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RECORDS OF PAST FLOOD IN CAVES OF THE CENTRAL PYRENEES

Sedimentary evidence and quantification methods

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Changes in rainfall patterns, driven by climate change, are intensifying extreme rainfall events and floods, posing significant social, ecological, and economic challenges. Understanding and predicting flood variability across time and space is crucial, but the instrumental record is too short for accurate long-term analysis. Geological records, particularly those located in caves, offer valuable insights due to their precise chronology, broad temporal range, and preservation. Despite their potential, stalagmites and cave detrital infills remain underutilized for flood studies. Analysing these records, alongside karst hydraulic models and water-level monitoring, can improve our understanding of flood-climate relationships and enhance predictions of flood variability in the context of global warming.

Keywords: **floods**, **paleofloods**, **caves**, **stalagmites**, **climate change**, **cuantification of past floods**.

Global warming has raised widespread concern about the increasing frequency and severity of river floods around the globe. In Europe, there has been a dramatic increase in flood events over the last thirty years, a trend primarily associated with shifts in seasonal rainfall patterns (Blöschl et al., 2020). This rise in flood activity has social, environmental and economic impacts that may intensify in the coming decades. Climate models predict that extreme torrential events will become more intense as a result of climate change, leading to increased risks in vulnerable regions (Merz et al., 2021). However, there is still considerable uncertainty in the models regarding regional variations in flood patterns, as these emerging trends are complex and not yet fully understood.

The unpredictability of regional flooding is especially challenging in Mediterranean regions, where rainfall is irregular and extreme weather events are difficult to predict (Kundzewicz et al., 2017). In these regions, different weather patterns create specific flooding scenarios, making predictions highly variable. In the Pyrenean region, a mountain range with East-West orientation and located in the Western Mediterranean, for instance, the characteristics of flood events differ markedly between seasons. In winter, flooding is primarily caused by Atlantic weather fronts that sweep across the mountain range, bringing widespread rainfall. In contrast, during the summer and autumn months flooding comes mostly from isolated, intense torrential rains, linked to convective storms with a southern component or disconnected from the general atmospheric circulation. These seasonal shifts underscore the complexity of flood dynamics in the Pyrenees.

