Journal of Hydrology 529 (2015) 480–489

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Can tree tilting be used for paleoflood discharge estimations?

J.A. Ballesteros-Cánovas [a,b,*], J.F. Márquez-Peñaranda [c], M. Sánchez-Silva [c], A. Díez-Herrero [d], V. Ruiz-Villanueva [a], J.M. Bodoque [e], M.A. Eguibar [f], M. Stoffel [a,b]

[a] Dendrolab.ch, Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland
[b] Institute for Environmental Sciences, University of Geneva, 7 route de Drize, 1227 Carouge, Geneva, Switzerland
[c] Department of Civil and Environmental Engineering, Universidad de Los Andes, Bogotá, Colombia
[d] Department of Research and Geoscientific Prospective, Geological Survey of Spain (IGME), Ríos Rosas 23, Madrid E-28003, Spain
[e] Mining and Geological Engineering Department, University of Castilla-La Mancha, Campus Fábrica de Armas, Avda. Carlos III, Toledo E-45071, Spain
[f] Institute for Water and Environmental Engineering (IIAMA), Technical University of Valencia, Department of Hydraulic Engineering and Environment, Valencia, Spain

ARTICLE INFO

Article history:
Available online 18 October 2014

Keywords:
Paleohydrology
Tree rings
Tilted trees
Flood
Peak discharge

SUMMARY

Paleoflood hydrology typically deals with the reconstruction of floods in ungauged and poorly gauged basins by combining different sources of indirect evidence. Botanical indicators have been used repeatedly in the past, mostly through the study of scars in trees or germination dates of plants on newly created surfaces. In this paper we test the hypothesis that the inclination of trees – as induced by floods – can provide information on flood magnitude, and that this source of information can therefore be used for flood reconstructions. We used a mechanical root-plate rotational stiffness model in three gauged river reaches in Central Spain to test our hypothesis and combine approaches typically applied in dendrogeomorphic, dendrometric, mechanical structure, and hydraulic research. Results show a correlation between modeled and observed deformation at the stem base of trees induced by floods (coefficient of correlation 0.58 for all observations). However they also point to a clear underestimation of peak discharge reconstructions. We used different efficiency criteria to test the reliability of results and differences between river reaches. In addition, we carried out a sensitivity analysis and discussed sources of uncertainties which may reach up to 112%, mainly due to difficulties to determine the rotational stiffness of the root plate system a posteriori. The approach presented here is promising, but more research is clearly required to improve the quality of peak discharge estimations based on stem tilting.

1. Introduction

The scarcity of instrumental data and the shortness of records severely hamper the acquisition and development of reliable and representative flood time series and add considerable uncertainty to flood hazard assessment (Brázdil et al., 2006). This lack of data also largely hinders the analysis of flood magnitude and frequency and calls for the application of alternative and/or complementary approaches. Paleoflood hydrology deals with the reconstruction of the magnitude and frequency of recent, past, or ancient ungauged floods by combining indirect evidence, hydraulic methods and statistical techniques (Baker et al., 2002; Benito et al., 2003). Over the last 30 years, paleoflood hydrology has achieved recognition as a new branch of geomorphology and hydrology (Baker et al., 2002; Benito and Thorndycraft, 2005; Baker, 2008) by employing geologic, hydrologic, and fluid dynamic principles to infer quantitative as well as qualitative aspects of unrecorded floods (House et al., 2002). Therefore, it has been recognized that the use of paleohydrologic techniques provides one means of evaluating the hydrologic effects of long-term hydrologic variability and climatic change at ungauged locations, and is useful to decrease uncertainty in hydrologic estimations (Jarrett, 1991).

Botanical evidence represents an indirect indicator of past flood events (Sigafoos, 1964; Baker, 2008). Botanical evidence can be interpreted by means of dendrogeomorphic approaches (Stoffel et al., 2010; Stoffel and Corona, 2014; Ballesteros-Cánovas et al., in preparation) and has been demonstrated to be a very reliable tool for the spatio-temporal reconstruction of past floods in mountain environments (Ballesteros et al., 2010; Ballesteros-Cánovas et al., 2011a,b; Arbellay et al., 2012). Among all existing botanical flood evidence, scars (injuries) on stem have been used most extensively because of their ability to provide information about the

* Corresponding author.
E-mail addresses: juan.ballesteros@dendrolab.ch (J.A. Ballesteros-Cánovas), jf.marquez53@uniandes.edu.co (J.F. Márquez-Peñaranda), msanchez@uniandes.edu.co (M. Sánchez-Silva), andres.diez@igme.es (A. Díez-Herrero), virgina.ruiz@dendrolab.ch (V. Ruiz-Villanueva), josemaria.bodoque@uclm.es (J.M. Bodoque), meguibar@hma.upv.es (M.A. Eguibar), markus.stoffel@dendrolab.ch (M. Stoffel).

