Flash flood events reconstruction in Kullu district (Himachal Pradesh): local-to-regional implication in flood hazard assessment

EXECUTIVE SUMMARY

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Study highlights:

- This study combines multidisciplinary approaches to provide a baseline data on unrecorded extreme monsoon flash flood event in Kullu district (Himachal Pradesh) for flood risk assessment. By mean of the analysis of three selected cases, we highlight the problematic derived from the lack of implementation of the flood disaster risk management strategies (DRM) and its linkages with the lack of data/knowledge about flood processes.

- Our findings demonstrate that flash flood have took place frequently in the past in all studied valleys, and consequently, it is plausible future intense events took place in the next decades. Since 1910, we have dated at total of 34 ungauged events using tree-rings. Including the analyses of the flow series, at least 68 flood incidents can be recognized at Kullu district, pointing out an average frequency by almost 0.6 events/yrs at long term (since 1910). At short-term (1970-to-present), this frequency increase up to 1.3 events/yrs.

- At Kullu district, we can recognize both flash flood patterns: regional scale and catchment-specific scale. At least 5 past flash floods had a very large (more than 4 catchment) imprint, suggesting the extraordinary of those events and evidencing different climate triggers from those exclusively related with a catchment.

- Our analyses highlight five different flood activity phases: i) high flood activity between 1977-1981; 1988-1995, and 2003-2014; and ii) low flood activity between 1981-1987, and 1996-2001, probably reflecting the impact of large-scale multiannual weather conditions.
- The analyses of the specific discharge based on the here reported and available flow dataset, suggest largest flood hazards indexes in the upper Beas River (up to Manali), and highlight the importance of the Beas reach up to Bhuntar and Thalout (percentile > 75%), as well as Beas at Pandoh, Sainj at Larji and Thiertan at Larji (percentile between 50-75%).

- The inclusion of ungagged extreme flood event into the regional flood frequency has evidence that using systematic data, the flood hazard is systematically underestimated. Therefore, tree-ring dataset has allowed: 1) modify significantly the flood-quartile; 2) reduce significantly the uncertainties in the flood quartile estimation.

- By analyzing and reconstructing three selected studies cases where flood disaster occurred in the recent past, we highlight the impact of lack of data in the role that main actors (i.e. engineering, local authorities and locals) plays in the implementation of flood disaster risk management. These analyses show that more efficiency and reliable DRM implementation at different levels are critically needed and it is conditioned by lack of data to characterize the flood process. The human-attribute of recent flood disasters has been as well detected as an important factor. Building population resilience against future extreme events will be enhanced with improved flood understanding and its rigorous implementation in disaster risk reduction (DRR) strategies.

1. Introduction

The Indian Himalaya (IH) region is subjected to intense and frequent natural hydrometeorological processes such as flash flood, snow avalanches or landslide among others. Extreme hydrometeorological hazards are characterized by the influence of the large lift of humid monsoon air mass along the Himalaya relief, and intense orographic rainfall (i.e. cloudburst), often combined with snowmelt (Saczuk, 2001; Gardner 2002; Gardner and Saczuk 2004). Both, the physiographic and climatic characteristics, together with an increase in human activities, make IH highly susceptible to hydrometeorological hazards and intense erosion processes (SAARC 2008). Specifically, flash floods are considered the major threat in Himachal Pradesh (northern India). In this region, frequently, inhabited valleys are affected by persistent monsoon rainfall, short-lived precipitation during cloudburst disturbing the status quo of the communities, stressed the future welfare and condition their economic development, especially on highly vulnerable people with limited economical resources.

Adaptation policies on climate-related hazards refer to a set of global-to-local strategies aimed to reduce the vulnerability of socio-economic systems under a certain risk under climate change. In view that climate-related extreme events may increase in the next decades as response to global climate change (IPCC, 2012), adaptation policies (AP) and programs needs to be implemented to improve the resilience of population against these natural hazards. This issue is being especially relevant in countries with economic in transition, where populated areas at risk are continuously growing. However, the implementation of these AP is still an issue in such as countries, and especially problematic in remote mountain areas. Several issues may contribute to a partial implementation of policies. For instance, global-to-local responsibilities of disaster management (DM) are not well defined, especially at local scale (IFRC, 2012). This fact clearly contributes to failure in the AP implementation. The insufficient coordinator and lack of efficient communication among key actors evolved in DM are therefore an important issue that affect the success of DM implementation. On the other hand, the risk perception from local communities plays as well an important role in their preparedness and adaptation policies. The lack of knowledge or perception from local communities can cause critical situations, mostly related with the occupation of unsafe floodplain areas.

Consequently, there is a clear needed to improve our knowledge about past disaster, especially in areas such as Kullu district, characterized by a scarcity of long-term data. Due to the localized-character of flood processes in mountain areas, it has been demonstrated that historical records or available flow gauge station alone may present significant biases/or be insufficient for the discharge estimation of rare events (Borga et al., 2014; Ballesteros-Cánovas et la., 2015). Therefore, the hypothesis that the incorporation of lesson from past flood event should improve the efficiency in the anticipation of future disaster has been successfully tested in many mountain areas worldwide. In this scientific report, we combine innovative paleohydrologic, stochastic and climate analysis techniques to contribute with the characterization of extreme flash flood events at Kullu district to be used as baseline data for flood risk assessment. We apply tree-rings techniques to reconstruct the frequency and magnitude (i.e. peak discharge reconstruction) of past flash flood events in the main four catchment of Kullu district, i.e. Beas River, Parvati River, Sainj River and Thiertan River. By combining our peak discharge reconstruction as non-systematic data with existing flow discharge data, we provide more robust flood frequency analysis at-site useful for engineer and disaster manager. Based on this baseline dataset, we highlight the impact of gathering data on risk management involving several actors (i.e. engineering, local authorities and locals) in the Disaster Risk management Scheme. Within the framework component for disaster risk assessment in Kullu, the present study is addressing three main components related with: i) the analyses of hazards (by identifying the frequency and magnitude of events), and ii) the analyses of exposure (by identifying how the elements and infrastructure interact with events).