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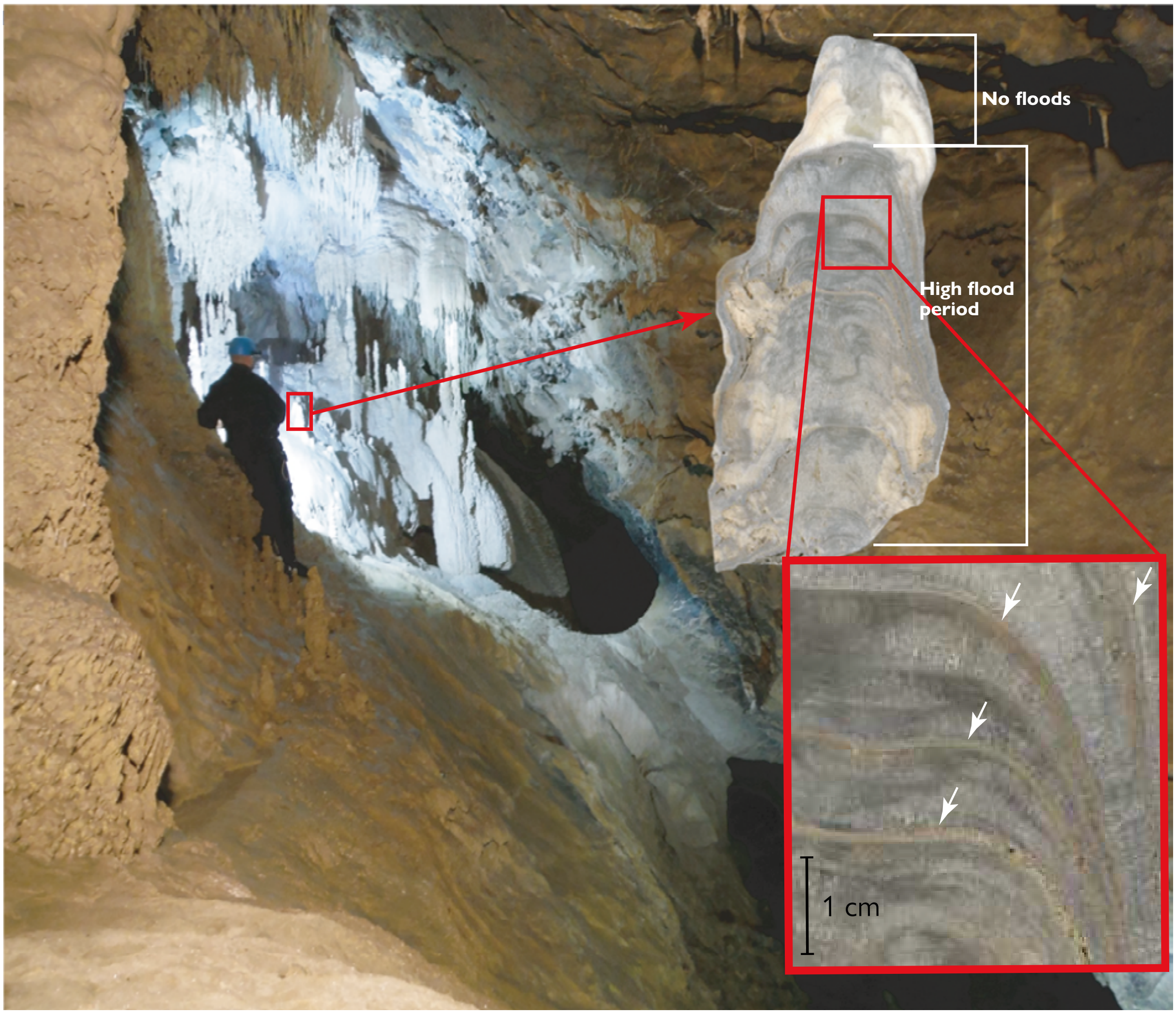

Speleothems located at approximately 9 m over the current cave riverbed. Section of a stalagmite from this area, where periods of both non-flooded and highly flooded are visibly distinguishable, along with a detailed view of the preserved sand-silt layers within the stalagmite (white arrows).

A systematic analysis of flood events in the Pyrenean region from 1981 to 2015 emphasized the severe social and economic impact of these events. This dataset recorded a total of 181 floods resulting in 154 fatalities, highlighting the human toll of these natural disasters. In the Spanish Pyrenees (south face of the range) alone, compensation payments for flood-related damages between 1996 and 2015 amounted to 142.5 million euros (Llasat et al., 2024).

One of the most devastating floods in recent times occurred at the Biescas campsite in the southern central Pyrenees. On 7 August, 1996, an intense storm hit the Arás stream basin, with 178 mm of cumulated rainfall over a 70-minute period and reaching a maximum intensity of 153 mm/h (Gutiérrez Santolalla et al., 1998). The flood destroyed 31 out of the 36 check dams along the Arás creek and the sediment stored in these dams was released downstream, blocking a diversion canal at the apex of the alluvial fan (Benito et al., 1998). As a result, the water and sediment discharged into the mid-distal alluvial fan where the «Las Nieves» campsite was located. Tragically, the flood claimed 87 lives and caused financial losses totalling 81 million euros.

Recent floods in the Pyrenees keep underscoring the region's vulnerability to extreme weather events. For example, in 2012, a flood in the upper Aragón River basin brought over 200 mm of rain in just 48 hours, resulting in significant infrastructure damage (Acín et al., 2012; Giménez et al., 2024; Serrano-Muela et al., 2013). These events highlight how the combination of intense rainfall and the steep topography of the region can quickly lead to destructive flooding.

