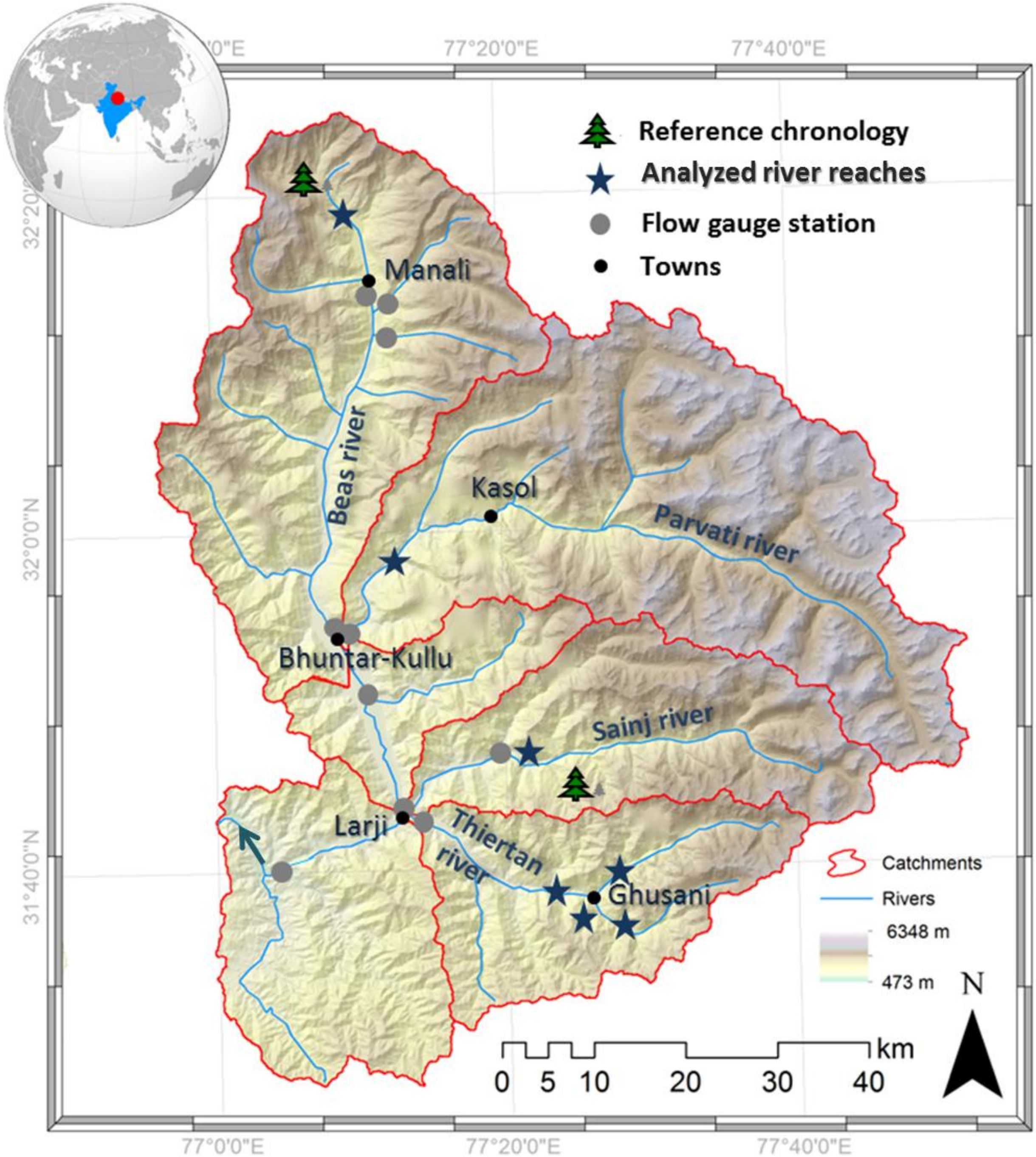
Table 3: Comparison of the 100-year flood and uncertainties between the regional flood frequency (tree-ring and gauge station data) and the flood frequency at each gauge station.

