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Combining dendrogeomorphological and topographical techniques for hydraulic modelling in mountain streams

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Abstract. Flash floods are the main natural hazard in many mountain areas due to the high discharge and transport of sediment occurring in a few hours or even minutes. The hydraulic modelling of flash-flood process in ungauged mountain basins often requires the combination of different techniques to understand the processes and to evaluate the risk.

This paper reports on results derived from the use of high-detail topography obtained with a terrestrial laser scanner (TLS), classical topographical techniques and dendrogeomorphological evidences. These evidences can be seen in the impact on trees of rocks and woody debris transported during torrential past floods, which gives rise to paleostage indicators representing the minimum discharge elevation during floods.

The combined use of topographic data and dendrogeomorphological evidences to calibrate hydraulic models allowed us to characterize the magnitude of a singular flood event that took place on December 18, 1997, in the Arroyo Cabrera mountain stream (Gredos mountain range).

The methodology was implemented on a stream reach (500 m in length) featuring a hydraulic jump on stable bedrock, and numerous scarred trees on its banks due to past floods. A high-resolution digital elevation model (DEM) based on more than 4 million points was taken with a TLS, with an average error of 5mm . Stream cross-sections and morphometrical measurements of trees were subsequently collected with Total Station and classical topographical techniques in order to calibrate the model. In addition, paleostage indicators (PSIs) located on trees were dated using dendrogeomorphological methods.

A 2D numerical flood model, based on a finite differences approach, was performed to estimate the peak discharge of the flood. PSIs were used as input to the hydraulic model in order to calibrate it. The methodology developed provides useful information to reconstruct the magnitude of the flood, such as mapping the flooded area on the DEM; the water depth, or the pattern of the flow speed. The knowledge of the advantages and disadvantages derived from combining the techniques used in this work brings useful information for the elaboration of future flash flood hazard maps in ungauged mountain catchments.

Keywords: *natural hazards, flash flood, paleoflood hydrology, hydraulic modelling, terrestrial laser scan, dendrogeomorphology, Gredos mountain range*

1. INTRODUCTION

Flash floods are a fast flooding of water often combined with sediment transport that usually takes place in high-gradient streams, although they can occur in many other settings. They are caused by heavy rainfall, rapid snow melt cover, or the failure of dams situated in the upper part of the basin. These processes are especially common in Mediterranean mountainous areas, and pose a serious hazard to society due to their practically instantaneous occurrence, as well as to the general lack of risk perceived by the population in torrential ephemeral rivers (Roca et al., 2008). In Spain, the economic losses generated by intense floods were estimated at twelve billion euros (between 1987 and 2001), and caused 207 deaths during the decade 1995-2005 (Díez-Herrero, 2008).

For planners and engineers, the understanding and accurate assessment of extraordinary flash floods are essential for risk management, land-use planning and the correct design of hydraulic structures (Enzel et al., 1993). To this end, systematic data records on precipitation and flow have been used to develop different hydrologic and hydraulic models. However, it is difficult in mountain catchments to find available instrumental records and when they exist; they usually have temporal limitations or do not have sufficient spatial-temporal representatives (Díez-Herrero, 2008). In addition, during extreme floods, flow gauges may have been inundated, damaged or destroyed and may therefore have been prevented from recording data accurately (Benito and Thorndycraft, 2004). Non-systematic data such as historical and written records, geological indicators (Benito and Thorndycraft, 2004) or dendrogeomorphological evidence on trees (Díez-Herrero et al., 2008) provide valuable information when reconstructing ancient floods.

