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Research papers

Towards the use of acoustic monitoring in karst networks to infer hydrological dynamics during flood events

Alessandro Mastella [a], Francesco Sauro [b,*], Michel André [c], Mike van der Schaar [c], Maria Filippini [a], Guido Rossi [d], Guido Gonzato [d], Ennio Nicolini [e], Jo De Waele [a]

[a] Department of Biological, Geological and Environmental Sciences, Italian Institute of Speleology, Bologna University, Via Zamboni 67, 40126 Bologna, Italy
[b] Department of Geosciences, University of Padova, Via Gradenigo 16, Italy
[c] Laboratory of Applied Bioacoustics, Universitat Politècnica de Catalunya, BarcelonaTech, Passeig Maritim 1, Vilanova i la Geltrú, Barcelona, Spain
[d] Unione Speleologica Veronese, Via Bionde 61, 37139 Verona, Italy
[e] Associazione Troglobius APS, Bosco Chiesanuova, Italy

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ABSTRACT

Monitoring flood events in caves is a significant challenge due to the high energy and destructive nature of floods, which pose risks to submerged sensors and data transmission systems. This has resulted in a scarcity of studies focusing on flood propagation and its effects on air–water interactions. Notably, previous research has largely overlooked the integration of acoustic monitoring with traditional hydrological parameters.

This study addresses this knowledge gap by testing a multiparametric hydrological and acoustical monitoring within Spurga delle Cadene (Lessini Mountains of Verona, Italy). This cave acts as temporary overflow karst spring with high water discharge during flood events. Infra-to-audible sound acoustic alongside water level and air pressure monitoring was employed to investigate the hydraulic functioning of the cave-spring system. Integrating these different methodologies revealed that the compression, isolation, and subsequent release of trapped air volumes in various cave compartments fundamentally influence water-level rise, pressure evolution, and flood propagation, through a newly identified process called the “Plunger Chamber Effect”. Additionally, a detailed analysis of low frequencies (<50 Hz) revealed specific repetitive acoustic patterns that consistently preceded the flood rise and accompanied its recession. These sounds are related to the release of air pockets associated with conduit morphologies and water levels. Identifying these repetitive sound patterns paves the way for the deployment of cave-specific early warning flood alert systems. This case study not only underscores the importance of integrating acoustic monitoring with classical hydrological methods providing a more comprehensive understanding of flood mechanisms in subterranean environments.

1. Introduction

Water flow and flood events in confined conduits, such as active karst systems, can produce peculiar sounds related to flow regimes, water–air interactions and geometries of the conduits (De Waele and Gutiérrez, 2022). Despite the fact that these phenomena have rarely been analysed and monitored in detail, their nature could reveal interesting insights on flow dynamics in underground systems, including the possibility to forecast or provide alerts for the onset of extreme hydrological events. Recently, Pantiga et al. (2025) successfully applied noise monitoring of seismic infrasounds (at 7–12 Hz) to characterise the flow dynamics in a French karst system with surface-based seismometers, while Luhmann et al. (2025) have applied ambient seismic noise to monitor injection experiments in karst aquifers, showing that most of the noise is probably originated by overpressurised air pocket release during rising floods. Sauro (2023) has discussed the potential of infra to ultra sound monitoring in cave environments for different applications, ranging from hydrology, seismic events, biology and human impacts to the subsurface environment, while Piechowicz et al. (2018) has discussed the different acoustic behaviour of caves carved in different materials. The advantage of acoustic monitoring lies in the simple use of one single recorder inside the cave environment able to capture all different sound events across the environment.

Until now, monitoring underground extreme hydrological events

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* Corresponding author.
E-mail address: francesco.sauro@unipd.it (F. Sauro).

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such as floods with *in situ* instrumentation has been challenging due to the high energy of these phenomena, putting at risk submerged monitoring sensors, data loggers and transmission cables, which are necessarily installed within or in proximity of the water flows. Because of these reasons, studies on flood propagation and its effects on cave chamber air–water pressure interactions are still very limited and mainly related to peculiar situations (Bonacci and Bojanić, 1991; Sanz Pérez et al., 2016; Stroj and Paar, 2019; Pellet et al., 2024). None of these studies has ever considered the possibility of associating sound monitoring with other parameters like air pressure and water levels to better understand flood mechanisms. Continuous monitoring of sound in air-filled cave chambers, especially in high areas not reached by flood waters, could represent a novel remote sensing method in karst systems, providing new insights on still poorly known hydrological phenomena. Sound monitoring could be feasible in cases where the karst system is partially accessible during periods of low water levels. In addition, for a safe instrument deployment it is necessary to identify at least a cave chamber or conduit ceiling that is never reached by floods. Such intermittent springs and epiphreatic karst networks with multilevel conduits are common in karst regions and often allow speleological access for hydrological monitoring only during periods of low water levels (Gabrovšek et al., 2018; De Waele and Gutiérrez, 2022). Installing acoustic recorders would enable the monitoring of hydrological behaviour during periods of hydrological activation precluding safe direct speleological visits and observations.

The purpose of this study is to investigate the hydraulic functioning of a temporary spring cave system (Spurga delle Cadene) during flood events by combining acoustic with classical hydrological monitoring (water levels and air pressure). Flood events in this cave are charachterised by different sound sources, potentially analogues to those recorded during fluvial flood events at the surface (Osborne, 2022) or also to peculiar processes happening in the confined cave environment, as the release of air pockets that have been compressed in confined spaces as a result of the flooding (Wright et al., 2017; Luhmann et al., 2025). To explore potential mechanisms behind these sounds, we implemented a pioneering approach based on continuous acoustic environmental monitoring across the infra- to audible range within aerial cave chambers situated in the vicinity of cave channels with occasional water flow. During floods, the acoustic instrument captured signals spanning a wide frequency spectrum (under 10 Hz to 16000 Hz), yielding unprecedented data that could be correlated with hydrological dynamics inferred from water level and air pressure measurements. This

