Sociedad Geológica de España
GEOGACETA, 75, 2024

Extreme flood events in the western Mediterranean: integrating numerical MODelling and flood records in KARST systems (MODKARST project)

Eventos extremos de inundación en el Mediterráneo Occidental: integrando modelos numéricos y registro de inundaciones en sistemas kársticos (proyecto MODKARST)

Miguel Bartolomé[1, 2, 3]*, Marc Luetscher[2], Heather Stoll[3], Ana Moreno[4] y Gerardo Benito[1]

[1] Departamento de Geología. Museo Nacional de Ciencias Naturales (CSIC). C. de José Gutiérrez Abascal, 2, 28006 Madrid, Spain.
mbart@mncn.csic.es
[2] Swiss Institute for Speleology and Karst Studies (SISKA), La Chaux-de-Fonds, Switzerland. Rue de la Serre 68 2300
marc.luetscher@isska.ch
[3] Geological Institute, NO G59, Department of Earth Sciences, Sonneggstrasse 5, ETH, 8092 Zurich, Switzerland.
heather.stoll@erdw.ethz.ch
[4] Departamento de Procesos Geoambientales y Cambio Global. Instituto Pirenaico de Ecología (CSIC). Avenida de Montaña, 1005, 50059, Zaragoza, Spain.
amoreno@ipe.csic.es
**Corresponding author*

ABSTRACT

Changes in rainfall patterns are a direct consequence of the current climate change. Climate projections indicate an intensification of extreme rainfall events, which will directly affect social, ecological, and economic systems.One of the most significant challenges in the field of climate science lies in comprehending, modeling, and forecasting the fluctuations in flood occurrences derived from these extrem rain events. The uncertainties in projected rainfall remain notably elevated, especially in Mediterranean where the climate is characterized by extreme and sudden rainfall events. The instrumental record is too short to correctly estimate flood return periods. Hence, geological records are required to better understand the long-term variability, from millennial to decadal scales, of natural extreme flood events. MODKARST is a MSCA-GF project awarded by the European Union, to develop a quantitative flood database for the Western Mediterranean realm based on speleothems. The action plans to infer past flood events from the last 18 ka based on detrital layers recorded in stalagmites from 5 different caves in the north of Spain, in combination with karst hydraulic models and water-level monitoring. MODKARST will help to better disentangle the relation between flood recurrence and climate changes, and will shed light on how to better predict the variability of floods in the context of present-day global warming.

Key-words: *Paleofloods, Hydrology, climate change, speleothems.*

RESUMEN

Los cambios en los patrones de lluvia son una consecuencia del cambio climático actual. Las proyecciones climáticas indican una intensificación de los eventos extremos de lluvia, que afectarán a los sistemas sociales, ecológicos y económicos. Uno de los mayores retos de la ciencia climática es comprender, modelar y predecir la variabilidad de las inundaciones derivadas de estas lluvias extremas. Las incertidumbres en las proyecciones de las precipitaciones futuras siguen siendo elevadas, especialmente en el Mediterráneo donde el clima se caracteriza por lluvias extremas y repentinas. El registro instrumental es demasiado corto para estimar correctamente los períodos de retorno. Así, el registro geológico es fundamental para conocer la variabilidad a largo plazo de los eventos naturales de inundaciones extremas. MODKARST es un proyecto MSCA-GF otorgado por la Unión Europea, para desarrollar una base de datos cuantitativa de inundaciones para el Mediterráneo occidental basada en espeleotemas. Este proyecto pretende inferir inundaciones pasadas de los últimos 18 ka registradas en estalagmitas de 5 cuevas del norte de España, combinando modelos hidráulicos y monitorización del nivel del agua. MODKARST ayudará a comprender mejor la relación entre la recurrencia de inundaciones y los cambios climáticos, así como también ayudará a predecir mejor la variabilidad de las inundaciones en el contexto del calentamiento global actual.