2. Study area

The study areas are located at the upper Beas, upper Parvati, Upper Sainj and Upper Thierthan catchments. A total of 6 reaches of 4 different rivers located in Kullu district have been analyzed. The Table 1 shows the exact location of the studied areas as well as the specific goal at each study site.

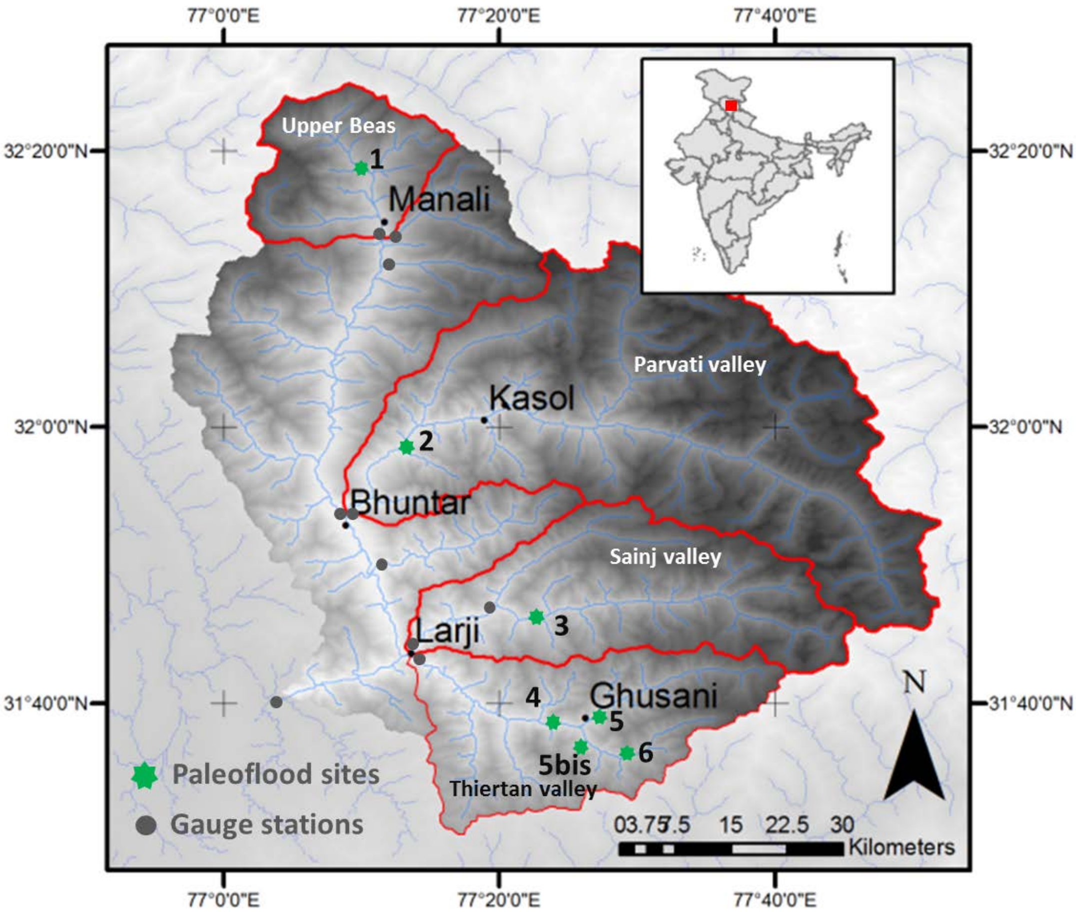

Figure 1. Location of available gauge station and studied reach river at the main catchment of Kullu district

Table 1. Locations and geo-coordinates of the study sites.

N°	Catchment	Site	Coordinate	Specific aims
1	Beas	Palchan	Lat: 32.30° Long: 77.17°	Flood magnitude Risk assessment
2	Parvati	Shat	Lat: 31.97° Long: 77.21°	Flood chronology
3	Sainj	Ropa	Lat: 31.76° Long: 77.35°	Flood chronology Flood magnitude
4	Thiertan	Nagini	Lat: 31.64° Long: 77.39°	Flood chronology Flood magnitude Risk assessment
5 and 5bis	Thiertan	Gushaini	Lat: 31.63° Long: 77.43°	Flood chronology Risk assessment
6	Thiertan	Bathad	Lat: 31.60° Long: 77.48°	Flood chronology

3. Baseline datasets

- Database on flash flood events based on increment cores samples taken from disturbed tree by past flood events.
- Topographic data based on field survey. Topographic data for basin analysis are based on the ASTER GDEM at 30 m resolution. Aerial picture of the study site has been obtained from Google Earth.
- Historical floods events and flow gauge records from Allain Nallah at Zabr; Allain Nallah nearAlau; Allew Nallah; Baragarn Nallah; Baragarn Nallah; Dat of Sainj River at Larji; Duagen Nalla near Jagatsukh; Duhangan Nallah at Chikka; Hurla at Shilargarh; Hurla Nallah near Garsa; River Sainj at Larji; River Sainj at Talara Dam Site; Sainj at Larji; Sainj River at Talara Dam site at Bihali; Sainj to Larji; Sarwari Nallah at Bharai; Thiertan River at Larji; Turthan at Larji (among others). Discharges of tributaries River Beas as collected from HPPCL Sunder Nagar 5th (july 2013).
- Data contained in the report of 2014 " Mathematical model studies for flood protection works from Palchan to Larji on river Beas, Himachal Pradesh" Executive Engineer report, Kullu No: 728.

