The importance of robust baseline data on past flood events for regional risk assessment: a study case from the Indian Himalayas

Juan A. Ballesteros-Cánovas,

Climate Change Impacts and Risks in the Anthropocene (C-CIA), Institute for Environmental Sciences, University of Geneva, Geneva, Switzerland; and Dendrolab.ch, Department of Earth Sciences, University of Geneva, Geneva, Switzerland

Simon Allen,

Climate Change Impacts and Risks in the Anthropocene (C-CIA), Institute for Environmental Sciences, University of Geneva, Geneva

Markus Stoffel,

Climate Change Impacts and Risks in the Anthropocene (C-CIA), Institute for Environmental Sciences, University of Geneva, Geneva, Switzerland.; Dendrolab.ch, Department of Earth Sciences, University of Geneva, Geneva, Switzerland; and Department of F.A. Forel for Aquatic and Environmental Sciences, University of Geneva, Geneva, Switzerland

Abstract

According to the Sendai Framework for Disaster Risk Reduction, the understanding of the frequency, magnitude, and impact of recent and past extreme events is a cornerstone for coping with future disasters. Nevertheless, baseline data is often scarce, especially in mountain environments. Here, we show with an example how extending the records of past flooding contributes towards a more robust flood risk assessment in a poorly gauged, but highly populated mountain region in the Indian Himalayas (Kullu district; Himachal Pradesh). Drawing from tree-ring -based evidence of past floods, we reconstruct the occurrence of thirty-three flood events over the last century. This reconstruction complements substantially the existing records. We also used field-based and hydraulic modeling to estimate flood magnitudes, which were used to deriving a regional flood frequency. Finally, we show how this regional flood frequency can be merged with freely accessible spatial (i.e. aerial or satellite imagery and topographic data) and socio-economic (i.e. Indian Census) information to perform a flood risk assessment for Kullu district. Our reconstruction highlights the existence of an important number of floods over the last six decades that were not previously recorded (~60% of cases), which defines a high frequency of events in the region (up to 1.1 events per year). The inclusion of this information in the regional flood frequency demonstrates that the flood hazard is underestimated if only data from gauge stations are considered in this assessment. These outcomes reinforce the idea that comprehensive risk assessments should be complemented with evidence-based data on past extreme floods. Therefore, acquiring qualitative and quantitative baseline information in poorly gauged regions should be prioritized to provide the necessary robust foundation for adaptation planning.

1. Introduction

Floods represent the most frequent and widespread hydrological disasters worldwide (Hirabayashi, et al., 2013; Arnell and Gosling, 2014), causing large economic losses and deaths. Extreme floods are especially common in high mountain regions. The causes of extreme flood disasters in mountain environments include: (i) long-lasting rainfall events, (ii) cloudbursts due to localized and intense downpours, (iii) glacier lake outburst floods (GLOFs) caused by the sudden outburst of glacier lakes and/or (iv) landslide lake outburst floods (LLOFs). Especially, in the Himalayan region, monsoon floods occur with a very high frequency (Ballesteros Cánovas, et al., 2017), causing disruption to the landscape and livelihood of the population (Gardner and Saczuk, 2004).

Recent examples of flood disasters in the Himalaya region have underlined the high vulnerability of people living in the mountain valleys. For example, in August 2010, an intense flash flood followed a heavy downpour in Ladakh (India), killing more than 250 persons and damaging 71 villages. Later, in June 2013, the early onset of unusually intense monsoon rainfalls and the outburst of a small glacial lake in Kedarnath (Uttarakhand, India) caused the death of more than 6000 pilgrims (Allen, et al., 2015). Recently, in September 2014, northwest India and northeast Pakistan experienced long-lasting rainfalls, which were particularly intense in the mountain region of Jammu and Kashmir, causing massive floods and debris flows (Kumar and Acharya, 2016). Among others, these examples show an increasing problem that is negatively impacting upon the socio-economic development of the region.

According to the IPCC, the frequency and magnitude of extreme flood events is likely to increase as result of the greater water-holding capacity of a warmer atmosphere (IPPC, 2014). Thus, in the Himalayas arch, an intensification of monsoon and cloudburst activity is expected in the next decades (Hirabayashi, et al., 2013). Besides, the warmer temperatures will favour changes in the cryosphere that can severely affect runoff (Archer and Fowler, 2004; Barlow and Tippett, 2008; Huss and Hock, 2018). The situation could be aggravated due to the effect of land use and land cover changes, which may condition the quantity and quality of water and sediment transported during flood events (Bathurst, et al., 2007; Birkinshaw, et al., 2011) and due to the increasing demographic over floodplains areas (Hirabayashi, et al., 2013; Gardner, et al., 2015).

