Title
Flood reconstruction in Kullu valley, Himachal Pradesh (India): Implications for Disaster Risk Reduction strategies

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Biography of Presenting Author
Juan A. Ballesteros-Cánovas works on fundamental and applied research projects in the field of natural hazards. His background is in forest engineering and he is currently working as a PostDoc researcher at the Institute for Environmental Sciences (University of Geneva). His PhD aimed at integrating paleohydrological techniques in rational flood risk assessments. He has been involved in several European and national projects and has been working in Colombia, Ecuador, Poland and Spain before having joined a project on Climate Change Adaptation in India.

Abstract:

The Western Himalayan region is subjected to intense and frequent disasters, resulting from intense rainfall and its steep topography. These characteristics, together with human activities concentrated in the valley, make this region highly susceptible to hydro-meteorological hazards, and frequently led to human losses. In this context, Disaster Risk Management (DRM) policies are the basis for the application of pro-active risk prevention and risk reduction strategies. However, their success will critically depend on system knowledge and hence reliable baseline data of past disasters are pre requisite. Here, we test how newly gained knowledge of past disasters can improve the assessment of hazards and risks and, thus, facilitate the definition of adaptation options, also for future disaster scenarios. To this end, we combined several approaches to compile and understand past flood events and their role in causing recent disasters in Kullu, Himachal Pradesh (India). This study demonstrates that the consideration of past extreme events, not gauged by conventional devices, can clearly modify the hazard assessment. Through a detailed analysis of three flood disasters in the region, we also highlight paradigms of short-comings of conventional, but short time-series in DRM implementation and the role and interaction of civil engineering, public and private sectors as well as end-users on the severity of floods.

Keywords: Flash flood, paleohydrology, tree-rings, Disaster Risk Management, Kullu district.

1. Introduction

Several Himalayan sites are subjected to intense and frequent hydro-geomorphic process activity (Kattelmann, 2003), especially during the monsoon season which is characterized by persistent rainfall (Rasmussen et al., 2012). In Himachal Pradesh, a north Indian State of the Western Himalayas, intense flood events usually take place when humid monsoon air is lifted along the Himalayan relief, creating intense orographic rainfall which is often combined with snowmelt (Gardner and Saczuk 2004). This process is considered the major natural threat in the region, and frequently affects inhabited valleys, disturbing the status quo of communities, and stressing future welfare and economic development (Gardner et al., 2002). Over the past few years, several disasters took place in the nearby region, such as the August 2010 heavy downpour in Ladakh followed by flash floods, killing more than 250 persons and damaging 71 villages. Further examples include the unusually intense monsoon rainfalls in and around Kedarnath (Uttarakhand) in June 2013, resulting in more than 6000 causalities, and the recent flood events in Jammu and Kashmir during September 2014 and March 2015. The causes of these flood disasters have been attributed among others to climate changes, but were certainly also exacerbated by an increase in intense economic development in the region. Given the assumption that climate warming may impact on monsoon pattern and extreme precipitation (Wang and Ding, 2006), and the fact that local resilience of Himalaya communities tends to be rather low in view of the above processes (Gardner and Dekens, 2007), the implementation of adaptation policies in this region is critically needed.
In this regards, adaptation policies on climate-related hazards refer to a set of global-to-local strategies aimed at reducing the vulnerability of socio-economic systems under a certain risk under climate change (IFRC 2012). The increases of the reliability of mitigation infrastructures, as well as the improvement on the preparedness of local communities are key issues for disaster management under climate change. However, the complexity of disaster management processes, which involve a large number of local-to-governmental actors and require a robust knowledge of the processes, makes risk reduction a scientific and technical challenge (Kappes et al., 2012).

In India, the paradigm shift in DRM from reaction to a holistic mitigation strategy based on pre-disaster preparedness has recently been embedded into a suitable development process (Disaster Management Act, 2005 and National Disaster Management Policy, 2009). These regulations are the basis for the application of pro-active prevention strategies in DRM. However, their successful application is critically conditioned by the quality and quantity of existing databases on past disasters. It has been recognized that the lack of systematic data leaves an important imprint on risk perception at all socio-economic levels, including local populations, private and public sectors; and, consequently may represent a major drawback for the successful implementation of DRR strategies, including early-warning system (EWS, Gardner and Dekens, 2007). Here, we address this topic by focusing on flood risk assessments in the Western Himalayas. Based on a multidisciplinary, paleohydrological approach, we reconstruct past flood activity in several ungauged (or poorly gauged) catchments at the regional scale, and analyze its impact on flood hazard assessment. Through a detailed analysis of three flood risk hotspots, we demonstrate how the newly gained knowledge on past flood disasters derived from indirect proxies can explain failures in the implementation of the DRM.