Most recently, in the September of 2024, an intense storm produced 288 mm of rain in less than 48 hours in the Ordesa and Monte Perdido National Park, causing extensive damage to roads, trails, and bridges, with the damages estimated at over 600,000 euros. Several roads on the northern slopes of the central Pyrenees were also completely destroyed, forcing closures that lasted for months. However, these events were «minor» compared to the severe flooding that struck the Mediterranean region, particularly in Valencia, in October 2024. This was partly due to the lower population density of the Pyrenees area. There, torrential rains cumulated locally 771.8 mm in 24 hours (Agencia Estatal de Meteorología, AEMET), resulting in more than 200 fatalities, and the initial damage estimates exceeded 12 billion euros. Both rainfall events in the central Pyrenees and Valencia were associated to a DANA situation. *DANA*, a spanish acronym for «Depresión Aislada en Niveles Altos» (‘isolated depression at high levels’), refers to a low-pressure system in the upper levels of the atmosphere that has become completely detached from the general atmospheric circulation. These high-altitude depressions bring very cold air to our latitudes and can remain isolated for several days. They often follow erratic trajectories, occasionally moving in a retrograde pattern, from east to west, or remain stationary for hours as in Valencia on 29 October 2024.

These examples highlight the scale and potential impact of intense rainfall across different regions and the land uses, with Mediterranean areas experiencing some of the most catastrophic events.

Historical records also shed light on extreme rainfall events and their impact on regional infrastructure. Documentary descriptions and limnimarks on buildings and bridges serve as records of past floods, providing valuable insight into the magnitude of these natural events in the Pyrenees. Notably, Baringo Jordán and Baringo Ezquerra, (2016) documented several significant historical floods along the Cinca River. In particular, a severe flood occurred on 8–9 November 1982, when the authorities reported a discharge of 4,200 m^3/s in Fraga, a town on the lower Cinca River. The peak discharge may have been as high as 5,500 m^3/s.

These records of past and recent floods highlight the continuing vulnerability of the Western Mediterranean realm to extreme weather events. Understanding these floods is essential to improve forecasting methods, enhance preparedness, and reduce future losses in a region where the effects of climate change are likely to increase flood risk.

THE ISSUE

Accurate precipitation records are essential for estimating flood return periods, but in many cases, these records are too short (Hall et al., 2014) or even non-existent. This lack of long-term data makes it challenging to reliably estimate the recurrence intervals of extreme flood events. To overcome this, it is essential to understand natural flood patterns prior to the human impacts on climate. Extended records are critical for examining the long-term variability of floods on decadal to millennial scales. Paleoflood records, derived from sedimentary layers in rivers or lakes and botanical evidence, allow scientists to quantify flood magnitude and frequency beyond the reach of conventional measurement tools (Wilhelm et al., 2018). Furthermore, environments such as caves – particularly those with internal rivers – offer promising locations for reconstructing local past flood records through speleothems, or clastic infills.

RECORDING FLOODS IN SPELEOTHEMS AND CLASTIC INFILLS

Speleothems, which are carbonate deposits within caves, serve as valuable palaeoenvironmental archives as they can be precisely dated using the uranium–thorium method. Although speleothems have seldom been used specifically for flood reconstruction, recent studies highlight their potential (Denniston & Luetscher, 2017, and references therein). In karst areas, heavy rainfall affects caves and karstic systems with underground rivers, causing them to flood. During a flood within a cave system, sands and silts are carried through the cave and deposited onto speleothems. When the water recedes, speleothem formation resumes, trapping these detrital layers within newly formed carbonate.

«Recent floods in the Pyrenees keep underscoring the region’s vulnerability to extreme weather events»

Over centuries or even millennia, this process creates a layered palaeoflood record unique to a given region. The location of the speleothem within the cave also determines the type of floods it records. Speleothems near streams capture regular flood events, while those positioned further from the river or at higher elevations only register the most significant and extraordinary floods. In some cases, sediments accumulate in blind or sheltered cave galleries, forming thick detrital deposits that provide additional insight into flood history. These deposits consist of paired layers: sand is deposited as floodwaters recede, followed by silts or clays.