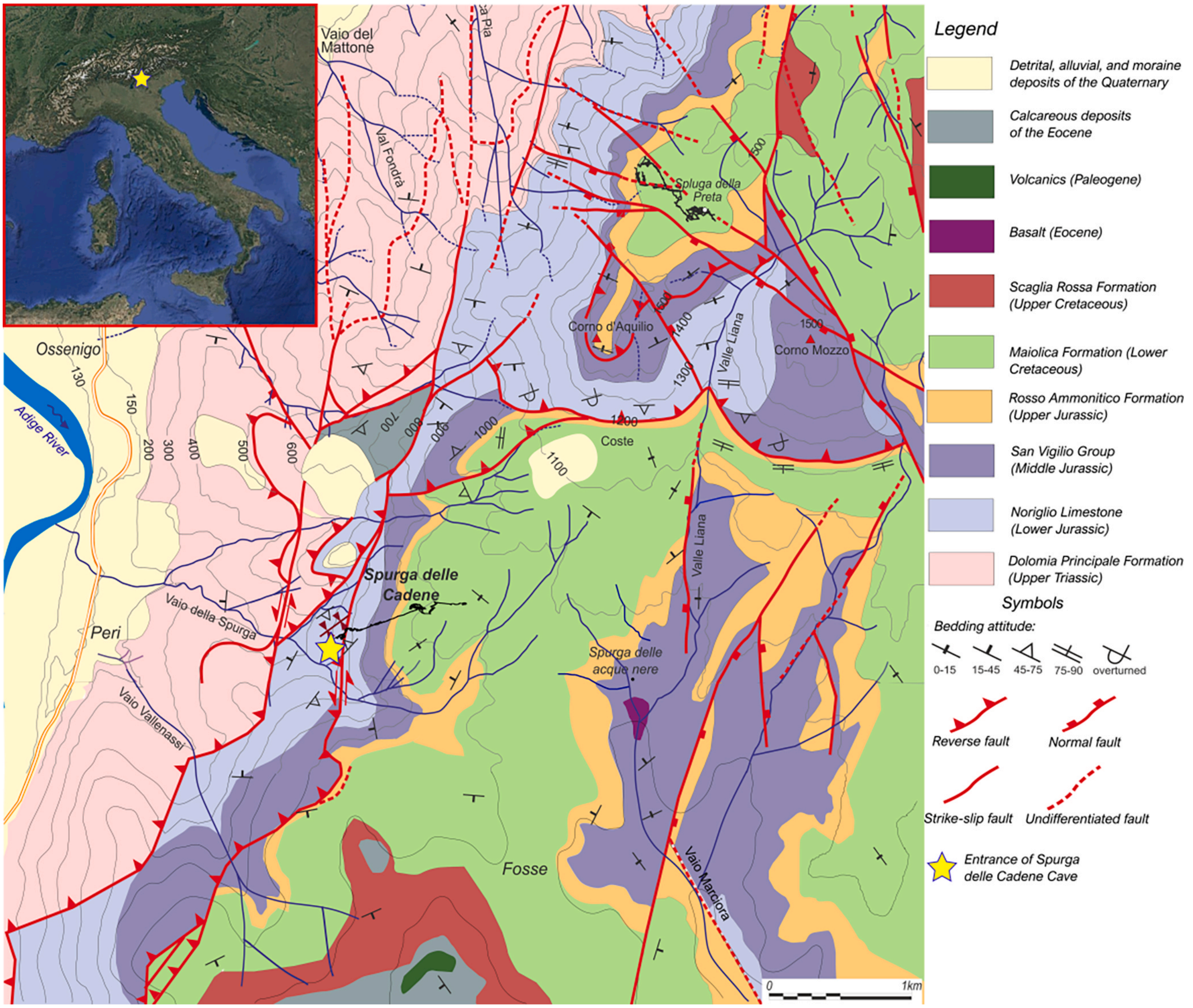

Fig. 1. Simplified geological map of the Val d'Adige-Slopes where Spurga delle Cadene is situated (from Menichetti et al., 2011). The recharge basin of the spring is situated between Spurga delle Acque Nere and across the Valle Liana and Corno Mozzo mountain.

integration could provide new insights into the role of water–air interactions in controlling flood dynamics within karst conduits. The primary objective of this study was to evaluate the possibility to identify sounds related to key water–air processes governing flood dynamics. As a secondary perspective, the monitoring was used to test the potential presence of sounds anticipating the flood allowing the potential development of future site-specific early-warning technologies for extreme events. Overall, this case study introduces a powerful new methodology for monitoring flood phenomena in accessible karst systems and offers valuable perspectives for karst hydrology research.

2. Study area

2.1. Geographical, geological, and climatic settings

The investigated spring cave system is known as “Spurga delle Cadene” and is located in the Lessini Mountains, the southernmost extension of the eastern Sudalpine domain, considered as the weakly deformed foreland of the Neogene-Quaternary South Alpine Chain (Sauro et al, 2012) (Fig. 1). The Lessini Mountains constitute an extensive karst plateau incised by valleys predominantly oriented N–S, developed along faults and tectonic lineaments that control both morphology and subsurface groundwater circulation. The plateau represents one of the major karst regions in Italy, with more than 850 mapped caves (Mietto & Sauro, 2000). Surface drainage is limited and strongly subordinated to karst processes, with rapid infiltration of meteoric waters and recharge of a deep karst aquifer. Lithology plays a key controlling role: Jurassic limestones host the main karst conduits, whereas the Maiolica Formation, characterised by semi-permeable behaviour, acts as a reservoir rock by modulating groundwater storage and delayed release. Erosion in the area operates selectively according to lithological properties, controlling the development of both surface and subsurface karst landforms (Mastella, 2024). The Lessini Mts. are characterised by a predominantly monocline structural configuration with limited tectonic deformations. Spurga delle Cadene Cave opens on the western border of the Lessini block on the slopes of the deep glacial incision of the Southern Adige Valley (Vallagarina; Bassetti and Borsato, 2005). This area is characterised by NNE-SSW faults pertaining to the Adige Valley tectonic system. The entrance is located at 567 m a.s.l., approximately 400 m below the summit plateau of Fosse. The entrance area is characterised by the presence of two main subparallel faults with a NNE-SSW direction, approximately 300 m apart. The faults exhibit reverse kinematics with a strike-slip component, and their inclination is slightly greater than that of the eastern slope of the Vallagarina. The two main faults delineate a pervasively deformed tectonic block where the Spurga delle Cadene Cave opens at the core of a spectacular syncline. The cave is formed within the Formazione di Rotzo (Calcari Grigi Group) and is intersected in multiple points by tectonic structures belonging to the Adige Valley tectonic system, which largely influence its morphology and hydrogeological regime (Rossi and Zorzin, 2011). The recharge area has been identified in the Fosse plateau area and particularly in the *Vajo delle Acque Nere* karst sinks approximately 1700 m to the east of the cave entrance (Rossi, 1987). Nonetheless, the flood response time and duration associated to the precipitation distribution on the plateau (measured at the rain gauges of Fosse and Passo Fittanze) indicates that the cave system is probably also the main outlet for other distant areas situated more to the north-east of the Fosse village, like Valle Liana and Corno Mozzo (Mastella, 2024).

2.2. The Spurga delle Cadene morphology and hydraulic behaviour

Spurga delle Cadene Cave has been explored by speleological expeditions to a mapped length of approximately 1250 m (Rossi and Zorzin, 2011). The cave functions as a large temporary overflow karst spring, with water emerging from its entrance only during periods of flood, which coincide with intense precipitation in the recharge area of the plateau (Figs. 1 and 2). During such events, water flows out of the entrance portal with high discharge, driven by the overpressures developing within the karst network, with rates in the order of several hundred litres per second (Fig. 2; Zorzin, 1996). During dry periods, instead, the perennial stream within the cavity is entirely drained by a fault intersecting the cave 150 m from the entrance, leaving the cave entrance dry (Artoni and Rebesco, 1990).

The cave’s most peculiar feature lies in its name, likely given several centuries ago, which reflects the sounds emanating from its entrance during high flood events. In ancient times, the local inhabitants associated these rumbling sounds with the noise of shaking chains ('cadene' in the local dialect) and named the cave accordingly. These sounds, which could be heard from a great distance, were traditionally believed to anticipate the arrival of the flood wave. The hydraulic properties of the cave derive from its peculiar morphology and geological setting, mainly due to an elevation difference between two distinct sectors of the conduit. From the entrance, the cave develops along the axial plane of the syncline (Rossi and Zorzin, 2011). This section, termed the “Upper Channel”, is usually dry and is reached by the stream only during important flood events. Approximately eighty meters from the entrance, the cave intersects a fault of regional significance that marks the boundary of the heavily deformed block to which the syncline belongs. From this fault onwards, the cave morphology changes. The conduit descends 6 m through a narrow and inclined corridor until reaching the “*Lago Pensile*” (Hanging Lake), where the perennial underground brook appears. During low-flow periods the internal stream flowing from the Hanging Lake sinks and disappears along the fault, which functions as a primary drainage route in normal flow regimes. This cave section is referred to in the present study as the “Lower Channel”. Beyond the fault (and this sinking point) and the Hanging Lake, following the underground watercourse upstream, the cave opens in the large chamber named “*Sala delle Meraviglie*” (Hall of Wonders). This chamber, situated upstream of the narrow sinking point, plays a fundamental role in the hydraulic mechanism, since it works as a large air volume that can be isolated from the other cave conduits and chambers when the water level rises during floods. While the monitoring has been focused on these two sectors of the cave (upper dry entrance channel and lower active channel), the cave continues upstream of the Hall of Wonders with a series of beautiful conduits and canyons up to a 60 m long, 5 m deep submerged passage explored by cave divers. On the other end of this underwater tunnel the cave opens again in air-filled conduits for approximately additional five hundred meters, including another big chamber (*Sala Faccioli*), until becoming too narrow for further human exploration. The entire cave survey (plan view and profile) is provided in the Supplementary Materials Fig. 1.