2. Study site

The studied Kullu Valley (population >4x10^5 and area ~5.5x10^3 km^2) is located in Himachal Pradesh and close to the Great Himalayan National Park (around ~32° N and 77°2’ E; Fig. 1). This mountain area is characterized by a north-south valley, formed by the Beas River; as well as tributary valleys formed by the Parvati, Sainj and Thirtan Rivers. The Kullu Valley is characterized by wide floodplains at the valley bottom, where population and transport corridors are concentrated; and, narrow side valleys, where inhabitants are forced to live on steeper slopes or on rare, yet exposed, flatter surfaces. The forest cover represents 35% at Kullu district; however, it has suffered from intense deforestation in recent years (Gardner, 2002). Climate is considered as sub-tropical monsoonal, with cool and snowy winters, and warm and wet monsoonal summer. Agriculture represents the major economic activity; however, in recent years, tourism (both national and international) has been increasing significantly. Natural hazards (including floods) pose a serious problem and are responsible for large economic losses and fatalities each year (Gardner, 2002).

![Figure 1. Overview of Kullu district with location of available gauge stations as well as study sites for paleoflood analysis.](image-url)
3. Methodology

a. Dating extreme flash flood events in ungauged catchments

We first relied on a geomorphic reconnaissance field survey and remote sensing analysis to identify the most suitable river reaches to carry out the flood reconstruction. Analyses included field recognition, interpretation of aerial pictures of several generations, and interviews with locals and experts working in the field. After that, we used tree-ring analysis of affected trees growing on the floodplain combined with classic paleohydrological techniques to reconstruct the regional flood activity (Ballesteros-Cánovas et al., 2015). In the field, cores from disturbed trees were obtained by extracting increment cores. Eventually, wedges from scarred trees and cross-section from injured branches and roots were also collected as well. We focused on the sampling of scarred trees that were impacted by the transport of debris during flood events (Fig. 2) and thus represent paleostage indicators (PSI) of past floods. This disturbance has been widely used for flood reconstructions and is considered the most trustable signal, providing the exact moment of the event (i.e. with seasonal precision) and the minimum water level reached during a specific event (Ballesteros-Cánovas et al., 2015). For each sampled tree, we also recorded information such as the typology of disturbance, geographic location and sketches that assist the interpretation in the laboratory. The position of trees showing PSI was recorded with a handheld GPS (metric precision). Additionally, we used a laser distance metre (centimetre precision) and flexible measurement tape to survey river cross-sections as well as the distance of trees with respect to the thalweg and scar height. The methodology used to date flash floods involves the following steps (Stoffel and Corona, 2014): (i) sample preparation, (ii) cross-dating procedures using point years, (iii) identification of growth anomalies, and (iv) definition of events based on weighted index (Kogeling-Mayer et al., 2011). Finally, at three selected sites, where extreme events have produced scarred trees caused by past floods, a detailed post-field event recognition analysis was performed, including interviews with locals and local authorities (Borga et al., 2008), so as to maximize the acquired data, such as detailed explanation, pictures and videos.

Figure 2. Two examples of trees showing scars on their stems caused by past floods at Sainj river at Ropa (left) and Beas river at Palchan (right).

b. Peak discharge reconstruction

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 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 a one-dimensional model based on Manning’s equation to transform the height of a scar into average peak discharge at a site (Chow 1964). 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). Although this approach may induce systematic uncertainties, other methods cannot be applied in this case due to the lack of accurate topographic information. Nevertheless, when it was possible, we sampled critical sections characterized by abrupt changes in channel slope or narrow channel conditions (Bodoque et al., 2015; Ballesteros-Cánovas et al., 2015).

c. Flood-frequency analysis

The regional flood frequency analysis has been based on a regionalized flow-index and Bayesian Markov Monte Carlo Chain algorithms (Gaume et al., 2010) using the R package nsRFA (Vignole et al., 2013). This procedure is based on the facts that (i) the temporal distribution of a specific flow discharge is comparable in different
catchments within a homogenous region, and that (ii) the available dataset can be merged with non-systematic data for quantile estimation, thereby taking account of existing and uncertainties quantitatively. The robustness of this method has been tested previously in other mountain regions (Gaume et al., 2010). An in-depth theoretical and practical description of the procedure followed in this contribution can be found in Gád et al. (2010). At the study sites, reconstructed peak discharge has been included with a certain range determined by ±25% of the obtained results from the Manning coefficient. A Generalized Extreme Value (GEV) distribution has been used then to derive the quantiles. In order to analyse the homogeneity of the existing systematic flow series, a homogeneity test based on the Hosking and Wallis (1997) algorithm has been performed. Our analysis, therefore, focused on a comparison of the impact on quantiles and uncertainties at each study catchment after including extreme ungauged events in the systematic series. Finally, we have used all available 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.