These circumstances call for the development of suitable adaptation measures based on robust scientific assessments. However, this task requires appropriate process understanding. Thus, the characterization of extreme flood events is crucial for carrying out flood hazard zonation and for the design of structural and non-structural measures to reduce levels of flood risk (Ballesteros-Cánovas, et al., 2013; Merz, et al., 2009). However, the general lack of long-term flow records and documentation of historical flood disasters severely jeopardize this task (Benito, et al., 2003, 2015). As commonly recognized in the Hyogo Framework (ISDR UN, 2005), acquiring knowledge based on past flood disasters represents one of the main challenge to implement Disaster Risk Management. Thus, for as long as such data are missing, rational flood hazard and risk assessment as well as the proper awareness of local citizens and authorities will remain rather constrained.

The lack of records on extreme events calls for the use of alternative approaches able to track the occurrence and magnitude of unrecorded flood events at different spatio-temporal scales (Baker, 2008; Wilhelm, et al., 2018). Specifically in mountain catchments, botanical evidence allows to extend back the knowledge on frequencies and magnitude of past ungauged flood events (Ballesteros-Cánovas, et al., 2015). This approach is based on the analysis of growth-ring series from trees growing in the floodplains, damaged by past flood events. Tree-ring based flood reconstruction has been applied to develop flood chronologies at the catchment scale (i.e. St. George and Nielsen, 2003; Ballesteros-Cánovas, et al., 2015; Zaginaev, et al., 2016), but also at regional scale (i.e. Ballesteros-Cánovas ,et al., 2015; Šilhán, 2015; Rodriguez-Morata, et al., 2016). Botanical evidence has also been used to calibrate hydraulic models for determining magnitudes of past floods (Ballesteros Cánovas, et al., 2011; Ballesteros, et al., 2011; Ballesteros-Cánovas, et al., 2015), which has contributed to improved understanding of return periods for extreme flood events in ungauged mountain catchments (Ballesteros et al., 2011). This baseline information is considered more robust in comparison with gauge data alone, and can be used for framing adaptation strategies (Bodoque, et al., 2015, 2016; Allen, et al., 2018).

In this paper, we demonstrate the added value of extending the flood records for flood hazard and risk assessment. Concretely, we present a case study located in the Indian Himalayas, where flood records have been developed from tree rings. This flood record has been used to extend existing observations and derive a regional flood-frequency assessment. Our results demonstrate that gathered data on past extreme floods contributes to improved understanding on the spatio-temporal representativeness of this natural hazard in the region. We also

show that the information related to the reconstructed floods are able to modify the flood-quartile estimations, which are the basis for flood hazard zonation and engineering purposes. Thus, we demonstrate that flood hazards are underestimated if only data from gauge stations is considered in the assessment. We conclude that in poorly ungauged mountain catchments, a field-based robust scientific assessment aimed at characterising past flood events is essential to improve the reliability of future disaster risk reduction (DRR) plans.

2. Study site

Kullu district (population >$4x10^5$ and area ~$5.5x10^3$ km^2) is located in Himachal Pradesh (Northwest India), and includes the Great Himalayan National Park (Fig. 1). The altitude ranges between ~6500 and 900 masl and Kullu is characterized by the north-south Beas river valley and main tributaries, namely Parvati, Sainj, and Thirtan Rivers. Valley bottoms of the main rivers are characterized by floodplains occupying large parts of the wide U-shaped valley floors, where population and transportation infrastructures are developed. By contrast, the valley bottoms of tributaries are narrower, which constrains the living spaces to areas close to the rivers. Forest degradation has been observed in the region, accompanying an increase in population during the last decades (Gardner, et al., 2015). Nowadays, forest cover represents 35% of the surface, comprising both broadleaved and conifer taxa. Form the climate perspective, the region is influenced by both westerlies and monsoon seasons. The climate in the region varies from alpine, cold temperate, warm temperate to subtropical. In the city of Kullu, the average air temperature range from -4° in winter to 35°C in summer, with monthly rainfall exceeding 150 mm during the monsoon season. The most important economic sector in the region is agriculture and horticulture, which represents 74% of the GDP. However, during recent years, tourism (both national and international) has gained momentum and increased significantly in the area (Sah and Mazari, 2007). Hydro-meteorological data from Kullu district that were available for this study consists of two rain gauge stations and twelve flow gauge stations. Nevertheless, the flow gauge records are highly fragmented, and insufficient for deriving the medium-to-long-range flood return periods required for the implementation of any hydrological project.

