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Challenges in paleoflood hydrology applied to risk analysis in mountainous watersheds – A review

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SUMMARY

In many regions of the world flood events in mountain basins are one of the greatest risks to the local population, due to the pressure placed on land use by social and economic development. Conventional hydrologic–hydraulic methodological approaches are not usually feasible in mountainous basins because they are not gauged at all or, in the best-case scenario, are poorly gauged. In this context, palaeohydrological research offers a valuable alternative to the above approaches. However, many palaeohydrological data sources and associated methods have been proposed and initially used in large basins with extensive floodplains. As a result, when they are used in mountainous areas they must be adapted to include different techniques, since the problems to be addressed are different and less data is usually available. In this paper, we review classic data sources and different analytical methods and discuss their advantages and shortcomings with particular attention to mountain basins. For this purpose, examples are provided where improvements in the palaeohydrologic methods are proposed by incorporating uncertainties, describing sources of error or putting forward hypotheses for hydraulic calculation to make palaeoflood hydrology more objective and useful in risk assessment.

1. Introduction

Until the recent availability of high resolution global data sets, the definition of mountains and other major relief features such as plains, hills and plateaux was vague. Authors including Meybeck et al. (2001) published global mountain classification maps based on a combination of elevation and slope. In terms of the hydrological network, there is no consensus about the threshold slope for establishing that a river drains a mountainous area. Jarrett (1984, 1990) therefore defines higher-gradient streams as those with slopes greater than 0.002, in agreement with the findings by Wohl and Merritt (2008). Chiari et al. (2010) defined a mountain stream as one with a slope higher than 0.01, whereas Rickenmann and Koschni (2010) classified a reach as mountainous when the slope is higher than 0.05 and the upstream basin is less than or equal to 25 km^2.

Mountain basins often respond rapidly to intense rainfall rates because of their high slopes and quasi-circular morphology and consequently strong connectivity (Ruiz-Villanueva et al., 2010). Additional physical properties (e.g. fraction of impervious area, land uses, soil types) together with time-varying states (e.g. soil moisture) will also help to modulate the flash flood potential of heavy rainfall (Hapuarachchi et al., 2011). Precipitation also has an important orographic component in these basins. As a result, precipitation is very variable from a spatio-temporal point of view (Rotunno and Houze, 2007). The above factors determine that mountainous basins are highly prone to extreme precipitation events, in terms of both total volume and intensity. The resulting floods have a rapid hydrological response, characterized by "peaky" hydrographs (i.e. short lag time). The flow peaks are reached within a few hours, thus giving little or no advance warning to mitigate flood damage (Borga et al., 2007, 2008). As a result, floods in mountainous basins are usually defined as flash floods, as they are characterized by a rapid onset, i.e. within six hours of rainfall (Hapuarachchi et al., 2011). One of the greatest difficulties encountered when defining them is that for a given event several

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processes may take place concurrently (i.e. debris flows, hyperconcentrated flow, and clear water flow), with different rheological characteristics or a different number of phases involved (Bodoque et al., 2011).

Mountainous basins often have a high landscape value, and are used for recreational purposes. (Seger, 2009). But with the characteristic hydrological response of these basins this may result in a high social risk, as shown for instance by the 1997 Biescas disaster in Spain (Benito et al., 1998). However, the analysis and management of flood risk are clearly conditioned by data availability, especially in mountain areas. So, flow quantile estimates can be obtained directly by performing frequency analysis of maximum discharges provided that the time series are statistically significant (Yue et al., 1999). When flow data is unrepresentative, but there is enough precipitation data, the alternative is to run, calibrate and validate hydrologic models, which provide the output data to determine the flooding area and the hazard parameters (Knebl et al., 2005). Nevertheless, in mountain basins there is often insufficient data either because the data does exist or because it is not accurate in terms of spatio-temporal statistical significance. In addition, when flow data is available maximum annual values are generally not as reliable as average flow values, since conventional stream gauge stations may be destroyed in extreme floods, leading to gaps in the time series (Benito et al., 2004).

Using indirect methods to characterize floods has now become an alternative. Different palaeostage indicators (PSI) and high water marks (HWM) have been used to characterize floods, and their use constitutes the foundation of palaeoflood hydrology (Kochel and Baker, 1982; Baker, 1987, 2008; Benito et al., 2004; Benito and Thorndycraft, 2005). This approach can be used individually, when there are no additional sources of information, or may combine natural palaeoflood evidence with documentary and systematic data (Pruess et al., 1998; Benito et al., 2004). The uncertainty of flood frequency estimates, hazard assessment and risk analysis can thus be reduced. Nevertheless, the classical data sources and methods usually applied in palaeoflood hydrology have important shortcomings in mountain areas and there are very few studies available in these areas incorporating this kind of data and techniques.