4. Methodology

4.1 Dating extreme flash flood events in ungauged catchments

Due to the lack of available systematic data, in this study flash flood events have been reconstructed based on tree-ring analysis of affected trees growing on the floodplain. Classic paleohydrology analysis based on tree-rings have been tested and applied at the study site (Ballesteros-Cánovas et al., 2015). At the field, increment core samples from disturbed trees were obtained by using increment bores. Additional information such as typology of disturbance, geographical location and graphical information were recorded. At each disturbed trees, we also obtained river cross-section topography and recorded the maximum height of the scars (i.e. paleostage indicator, PSI). The dating flash flood methodology involves the following steps (e.g. Stoffel and Corona, 2014): i) sampling preparation, ii) cross-dating procedures by using point years; iii) growth anomalies identification; and iv) definition of events based on weighted index (Koeling-Mayer et al., 2011). The disturbed trees used as flash flood proxy was mostly trees showing scars on stems created by the impact of transported debris during flood events. This disturbance has been widely used for flood reconstruction and is considered the most trustable signal, providing the exact moment of the event (i.e. even at seasonality level) and the minimum water level reached during the specific event in this specific cross-section.

Additionally, geomorphology field survey, remote sensing and post event analysis procedures, including interview to locals and local authorities (Borga et al., 2008) have been performed in three selected sites where extreme events produced /can produce flood disaster. Different information such as detailed explanation, pictures, videos have been recollected. Based on pre- post- aerial picture imagery, we also interpret changes in the bankfull, channels and site-at risk.

4.2 Peak discharge reconstruction and flood-frequency analysis

Paleoflood discharge estimations require the resolution of a hydraulic equation with two degrees of freedom. In this regard, the height and location of a scar on a tree stem can be assumed to represent a paleostage indicator (PSI) of a past flood event, and consequently can be used for paleoflood discharge estimations (Ballesteros-Cánovas et al., 2015). In our analysis, due to the lack of accurate topographic data and the complexity to perform field surveys in the studied rivers, we have used one-dimensional model based on Manning equation to transform the height of the scar into average peak discharge at site (Chow 1964, Barnes 1967). In this equation, the Manning roughness coefficient defines the flow resistance of a unit of bed surface. The slope of the main channel and the hydraulic radius (as a function of the wetted perimeter and cross sectional area) need to be included. The assignment of specific roughness values has been based on the procedure described by Chow, (1964).

The regional flood frequency analyses have been based regionalize flow-index and Bayesian Markov Monte Carlo Chain algorithms (Gaume et al., 2010). To this end, we have used the R package nsRFA (Vignole et al., 2015). This procedure is based on: i) the distribution of a flow discharge from different catchment in a homogenous region is similar, and, ii) the likelihood of the available data set merging with non-systematic data for quantile estimation, taken into account the existing and quantified uncertainties. The robustness of this method has been tested previously in other mountain regions (Gaume et al., 2010). A depth theoretical and practical description of the followed procedure can be found in Gaál et al., (2010). At the studied cases, peak discharge reconstructed have been included has a certain range, provided by the obtained results from change ±25% the Manning coefficient. The Generalized Extreme Value distribution (GEV) has been here used to derive the quantiles. In order to analyses the homogeneity of the existing systematic flow series, a homogeneity test based on the Hosking and Wallis (1997) algorithm have been also performed. This test compares the variation between-site in samples L_{cv} (coefficient of L-variation) for the analyzed sites. Our analysis has been, therefore, focused to compare the impact on quantiles and uncertainties at-each studied catchment after including extreme ungauged events in the systematic series. Finally, we have used all flow discharge data to perform an intra-catchment comparison. To this end, we have used the average specific discharge, defined as the average flow of the period under consideration divided by the area of the basin of contribution.

5. Results

5.1 Available flow discharge at Kullu district

- We have analysed 10 flow discharge series at the study site, covering the period 1964 to 1998 (Figure 3-A). The contributing catchment areas ranked between 22 and 3836 km^2. After, inclusion the reconstructed peak discharges, the specific flow discharges (Q_s) ($m^3/s\ km^2$), ranked between 0.1 and 8.2 $m^3/s\ km^2$.

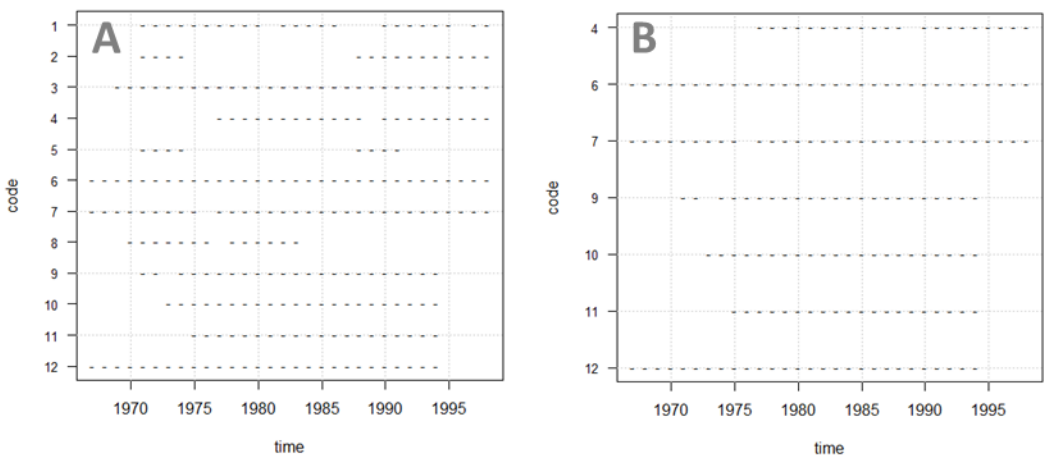

Figure 3: A) Available flow discharge at Kullu district for this report. Code: Zone 1) Allain Nallah at Zabra, 2) Duhangan Nallah at Chikka; 3) Hurla Nallah at Shilargarh; 4) Sainj River at Talara Dam; 5) Duagen Nalla near Jagatsukh; 6) Sainj to Larji; 7) Thiertan River at Larji; 8) Baragarn Nallah; 9) Beas at Bhuntar, 10) Beas at Manali; 11)Beas at Pandoh; 12) Beas at Thalout. B) Selected flow series for regionalization.