3. Methods

A monitoring campaign was designed involving the installation of various instruments for water level, air pressure and acoustic monitoring within the conduit from September 2023 to January 2024 (4 months). Discharge measurements with flow rate meters were considered impractical in the cave due to irregularity of passage morphologies and the high energy nature of the floods crossing the Upper Channel. The pluviometric data used in the study were obtained from the rain gauge station located in the village of Fosse, at 923 m a.s.l., within the main hydrological recharge basin of the cave.

3.1. Water level and air pressure measurements

Two HOBO pressure transducers (HOBO 1 and HOBO 2 in Fig. 3), model U20L (Onset), with sensitivity limits of 9 m and 4 m, were installed respectively downstream and upstream of the Hanging Lake. The instruments were configured to record a measurement every 15 min throughout the entire monitoring period. An additional HOBO U20L pressure transducer (PA1 in Fig. 3) with sensitivity limits of 4 m was

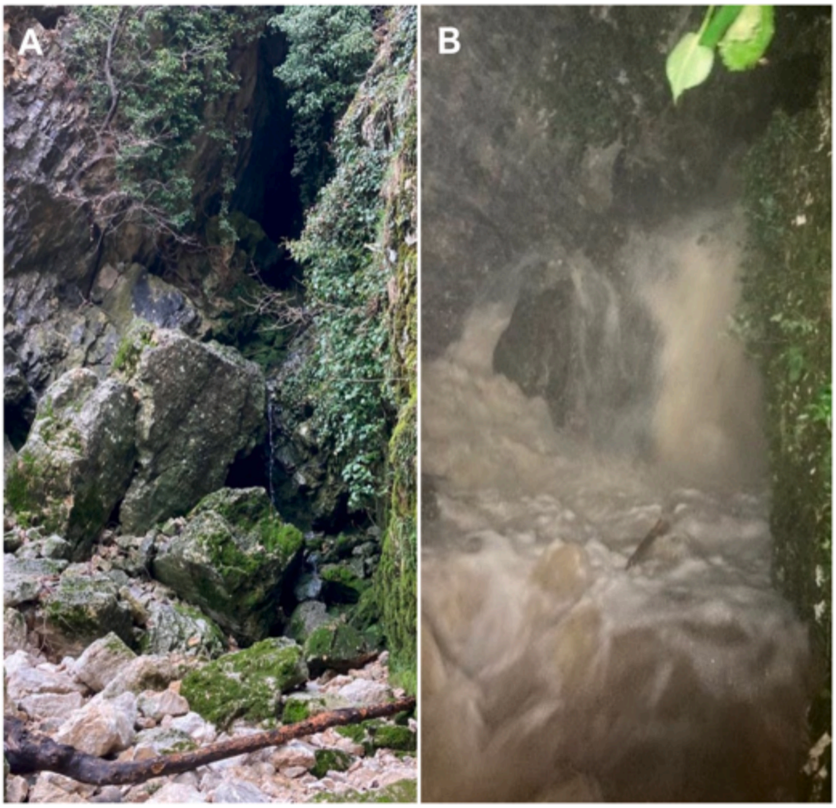

Fig. 2. Comparison between dry conditions (A) and a flash flood event (B) at the entrance portal of the Spurga delle Cadene Cave. Floods can be powerful with a water jet expelled for over four meters ahead of the cave entrance.

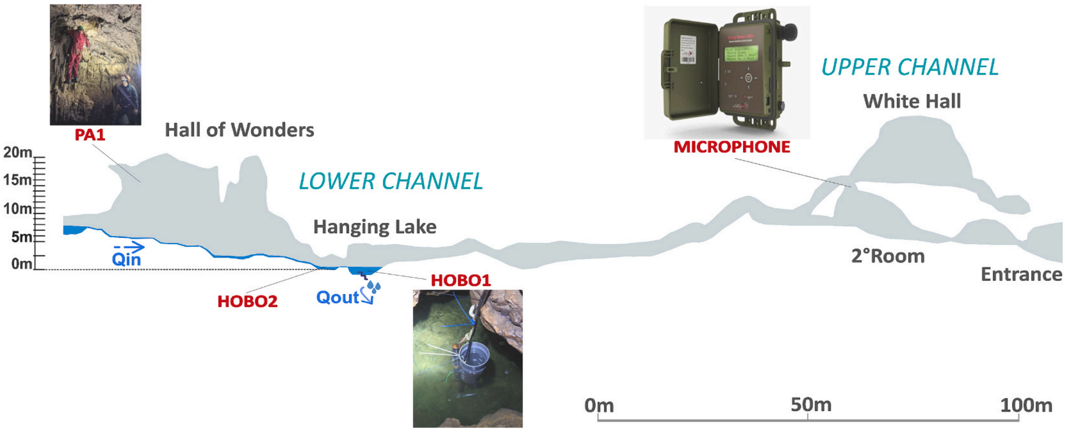

Fig. 3. Cave profile with location of the installed monitoring equipment. On the left, a Hobo monitoring atmospheric pressure device has been installed higher up the wall of the Hall of Wonders to avoid potential interactions with rising waters. In the centre, one of the two Hobo monitoring devices is positioned inside a protective tube to ensure protection during flood events. On the right, the SM4 acoustic monitoring device is installed in the upper White Hall chamber, just above the gallery where water flows during flood events.

positioned further upstream hanging in the air on the 12 m high roof of the Hall of Wonders to measure atmospheric pressure variations in this chamber. The atmospheric pressure data from PA1 were used to calibrate the two submerged pressure transducers HOBO 1 and HOBO 2.

3.2. Sound measurements

A bioacoustic recorder specifically designed for harsh environments was installed in the highest chamber of the cave, 15 m above the Upper Channel (*Sala Bianca*, or White Room, microphone in Fig. 3). Both the morphology of this chamber and the presence of intact fragile speleothems suggest that this height of the cave is seldom reached by rising waters during flood events, providing a safe place for the instrumentation even during flood events when waters are flowing also through the Upper Channel. The White Room chamber is close (approximately 20 m) to the cave passage connecting the lower and the upper channels, but far enough from the cave entrance (approximately 50 m, including two narrow passages less than 1 m high) excluding any sound disturbance from the exterior. The recorder was a Wildlife Acoustics Song Meter (SM4 model) equipped with two integrated omnidirectional microphones designed for high-quality recordings with a sample rate of 16000 Hz and a factory sensitivity of −35 ± 4 dB re 1 V/