CHALLENGES IN QUANTIFYING FLOOD MAGNITUDES IN CAVES

Reconstructing flood magnitudes from speleothem data is complex due to the variety of influencing factors, including changes in land use, sediment supply, and pre-existing water levels (Denniston & Luetscher, 2017). To accurately determine flood magnitudes within a cave, researchers must understand the origin of the cave river's water, monitor flow rates and water levels, and develop hydraulic models that capture the cave's three-dimensional conduit structure (Jeannin, 2001). Observing and monitoring extreme rainfall events is a challenging task, and given the rarity of such occurrences, it may not even be witnessed within a human lifetime. However, with the progression of climate change, the frequency of these extreme torrential events is expected to increase, creating new opportunities to monitor and study them. This trend highlights the importance of expanding monitoring efforts while also emphasizing the need for innovative approaches to better understand these extreme events.

In the absence of direct observations, hydrological modelling offers a valuable alternative for simulating such occurrences. Hydrological models can be calibrated using discharge and water level data, along with cave dimensions and the roughness of cave galleries. Once the model is fitted to current observations, it becomes possible to simulate various scenarios to estimate the amount of water (flow) needed to reach different levels within the cave and to correlate this flow with rainfall amounts through infiltration models (Jeannin et al., 2021). By integrating hydrological observations with cave-specific hydrological modelling, we gain a critical tool for estimating the magnitude of past floods recorded in speleothems or clastic deposits (e.g., Bartolomé et al., 2024). While monitoring and hydrological modelling are valuable tools in understanding past cave flooding, it is crucial to determine how extreme events may alter the cave morphology.

«Paleoflood records allow scientists to quantify flood magnitude and frequency beyond the reach of conventional measurement tools»

During such events, significant amounts of sediment can be transported into the cave, potentially, filling and reshaping the morphology of its galleries. This sediment influx may transform areas previously affected only by rare, extreme floods into zones that experience more frequent inundation, leading to changes on how water flows in the cave. Understanding the timing and nature of sediment deposits within caves is therefore essential. Mapping the exact location and age (using Optically Stimulated Luminescence [OSL] and radiocarbon [^{14}C]) of these sediments allows us to trace past morphological changes in the cave system. Integrating such morphological and geometrical changes into 3D models of the cave prior to hydrological modeling can, for example, help to explain the presence of sand layers recorded in elevated speleothems within the cave, where water would hardly reach under the cave's current configuration. Additionally, dating clastic sediments may support interpretation of sand layers found within speleothems. While such layers are often associated with extreme flood events, clastic deposits of similar age may instead indicate a rapid influx of sediment that significantly altered the gallery morphology. This integrated approach (cave monitoring, cave modelling and cave geomorphology) is crucial for making precise flood reconstructions based on speleothem deposits. Therefore, expanding this integrated approach to new areas and caves can significantly enhance our understanding of flood spatial variability over long timescales.

ADVANCES IN QUANTIFYING PAST FLOOD IN THE PYRENEAN CAVES

As we have shown above, quantifying flood events within caves requires a combination of continuous monitoring, modelling, and cave geomorphological studies. A particularly illustrative example of occurred between 19 and 21 October, 2012, when an extraordinary rainfall event with a return period estimated to between 74 and 200 years (Serrano-Muela et al., 2013) hit the central-western Pyrenees. This event severely affected the headwaters of the Aragón River basin (Acín et al., 2012; Serrano-Muela et al., 2013). Cumulated rainfall in 24 hours was 222.3 mm in Canfranc and 187 mm in Villanúa, resulting in multiple landslides and significant infrastructure damage, such as road destruction and even the collapse of a house near the Aragón River (Acín et al., 2012). These heavy rains triggered sudden hydrological responses in several caves within the Lecherines and Collarada massifs, including the caves in the Villanúa area, namely the Las Güixas, El Rebeco, and Esjamundo caves (Giménez et al., 2024). The Las Güixas and El Rebeco caves have an active stream that reacts to regular rainfall, while the appearance of streams in Esjamundo in response to heavy rainfall is unusual.