4. Results

A total of 177 trees (more than 250 increment core samples) disturbed by past flood events have been sampled and analyzed in the 6 reaches from 4 different river catchments. This dataset has allowed identification of 34 intense flood events since the 1910s, therefore complementing the existing flow gauge series, although the most reliable period for the reconstruction starts in 1965 (Fig. 3). Table 1 lists flood years dated with tree rings for each of the studied catchment. The largest, annually-resolved flood chronology was obtained in the upper part of the Sainj and Thiertan valleys, where well-preserved mature riparian forests still exist. In these valleys, intense floods have taken place frequently, exceeding the bankfull peak discharge and provoking severe damage to trees growing in the floodplains. By contrast, due to the small age of the existing forests, probably reflective of the highly dynamic fluvial system, only recent extreme events were dated in the Beas and Parvati valleys. By adding those years for which available flow discharge data exceeded the 90th percentile we obtain 68 flood incidents (or 0.29) since 1900 in Kullu District. For the period 1970-present, flood occurrences in Kullu District was 0.6, involving 62 flood incidents. Our observation suggests that past intense flood have taken place in Kullu following two clear spatial patterns, both at the regional and catchment-specific scales. In 56% of all cases, past floods took place in more than two different catchments, and in 15% of the cases, floods occurred in more than 4 catchments, thereby highlighting the large-scale regional hydrologic imprint of the process. Nevertheless, in 44% of all cases, floods were exclusively observed in a single catchment, suggesting the importance of catchment-specific trigger patterns at Kullu district. We have identified five phases with contrasting flood activity during the last decades: (i) high flood activity between 1977-1981; 1988-1995, and 2003-2014; and (ii) low flood activity between 1981-1987, and 1996-2001.

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<tr>
<th>Studied site</th>
<th>Flooded years dated by tree-rings</th>
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Figure 3. Flood occurrence at Kullu region based on tree-ring reconstructions and existing flow discharge measurements. The reliable period is defined here based on the number of available trees for reconstructions in a given year (i.e. sample depth). We consider that from mid 1960s, the occurrence of floods has been reasonably covered in the studied river reaches.
The peak discharge reconstruction procedure allowed estimation of flood magnitudes of ten intense flood events, which were not previously recorded at the respective sites. At Sainj valley, we reconstructed eight peak discharges since 1978 which ranged between 233 and 900 m$^3$/s. At Thiertan valley, we reconstructed a major flood event in 2005 at two different river reaches with 2200 m$^3$/s, whereas in the Beas river, we analysed a localised flood disaster at Palchan which took place in 2012. In this section, reconstructed peak discharges point to a strong contrast in flood magnitude (upstream = 316±172 m$^3$/s, Palchan cross-section = 10,000 m$^3$/s; and downstream at Manali 180 m$^3$/s) suggesting an unusually intense and localised in-channel sediment incorporation.

Figure 4 compares expected discharge values for certain return periods based on two approaches: the first approach includes only systematic data whereas the second is a combination of systematic data and reconstructed PSI. At Telara dam (Sainj valley), the incorporation of PSI leads to a ~7% increase in expected discharge from 586 to 628 m$^3$/s for a 100-year return period event (T=100). Moreover, our methodology is capable to reduce uncertainties by almost 90% for T=100 at this site. At Larji (Thiertan valley), the expected flood magnitude for T=100 rises from 331 to 914 m$^3$/s if data from PSI are incorporated. The comparison of quantiles suggests that flood hazards may be underestimated in case that only systematic data is considered and by almost 176%. Moreover, the methodology is capable to reduce uncertainties by almost 32% for return period T=100 for this river.