Pa (at 1 kHz). A gain of 10 dB was assumed for the level calculations. The recording system was not calibrated before deployment, since we considered of interest here only the relative change of sound levels as correlated with the change in other parameters, not per se the absolute levels. The huge amount of recorded sound (approximately 5 TB) was subsequently loaded into the ‘Listen to the Deep Ocean Environment (LIDO)’ system (http://lido.listentothedeep.com; Supplementary Materials), an international program led by the Laboratory of Applied Bioacoustics (LAB) at the Technical University of Catalonia, Barcelona Tech (UPC). The LIDO platform divides 1 h of sound recording in 225 segments of 16 s each. The segmentation allows extracting dB relative values for each selected frequency as time series, with sound pressure levels presented unweighted in dB relative to 20 μPa. In order to define the frequencies of interest for the study of cave flood dynamics, we based our selection on the work of Osborne (2022) showing that sound generated by flowing water arises from physically distinct processes, each characterised by specific frequency bands. Low-frequency components (within the 1–50 Hz interval) are associated with large-scale hydrodynamic oscillations, flow–bed frictions, channel-scale pressure fluctuations, and sediment transport (Osborne, 2022). In contrast, surface turbulence and air-entrainment (formation, transport, and breakup of air bubbles; Minnaert, 1933) should produce broadband acoustic signals at higher frequencies approximately in the ~0.4–2 kHz range. Following these considerations, we have extracted a set of representative frequencies in third octave bends (Crocker, 1998): 10 Hz, 15.8 Hz, 31.6 Hz, 100 Hz, 398 Hz, 1995 Hz and 6310 Hz (Figs. 5–6 and Supplementary Materials Figs. 2–4).

4. Results

Daily cumulative precipitation and pressure transducer at the Hanging Lake (Fig. 4) indicate that during the monitoring period eight flood impulses crossed the cave conduits, with a high water level peak ranging between 5.66 m and 6.65 m above HOBO2 position. The analysis reveals a clear correlation between intense daily precipitation events in the recharge basin and peaks in water column height, which directly correspond to flood episodes within the karst conduit. The floods at the cave arrive between 6 and 11 h after the peak of the precipitation events (Mastella, 2024). Such a response time is relatively fast for a karst system and is consistent with a well-developed conduit network, a behaviour typical of mature conduit-dominated aquifers (De Waele & Gutiérrez, 2022). Comparable rapid responses are observed at the Montorio springs—located at the foot of the Lessini Mountains—which show marked discharge increases shortly after rainfall events, confirming the high degree of karstification and conduit connectivity of the Lessini aquifer, within which such response times are fully consistent (Antonelli et al., 1991).

The pressure transducer (PA1) installed in the Hall of Wonders shows slight fluctuations of air pressure during periods of normal hydraulic inflow and outflow, easily correlated to meteorological and climatic variations (Fig. 5A). In contrast, during each recorded flood event, very pronounced positive air pressure peaks are observed, reaching values a few tens of kilopascals higher than those measured during ordinary periods. The data relating to atmospheric pressure and those relating to the water level height of the stream inside the cave show coincident growth phases (Fig. 5A).

The atmospheric pressure curve exhibits very similar and cyclical fluctuations across different flood impulses: it shows an initial increase with a variable maximum peak that coincides with the arrival of the flood in the upper channel, followed by a decreasing phase usually reaching values slightly below pre-flood levels with minor oscillations correlated with minimal variations in water level. Toward the end of the flood, the atmospheric pressure conditions experience a strong depressurization phase, with values 4000–5300 Pa lower than normal, coinciding with the end of the flood.

Regarding acoustic monitoring, the different frequencies show varying intensities, with a marked rise of over 50–60 dB consistent with hydrological changes (Fig. 5B and 6). The recorded data shows that the intensity of the sampled frequencies increases abruptly especially when the water column reaches the threshold allowing the flow in the upper channel (Fig. 6), while during the recession phase of the event, it tends to decrease more slowly. Beyond the overall trend, it is worth noting that all the three low frequencies (10 Hz in Fig. 6 and 10 Hz, 15.8 Hz and 31.6 Hz in Fig. 5B) show periods with additional spikes of shorter duration corresponding to the rising and recession phases of the flood. The behaviour of the low frequency curves (Fig. 5B, 6, 7 and 8) appears consistent with a period of great intensity oscillations and narrow peaks preceding the flooding of the Upper Channel and lasting for few hours during the recession phase, especially when the flow in the Upper Channel has ended. During the high flood phase, these narrow low frequency peaks disappear and the intensity curves exhibit highly variable behaviours, corresponding to fluctuations in the water column, and therefore in the flow intensity in the Upper Channel (Fig. 6). While frequencies >50 Hz could be useful to correlate overall sound intensities to flow discharge, the low frequencies < 50 Hz are showing spike sound events probably unrelated to the flow itself. During the rising phase, these peaks are clearly visible in all three low frequency bands, but they can be more distinctly tracked at 31.6 Hz (Figs. 5B and 7). Similarly,

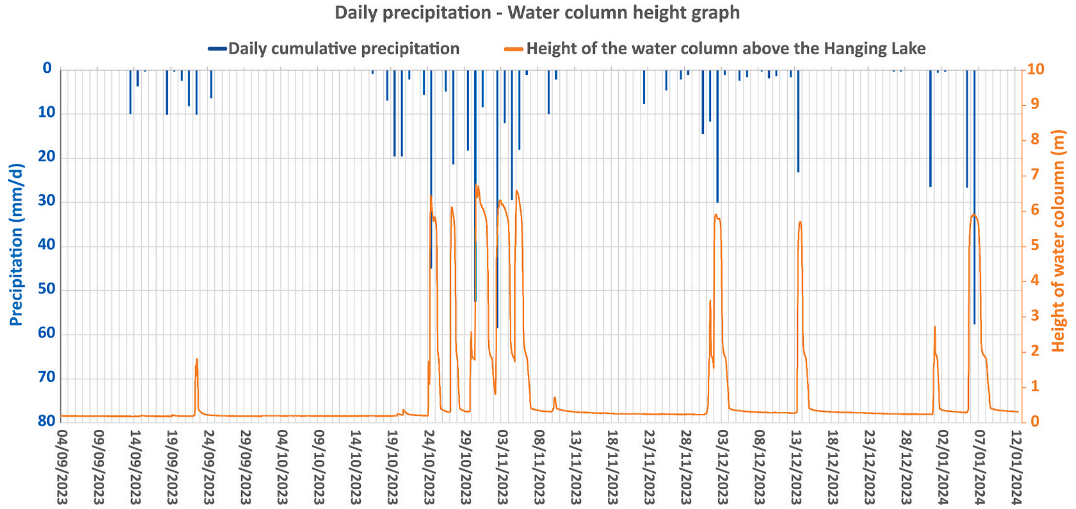

Fig. 4. Summary chart of the monitoring period showing daily cumulative precipitation and water column height measured at the Hanging Lake (HOBO2). Precipitation between 30 to 40 mm/day are triggering the flood events.