In fact, different features are left by floods. Paleostage indicators (PSIs), which report the minimum water surface elevation; and high-water marks (HWMs), which indicate the highest level reached by a body of water from recent floods, have been widely used to estimate peak discharges of paleofloods (Jarret and England; in House et al., 2002). Traditionally, various methods have been used to transform the information obtained from PSIs and HWMs into peak discharges, all based on one-dimensional hydraulic models (Webb and Jarret; in House et al., 2002). Basically these methods are: slope-conveyance; slope-area; step-backwater, and critical-depth methods. However the critical-depth method is especially advantageous when PSIs are found in a reach where critical flow can be assumed and validated, because at critical flow, the stage-discharge relation is a function of channel shape and not channel roughness; therefore, the water-surface elevation is critical depth (Webb and Jarret; in House et al., 2002). However, despite the development of 2D numerical flood models and the improvement in results that these models offer, they are not used in many paleoflood studies, and have never been used when PSIs come from dendrogeomorphological evidence. With regard to dendrogeomorphology, some authors (e.g. Bollschweiler et al., 2008) affirm that information from tree-rings is one of the most viable sources of data for studying past floods over several centuries, especially in mountain catchments where other non-systematic source data is available (Díez-Herrero et al., 2008).

In the present study, we report on the preliminary results derived from the reconstruction of the magnitude of a singular flash flood that took place in 1997 in the Arroyo Cabrera stream. We have used highly accurate topographic data (obtained from terrestrial laser scanning –TLS–) combined with dendrogeomorphological evidence in order to infer the PSIs were produced by the 1997 flood, and thereby to estimate peak discharge. For three different scenarios, we used an iterative method based on 2D numerical flood models to the paleoflood discharge estimation.

2. STUDY SITE: ARROYO CABRERA

The Arroyo Cabrera (40º 24’ 28’’ N; 4º 39’ 25’’ W) is a fluvio-torrential stream tributary of the Alberche River in the Tagus Basin (Central Iberian Peninsula). The catchment has an area of 15.75 km^2 and is formed by the confluence of several streams that descend from the Exclusa summit (1,960 masl) to the junction with the Alberche River (725 masl) for 5,500 m on the northern slopes of the Sierra del Valle (Gredos mountain range, Spanish Central System –Figure 1), defining an average slope of 21.6%. Arroyo Cabrera is characterized by high torrential dynamic activity owing to persistent and heavy rainstorms, especially during the winter, as well as a steep slope in the headwater, which facilitates the triggering of shallow landslides that mobilize abundant solid material into the channel.

The flash flood studied took place on December 18, 1997. That night, stationary rain cells caused heavy rainfall, triggering a shallow landslide in the headwater of the basin, which mobilized abundant solid material into the channel. This gravitational process was facilitated by an antecedent rainfall of about 817 mm during the two previous months to the triggering flood (Bodoque et al., 2006). As a result, a flash flood highly laden with sediment routed downstream, redefining the stream architecture and causing considerable damage to the adjacent vegetation, consisting mainly of Mediterranean conifer trees and riparian species.