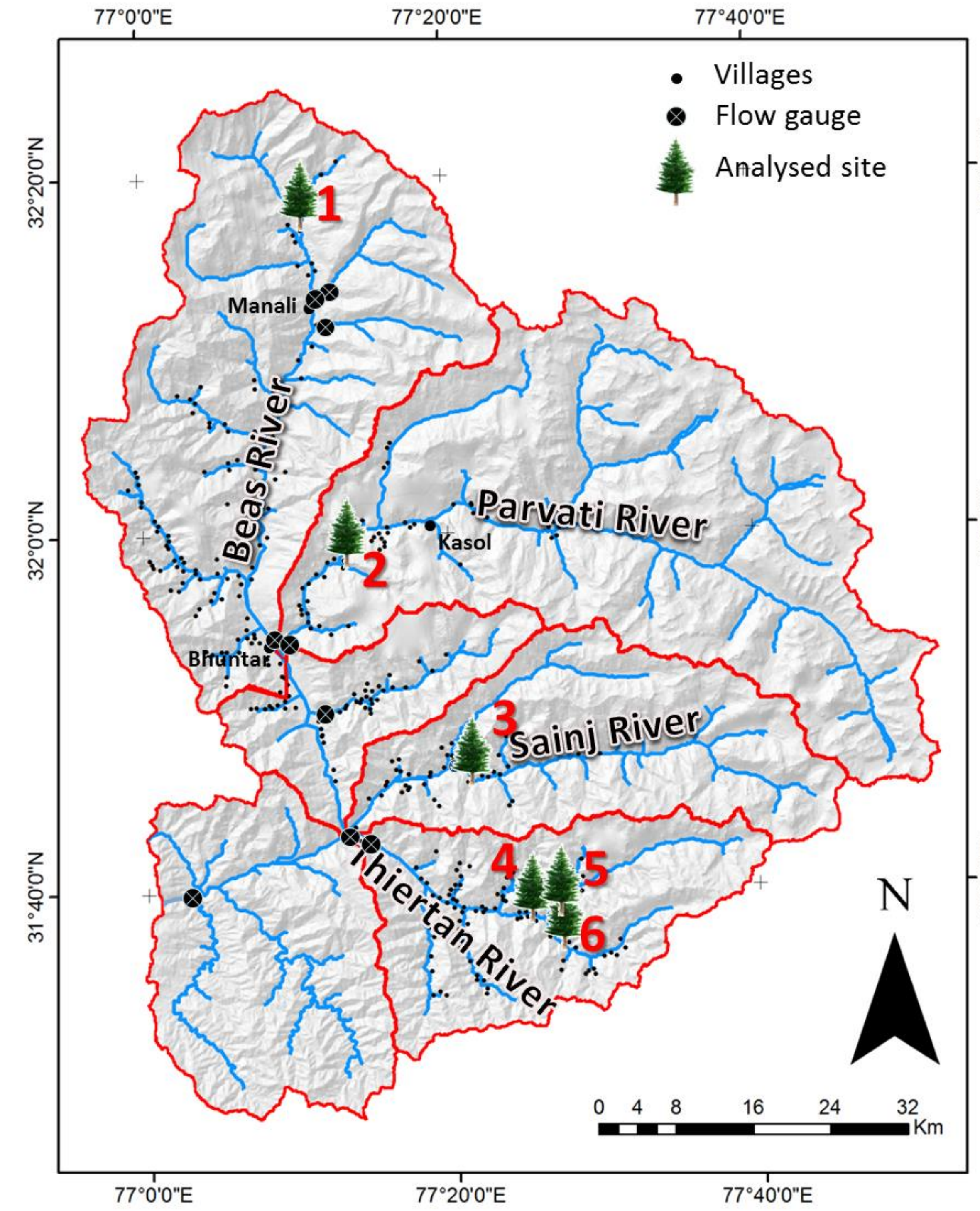

Figure 1: Schematic view of the studied catchments in Kullu district, showing the location of the flow gauge measurements and the six tree-ring flood reconstruction sites.