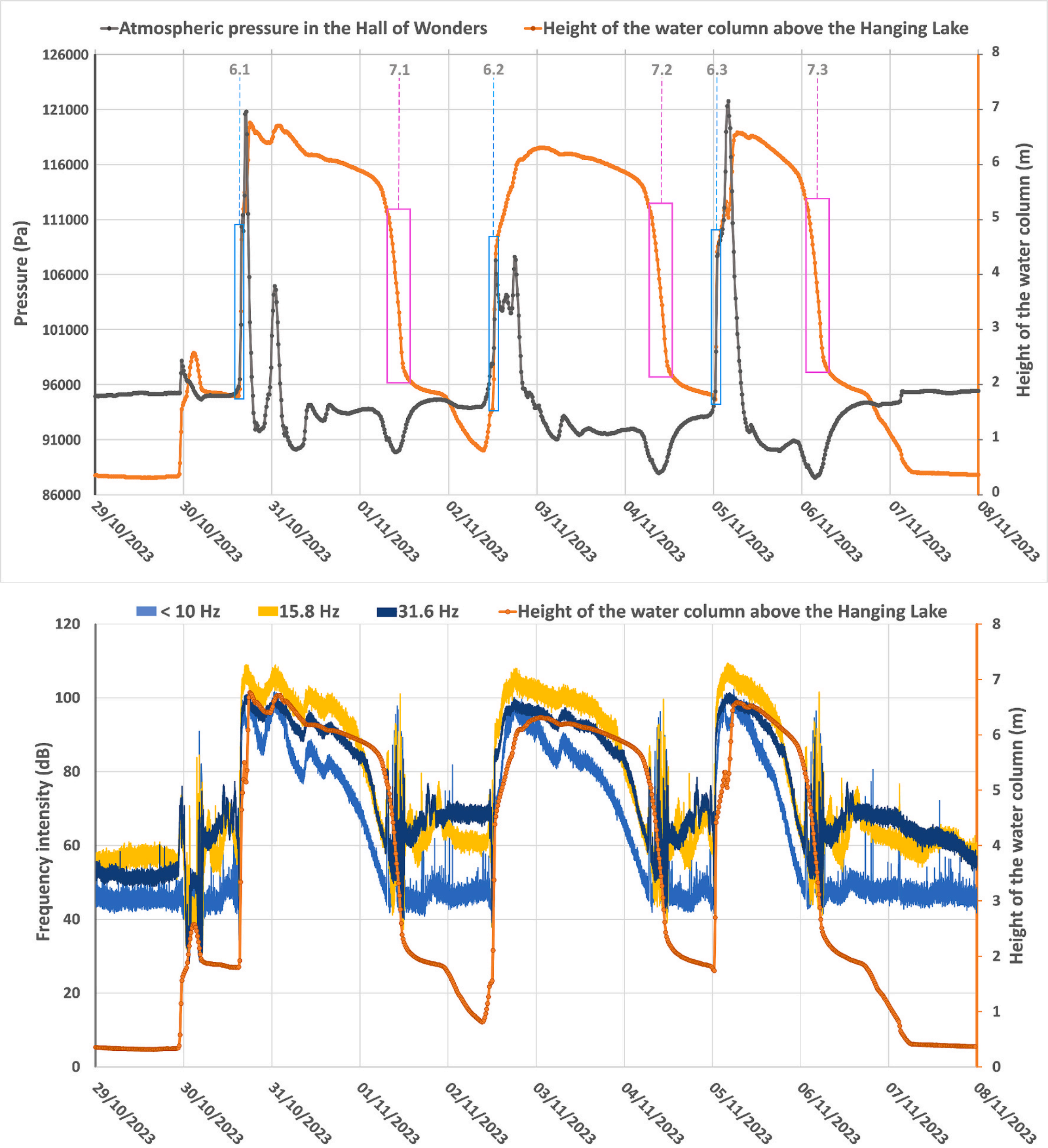

Fig. 5. Example of variations in water level (at HOBO2) and air pressure (A), water level and sound frequency intensities (B; low frequencies: <10 Hz, 15.8 Hz, and 31.6 Hz) for three flood events occurring between October 29 and November 8, 2023. Boxes and numbers in A are indicating some of the peak intensity series illustrated in Fig. 7 and 8 during the rising and recession phases.

during the recession phase (Fig. 5B and 8), a marked disturbance is observed in the low frequencies, characterised in this case by short and prolonged peaks of high intensity, that are best resolved at 10 Hz. All these peaks repeat with the same pattern (in the rising or recession phase) in all flood events recorded.

5. Discussion

5.1. *Air-water dynamics during flood events*

A simplified conceptual model of the air–water interactions in the cave during flood events was developed based on water level and air pressure monitoring (Fig. 9).

Under intense precipitation conditions in the recharge area, the infiltrating waters reach the cave system within a few hours (between 6 and 11 h; Mastella, 2024), causing an increase in upstream inflow from *Qin*-1 (Fig. 9A) to *Qin*-2 (Fig. 9B). As the excess water cannot be efficiently discharged through the narrow crack present in the Hanging Lake (*Qout*), water begins to accumulate, and consequently, the piezometric level in the lower channel tends to rise.

Analysis of data collected during various recorded flood events has shown that the overflow of the water in the upper channel systematically coincides with a marked increase in atmospheric pressure recorded in the Hall of Wonders. A closer examination of what occurs in this chamber shows that, during the rising phase, the water level builds up until isolating an air mass, occluding the narrow passage of the Hanging Lake which usually connects this chamber to the upper conduits. Since also the gallery upstream of the Hall of Wonders is completely flooded, the air is trapped. The progressive increase in the piezometric level tends to compress the air. Fracture permeability in the rocks surrounding this chamber evidently does not allow air to escape fast enough to avoid air pressure increase. Upon reaching a critical value, the internal

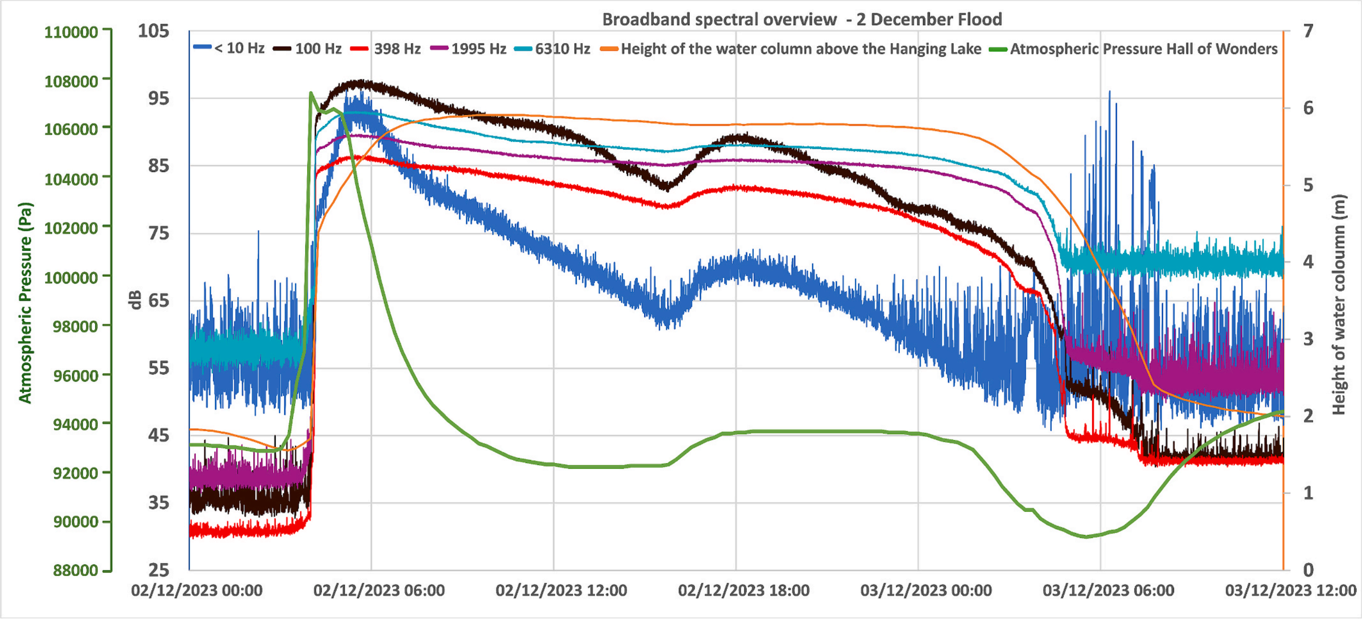

Fig. 6. Example of variations in water level (at HOBO2), air pressure and sound intensities at different frequencies (10 Hz, 100 Hz, 398 Hz, 1995 Hz, 6310 Hz). Compared to the others, low frequency 10 Hz contains much more disturbance during the rising and recession phase of the flood.