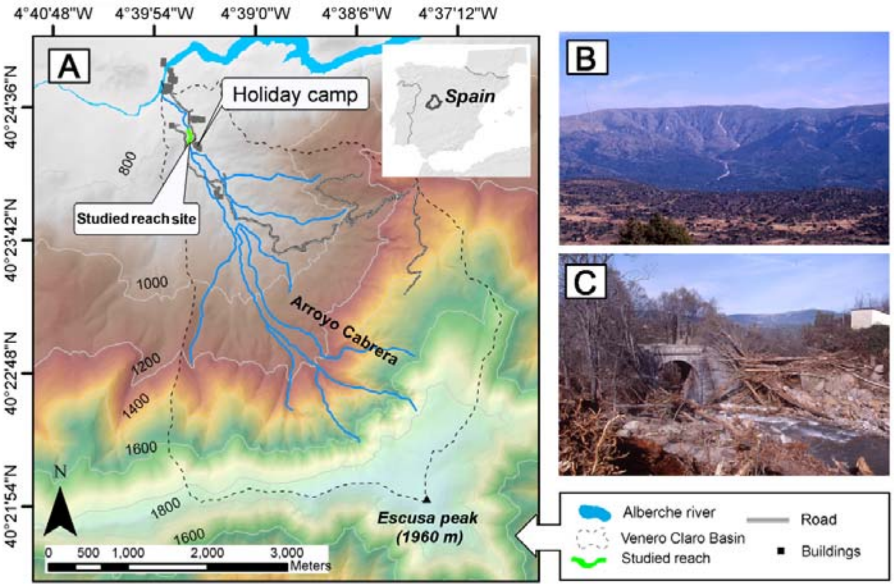

Figure 1. A) The Arroyo Cabrera's catchment. The modelled area (segment in green) is located in the lower part of the basin and downstream from the buildings of a holiday camp. B) Front overview of the Sierra del Valle. The catchment observed below the Arroyo Cabrera. C) View of the bridge located in the upper part of the modelled area after the 1997 flood.

The study was conducted along a reach of about 500 m in length situated in the lower part of the catchment. The reach has an average slope of 0.231 m/m, which favours supercritical flow. This reach was also chosen due to its stable bedrock, to ensure that the channel geometry did not change during the flood. Dendrogeomorphological evidence caused by the impact of debris and woody debris transported during past flash-floods can be found on trees located close the stream. The sediment transported by the flow was relatively slow in this reach , because most debris and boulders were deposited on an alluvial fan located in the middle part of the basin ?, as well as upstream from three small bridges and one reservoir situated in the upper part of the basin, thereby laminating the flows (Bodoque et al., 2006).

3. DATA ACQUISITION

3.1. Using dendrogeomorphological evidence as paleostage indicators

Impacts on trees caused by debris and woody debris transported during flash floods prompts the abrasion of the external bark (Zielonka et al., 2008; Stoffel and Bollseweiler, 2008; Fig. 2-A,B). Consequently cambium tissue, which has the function of producing wood and bark, is destroyed in the affected area. However, in the years after the scar is produced, the cambium continues to differentiate new wood and bark layers in the unaffected area around the wound. This botanical paleoflood evidence (Díez-Herrero et al., 2008) enables us to date past floods (Zielonka et al., 2008) and provides valuable information on the high-water marks (HWMs) (Yanosky and Jarret; in House et al., 2002) reached during flood episodes, and thereby defines PSIs (Benito and Thorndycraft, 2004).

Based on this dendrogeomorphological evidence, a sampling strategy was designed to ensure that all PSIs observed on trees and associated to the 1997 flood were taken into account in the calibration of the hydraulic model. To this end, 26 trees with scars facing the flow direction were located and sampled (Fig. 2-A). We were particularly careful to exclude elongated scars, which might have been formed by other factors such as the fall of neighbouring trees or lightning strikes. Woody wedge samples (Fig. 2-B) from scars with a perpendicular face, and following the longitudinal direction of growth, were collected using a handsaw. At the same time, additional information was obtained including scar sizes, tree height, diameter at breast height, as well as sketches and description of the geomorphologic position.

Laboratory procedures for sample preparation (cutting and sanding) were carried out previously to facilitate a clear observation of the tree-ring record. Tree-ring series of all samples were subsequently counted in the laboratory using a digital LINTAB positioning table connected to a stereomicroscope (magnification x5) and a TSAP 3.0 system. The flash flood was dated by subtracting the number of tree rings along the scar-containing radius from that of the intact radius (Yanosky and Jarret; in House et al., 2002; Zielonka et al., 2008; Ballesteros et al., unpublished results). Table 1 summarizes the main information obtained from dendrogeomorphological evidence.

Figure 2.A) Typical scars on alder stems formed as a consequence of the impact of debris transported during the flood. B) Wedge sample obtained from the scars. Although the wound is closed, the impact damage can be seen in the cross-sectional face and the flood year can consequently be dated in the tree-ring record.

Tree species	Sampled paleostage indicators	Flood date (No. samples)	Size of wound		
			Average area	**No. of wounds** area < 400 cm^2	**No. of wounds** area > 400 cm^2
Alnus glutinosa* *Fraxinus angustifolia	23 1997	(23)	912 cm^2 (± 811.2 cm^2)	7 16	

Table 1. Factors that allow characterization of the flood date from dendrogeomorphological evidence.