Flow gauge station/site	Area (km2)	Reconstructed regional flood frequency (m^3/s)		Flood frequency at gauge station (m^3/s)		∆ T100	∆ 90IC
		T100	∆ 90IC	T100	∆ 90IC		
Thiertan at Larji	658	909	500	1182	4636	77	11
Sainj at Larji	920	1250	625	500	581	250	108
Sainj at Telara Dam	647	889	480	516	2116	172	23
Baragarn Nallah	22	44	22	47	110	94	20
Allain Nallah	176	280	133	107	213	263	63
Hurla Nallah	232	379	172	121	466	314	37
Beas Bhuntar	3826	4545	3182	2500	2500	182	127
Beas Manali	349	500	250	565	739	88	34
Beas Pandho	6264	7692	4615	6154	6538	125	71
Beas Talhout	5788	7143	3929	3667	4000	195	98
					Average	176	59
					STDEV	81	40


Reference chronology
Analyzed river reaches
Flow gauge station
Towns
Manali
Beas river
Kasol
Parvati river
Bhuntar-Kullu
Sainj river
Larji
Thiertan river
Ghusani
Catchments
Rivers
6348 m
473 m
N
0 5 10 20 30 40 km
77°20'0"E
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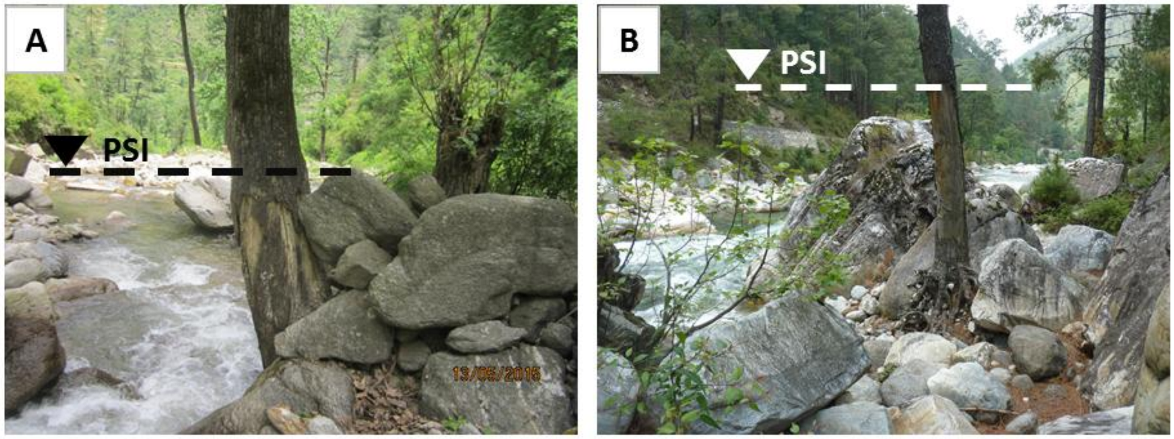