atmospheric pressure in this chamber constitutes the propulsive element capable of triggering the violent water outflow through the upper channel. The driving force of the process is represented by the pressure exerted by the compressed air mass in the Hall of Wonders on the water column. This phenomenon can be explained by two fundamental principles of fluid physics: Stevin's law and the principle of communicating vessels (Spellman and Whiting, 2004). The latter describes how, under equilibrium conditions and uniform atmospheric pressure, a fluid in interconnected conduits attains the same level throughout, reaching a uniform equipotential surface. Collected data indicate that air pressure is not uniform in the different cave chambers. Considering a simplified system with two interconnected arms A and B (for Spurga delle Cadene identified as "Lower" and "Upper" channels respectively in Fig. 9) containing a liquid, in arm A, the liquid is subjected to an internal air pressure P1, while in arm B it experiences atmospheric pressure Patm, with P1 ≫ Patm.

According to Stevin's law, the total pressure at the separation surface, i.e., at the central point of the system, must be equal in both arms:

$(1)\ P1 + \rho g hA = Patm + \rho g hB.$

Where ρ is the fluid density (mass per unit volume), g is the gravitational acceleration, *hA* and *hB* are the liquid column heights in arms A and B respectively, *P1* is the internal air pressure in the Hall of Wonders, and *Patm* is the atmospheric pressure outside the cave. As an example, data from the flood on October 30, 2023 (Fig. 5) show that in an initial phase, instrumentation recorded in Hall of Wonders a $hA = 4.64$ m with an internal air pressure of 110,257 Pa, while atmospheric pressure along the upper channel was 95,058 Pa. Therefore, applying Stevin's law the water level in *hB* was 6.19 m.

During the flood event, pressurisation of the Hall of Wonders caused an increase in the water column along arm B (Upper Channel) of 1.55 m compared to arm A (Hall of Wonders). This pressure and water height difference allows the flood to reach a height sufficient to overcome the elevation difference with the Upper Channel with significant rates of water rise (between 6 and 17 cm/min). The air pressure difference between the Hall of Wonders air pocket and the atmospheric pressure in the Upper Channel, which is in equilibrium with the exterior atmosphere, is driving the height difference of the water column between the two areas of the cave. This phenomenon is probably characteristic of irregular karst conduits characterised by big chambers alternating with narrow passages; therefore, we propose to name it the "Plunger-Chamber Effect".

Once the threshold is overcome, the flood wave flows with high discharge through the upper channel (see Supplementary Materials), exiting from the cave entrance with a turbulent jet governed by the overpressure exerted by this peculiar process (Fig. 2). The analysis of the recorded data has shown that the Plunger-Chamber Effect is consistently associated with the water level reaching an elevation between 4,3 and 4,6 m in *hA* (approximately between 5.5 m and 6.2 m in *hB*). In all observed events, the onset of flow along the upper channel is marked by an inflection in the rising curve of the internal air pressure within the Hall of Wonders. This inflection represents the stage when the water finds a pathway through the upper channel. The newly activated flow path, which until that moment had only been filling above the Hanging Lake, acts as a release mechanism, attenuating the rise of the hydraulic level in the lower channel and, consequently, also mitigating the increase of atmospheric pressure in the Hall of Wonders. In this phase, the upstream inflow corresponds to *Qin-3* (Fig. 9C), while there are two outflows: *Qout-3a*, which disappears through the fault sink located below the Hanging Lake, and *Qout-3b*, of much greater magnitude, which exits from the cave entrance. The process continues until *Qin-3* < *Qout-3a* allowing the water column to decrease until the level in the Hall of Wonders drops below the discharge elevation coinciding with the Upper Channel.

On the other hand, the negative atmospheric pressure peak observed during the recession phase is associated with the expansion of the air mass present in the Hall of Wonders. The air in this chamber has been partially expelled during the rising phase, probably flowing through narrow rock fractures in contact with external surface and other cavities. Therefore, the amount of air is reduced compared to the initial value and, having a larger space available, the chamber reaches depressurised conditions. The depressurisation continues until the receding water levels allows again the connection of the Hall of Wonders with other cave compartments, or when the fracture network connectivity to the surface is freed by flood waters (Fig. 6). In addition, we have to consider that the phenomena of air entrainment in the turbulent waterflow in the cave conduits during the flood could also contribute to the decrease of air availability, fostering the deporessurisation effect during the receding phase (Ervine, 1998; Chanson, 2013).