- The homogeneity test on the ten longest flow series form Kullu district. We obtained a H1 = 1.8 (Observed S.D. of group L-CV), a H2=1.4 (Observed Ave. of L-CV / L-SKEW distance); and a H3= 0.8 (Observed Ave. of L-SKEW/L-KURT distance). These results suggest that the dataset from the entire region may be considered as potential heterogeneous ($1<H1<2$). After removing shorter flow series (see Figure 3-B), we obtained a H1 =1.1, which indicate that dataset can be assumed as homogeneous. We therefore, performed the regional-flood frequency, although we exclusively considered those flow available series.

- Figure 4 shows obtained values for each site, including reconstructed peak discharge. Q_s higher than 75% percentile were observed in Beas River, specifically at Manali, Bhuntar and Thalout, being Manali the higherst one with an average Q_s by almost 8.2 m^3/sKm^2. Q_s higher than 50% percentile and lower than 75% percentile were found in Beas at Pandoh, Sainj at Larji and Thiertan at Larji. By contrast, lower Q_s than 50%percentil were observed in remain series, being the lowest Q_s at Hurla at Shilargarh ~0.2 m^3/sKm^2

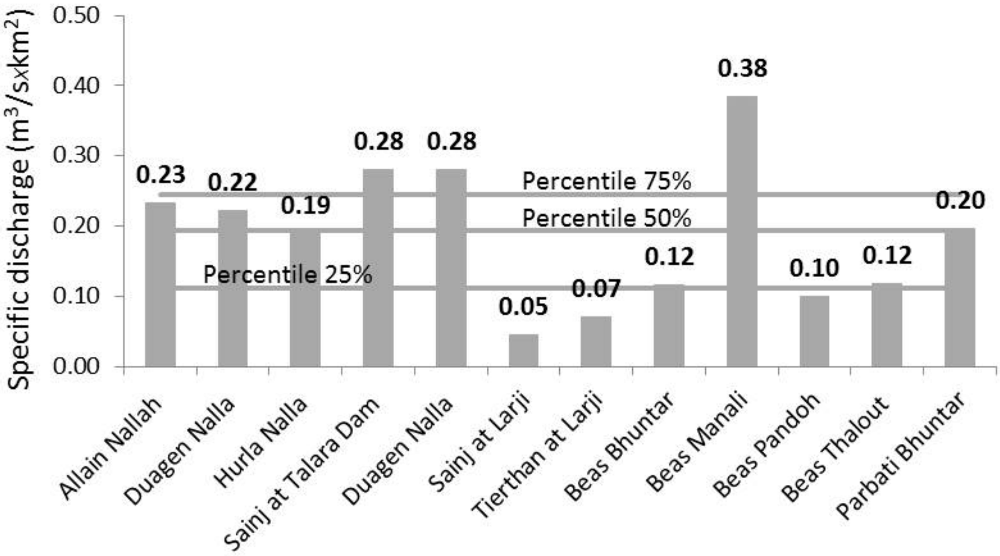

Figure 4. Specific peak discharge obtained for the flow series analysed (Parvati River based on 5 observations).

5.2 Baseline data reconstruction on flash flood events at Kullu district

- More than 250 samples from 177 disturbed trees due to flash flood events in the 6 reaches from 4 different rivers have been analysed. This dataset has allowed to identify 34 intense past flash flood events since 1910's, completing the existing flow gauge series.

Table 2. Flooded years dated by tree rings at Kullu District.

Studied site	Flooded years dated by tree-rings
Sainj (Ropa)	1977,1988, 1995, 1997, 2001, 2003, 2005, 2006, 2009, 2010, 2011
Beas (Palchan)	2005, 2006, 2010, 2011, 2012
Shat (Parvati)	1993, 2003, 2005, 2008, 2010, 2011, 2013, 2014
Theirtan	1910, 1919, 1971, 1974, 1980, 2002, 2005
Torrential stream (Thiertan valley)	2005, 2008, 2010

- The Table 2 shows the flooded years dated using tree-rings per studied catchment. The largest annual-resolved flood chronology was obtained in the upper part of the Sainj and Thiertan valley, where there is a well-preserved mature riparian forest. In these valleys, intense floods have taken place frequently; exceeding the bankfull peak discharge and provoking sever damages to the trees growing at the floodplain. By contrast, due to the short age of the existing forest, probably due to the highly dynamic fluvial system, only recent extreme events were dated in the Beas and Parvati valley.
- Including those years when flow discharge of each gauge available station was exceeding the 90th percentile, flood occurrence years in Kullu District at long term (since 1900) was by almost 0.29, with almost 68 flood incidents. For the period between 1970-to-present, the flood occurrence in Kullu Distric was 0.6, involving 62 flood incidents. For this period, we detected five differentiated flood activity phases: i) high flood activity between 1977-1981; 1988-1995, and 2003-2014; and ii) low flood activity between 1981-1987, and 1996-2001. Differences between both periods (1900- and 1980-to-present) are biases by the sampling depth and the availability of flow discharge measurement. Therefore, at long-term the reconstruction is showing a minimum flood frequency. However, at short-term the flood frequency is indicating almost an important flash flood event per year in the study region. These findings, therefore demonstrate that at all studied valleys, intense flash flood event took place in the recent past. Consequently, it is expected that intense and frequent flood events take place in the near future.