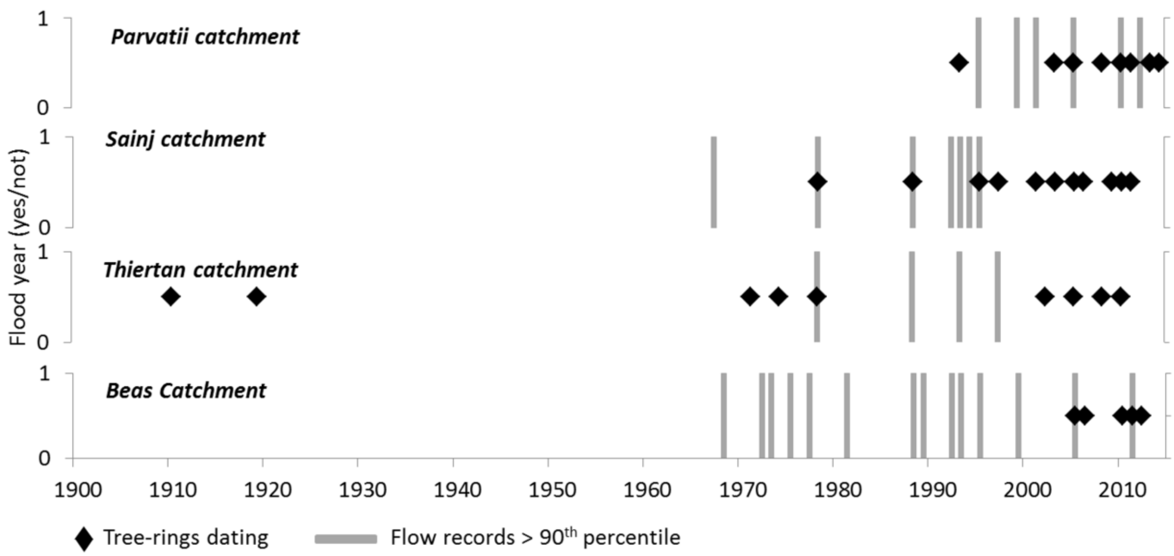
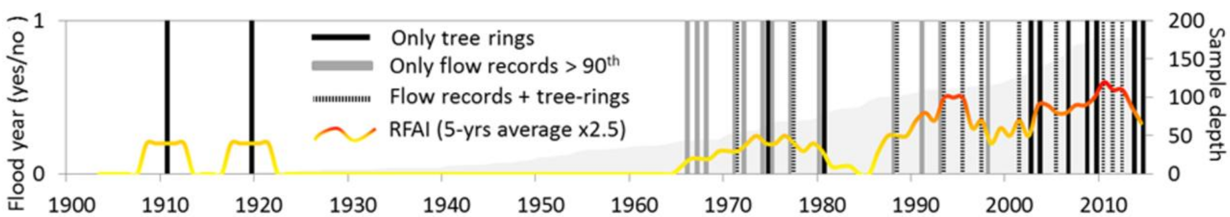
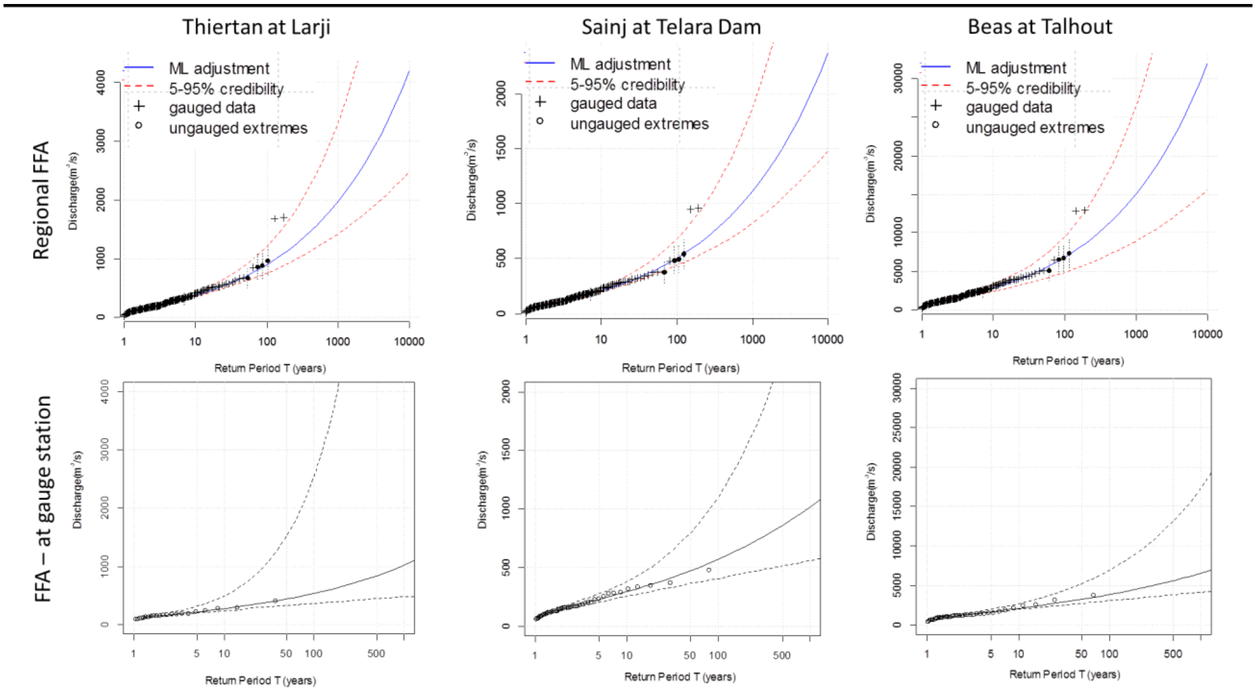
77°0'0"E
32°20'0"N
32°0'0"N
31°40'0"N


A
PSI
B
PSI


Parvatii catchment
Sainj catchment
Thiertan catchment
Beas Catchment
Flood year (yes/not)
1
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Tree-rings dating
Flow records > 90th percentile


Only tree rings
Only flow records > 90th
Flow records + tree-rings
RFAI (5-yrs average x2.5)
Flood year (yes/no)
Sample depth
0
50
100
150
200
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010



Highlights:

- The implementation of Disaster Risk reduction strategies is hampered by the lack of data in the Indian Himalaya region
- Tree ring based paleoflood reconstruction complement the limited existing flow gauge records
- The inclusion of extreme unrecorded flood events in upper catchments improve the regional flood frequency assessment