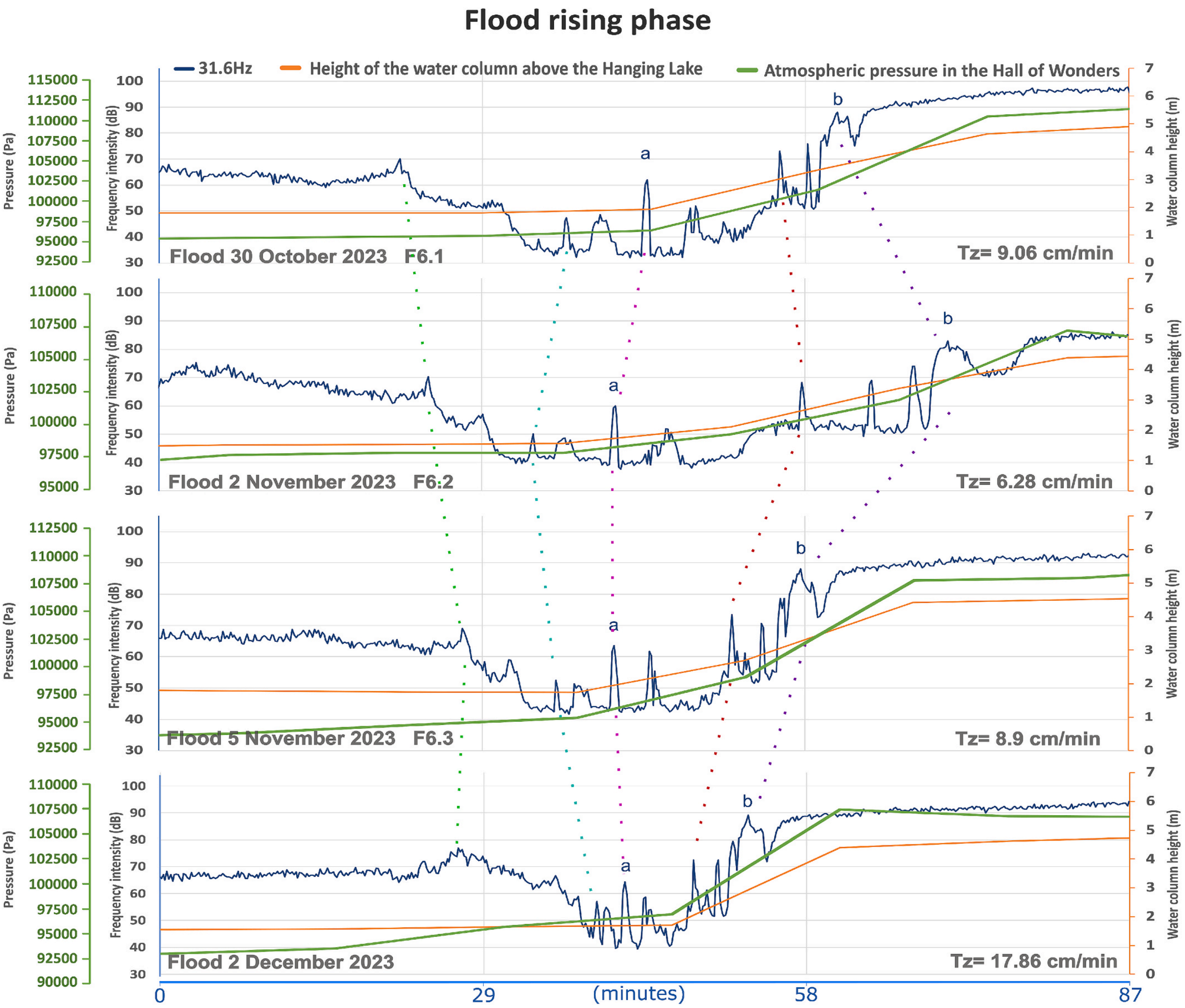

Fig. 7. Peak intensity chart at 31.6 Hz during the rising phase for different flood events recorded during the monitoring period. Letters a and b indicate specific peaks used in subsequent analyses (Fig. 10). The dashed lines track specific peaks through the flood episodes, each identified by a different colour, highlighting the recurrent behaviour of most peaks across the various events. The water level rising rate and air pressure evolution (in Hall of Wonders) of each event is also reported.

Pressurisation processes, similar to “Plunger-Chamber Effect” described in this article, have been described to happen in stormwater storage tunnels in urban environment, where rapid flood waves can create overpressurised air pockets through specific geometries of the conduit (Wright et al, 2017; Vasconcelos et al. 2024). In wide karst aquifers, with large volumes of water increase during flood events, the water–air pressurisation phenomena could also be responsible of local geodetic deformation as shown for the case of the Reka-Timavo System (Braitenberg et al., 2019).

5.2. Comparison between flood hydrology and acoustic signals

Fig. 6 displays several frequency intensities during the 2nd to 3rd December flood, mirroring similar behaviours observed for all monitored flood events (Fig. 5B and Supplementary Materials). Before the flood the sound in the chamber is dominated by drippings of water falling from the ceiling to the floor and few water film flows along the walls (see and listen Supplementary Materials for the sound wave analysis).

Sound intensities in all frequencies experience an abrupt increase (in the order of 40–60 dB, depending on the analysed frequency) when the height of the water column reaches approximately 4.3 m in the Hall of Wonders. This corresponds to the moment when water reaches the overflow in the Upper Channel and begins to flow just below the microphone (Fig. 3), propagating through the cave passages toward the exit. As found by Osborne (2022) these high intensities spanning a wide range of frequencies are due to the high hydrodynamic energy causing flow–bed frictions, channel-scale pressure fluctuations, loose rock vibrations and sediment transport. Increased intensities in the high frequency range (1995 and 6310 Hz) could be also related to surface turbulence and air-entrainment along the flow (Minnaert, 1933). The highest peak of intensity for all frequencies is reached at the moment of the overflow when the Plunger Chamber Effect is providing more pressure and consequently a higher flow rate (Jakobs et al. 2015; Anthony et al., 2018). Despite technical challenges have prevented to obtain quantitative discharge data during floods in the Upper Channel, we assume that intensity variations mirrored at the different wavelengths (as Sound Pressure Levels) represent changes in the water discharge and

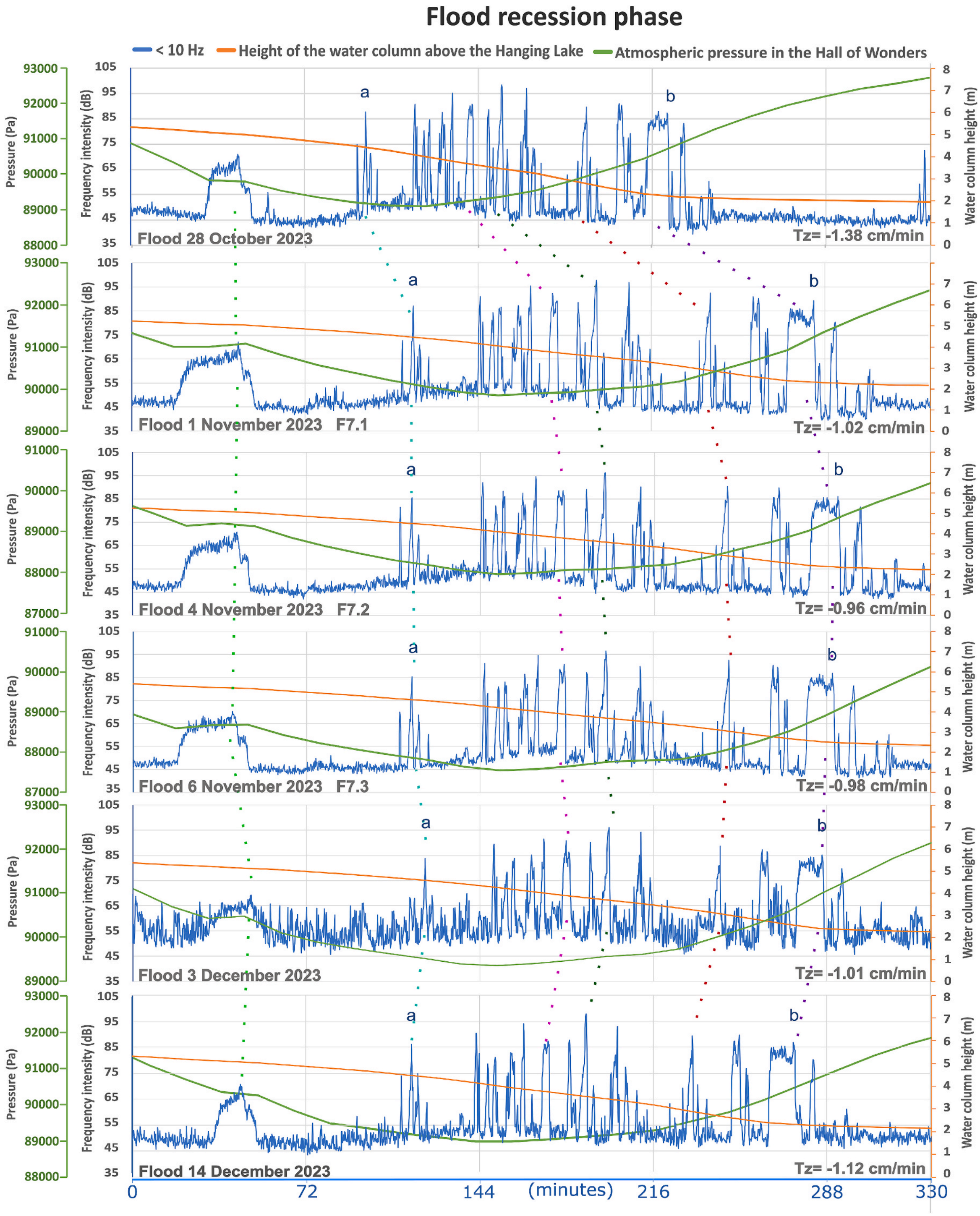

Fig. 8. Peak intensity chart at < 10 Hz during the recession phase for different flood events recorded during the monitoring period. Letters a and b indicate specific peaks used in peak distance analyses (Fig. 10). The dashed lines track specific peaks through the flood episodes, each identified by a different color, highlighting the recurrent behavior of most peaks across the various events. The recession rate and air pressure evolution (in Hall of Wonders) of each event is also reported.

flow rate, as clearly demonstrated by Osborne et al. (2021) for surface rivers and streams. Similar low frequency ambient noise monitored from the surface has been attributed to increasing discharge levels in a karst system by Pantiga et al. (2025). After reaching the Upper Channel, the flow continues for several hours until the recharge from *Qin-3* decreases below the maximum capacity of *Qout-3* (Fig. 9). At this point, the water column drops below the Upper Channel overflow, causing sound intensities across all frequencies to rapidly decline to values only 5–8 dB above pre-flood levels. The water is no longer flowing below the microphone, but we can expect that some time is needed for water films and basins to drain, producing still some minimal flow friction and dripping noises.