Palabras clave: *Paleoinundaciones, Hidrología, cambio climático, espeleotemas.*

Geogaceta, 75 (2024), 95-98
https://doi.org/10.55407/geogaceta100997
ISSN (versión impresa): 0213-683X
ISSN (Internet): 2173-6545

Fecha de recepción: 16/07/2023
Fecha de revisión: 24/10/2023
Fecha de aceptación: 24/11/2023

Introduction and motivation

Climate change represents one of the greatest challenges for our society. Global warming has led to concerns about the increase in frequency and intensity of river floods all over the world (IPCC, 2021). In Europe, the last three decades have been the most flood-rich periods of the last 500-years (Blöschl *et al*., 2020). Climate models show an intensification of extreme torrential events in the next decades as a result of climate change (Kleinen and Petschel-Held, 2007). However, there is still a high uncertainty with respect to projected changes at regional scale since the trends are not yet robust. These uncertainties are greater for the Mediterranean areas where the irregular precipitation patterns and extreme events are intrinsic and difficult to model (Kundzewicz, Z. W. *et al*, 2017). Precipitation records, which are used to evaluate the return periods of floods, are too short (Hall, J. *et al*., 2014) or even absent in many regions. This complicates the accurate estimation of recurrence intervals of natural extreme flood events. Thus, understanding the natural patterns of extreme flooding in response to climate variability prior to the era of significant anthropogenic intervention in the climate system is required.

Paleoflood archives (Wilhelm *et al.*, 2019), based on sedimentary evidence from rivers and lakes, have been used to quantify flood discharge and frequency beyond the instrumental record. Although speleothems are cave deposits widely used as paleoenvironmental archives (e.g. Bartolomé *et al.*, 2015; Cisneros *et al.*, 2016) due to the possibility to date them accurately, they have rarely been exploited to reconstruct past floods (Denniston and Luetscher, 2017 and references therein), especially in the Western Mediterranean area, where only a few studies exist (e.g. González-Lemos *et al.*, 2015a, b; Gázquez, *et al.*, 2014; Bartolomé *et al.*, 2021; Cisneros *et al.*, 2023).

The five selected caves for this project form a transect from the Pyrenees; 1) Osotolo cave, (Bernal-Wormull *et al.*, 2021) Arantza, Navarra; 2) Güixas-Rebeco caves, Villanúa, Huesca (Giménez *et al.*, 2021; 3) B1 cave, Escuaín, Huesca) to the Iberian Range (Ojo de Valjunquera cave (Bartolomé *et al.*, 2021), 4) Ambel, Zaragoza) and 5) Ubriga cave (Bartolomé *et al.*, 2023), El Vallecillo, Teruel. (Fig. 1).

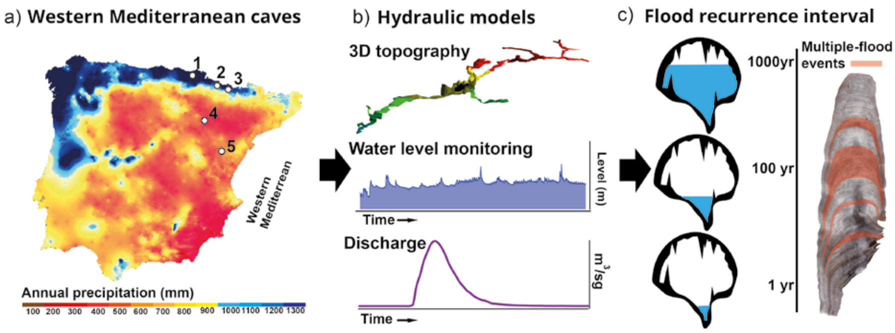

Fig. 1. a) Selected Western Mediterranean caves (Nothern Iberia) (1, Ostolo (Navarra); 2, Las Güixas-Rebeco (Huesca); 3, B1 (Huesca); 4, Ojo de Valjunquera (Zaragoza); 5, La Ubriga (Teruel). b) Examples of the required data (3D cave model, water level monitoring and discharge measurements) for hydraulic modelling. c) Example of flood recurrence interval inferred from detrital layers from speleothems. See the color figure in the web version.