3. Methodology

3.1 Using botanical evidence to reconstruct past extreme flood events

We used botanical evidence (Ballesteros-Cánovas, 2015; Sigafoos, 1964) to extend the flow records at the study site. This method consists of dating growth anomalies identified in the tree-ring records, related to disturbances caused by the occurrence of floods. This approach was applied in six river reaches in the Upper Beas, Paravati, Thiertan, and Sainj catchment rivers. First, within each studied river reach, we carried out tree-ring sampling using an increment borer and sampled affected trees growing along the channel and in the floodplain, and those undisturbed forest stands growing above the bankfull cross-section (for control). The sampling focused on scarred trees, because they represent paleostage indicators (PSI; Jarrett and England, 2002; Baker, 2008) that allow estimation of flow magnitude in combination with hydraulic equations (Webb and Jarrett, 2002; Ballesteros Cánovas, et al., 2011). We took additional information about fluvial geomorphology, cross-section topography, geographical location, and whenever possible, historical accounts of past floods based on eyewitness interviews. Then, in the laboratory, wood samples were sanded and polished. We used a microscope to observe the growth anomalies in the tree-ring series. We applied classical dendrogeomorphic methods (Stoffel and Corona, 2014) to date them and to derive the flood chronologies of each river reach. To reconstruct the flood magnitude, we used the height of the scars, which provide benchmarks to identify the probable water stage during floods. Thus, we used the Manning's equation to transform the height of dated scar on trees into peak flow discharge at each surveyed cross section (Webb and Jarrett, 2002). In order to avoid uncertainties due to changes in channel topography, our assessment was restricted to river reaches showing bedrock or stable flood plains. Due to the impossibility to obtain high-resolution bathymetry and surface digital elevation models, we could not apply other hydraulic methods. We are therefore aware about possible biases due to initial assumptions and difficulties for roughness calibration (Webb and Jarrett, 2002; Bodoque, et al., 2015). The roughness values varied by ±25% around the in-field assigned value.

3.2. Improving the regional flood frequency for Kullu District

Long-term records are essential to derive flood quartiles with a specific probability of exceedance (Benito and Thorndycraft, 2004; Baker, 2008; Salgueiro, et al., 2013; Benito, et al., 2015). Several studies have

suggested that including information about past extreme events changes significantly the estimated flood return period (see Benito and Thorndycraft, 2004), with major implications for hazard and risk estimation. Here, we combine the existing flow records with the reconstructed peak discharges and its related uncertainty to derive a regional flood frequency analyses based on Bayesian Markov Monte Carlo Chain algorithms (Gaume, et al., 2010), given that the homogeneity test was passed (Hosking and Wallis, 1987). We used Generalized Extreme Value distribution (GEV). The analysis was performed using the R package nsRFA (Vignole et al., 2013). The regional flood frequency analysis allows to include estimation of flood quantiles at different catchment locations, by flow-index regionalization. This approach has been previously performed in other mountain regions (Gaál, et al., 2010; Gaume, et al., 2010).

3.3. Assessing the regional flood risk

As an applied study to assist the prioritization of DRR strategies in Kullu district, we used the derived flood frequency analysis to assess the flood risk at a regional scale. To this end, we followed the integrative concept of climate risk as presented by the IPCC (2014), where the hazard, vulnerability, and exposure components are included (Allen, et al., 2018). The flood hazard is quantified along the channel at points separated by 1km. This index is defined as the ratio between the 100-year flood discharge derived from the FFA and the bankfull discharge level (Q_b) (equivalent to a return period of 3 years) multiplied by the channel slope. The exposure is given by the relative vertical and horizontal distance of each element (i.e., buildings) located in a buffer zone of 200 m to the river. This information was obtained by mapping and digitizing of google earth satellite imagery using a hydrologically corrected version of the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) at 30-m resolution. Finally, the vulnerability index is derived from available and selected indicators from the 2011 Census India. We chose indicators that potentially are able to capture societal capacities to anticipate, respond to, and recover from a flood disaster at village or community scale (Allen et al., 2018). The three components were standardized to a common range (1-to-10) and then multiplied to provide a final risk value for each element, classified according to 5 quantile ranges.

4. Results

4.1. The occurrence of extreme flood events in Kullu district

The use of botanical evidence has allowed us to date 33 past floods in Kullu district since the early 20th century, based on the analysis of 256 increment cores and 27 cross-sections and wedges sampled from 177 disturbed trees. This information complements the existing flow measurements. Thus, together with measured flows higher than the 90th percentile, at least 66 floods events have taken place in Kullu district (i.e. Beas, Parvati, Sainj, and Tirthan Rivers), which defines an average frequency of 1.1 events per year. In many cases (40 %), reconstructed flood events match with flow measurements downstream. Yet, 60 % of events were not previously observed and therefore indicate the added value of the newly generated flood reconstruction.