http://dx.doi.org/10.1016/j.jhydrol.2014.10.026
0022-1694/

Nomenclature

ac	aplication center of the drag force (m)
Arw	*unidimensional* parameter comparing the proportions of the root-soil plate weight of the total below-ground anchorage (Coutts, 1983)
cgc	crown centroid (m)
cgt	tree centroid (m)
cgs	stem centroid (m)
DBH	diameter at breast height (m)
D_c	drag coefficient (dimensionless)
Fd	drag force (N)
F_{wd}	equivalent force generated by the woody material (N)
g	gravity (m s^{-2})
hc	crown height (m)
hs	stem height (m)
ht	height of tree (m)
hw	thickness of woody debris (m)
k_i	rotational stiffness of the root plate system (Nm/rad)
K_m	maximum rotational stiffness of the root plate system (Nm/rad)
M_{base}	bending moment acting at the stem base (Nm)
M_{res}	maximum (resistant) stem base bending moment (Nm)
mwd	floating wood mass (kg)
RPD	root plate depth (m)
RPL	root plate length (m)
RPW	root plate width (m)
S	tree surface exposed to flow (m^2)
V	flow velocity (m s^{-1})
W	tree weight (N)
W_D	water depth (m)
W_c	crown weight (N)
W_s	stem weight (N)
ρ_s	bulk soil density (kg m^{-3})
ρ_w	wood density (kg m^{-3})
ρ_c	crown density (kg m^{-3})
θ	deformation at the base of the tree (rad)
θ_i	initial deformation (residual) at the base of the tree (rad)
θ_e	elastic limit deformation at the base of the tree (rad)

timing and the level reached during a flood (Gottesfeld, 1996; Yanosky and Jarrett, 2002; St. George, 2010; Ruiz-Villanueva et al., 2010; Ballesteros-Cánovas et al., 2011b). Other botanical evidence is tilted trees. This evidence is due to a structural deformation of a tree resulting from unidirectional, hydrodynamic pressure on the stem during floods. Stem tilting will be accompanied by the formation of reaction wood in the tree-ring record, which can be used to date past geomorphic events (Stoffel et al., 2010).

On the other hand, structural analysis of trees under external loads has been studied over the last decade as well, but with a focus on root-soil interactions. Field experiments have been used to show the role of roots and soil tension and root plate size in root-plate anchorage of trees under external loads (Coutts, 1983; Stokes, 1999; England et al., 2000; Dupuy et al., 2005, 2007; Fourcaud et al., 2008). In addition, various engineering approaches – including Euler–Bernoulli beams analysis – have been proposed to describe elastic deflection and ultimate resistance of trees (Neild and Wood, 1999). Most efforts have been focused on wind force as the main external load (Gardiner et al., 2000; Watson, 2000; Ancelin et al., 2004; Danjon et al., 2005; Peltola, 2006; Coder, 2010), whereas impacts of other external loads such as snow accretion (Kato and Nakatani, 2000), typhoons (Chiba, 2000), or rockfalls (Stokes et al., 2005) have been less profusely analyzed. In the same line of thinking, it seems appropriate to think that tilted trees growing in floodplains may exhibit reactions induced by flood, and that their structural behavior could be linked to flow conditions and ultimately flood magnitude.

In this paper, we will therefore explore the utility of tilted trees for peak discharge estimation of paleofloods through the application of a mechanical model to reproduce the base deformation of trees under hydrodynamic forces during floods. We compare results with deformation values observed in the stem base of 35 trees (i.e. *Alnus glutinosa*, *Fraxinus angustifolia*, and *Pinus sylvestris*) tilted by floods. Our paper represents a multi-disciplinary approach and combines dendrogeomorphic, dendrometric, structural mechanics and paleohydrologic techniques to determine if, based on our observations, it is possible to estimate peak discharge of past floods using stem tilting in trees.

2. Material and methods

2.1. Conceptual model of tree-deformation

Trees exposed to hydrodynamic forces will deflect in natural environments. For this reason, we use a conceptual approach where the rotational stiffness of the root-plate system represents the response to the moment generated by the hydrodynamic force and tree weight (Fig. 1).

In this approach, the rotation of the root-plate soil θ_i is considered equal to that of the stem base, so that the value of θ_i can be approximated following Jonsson et al., (2006, Eq. (1)):

$$\theta = \theta_i + \frac{M_{base}}{k_i} \tag{1}$$

where θ_i (*rad*) is the initial rotation of the root-soil plate, which was assessed null for the purpose of this study; k_i (*Nm/rad*) the rotational stiffness of the root plate; M_{base} (Nm, Eq. (2)) the stem base bending moment related to the demanding forces, i.e. the drag force (Fd, N, Eq. (3) and F_{wd}, N), tree weight ($W = W_s + W_c$, N, Eqs. (4) and (5)) and the force induced by wood deposited against the stem (F_{wd}, N, Eq. (4)). The lever arm of each force (measured from the stem base) is obtained by considering the real moment arm. Details on the application points and corresponding abbreviations are given in Fig. 1 and will be described in the following:

$$M_{base} = (Fd \times ac \times \cos\theta) + (W \times cgt \times \sin\theta) + (F_{wd} \times W_D) \tag{2}$$

The point ac is located at 50% of water depth, whereas cgs, cgc, cgt represent the position of the stem, crown and tree centroids, respectively, W_D is the total water depth.

The drag force Fd in Eq. (3) is associated with (i) water density (ρ), (ii) drag coefficient (D_c), (iii) tree surface exposed to the flow (S, m^2); and (iv) flow velocity ($\overline{V}$, m s^{-1}). Water density was assessed as $\sim$1000 kgf m^{-3}. The expected initial drag coefficient D_c is considered to be equal to 1 based on Bruschi et al. (2003). D_c is a dimensionless measurement used to represent the resistance imposed against flow by an object within a fluid environment, it can decrease exponentially with flow velocity (Vogel, 1989).