In Esjamundo cave, for example, water emerged from the cave entrance for the first time in the memory of the nearby village of Villanúa. The stalagmites in the

Analyzing and characterizing flood layers preserved in the clastic infill of a Pyrenean cave. Each flood event is represented by a sand layer overlain by a silt or clay layer.

flooded galleries of Esjamundo contain layers of sand, suggesting that these speleothems recorded similarly rare rainfall events in the past. Still, the rainfall amounts required to trigger such flooding events, particularly at Esjamundo, remains uncertain, but is estimated to be between 100 and 187 mm (in 24 hours), with some events potentially exceeding 220 mm. In this case the hydrological modelling would help to simulate the minimum amount of water required to inundate the gallery. This provides an opportunity to use these speleothems to reconstruct extreme flood events, thereby improving our understanding of long-term climate and hydrological trends.

Another extreme event was observed at the Artiguo Bajo cave, located near the abandoned village of Estaroniello in the Ordesa and Monte Perdido National Park. This cave, which is still under exploration, contains a wealth of speleothems in areas more than 9 meters above the current streambed. Although the origin of the water that feeds into Artiguo Bajo cave is unclear, recent monitoring shows that its water level responds to rainfall as recorded at the nearby meteorological station. Observations suggest that the water can rise to levels that inundate the higher areas, reaching stalagmites that can record flow events associated with accumulated rain events exceeding 60 mm in 24 hours, depending on water storage in the system. Approximately 11 m above the current water level in the cave, there is a deposit of slackwater sand covering a stalagmite. This deposit shows several flood sequences, possibly associated with rainfall events exceeding 100 mm. During the current observations this sandy deposit never has been affected by floods even with events higher than 100 mm. These examples illustrate how sedimentary layers within cave stalagmites can serve as a natural record of past flood and heavy rainfall events, capturing evidence at different elevations within the caves, and therefore the magnitude of the floods. Quantitative data from monitoring and modelling enhances our ability to interpret these records accurately.

Two stalagmites from the main gallery in Esjamundo cave, which was flooded in 2012, show how the silt deposited during the flood is partially remobilized toward the flanks of the stalagmites. This silt has been cemented by carbonate precipitation. The layers of sand within the stalagmites in Esjamundo's flooded galleries suggest that these speleothems have recorded unusual rainfall patterns in the past.

This stalagmite is covered by a slackwater deposit and is located more than 11 metres above the cave riverbed in Artiguo Bajo, Ordesa and Monte Perdido National Park. The site exhibits evidence of multiple flooding events, potentially linked to rainfall exceeding 100 mm. However, during ongoing observations, the deposit has not been impacted by flooding.

Another example is the Cañón de Aso cave, near the confluence of the Aso and Bellos rivers in the Ordesa and Monte Perdido National Park. The Aso Canyon cave offers a fascinating insight into the region's hydrological history. Inside the cave lies a sequence of over 100 flood events that have yet to be dated, demonstrating the dynamic interplay between rainfall, sediment transport, and the hydrology/hydrogeology. The Aso river is predominantly dry, and only its final stretch, before it joins the Bellos river, maintains a perennial flow fed by a spring. However, rainfall events of more than 20 mm are sufficient to activate the river, causing it to inundate the cave and introducing fine sediment and plant debris. More intense precipitation triggers the cave's internal river system, forcing water outwards. This causes the erosion of previous sediments, which could explain the complex stratigraphy of the aforementioned deposit.

In a nearby cave, sedimentary deposits located in rock shelters reveal past floods in the area. In one of the rock shelters, at an elevation of 4.4 m from the riverbed, nine distinct flood layers have been identified. Preliminary hydraulic modeling suggests that a flow rate of 55 m^3/s is required for producing deposition inside the rock shelter. Meanwhile, a historical flood mark located downstream of the Aso-Bellos confluence reminds us that, on 21 October 1977 the flood reached a staggering height of 15–20 meters above the riverbed.

Overall, these findings highlight the value of integrating monitoring, modelling, and cave geomorphology to understand the dynamics of the cave flooding. Observations and monitoring of rare flood events offer insights to calibrate flood layers in speleothems to reconstruct long-term hydrological patterns and their potential links to climate variability. By further refining these methods, scientists can gain a deeper understanding of both past and future flood risks in karstic mountain regions. ⊕

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This plaque in the Aso Canyon cave, located within the Ordesa and Monte Perdido National Park, indicates the height that the floodwaters of the Bellos (or Vellos) River reached on 21 October 1977.

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