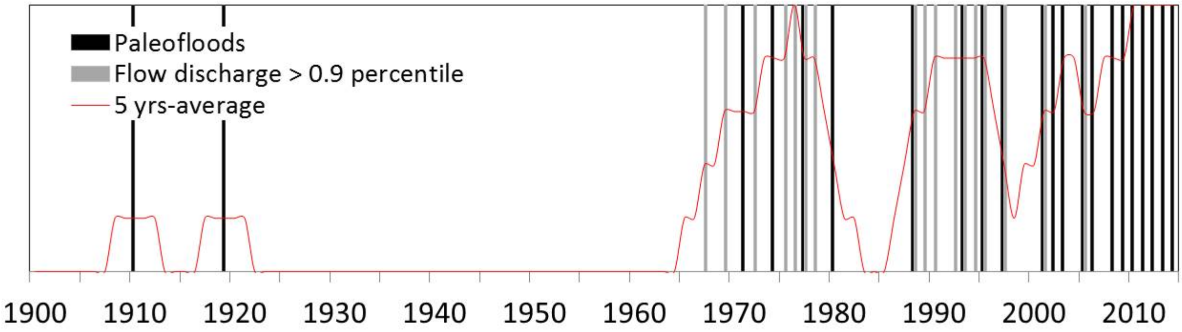

Figure 1. Flood occurrence years in Kullu District.

- The tree-rings dataset and flow discharge series suggests that past intense flash flood have taken place in Kullu following two clear spatial patterns: regional and catchment-specify scale. The Table 3 shows the years affected one, two-to-three and more than three different catchment, including the flow discharge data (flow discharge > 90th percentile of the measurement). In a 56 % cases, past flash flood took place in more than two different catchments, and in a 15 % cases, past flash flood events took place in more than 4 catchments, highlighting the large-scale regional hydrologic imprint. Nevertheless, the 44% cases of flash flood events were exclusively observed in a catchment, suggesting as well the importance of catchment-specify trigger pattern at Kullu district.

Table 3. Flooded events per catchment, including those dated by tree-rings (highlighted) and those major recorded event in the flow series analyses

N° flooded catchment	Years
1	**1910**, **1919**, **1971**, **1974**, 1976, **1980**, 1989, 1990, 1992, 1994, 2012, **2013**, **2014**
2 – 3	1967, 1969, 1972, 1975, 1978, **1995**, **1997**, **2001**, 2002, **2003**, **2006**, 2008, **2009**, **2011**
≥ 4 (up to 7)	**1977, 1988**, **1993**, **2005**, **2010**

5.3 Peak discharge reconstruction and flood frequency analysis

- We have reconstructed the peak discharge of ten intense flood events, previously not-recorded at-each-site. At Sainj valley, we reconstructed eight peak discharges from 1978, ranked between 233 and 900 m^3/s. At Thiertan valley, we reconstruct a major flood event took place in 2005 at two different reach rivers (2200 m^3/s); whereas in Beas river (at Palchan location), we analysed the localised flood disaster event took place in 2012, providing the following values: i) upstream hotpots flood disaster 316 ± 172 m3/s, ii) at the hotspot crossection up to 10000m^3/s; iii) at Manali 180 m^3/s.

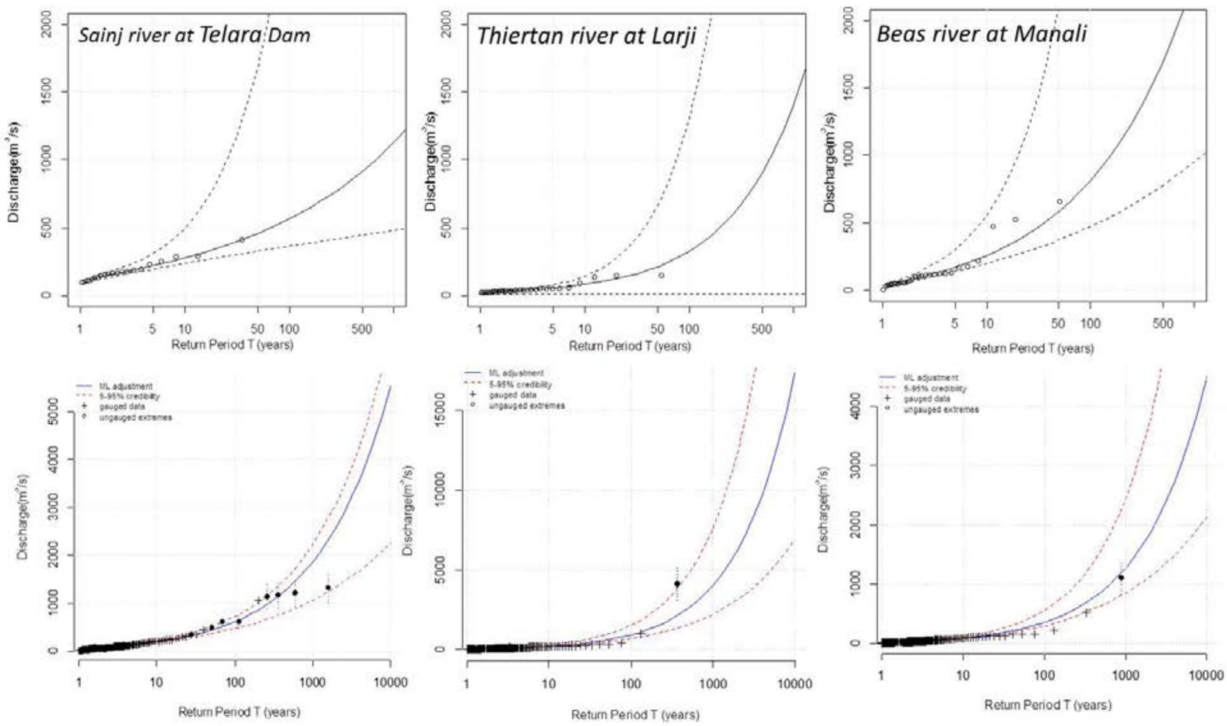

Figure 2. Flood-frequency distribution at each study site, including and not-including the extreme flood reconstructed events.