In the case of the Beas river at Manali, the expected flood event T=100 including PSI data is 468 m$^3$/s, whereas 250 m$^3$/s were expected by taking only systematic data into account. Moreover, the methodology is capable to reduce uncertainties by almost 63% for T=100 at this site. On average, the comparison of quantiles suggests that PSI reconstructions of the extreme event that took place in 2012 at Palchan reveals an increase in flood hazards by almost 240% compared to estimations based exclusively on systematic data; although this should be considered with caution, as the event was highly localized and limited to a specific reach (see explanation of the event below).

Figure 4. Flood-frequency distribution at each study site, not-including (above) and including (below) the reconstructed extreme flood events based on tree-rings and paleoflood techniques.

5. Potential impact on local development

The long-term flood reconstruction provided in this study is indicating an intense flood activity in the studied region. Our findings demonstrate that intense flood events took place in the recent past in all valleys. Our results also suggest that the flood hazard has been systematically underestimated at the study sites and provide new insights on flood quantiles.

In the following paragraph, we show how the major benefits of this work and how the gained information could modify risk perception of three common actors and/or levels, i.e. technical actors (responsible for the design and construction of infrastructures in river domains), the public sector (responsible to plan and allocate economic
resources); as well as the private sectors and end-users (main players inside or next to the fluvial domain), and consequently be the basis for a more realistic flood hazard- and risk management. The three real cases illustrated can be explained by the past lack of baseline data, and therefore represent paradigm cases of past short-comings in data availability and their impacts on DRM strategies in the region (Fig. 5).

The first case illustrates intense changes in reconstructed peak discharge within a short distance and highlights how human (i.e. technical) interventions in the fluvial domain can cause man-made flood disaster. The case study site is located in the Beas river, at Palchan, where a flood disaster downstream of Palchan village caused the complete destruction of the primary school (Fig. 5A), road, and bridges in July 2012 and led to severe damage of the hydropower plant. At this river reach, construction works of a new bridge connecting Palchan and Solang caused severe modifications of the river channel. The pillars of the bridge (built inside the main channel) apparently caused a significant reduction in cross-sectional area and a flow deflection. As a result, peak discharge during an ordinary flood event (reconstructed upstream the bridge at 316 ± 172 m³/s) was deviated to a formerly stable river bank causing widespread bank failures and substantial entrainment of unconsolidated material. This geomorphic change then caused an avulsion which in turn resulted in important flow path changes, with the new channel directing flows straight to the school and the hydropower plant. At this section, the reconstruction suggests that the amplification of the peak discharge was >300% in < 1km of river length (i.e. peak discharge reconstructed with high water marks and scars on trees), which caused the washing away of a major road bridge. In the current situation (spring 2015), the pillar of the bridge still exists in the main channel, whereas a new bridge has been built with an estimated capacity of 4747±1124m³/s, which is, however, still only 50% less of the reconstructed magnitude of the flood causing the disaster.

The second case illustrates how data gathered from tree rings can be used to track the geomorphic effects of intense flood events, causing severe damages to public facilities (i.e. public sector). The study site is located at Ghusani village, in Thiertan valley (Fig. 5B) where a primary school building was erected in a flood-prone area. Upstream of this site, the Thiertan River is defined by a wide gravel bar channel characterized by high channel mobility, such as changing cross-sectional areas and positions as well as the occurrence of bank failures. Tree-ring analysis at this site indicates that during the intense flood of 2005, the river channel experienced important geomorphic changes. These changes were caused by a flood triggered by the outburst of an ephemeral landslide lake (reconstructed peak discharge by almost 2,153 m³/s). The resulting event mobilized a large amount of sediment causing an avulsion in the main channel in the Thiertan valley and the creation of a secondary channel. As a result, the flow and transported sediments (boulders of up to 2 m in diameter) was redirected to the new school building, and washed away the existing infrastructure. Nowadays, the new school facilities have been placed downstream and on the opposite side of the current channel, and more precisely at a location where the channel used to pass before the 2005 event. However, our analysis underlines the possibility of small torrential tributary catchments to produce intense floods like the one in 2005 in the future, which will likely cause further dams and related outburst floods and which could then again led to channel migration within the alluvial corridor.

The third case illustrates how the lack of risk perception causes an increase of elements-at-risk in a flood-prone area of the Thiertan valley as well, roughly 10 km downstream Ghusani village. At this site, tourist facilities (i.e. hotel, private sector) have been erected in the middle of an internal gravel bar of the Thiertan valley (Fig. 5C). The large amount of flood marks on trees suggests that the area, where the hotel is now placed, has been flooded recently. Our scar-based peak discharge reconstruction suggests that the peak discharge at this cross-section was 2694±638 m³/s, and therefore significantly higher than the bankfull discharge. Despite the clear signs and existing documents about recent events in 2005 (and before), the hotel was constructed in this flood-prone area in 2006.