Fig. 1.- Cuevas seleccionadas del Mediterráneo Occidental (Norte de Iberia) (1, Ostolo (Navarra); 2, Las Güixas-Rebeco (Huesca); 3, B1 (Huesca); 4, Ojo de Valjunquera (Zaragoza); 5, La Ubriga (Teruel). b) Ejemplos de los datos requeridos (modelo de cueva 3D, monitoreo del nivel de agua y mediciones de caudal) para el modelado hidráulico. c) Ejemplo de intervalo de recurrencia de inundaciones inferido a partir de capas detríticas de espeleotemas. Ver la figura en color en la versión web.

Trapping floods in speleothems

During a cave flood, sands and silts are transported through the cave system and a coating of this detritus is deposited on speleothem surfaces (Wilhelm *et al.*, 2019; Denniston and Luetscher, 2017, Cisneros *et al.*, 2023) (Fig. 2a, b, c.). After water recedes the carbonate deposition is re-initiated and detrital coatings are trapped inside the speleothem layering (Fig. 2 b). This process is repeated for centuries or millennia along the growth axis providing a unique and continuous record of paleofloods in a particular region (Fig. 2d). Speleothems forming next to streams inside the cave can therefore record ordinary floods while speleothems hosted in areas located far from the river or in the upper levels will only record extraordinary floods.

Assigning the cave flood magnitude to meteorological events is not straightforward since it may respond to different factors such as land use, changes in the sediment supply, and other preconditioning factors (Denniston and Luetscher, 2017). For all these reasons, cave hydraulic modelling (Jeannin, 2001, Jeannin *et al.*, 2021) ideally including the 3D structure of the conduit network as well as discharge measurements in the springs (e.g. salt gauging) and water-level monitoring must be carried out to quantify flood magnitude and timing. Moreover, speleothems allow discerning the links between periods with frequent flooding and the prevailing climate conditions namely water availability and temperature changes (inferred from the analyses of $\delta^{18}O$, $\delta^{13}C$, and trace elements).

Using speleothems for paleoflood reconstructions in combination with numerical modelling and water-level monitoring creates new opportunities for quantifying extreme past flood events in a large temporal and spatial window.

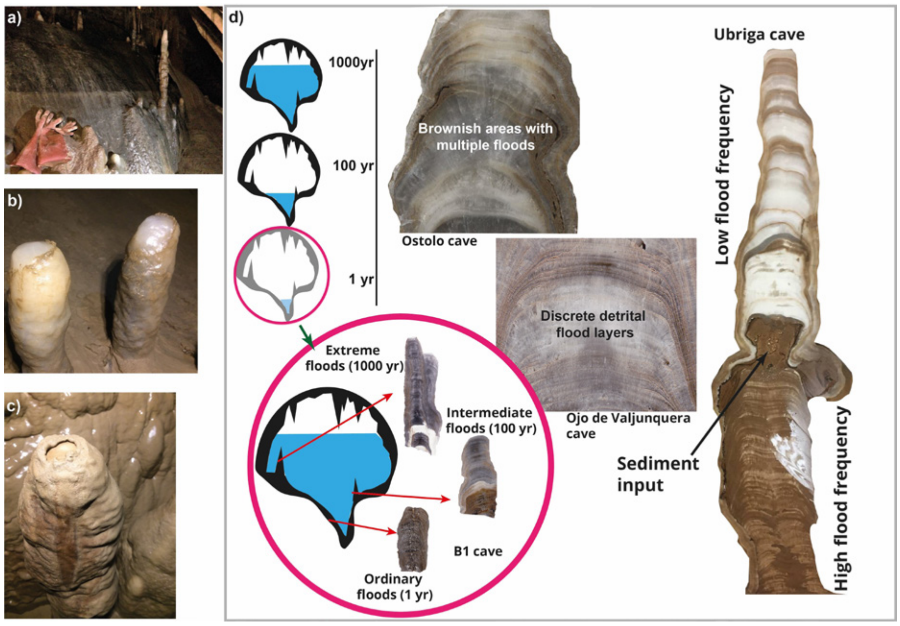

Fig. 2.- a) Inundation mark on a flowstone after a flood in one the most elevated areas in a cave. b) c) Two stalagmites with very active drips, in which the remobilised sand has been trapped during an extreme event, and a stalagmite with a thicker coat of sediment partially eroded by the impact of dripping water. d) Mechanism of flood-recording in speleothem and different types of detrital layers. See color figure in the web version