- After the incorporation of extreme reconstructed flood event, at Telera dam, in the Sainj valley, the expected flood event at 100 yrs. is 628 m^3/s (max-min: 714, 476 m^3/s), whereas taken into account only systematic data, the expected flood of T= 100 yrs. was 586 m^3/s (max-min: 2672, 379 m^3/s). Our methodology suggests that using exclusively systematic data, the flood hazard is underestimated at Sainj valley by almost 10%. Moreover, our methodology is capable to reduce the uncertainties by almost 90% for for T=100.

- For the Thiertan valley, at Larji, the expected flood event at T=100 is 914 m^3/s (max-min: 1485, 571 m^3/s), whereas taken into account only systematic data, the expected flood for T=100 was 331 m^3/s (max-min: 34, 1365 m^3/s). On average, the comparison of quantiles suggests that flood hazards may be underestimated if only systematic data is considered, by almost 176%. Moreover, the methodology is capable to reduce the uncertainties by almost 32% for T=100.

- In the case of Beas river, at Manali, the expected flood event at T=10 0 yrs. is 468 m^3/s (max-min: 1602, 255 m^3/s), whereas taken into account only systematic data, the expected flood at T=100 was 250 m^3/s (max-min: 1063, 133 m^3/s). On average, the comparison of quantiles suggests that flood hazards have increased by almost 240% after the extreme event took place in 2012. Moreover, the methodology is capable to reduce the uncertainties by almost 63% for T=100.

5.4 Flood risk study cases: using past flash flood event to report DRM strategies

- Post-event analyses based on geomorphological recognition in the field and on periodical aerial pictures, tree-ring analysis, and interviews with local inhabitants. Analyses allow to highlight three remarkable flood disaster in Kullu district. These three examples represent paradigms of short-comings on the flood disaster risk management strategies (DRM), since involve three common actors e.g. civil engineering (responsible to design and construct infrastructures in river domains), public sector (responsible to plan and allocate economic resources); and private sectors and end-users (main players of the fluvial domain). These three paradigms are closely related with the lack of knowledge of past flood events.

- ***First study case: human intervention in the fluvial domain can cause man-made flood disaster.*** The first post event recognition is located in the Beas river, at Palchan village. In this area, we identify that human modification of the fluvial geomorphological domain can provoke severe modification of flow directions and initiate a chain of processes resulting in considerable damage. In July 2012 a flood disaster downstream at Palchan villages, caused the complete destroy on the primary school, the road, bridges and sever damages to the hydropower plant. In this area, the construction of the new bridge for the road connecting Palchan and Solang caused sever modification of the river channel. The pillars of the bridge over the main channel apparently caused significant cross section area reduction and flow deflection. Our analyses suggest that these two factors contributed considerably to the flood disaster, stressing the importance of incorporating into the engineering activities, a deeper knowledge about the fluvial geomorphology. Therefore, tree scar-based reconstructed peak discharge upstream the bridge under construction was much lower (316 ± 172 m^3/s), than the reconstructed peak discharge (10367 ± 2456 m^3/s) at the school and hydropower section located < 1km downstream. The detailed analysis based on pre- post- aerial picture, picture and videos during the events revealed that columns of the bridge located in the middle of the channel causing the concentration of flow during the event to the opposite bank. This effect likely caused the failure of the bank, destroying a road and allowing the incorporation of large amount of sediment into the channel, which caused an avulsion and important changes in the channel direction. As results, the flow with a large amount of sediment was re-directed to the school located downstream on the left bankfull. The score erosion and channel incision provoked several damages to the school structure and wash away important facilities. At this section, the amplification of the peak discharge was > 300% in < 1km of river length. Downstream, the event caused severs damages in a hydropower and washed away a major bridge that was posteriorly reconstructed, however at Manali station, the flow was categorized as a normal flood with a flow discharge by almost

180m^3/s, supporting the idea of localised intense flood amplification due to external drivers (i.e. infrastructures on the river channel). The capacity of the new bridge was estimated in 4747±1124m^3/s, a 50 % less that the magnitude of the flood causing the disaster. This findings support the idea that more reliable infrastructures (and consequently investments) should incorporate information from past events coming from systematic or non-systematic source of data.