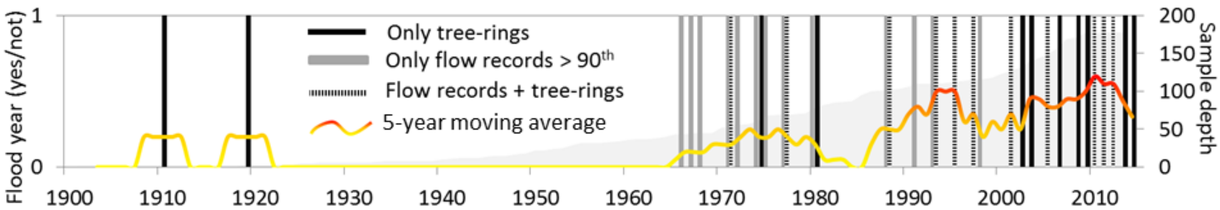

Figure 2: Composite representation of the flood records dated by tree-rings with those years with flow measurement exceeding the 90th percentile at Kullu district (robust period since mid 60's) (Ballesteros-Cánovas et al., 2017).

A spatial inter-catchment comparison of flood records suggests that processes operate at both regional and catchment-specific scales. 56% of floods took place in > 2 catchments (from which 15% of cases were observed in > 4 catchments), while 44% of floods were exclusively observed in a specific catchment. This suggests triggers related to local and larger scale 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). Looking at the composite flood trend, the records also suggests dissimilar flood activity over the past few decades, with contrasting rich (1977-1981, 1988-1995, and 2003-2014) and poor (1981-1987 and 1996-2001) flood periods.

Field observations have allowed us to hypothesize that human activity may have played an amplifying role in regards to recent flood disasters. This is exemplified in the following cases (Figure 3):

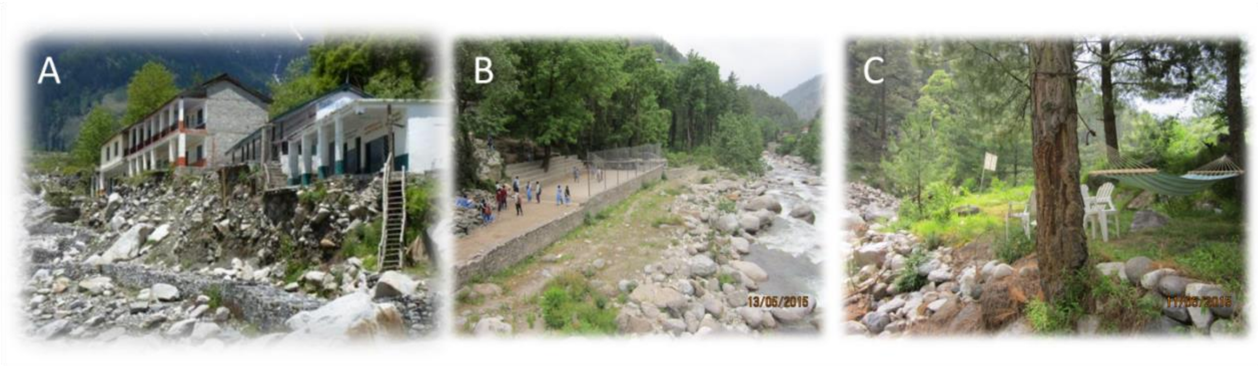

Figure 3. A) Pictures of the damages caused to school facilities after the 2012 flood event at Palchan; B) Location of the new school on the river channel configuration previous to the 2005 flood event; C) Scarred tree used as anchorage for a hammock at a tourist facility located on an inner river bar after the 2005 flood disaster.

Case A: Road construction in the floodplain of upper Beas could favor flood disasters. This is observed at Palchan village, on the banks of the Beas River. At this river reach, the construction of a new bridge pillar in the middle of the channel diverted and concentrated the flow on the right river bank during a moderate flood that took place in July 2012. This led to bank failure, resulting in significant changes in river morphology. As a result, the channel direction was modified and directed towards a school and a hydropower plant placed on the opposite bank. The large amount of sediment destroyed these infrastructures and a major bridge located immediately downstream (Figure 3a).

Case B: Lack of hazard zonation/risk perception predisposes towards future flood disaster. In July 2005, a generalized rainfall event affected the entire region. At Thiertan valley, just above Ghusani village, active debris flows were partially blocking the main channel of Thiertan River. When the water pocket was released, major fluvial geomorphic changes modified the channel at Ghusani village, where severe damages to school facilities and houses were reported. Despite the occurrence of this large event, a new school and other infrastructure have been later constructed in the now-abandoned channel, which was the one that was active before the flood event (Figure 3 b).