Fig. 3.- a) Marca de inundación en una colada tras una avenida en una de las zonas más elevadas de una cueva. b) y c) Dos estalagmitas con un goteo de agua muy activo que han removilizado y atrapado la arena tras un evento extremo, y estalagmita con una capa más espesa de sedimentos parcialmente erosionados por el impacto del goteo de agua. d) Mecanismo de registro de inundaciones en espeleotemas y diferentes tipos de capas detríticas. Ver figura en color en la versión web.

Scientific objectives and methods

The aim of MODKARST is to assess the long-term (last 18 ka) flood variability in the western Mediterranean. Focusing on the magnitude and timing of past floods recorded in speleothems, we will use karst hydraulic models to quantify the recharge (and thus meteoric precipitation) in the cave's hydrological catchment area. The specific goals are: i) the implementation of the hydraulic models in caves based on the 3D-structure of the conduit network, discharge measurements, as well as calibration data from water-level monitoring to quantify the magnitude of past floods recorded in stalagmites; ii) identification, characterization (multi-proxy approach) and dating of flood layers in stalagmites from the northeastern Iberia using stalagmites at different positions in the galleries, and iii) to establish the relationship between long-term flood patterns and past climate variability at local, regional and sub-continental scales during the late glacial and the Holocene. Thus, MODKARST is a multi-disciplinary action that combines and integrates different scientific disciplines such as computer science, cave geomorphology, sedimentology, statistics, hydrology, and atmospheric science.

Modelling karst aquifer

Data of the spring discharge and the site-specific infiltration rates (rainfall, evapotranspiration, runoff, water retention capacity, and snowmelt) will allow quantifying the net aquifer recharge from meteorological data (Malard, *et al*., 2016). This will be used to establish an empirical relationship between the aquifer recharge and the water flow in the active conduit system. A synthetic pipe-flow model will be constructed (Jeannin *et al*., 2021) based on the 3D model of the cave conduits using the EPA Storm Water Management Model (SWMM), which is a dynamic rainfall-runoff model well-suited for flow simulations in karst aquifers. This model effectively solves the 1D Saint-Venant equation based on conservation of mass and momentum and respects the hydraulic principles of the Darcy-Weisbach formula. It implicitly assumes i) circular pipes of defined roughness and, ii) regular head losses following a quadratic function (Jeannin, 2001). Once fitted to modern conditions, the hydraulic model will be used to simulate discharge at the main karst springs under different scenarios. This model will support quantification of the water discharge necessary to flood the speleothems at different positions in the galleries (Fig. 1).

Reconstruction of paleoflood series from stalagmite records

The stalagmites selected from caves (Fig. 1) were located at different elevations and/or similar position in the cave allowing the replication of flood layers among coeval samples. The speleothems present two sets of flood layers: i) discrete detrital layers and, ii) brownish areas characterized by multiple flood events (Fig. 2d). Both types are perfectly recognized macroscopically or under the binocular microscope. The detrital layers will be counted using a binocular microscope, confocal microscopy and high-resolution images allowing for color detection. The age-model will be based on novel algorithms designed for speleothems.

Paleoflood frequency patterns under variable climate conditions

One of the advantages using speleothems as paleoflood records is the concomitant opportunity to infer past climate conditions based on the analysis of stable isotopes ($\delta^{18}O$ and $\delta^{13}C$). This will allow us to compare paleoflood frequencies under contrasting climate conditions at local/regional scale inferred from stable isotopes. Flood time-series will be presented as bimodal (flood-no flood) and/or running average, to obtain a homogeneous and comparable flood speleothem record.