3.2. Topographical information

The representative and accurate topography of the floodplain and main channel is one of the most important elements required to carry out hydraulic models of past floods. In accordance with this requirement, in this study we have used a terrestrial laser scanner (TLS) to obtain accurate information on the topography of the 500-m study reach. This technology allows us to record millions of highly accurate points over a surrounding scene or object. XYZ information is recorded and displayed as a "point cloud" which can be viewed, measured and navigated as a 3D model (Fig. 3). The scanner used (CALLIDUS CP 3200) has a maximum scope of 32 m, a precision of 5mm on average and one speed of sweep of 1750 p/s (Callidus 2004).

Both the limited scope and the highly irregular topography of the reach as well as the vegetation at the study site made it necessary to use successive topographic stations to complete the scan of the whole model. Because TLS technologies are not available to characterize topography below water, classical topography based on Total Station surveying was used to obtain the bathymetry of the main channel. In addition, the maximum heights of the scars, as well as the position of all trees with dendrogeomorphological evidence in the sample were obtained.

After the acquisition of the topography in the field, all data were registered and filtered to eliminate possible interferences. On account of the high density of points taken in the field (over 4 millions points, 700 points/m^2), the initial data was filtered, and as a result only about 500,000 points were considered for building the three-dimensional model (90 point/m^2). This information was exported to the GIS software (ArcGIS 9.2; Esri 2009) and a digital elevation model (DEM) was built with a spatial resolution of 35x35 cm, showing the location of all the trees sampled.

4. PALEOFLOOD DISCHARGE ESTIMATION

4.1. 2D numerical flood model

Although one-dimensional models combined with PSIs have been successfully used in the past in paleoflood studies (O'Conner and Webb, 1988; Benito and Thorndycraft, 2004), in this study we chose a two-dimensional hydrodynamic model MIKE 21 developed by DHI (2008). This model simulates unsteady two-dimensional flows and describes the flow and water depth variations using the conservation of mass momentum integrated over t he ve rtical (technical in formation is av ailable in DHI, 20 08). Usu ally, 2 D numerical flood models require long computing times; nevertheless both the high accuracy of the results and the fact that supercritical flow regime can be modelled made its use advisable.

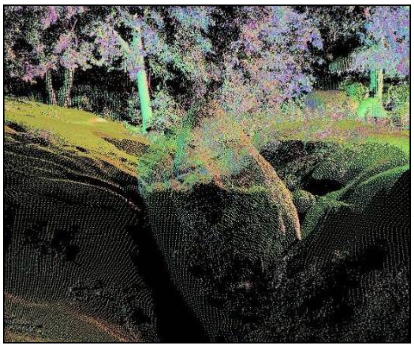

Figure 3. "Point cloud" obtained with terrestrial laser scan from a base station. For each base station, TLS turns around on itself and takes XYZ data. This way it is possible to distinguish different elements and makes the post-processing steps easier. This picture shows boulders in the foreground and mature trees in the background.

The following information is required to run the hydraulic model:

- <u>*Topographic description:*</u> a regular DEM (35 x35 cm) of the main channel and floodplain was built using the topographic information obtained from TLS.
- <u>*Boundary conditions:*</u> the esti mation of th e peak discharge supp oses an i nverse pr oblem in paleoflood studies (Benito a nd T horndycraft, 2004) which require s each sim ulated HWMs to be compared with the PSI m arks. Therefore, a constant discharge upstream has been assigned as t he initial conditions for each simulation.
- <u>*Roughness coefficients:*</u> MIKE 21 allows the roughnes s coe fficient t o be inc orporated with a constant value or a roughness grid file using either Manning's n values or Chezy's C values. In this study, we used a r oughness grid file based on Manning's values. In accordance with Cook (1987) who reported on the importance of the roughness coefficient in a hydraulic model, we mapped each homogeneous patch in the fi eld. Manning's values were assigned taking into account the nature of the main channel and the floodplains (Aldridge and Garrett, 1973). Nine homogeneous roughnesses were detected in twenty different areas. Manning's n varied between 0.02 and 0.15.
- <u>*Flow viscosity:*</u> eddy viscosity was estimated as approximately 0.0045 (m^2s^{-1}). This value represents the maximum eddy viscosity value obtained when the profile near the bed is compared for different sediment loads (Yoon and Kang, 2005).
- <u>*Computational time step:*</u> di fferent sim ulations were i mplemented usi ng di fferent com putational time ranges and steps to ensure that the model was stable. In the model we consider a computational time of 7 hours with a time step interval of 0.015 s.