Case C: Lack of hazard zonation/risk perception predisposes towards future flood disaster. The 2005 flood event affected the Thiertan river downstream of Ghusani village. However, despite the large amount of field

evidence as well as eyewitness records, massive construction work for tourist facilities started in the middle of the inner gravel bars in 2006 (Figure 3 c). The marks observed on trees related to the water stage of the 2005 flood event significantly exceed the level of the new tourism infrastructures.

4.2. Improving the regional flood quartiles based on past flood extreme events

We estimated the peak discharge of eight intense flood event in Kullu district, namely six at Sainj valley (peak discharges ranged from 233 to 824 m^3/s) and one at Thiertan valley (1869 ± 482 m^3/s). The Hosking and Wallis test supports the homogeneity of the flow series, yielding a H1 value of -0.05 (H1 ≤1), allowing us to perform the regional flood frequency assessment. Outcomes from the regional flood frequency assessment shows large differences in flood quantile estimations considering (not-considering) the reconstructed extreme flood events. We observed that for 100-year flood quartiles, average differences are up to +76±81%. In a similar way, mean differences in the uncertainties were up to −41 ± 59% (Table 3). These results demonstrate that flood hazards in Kullu district are systematically underestimated, if only the available set of fairly short and incomplete systematic records are considered.

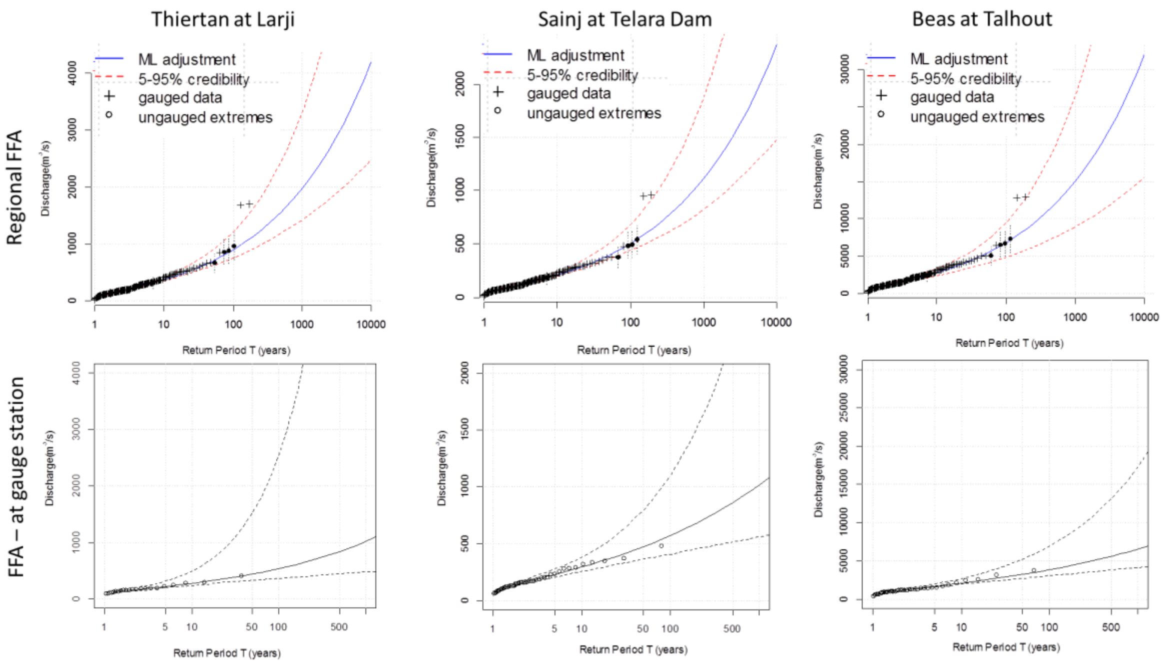

Figure 4. Graphs showing the flood-frequency estimates at each study site, including (above) and not including (below) the reconstructed flood events from tree-ring records. Important changes in the

magnitude of the floods at a given return period and in the uncertainty ranges is noteworthty (Ballesteros-Canovas et al., 2017).

4.3. Identifying flood risk hotspots at a regional scale

The flood risk assessment has been performed using more than 1700 elements (i.e. buildings) previously mapped along the main valleys of Kullu district. Overall, a large proportion of the mapped elements were categorized as having very high or high flood risk levels. Most exposed elements are located along the heavily populated floodplains of the main Beas river valley. However, proportionally, the remote valleys of Parvati, Sainj, and Tirthan face more moderate, high to very high levels of risk. The hotspot areas with high risk levels in these valleys have suffered damages in recent decades, highlighting that floods can indeedcause catastrophic impacts to these communities.