These three case studies underline the importance of solid baseline datasets on past disasters so as to improve the implementation of DRM strategies at the level of public and private sectors but also with respect to technical and end-user levels. As in other mountain areas, the systematic application of the methodology described herein may anticipate the causes and potential impact of future events (Stoffel et al., 2005), which in turn may have a clear impact on the resilience of inhabitants (Baker, 2008).
Knowledge on past floods in the Indian Himalayas (as in many mountain ranges worldwide) is characterized by a scarcity of data (or at best by the existence of short timeseries). Analysis of return periods of specific magnitudes is consequently difficult (if not impossible), as are realistic hazard or risk assessments. At the same time, a solid database on processes is essential for adaptation measures aimed to reduce the negative effects of natural disasters. Therefore, we strongly recommend follow up with the systematic compilation of flood records and documentation of past disaster based on (i) historical records, (ii) direct measurements, and (iii) paleoflood evidence.

Regarding future research, and despite their potential, we have noticed that paleoflood studies based on tree rings have been inexistent in the Indian Himalayas so far. As trees are ubiquitous and show discrete annual rings in many temperate and boreal areas, there is yet an enormous potential to exploit for the extraction of further information on past floods from tree-ring records (Ballesteros–Cánovas et al., 2015). The systematic application of this technique at the regional scale has a large potential to identify the full range of natural flooding variability in an area, potentially linking the floods to both climatic drivers, relevant catchment variables and anthropogenic influences (Ballesteros–Cánovas et al., 2015b). Therefore, in order to maximize the dataset, we recommend that future studies should be performed at the regional scale by combining different data sources, such as tree rings (or other indirect proxies), historical records and existing measurements. In addition, wood analyses based on both stable isotopes and chemistry may help to answer hypotheses about the quality and characteristics of water flow during past flood regimens (Masson-Delmotte et al., 2005; Ferrio et al., 2015). We have also noticed that flood-frequency results may include a bias due to the complexity involved in studying hydrogeomorphic behaviour. Whereas results seem more reliable when multiples peak discharge are included (case of Sainj River), they could be more questionable if only one peak discharge is included, specifically if the river responds to changes in system behaviour (i.e. Palchan case, Beas River) or, potentially, to a different process (i.e. hyperconcentrated flow in the case of Ghusani, Thiertan River). Since the regionalized flow-index is a function of the catchment area, the above-mentioned case does not match with the initial assumption of the method.

From a perspective, we notice that the gathered data is essential to improve the implementation of DRR strategies. Traditionally, DRM in India has been reactive, at least until the early 2000. Changes in the paradigm on Disaster Management did in fact occur at the end of 2005, when the Government of India enacted the Disaster Management Act, which was followed by the recent National Disaster Management Policy in 2009. With some exceptions, the philosophy and principles of these national laws are comparable with those existing in Europe, and suppose an existing basis for the present DRR strategy at the national scale and from a holistic and integrated perspective. However, major efforts are still critically needed in the systematic provision of fundamental baseline data. This should be done by facilitating the implementation of long-term systematic flow discharge monitoring at multiple sites, and by analyzing past, ungauged disasters. A long-term perspective will also help to integrate DRR into climate change scenarios, which in turn will lead to better adaptation policies. Once this knowledge is gathered, rigorous land-use planning should be a priority in the area so as to improve resilience in the long run (Aven, 2011). Based on the baseline data on past disasters, community awareness and preparedness programs should also be carried out so as to further strengthen the capacities of locals during response phases (Kappes et al., 2012). The value of enhancement of stakeholders and locals has been widely recognized (Andersson and Ostrom, 2008). Finally, we conclude that the reliability of the system at a longer-term perspective (i.e. in terms of infrastructures) is still pending. The difficulty to maintain highly degradable infrastructure subjected to intense and frequent shocks (events) requires a strong knowledge of potential impacts, and consequently reliable baseline datasets. Again, the gained knowledge should be fed such as analyses based on life-cycle assessment (Sanchez-Silva et al., 2011), which is especially the case in managed torrential system (Ballesteros-Cánovas et al., 2016).
Acknowledgement
This study was realized within and supported by the Indian Himalayas Climate Adaptation Program (IHCAP) of the Swiss Agency for Development and Cooperation (SDC).

7. References