4.2. Calibration using dendrogeomorphological evidence

Maximum heights of the dendrogeomorphological evidence were used to calibrate the 2D numerical flood models in order to reconstruct the peak discharge during the 1997 flood. To this end, water-surface elevations obtained from successive hydraulic simulations, based on an upstream-boundary condition peak discharge of between 20 m^3s^{-1} and 200 m^3s^{-1}, were compared with the maximum height of the PSIs. This method reports either the maximum or minimum flood elevation or the flood elevation that has been exceeded during a given flood (Benito and Thorndycraft, 2004). This is due to the fact that we do not know the depth that the debris was si tuated a t t he m oment of t he i mpact. I n t his st udy, we have t aken i nto acc ount t hree hy pothetical scenarios where heights of PSIs were estimated using the relation between a hypothetical depth of the impact scar and th e debris size (we assumed th at la rge debris caused scars greater th an 400 cm^2, and sm all debris caused scars of under 400 cm^2). Table 2 shows the criteria used to define these scenarios. For both small and large scars, the average deviation was calculated contrasting the average water-surface elevation obtained at around 1 m^2 by hy draulic si mulation wi th the hei ghts of PSIs est imated acc ording t o t heir si ze, for ea ch scenario. Fo r the thr ee hypothetical scen arios, t he m inimum av erage deviation obtained conv erged with differences within an interval of between 9.86% and 0.64%. Finally, the peak discharge was estimated to be 71 m^3s^{-1} (± 3 m^3s^{-1}) (Fig.4). However, although the average deviation obtained for this peak discharge was lower than 0.64%, not all PSI s reached this optimal value. Almost 11 PSIs had deviations of over 25 % with regard t o t he average de viation. T his su pposes co nsiderable di fferences of aro und 75 cm bet ween PSIs observed in the field and 1997 HWMs. Spatial disposition of trees and their adjustments can be seen in Fig. 5.

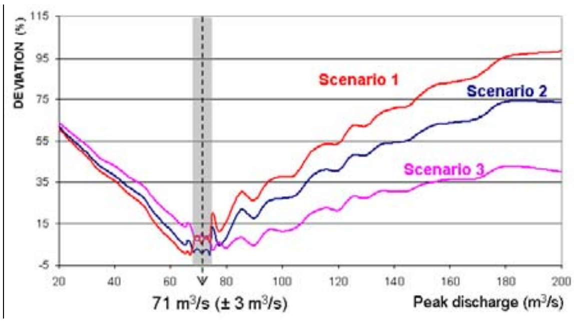

Table 2. Values of depth percentages, for each hypothetical scenario considered, used to estimate the desired water surface elevation with PSIs. Figure 4. Variation of the average error with peak discharge for the three scenarios considered.

Scenario	Depth percentage of the debris transported	
	Wounds > 400 cm^2	Wounds < 400cm^2
1	***80 %***	***100 %***
2	***90 %***	***70 %***
3	***75 %***	***45 %***

4.3. Hydraulic simulation of the 1997 extraordinary flood in Arroyo Cabrera

The 2 D numerical flood simulation and the results obtained for the peak discharge provided valuable information for understanding this extraordinary flood within the geographic context where it took place. Graphs and numerical information on flow velocities, flooded areas and water surface elevation were obtained. Fig. 5 shows some graphic results of the abovementioned information, as well as a plot that represents the stability of the model by means of the temporal variability of results at one point.