The information provided here can be used directly to prioritize adaptation plans aimed at reducing the risk levels in these communites. For instance, the database of all elements-at-risk (expanded also to include road reaches, bridges etc), including information about their geographical position, catchment area upstream, slope, channel morphology and flood hazard and exposure levels constitutes a valuable tool for desinging specific actions at a local scale, or even for implementing Early Warning Systems.

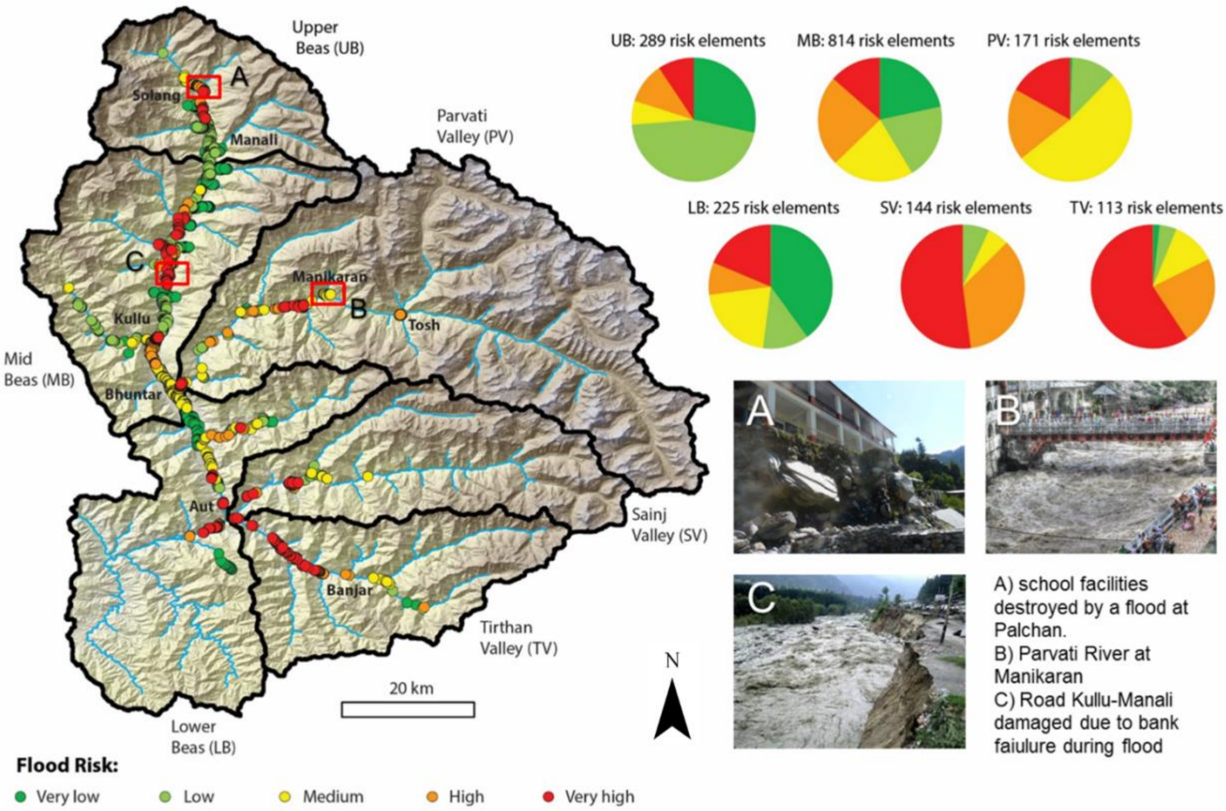

Figure 5: Integrated regional flood risk assessment for the main watershed areas of Kullu district, serving to identify main elements-at-risk and risk hotspots (adapted from Allen et al., 2018).