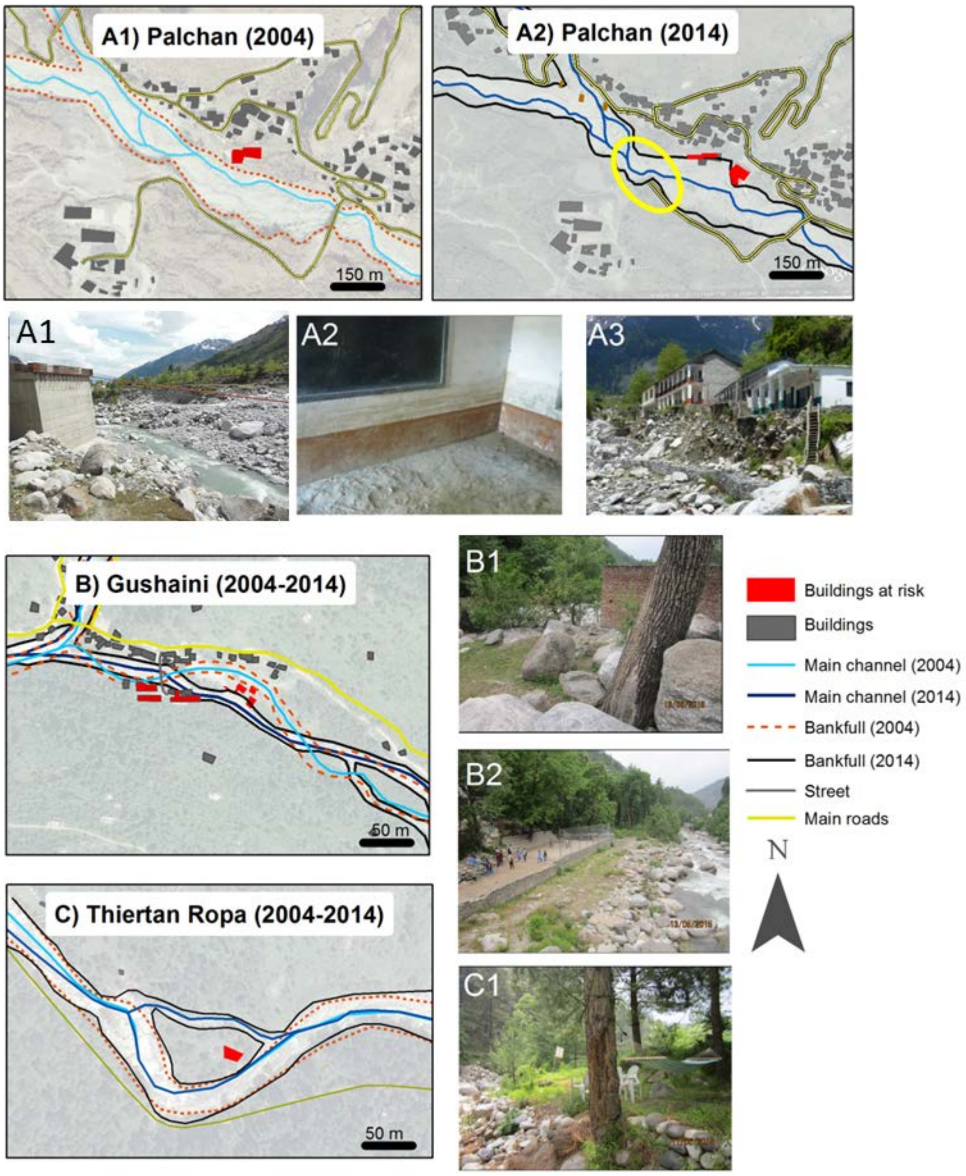

Figure 3. A) sketch of the Beas river reach at Palchan pre-event (A1) and post event (A2), picture A1: the column of the bridge under construction potentially change the flow direction to the opposite bankfull; A2: High water marks into the school used to reconstruct the flow level during the event; A3: Bank erosion and sever damages to the school facilities.

B) sketch of the Thiertan river at Gushaini showing intense changes in the channel morphology immediately upstream the village; B1:affetecd trees (i.e. scars on the stems) placed on the destroyed school facilities; B2) view of the new school facilities placed close to the river in the opposite side downstream. C) Changes in the channel morphology at Thiertan valley, and C1: example of lack of risk perception by locals, the scarred trees evidence flood hazard at tourist facilities instalations.

- ***Second study case: the impact of land manager on flood disaster in Kullu district***

The second post event recognition is located in the Thiertan valley, at Ghusani village. In this area, we identify that the primary school was placed in an inappropriate location. To this section, the Thiertan river is defined by a wide gravel bar channel. The mains characteristics of these geomorphological features are their high mobility and ephemeral channels morphology, capable to be modified during flood events. In this river, tree-ring analyses and geomorphic recognition has allowed to track the effect of the intense flood event took place in 2005, which has a important geomorphic imprint and caused severe damages in transport infrastructure and buildings, including the primary school. Results indicate that during the intense flood event, river channel experimented important changes. Those changes were caused by ephemeral landslide lake outburst (LLOF) upstream with an estimated area of, caused by the co-occurrence of an extraordinary peak discharge with large amount of sediments of a join tributary (catchment of 11 km^2), quantified based on scar-based peak reconstruction by almost 2153 m^3/s. This result underlines the capacity of small torrential catchment to produce intense debris flood and interact with main channels downstream. Therefore, this event caused a river blocking and create a small lake that suddenly outburst. The resulting event mobilized a large amount of sediment causing an avulsion in the main channel downstream and the creation of a secondary channel. As result, the flow and transported sediments (boulders up to 2 m diameter) was redirected to the school, washing away the existing infrastructures. Nowadays, the lesson from this recent disaster has not been incorporated to the DRM strategies, since the new school facilities have been placed close downstream on the past-channel configuration.

- ***Third study case: risk perception of inhabitants may result in future disaster***

The third post event recognition is located in the Thiertan valley as well, at 10 km downstream Ghusani village. At this site, we detected the construction of tourist facilities (private sector) in the middle of an internal gravel bar. Our scar-based peak discharge reconstruction suggests that this area was intensely flooded during the event took place in 2005. Therefore, our analysis suggests that the peak discharge at this cross section was 2694±638 m^3/s, significantly higher than the bankfull discharge. However, despite the clear signal on the field of the recent event, private initiative started to build a hotel in 2006 at bankfull level. Based on our analyses, the failure on the poor implementation of the DMS is here attributable to both: i) lack in the planning management procedures, and ii) risk perception and the acceptance of high risks from locals.