Paleoclimate interpretation based on geochemical proxies and reconstructed flood frequency will be analysed and compared with other local to regional Mediterranean paleoflood (and climate) records (e.g. Flood Working Group -PAGES) to evaluate flood patterns at sub-continental scale.

Overview

The MODKARST action will develop new methods for quantitative flood reconstructions in karst systems and will produce a high-resolution regional flood database in the western Mediterranean realm based on speleothems. This project hopes to generate a new quantitative paleoflood record based on speleothems. Its comparison with other European and WM paleoflood records (e.g. fluvial, lacustrine), will constitute a valuable set of paleohydrological data integrating spatial, temporal, and intensity information more comprehensively than a single record. We hope this action will be a benchmark for future research mostly focused on the timing and the magnitude of past flood events.

Author contribution

Original draft and figures: MB; Reviewing and editing: ML, HS, AM, GB.

Acknowledgement

We thank Reyes Giménez (IPE-CSIC), Guillermo Pérez-Villar (UNIZAR), Centro de Espeleología de Aragon (CEA), Juan Carlos Gordillo (Espeleo Club El Farallón), Jaume Mas, Xavier Fuertes (GEB), Alberto Gomollón (SECEM) for their help during the fieldwork in the caves. Miguel Bartolomé is supported by the HORIZON TMA MSCA Postdoctoral Fellowships - Global Fellowships 2022 MODKARST project (nº 101107943) funded by the European Union.

References

Bartolomé, M., Moreno, A., Sancho, C., Stoll, H.M., Cacho, I., Spötl, C., Belmonte, Á., Edwards, R.L., Cheng, H., Hellstrom, J.C., 2015. *PNAS* 112, 6568–6572. https://doi.org/10.1073/pnas.1503990112

Bartolomé, M., Benito, G., Luetscher, M., Badules-Iglesias, J., Pérez-Villar, G., Edwards, R.L., Moreno, A., 2021. *Cuaternario y Geomorfología* 35 (3–4), 11–28. https://doi.org/10.17735/cyg.v35i3-4.89413

Bartolomé, M., Giménez, R., Pérez Villar, G., Gisbert, M., Costa, A., Valenzuela, B., Sagarra, P., Gordillo, J.C., León, V., Luetscher, M., Moreno, A., Benito, A. (2023). *La Cija de Teruel*, nº 18, 15-19pp. D.L: TE 144-2018

Bernal-Wormull, J.L., Moreno, A., Pérez-Mejías, C., Bartolomé, M., Aranburu, A., Arriolabengoa, M., Iriarte, E., Cacho, I., Spötl, C., Edwards, R.L., Cheng, H., 2021. *Geology* 49, 999–1003. https://doi.org/10.1130/G48660.1

Blöschl, G., Kiss, A., Viglione, A., Barriendos, M., Böhm, O., Brázdil, R., Coeur, D., Demarée, G., Llasat, M.C., Macdonald, N., Retsö, D., Roald, L., Schmocker-Fackel, P., Amorim, I., Bělínová, M., Benito, G., Bertolin, C., Camuffo, D., Cornel, D., Doktor, R., Elleder, L., Enzi, S., Garcia, J.C., Glaser, R., Hall, J., Haslinger, K., Hofstätter, M., Komma, J., Limanówka, D., Lun, D., Panin, A., Parajka, J., Petrić, H., Rodrigo, F.S., Rohr, C., Schönbein, J., Schulte, L., Silva, L.P., Toonen, W.H.J., Valent, P., Waser, J., Wetter, O., 2020. *Nature* 583, 560–566. https://doi.org/10.1038/s41586-020-2478-3

Cisneros, M., Cacho, I., Moreno, A., Stoll, H., Torner, J., Català, A., Edwards, R.L., Cheng, H., Fornós, J.J., 2021. *Quaternary Science Reviews* 269, 107137. https://doi.org/10.1016/j.quascirev.2021.107137