4. Discussion and conclusions

Extending the information on past flood events is a priority for designing and implementing DRR strategies in poorly or ungauged basins, as commonly recognized by many international initiatives, such as the Sendai, Hyogo or IPCC frameworks. Thus, robust flood hazard assessments require the definition of scenarios where the interval of recurrence of a flood with a given magnitude is established. This task is normally addressed using statistic approaches (i.e. extreme value theory), which are highly reliant on long-temporal series about the occurrence of extreme events (Benito and Thorndycraft, 2004; De Haan and Ferreira, 2007). Long-term records are also needed to understand changes in hydrological responses to environmental and climatic changes. Even if we cannot expect stationary condition in the future (Milly, et al., 2008; Salgueiro, et al., 2013), long-term records based on evidence are essential to elucidated future flood scenarios (Baker, 2008; Wilhelm, et al., 2018). This is especially true in mountain regions where (i) large uncertainties owing to the lack of baseline (i.e. climate and hydrological

data), and (ii) the difficulty of models to simulate the complex interaction between processes involved in the evolution of flood disaster, makes model-based outcomes highly tricky. Even in the European context, where the availability of data is larger in comparison to other contexts, model-based future predictions have shown great discrepancies (Kundzewicz et al., 2017). Bridging the gaps between scientific models, reality and the required information is crucial, especially in such complex topographic regions like the Himalayas (Johnson et al., 2018; Sudmeier-Rieux et al., 2012).

Here we have presented a case where both existing flow measurements and tree-ring based flood reconstructions have been used. Specifically in mountain terrain, botanical evidence is especially suitable because of the widespread presence of trees forming annual growth rings in temperate ecotones (St. George and Nielsen, 2003; Ballesteros-Cánovas, et al., 2015) and the high temporal (up to monthly) resolution (see Wilhem, et al., 2018). Based on this approach, we have shown that the extension of flood information, even restricted to the last century, has a strong impact on the hazard and risk assessment. Our results show that floods in Kullu district have a recurrent pattern, operating at both local- and regional-scales, and defining an average occurrence of 1.1 event /year over the last century. The role of highly localized floods has been also underlined, which has implications for DRR since these types of events usually have large impacts (Borga et al., 2014; Gochis et al., 2015). Specifically, we were able to identify the occurrence of 33 ungauged floods since 1910. The historical and flow gauge record from the valleys (at least for the recent events) supports the reliability of the tree-ring based flood records. Thus, historical records from the EM-DAT (www.emdat.be) and DFO (www.dartmouth.edu) disaster databases, as well as derived works (Parthasarathy, et al., 1987) match with our flood reconstruction. Nevertheless, the tree-ring base flood reconstruction also points to the occurrence of 20 additional floods, not previously documented in Kullu. This suggests that these typical historical datasets tend to underrepresent flood occurrence in these mountain regions.

Besides, the inclusion of peak discharge reconstructions into the rational regional flood frequency analyses significantly changed the estimated flood quartiles, in term of magnitude and corresponding uncertainties. Therefore, the flood hazard can be underestimated if only the short-term systematic records existing in the region are considered. Similar results have been documented in other rivers using diverse records of past floods (Gaál, et al., 2010; Gaume, et al., 2010; Stedinger, 2001; Benito, et al., 2003; Kjeldsen, et al., 2014; Raška and Brázdil, 2015 ;

Ballesteros-Cánovas, et al., 2013; Ballesteros-Cánovas, et al., 2015, 2018). These findings have major implications for defining DRR strategies. Hence, with human activities mostly concentrated within the floodplains in these regions, we showed that the lack of regulating development or imposed zoning has contributed to increase the exposure of population and infrastructures, acting as a preconditioning factor for the occurrence of disasters.

The improved regional flood frequency here provided constitute a unique tool to make a transformative effect on risk reduction since can be used to estimate the flood return period at any point of the rivers. This is shown in the illustrated practical example, where this information is the basis to perform a flood risk assessment in a data-scarce mountain region, following the IPCC climate risk framework (Allen et al., 2018). To our knowledge, this study is one of the first to operationalize latest academic concepts of IPCC to generate meaningful results that can feed into on-ground adaptation action to reduce flood risk. Thus, according to the methodology described herein, we identified more than 1700 built elements at risk in the different valleys of Kullu district. More than 70% of all buildings were categorized to be at very high or high levels of flood risk. Therefore, the database of elements-at-risk includes key indicators about the catchment and river section, as well as information related to the flood quartiles and exposure levels. This information can be, therefore, used directly to prioritize adaptation plans and future hazard zonation by the regional and local administration.

Thus, despite the temporal limitation of the method here used, mostly related to the age of trees growing on the floodplains (usually spanning no more than a few centuries), we conclude that information from recent-past extreme flood events can contribute towards better process understanding on flood hazard assessment. Thus, an assessment of past (recent) flood events should be a pre-requisite step in an integrative approach to limit the impact of future disasters, especially in highly populated mountain valleys (i.e. Bodoque et a., 2016). As a cornerstone of DRR, more emphasis should be given to collecting, managing and properly using information on past (recent) flood disasters, especially in poorly gauged regions.

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