6. Discussion of results

This executive report provides a baseline data on flash flood disaster in Kullu district. Our analysis based on tree-rings and paleohydrologic techniques has allowed to track unrecorded flash flood events in four main catchment of Kullu district. This study has addressed different components of the disaster risk analyses: i) hydro-meteorological events (potential impacts and hazards), ii) exposure, and iii) vulnerability. Here, we were focused in the analyses of the frequency and magnitude of past flood events, and its impact in different systems.

Our flash flood chronology is reporting a minimum frequency of flood processes. The lower frequency at long-term was clearly biases by the sampling depth of analysed trees. Therefore, the change in the frequency at long and short-term can not be attributable here to CC impact. We have dated at total of 34 intense flash flood events. Our reconstruction matches well with the existing historical records in the nearby areas (Rhandawa et al., this volume). For instance, recorded floods took place in 1988, 1993, 1995, 2001, 2003, 2005 and 2009 (see Table 2 in Randhawa et al., this volume) were successfully reconstructed using tree-rings, as well as major flow measurement from the available gauge stations. Nevertheless, our chronology has allowed to extend back the exiting systematic data and has highlighted shortcoming in the DRM strategies. Moreover, our reconstruction represents the first attempt to provide long- annual-resolved flood analyses at-each catchment, rather than heterogeneous and unconnected historical archives. This match is therefore supporting the hypothesis about the utility of tree-ring to report flood history in Himalayas Mountains. The length of our reconstruction was therefore hampered by the average young ages of trees we observed, and therefore represented the main limitation of this study for long-term (i.e. multi century) analyses.

Scar-based peak discharge reconstruction allowed to estimate unrecorded extreme flash flood events and reports order of magnitude about the expected flow magnitude in the future. Our reconstruction has inherently uncertainties, mostly, due to difficulties on cross-sectional surveys since the hydraulic power of the streams, which allow to perform detailed bathymetries. The Bayesian regional approach here used allowed to include, however, the quantified uncertainties during the peak discharge estimation procedure. Therefore, the inclusion of those unrecorded event into the systematic records left an important impact in the Flood-Frequency analyses, mostly by changing the quantiles and reducing significantly the uncertainties in the estimations. Similar observation have been also obtained in European context (Gaume et al., 2010; Gàal et al., 2010; Vignole et al., 2015; Ruiz-Villanueva et al., 2013). This represent a major advance by increasing the reliability of flood-design with engineering and land manager proposes. However, the available flow discharge data was limited, and not updated to present. The regional analyses here showed represent therefore preliminary analyses, since further analyses with updated flow series should be considered. Nevertheless, the hypothesis about the add value of paleohydrology in flood-frequency estimation has been probed, since data from ungauged catchment allowed to: i) modify the mean quantiles and, ii) reduce the uncertainties.

Our approach represents an excellent opportunity to complement the scarce flow data in other mountain areas on the Himalayas and estimate flood risk at catchment level. For instance, as it has been demonstrated in Ballesteros-Cánovas et al., (2012), the inclusion of the ration between the bankfull peak discharge and the 50-yrs flood return period at each location can provide a quantitative index to compare different locations of different catchment. Moreover, these index can be complemented with the intra-catchment comparison here reported about specific flow discharge can also be used to understand differences in flood hazards between catchment. We hypothesize that, rather than geomorphic indexes, highly inaccurate in complex mountain terrains, the procedure here reported based on the inclusion of ungagged flood extreme into regional-flood analyses, together exposure, vulnerability indexes and information from specific peak discharge may report more robust results.

On the other hand, our analyses have allowed to report three disaster that represent paradigms in potential strategies for flood disaster reduction. In India, the main strategy to deal with disaster has been reactive since until mid-last decade. The change in the paradigm on Disaster Management did not take place until the end of 2005, when the Government of India enacted the Disaster Management Act, 2005, which was followed by the recent National Disaster Management Policy, 2009 (UNDP, 2012). Both national laws suppose the basis for the present disaster risk reduction (DRR) strategy at national scale and consider holistic and integrated approach as key issues. The main goal of this DRR is to reduce the triggers factor of disaster. In this regards, the baseline data here reported about past disaster is essential. By mean combination of multidisciplinary research, we have highlighted potential short-cummings in the DRR strategies implementation. Our analysis suggests that the implementation of past disaster lesson in the managing at three different levels, technical, public sector and private initiatives. We conclude that since these three study cases are not unique, and there are many other sites presenting same state of affairs, future flood disaster are expected in Kullu district. Given that negative impact due to changes in monsoon pattern and intensity of precipitation are likely increasing, we argue that flood risk reduction passes to perform on-field analysis, rather than large-scale-space-analysis, and incorporate the fluvial geomorphology imprint of large past/recent flood events into local-planning.

7. Work in progress

The Swiss-Indo join collaboration partner will analyse the climate triggers of the extreme event took place in 2005, as regional event, as well as climate footprint of cloudburst events. The Swiss-Indo partnership will continue implementing Flood risk assessments at regional scale, by using a peak discharge ration at each populated site.

8. Perspectives for upscaling

- The outcome of the study will help in addressing various issues related to flood risks, hazards and climate change, as incorporate both temporal and spatial dimension.
- Methodology is robust, and it has been previously applied in several mountain ranges worldwide. This methodology can be easily implemented in other ungauged areas.
- The Flood frequency analysis here reported, can be used to deliver peak discharge ratios related with the expected flood for T=100 and T=10 at each populated site. Together other local information, this data can be useful to deliver more reliable risk assessments at regional scale.

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