Cisneros, M., Cacho, I., Frigola, J., Moreno, A., Stoll, H., Fornós, J.J., Sigró, J., Barriendos, M., 2023. Quaternary Research 1–13. https://doi.org/10.1017/qua.2023.52

Denniston, R.F., Luetscher, M., 2017. *Quaternary Science Reviews* 170, 1–13. https://doi.org/10.1016/j.quascirev.2017.05.006

Gázquez, F., Calaforra, J.M., Forti, P., Stoll, H., Ghaleb, B., Delgado-Huertas, A., 2014. *Earth Surface Processes and Landforms* 39, 1345–1353. https://doi.org/10.1002/esp.3543

Giménez, R., Bartolomé, M., Gázquez, F., Iglesias, M., Moreno, A., 2021. *Frontiers in Earth Science* 9, 209. https://doi.org/10.3389/feart.2021.633698

González-Lemos, S., Jiménez-Sánchez, M., Stoll, H.M., 2015a. *Geomorphology* 228, 87–100. https://doi.org/10.1016/j.geomorph.2014.08.029

González-Lemos, S., Müller, W., Pisonero, J., Cheng, H., Edwards, R.L., Stoll, H.M., 2015b. *Quaternary Science Reviews* 127, 129–140. https://doi.org/10.1016/j.quascirev.2015.06.002

Hall, J., Arheimer, B., Borga, M., Brázdil, R., Claps, P., Kiss, A., Kjeldsen, T.R., Kriaučiūnienė, J., Kundzewicz, Z.W., Lang, M., Llasat, M.C., Macdonald, N., McIntyre, N., Mediero, L., Merz, B., Merz, R., Molnar, P., Montanari, A., Neuhold, C., Parajka, J., Perdigão, R. a. P., Plavcová, L., Rogger, M., Salinas, J.L., Sauquet, E., Schär, C., Szolgay, J., Viglione, A., Blöschl, G., 2014. *Hydrology and Earth System Sciences* 18, 2735–2772. https://doi.org/10.5194/hess-18-2735-2014

IPCC, 2021: Climate Change 2021. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*, Cambridge, UK and USA. https://doi.org/gsjt6f

Jeannin, P.-Y., 2001. *Water Resources Research* 37, 191–200. https://doi.org/10.1029/2000WR900257

Jeannin, P.-Y., Artigue, G., Butscher, C., Chang, Y., Charlier, J.-B., Duran, L., Gill, L., Hartmann, A., Johannet, A., Jourde, H., Kavousi, A., Liesch, T., Liu, Y., Lüthi, M., Malard, A., Mazzilli, N., Pardo-Igúzquiza, E.,Thiéry, D., Reimann, T., Schuler, P., Wöhling, T., Wunsch, A., 2021. *Journal of Hydrology* 600, 126508. https://doi.org/10.1016/j.jhydrol.2021.126508

Kleinen, T., Petschel-Held, G., 2007. *Climatic Change* 81, 283–312. https://doi.org/10.1007/s10584-006-9159-6

Kundzewicz, Z.W., Krysanova, V., Dankers, R., Hirabayashi, Y., Kanae, S., Hattermann, F.F., Huang, S., Milly, P.C.D., Stoffel, M., Driessen, P.P.J., Matczak, P., Quevauviller, P., Schellnhuber, H.-J., 2017. *Hydrological Sciences Journal* 62, 1-14. https://doi.org/10.1080/02626667.2016.1241398

Malard, A., Sinreich, M., Jeannin, P.-Y., 2016. *Hydrological Processes* 30, 2153-2166. https://doi.org/10.1002/hyp.10765

Wilhelm, B., Cánovas, J.A.B., Macdonald, N., Toonen, W.H.J., Baker, V., Barriendos, M., Benito, G., Brauer, A., Corella, J.P., Denniston, R., Glaser, R., Ionita, M., Kahle, M., Liu, T., Luetscher, M., Macklin, M., Mudelsee, M., Munoz, S., Schulte, L., George, S.S., Stoffel, M., Wetter, O., 2019. *WIREs Water* 6, e1318. https://doi.org/10.1002/wat2.1318