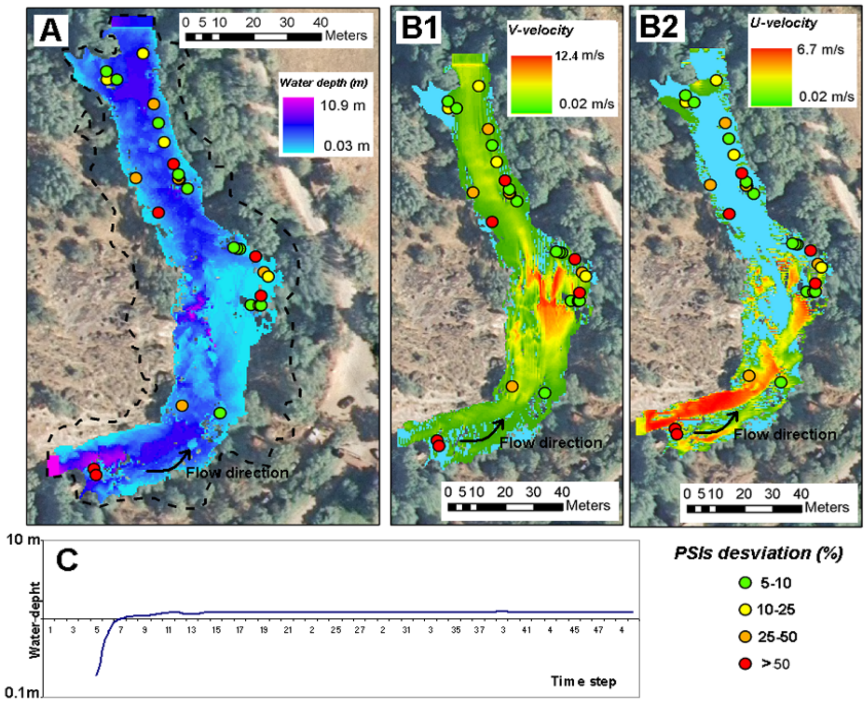

Figure 5. Location of trees with PSIs and their adjustment on the graphic results for water depth (A1); (B1) Velocity in y direction (V-velocity); and, (B2) Velocity in x direction (U-velocity). Graph C shows the variability of the water depth values in a random point throughout the compute time used.

5. CONCLUSIONS

The magnitude of a singular flash flood event in an ungauged catchment has been estimated using a 2D numerical model calibrated with dendrogeomorphological evidences used as PSIs. Despite hydraulic simulation on high gradient streams can supply results with some degree of uncertainty, this methodology can provide planners and decision makers with important information about the magnitude of floods, especially in ungauged catchments.

The abovementioned uncertainty is as a result of the fact that the transport height of the sediment load when the impact took place is unknown (Yanosky and Jarret; in House et al., 2002). However, the different scenarios stated during the simulation have enabled to estimate a peak discharge for the event of 71 m^{3}s^{-1} (± 3 m^{3}s^{-1}). This result has to be understood as the deviation among the three scenarios considered in the model rather than the error with regard to the real peak discharge of the studied event. In fact, for extraordinary floods on higher gradient streams deviation in the peak discharge estimation, often could be higher (Webb and Jarret; in House et al., 2002).It is owed to the uncertainty associated to the range of tree-scar heights that have to be taken into account as well as the difficulty to implement hydraulic model in high gradient streams.

The 2D numerical flood model showed that PSIs did not adjust as accurately. Major desviation in the adjustment were found in trees located on the right bank and trees situated immediately behind others. We consider that the geomorphologic position of trees in relation to the river dynamic can influence the use of dendrogeomorphological evidence as PSIs in paleoflood reconstruction. However, future studies are needed on the formation of dendrogeomorphological evidence, systematically conducting similar studies to determine flood magnitudes (and ages) in other ungauged basins, as well as on the incorporation of the sediment transported during floods into the numerical model.

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