Here we provide a comprehensive review of palaeoflood hydrology in mountainous basins with the following goals: (i) to offer a comprehensive review of the progress made in palaeoflood hydrology, highlighting advances in research and summarizing key findings; (ii) to evaluate the assumptions and limitations of the methodology, with particular reference to the findings made in the last thirty years; and (iii) to identify and outline what can still be done and what opportunities for innovation still exist.

2. Review of the main achievements in palaeoflood hydrology

2.1. Overview

Table 1 shows the major studies on the use of palaeoflood hydrology in hazard and risk analysis in mountain areas. Along with general details of location, some morphometric data and discharge estimates, it provides information on the methodological approach implemented, including the type of PSI used (i.e. geomorphologic, geologic and botanical evidence), and whether the main objective of the research was risk analysis, or simply hazard assessment.

Physical evidence showing the lasting effects of floods on the natural environment have been used since the first half of the twentieth century (Bretz, 1929; Bretz et al., 1956). However, the term and concepts of palaeoflood hydrology were formally introduced by Kochel and Baker (1982). This branch of science aims to reconstruct the magnitude and frequency of recent, past and ancient floods using signs and physical evidence left by floods. Basically, this evidence is of two kinds: palaeostage indicators (PSI) (Wohl, 1992; Jarrett and England, 2002; Webb and Jarrett, 2002) and high water marks (HWM) (Gaume and Borga, 2008; Lumbroso and Gaume, 2012).

PSI provide information about the minimum discharge resulting from the occurrence of a specific flood event and therefore, the results derived from their use in the characterization of hazard and risk are conservative (Benito and Thorndycraft, 2005). In contrast, their main advantage is that they can last hundreds or even thousands of years, so that the uncertainty of flood frequency (FF) analysis can be reduced and thus the reliability of risk analysis can be improved. PSI can have a geologic/geomorphic origin associated with the existence of elements of distinctive sedimentary origin, e.g. slackwater deposits and boulder flood bars (Ely and Baker, 1985; Waythomas and Jarrett, 1994; Ely, 1997; Jones et al., 2001; Benito et al., 2003; Zhang et al., 2012; Huang et al., 2013), or with the presence of erosional features on the channel margin or the floodplain, e.g., stripped soil, truncated alluvial fans, flood scarps (Komatsu and Baker, 1997; Bodoque et al., 2011). The most commonly used PSI are slackzwater deposits of silt and sand, deposited in areas with almost ineffective flow (Baker, 2008).

Floods in mountain watersheds are high-energy events. Thus, the evidence above is not always present and even when it is the PSI may not be spatially representative. In this context, dendrogeomorphology (Alestalo, 1971) can complement PSI of geologic/geomorphologic origin, or replace them if necessary. For this, the analysis of external evidence (e.g. height of tree scars) and anatomical response to flood disturbance are useful to determine the frequency and magnitude of past events, as well as the associated risk (Díez-Herrero et al., 2013a,b). The main advantage of HWM is that they enable the palaeoflood area to be reconstructed with reasonable reliability, as floating vegetation, silt lines and other flood-carried debris are used as physical evidence of flood occurrence. However, these water marks only persist for a short time, so that their use is mainly limited to post-flood field investigations (Gaume and Borga, 2008; Marchi et al., 2010). The physical evidence explained above allows palaeoflood water surface profiles to be determined along the flood plain, by applying either one- or two-dimensional hydraulic models (Ballesteros-Cánovas et al., 2011a,b). Likewise, it is possible to carry out FF analysis using methods such as optically stimulated luminescence (Sheffer et al., 2003), isotopic dating techniques such as radiocarbon and Caesium-137 (Thorndycraft et al., 2005a), or cosmogenic radionuclide surface exposure dating of flood-deposited large boulders (i.e. very large boulders, such as those deposited by outburst floods, that remain stable and unabraded by subsequent smaller floods) (Benn et al., 2006). In addition, botanical dating methods, such as dendrogeomorphology or lichenometry, can be implemented for this purpose (Macklin and Rumsby, 2007; Ruiz-Villanueva et al., 2010).

2.2. Palaeoflood hydrology based on geologic and geomorphic evidence

In mountain streams depositional evidence of flooding is not as widespread as in low gradient streams and bedrock canyons. In high-gradient streams, palaeoflood sedimentary records consist of slackwater flood deposits (SWD) (Kochel and Baker, 1982) and gravel and boulder bars (Kochel and Baker, 1988; Webb and Jarrett, 2002).

Slackwater flood deposits are fine-texture sediment accumulated from suspension during floods (Baker et al., 2003; Benito and O'Connor, 2013). Typical depositional areas include valley margins where eddies, backflooding, flow separation and water stagnation occurs during high flood stages (Baker, 1987; Benito