However, the most interesting data provided by the acoustic monitoring are the short-lasting intensity peaks well visible in all three third octave low frequencies (10 Hz, 15.8 Hz, 31.6 Hz), appearing approximately 25 to 50 min before the flood flow arrival and lasting up to 5.5 h after the flow cessation in the Upper Channel.

In order to better discuss these peaks, the analysis has been divided

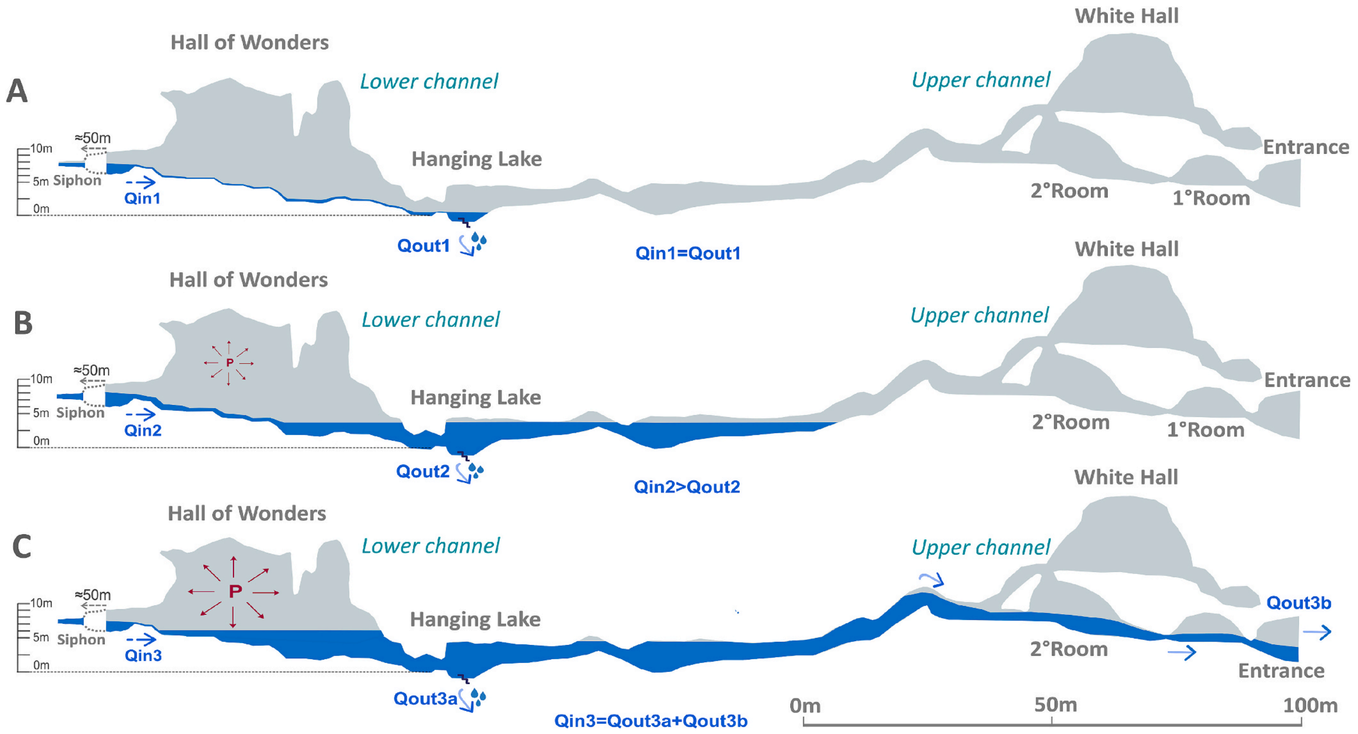

Fig. 9. Simplified section of the Spurga delle Cadene during subsequent phases of a flood event. A) Nominal conditions during low level flow, when the air volumes are connected through all cave chambers to the exit and Qout-1 at the fault passage works as the only drainage path for the cave stream. B) Flooding phase with the water rising (Qin-2 is more than Qout-2) and separating different air compartments, isolating Hall of Wonders where air pressure is rising with shrinking available volume. C) Flood expulsion phase when the water column is reaching the upper channel, and air pressure in Hall of Wonders is higher than atmospheric pressure.

into the flood rising and recession phases. All three low frequencies are clearly showing a series of peaks (Fig. 7, where only the 31.6 Hz is shown for clarity) in the rising phase of four different flood pulses observed between November and December 2023. All flood events are plotted over an equal 87-minute interval with the water level rising from approximately 1.7 m to 4.8 m, during the charging phase of the Plunger-Chamber Effect described above. Most of the acoustic spectra show a similar peak pattern, as clearly seen in the two floods of November. Conversely, the flood of December 2nd is an example where the peaks repeat with the same pattern but their temporal spacing differs (the spectrum appears squeezed). The same phenomenon is even more clear during the flood recession phase (Fig. 8, here visualised through the 10 Hz third octave band). All episodes recorded between September and January present nearly identical peak patterns within a normalised interval of 330 min. Each of the numerous peaks can be easily identified and correlated across different flood events, representing a true sound signature characteristic of this cave.

In both the rising and recession phases, the displacement of acoustic peaks along the sound intensity time series exhibits a significant linear correlation with groundwater level rise rates (Fig. 10). The faster the water level rises, the more compressed in time the acoustic peaks become. Notably, this correlation is stronger during the recession phase, likely because water level variations occur more gradually compared to the rising phase, even though pressure transducer measurements were recorded at the same frequency (15 min). During the rising phase, velocity values obtained by the water pressure transducer are in the order of 9 cm/min with wide variability up to ±8 cm/min. During the recession phase, the magnitude of velocity values is around −1 cm/min with a maximum variation between values of ±0.42 cm/min. This difference highlights how the rising phase is largely dependent on water arriving from upstream, and thus highly variable, while the velocity of the recession phase, once the flood flow through the upper channel has ended, depends mainly on the drainage capacity of the drainage crack below the Hanging Lake. The minimal variability observed in the recession phase depends on the amount of water coming from upstream, which can slightly alter the overall hydraulic pressure and thus the velocity at which the water is pushed through the crack.

It is also important to emphasise that, given the shorter duration of the rising phase, the calculation of water level growth rates reported in the graph of Fig. 10 is limited by the measurement frequency of the pressure transducer (every 15 min).

Because the rate of water level change reflects the underlying hydraulic response and flow dynamics, the sound peak analysis indicates that acoustic monitoring can serve as a reliable proxy for inferring subsurface hydrological processes. During all flood events, peaks in sound intensity correspond to particular heights attained by the water column, indicating that the sounds originate directly from the conduit's morphology, which remains unchanged throughout the duration of the floods. While not providing absolute water flow velocities or level rise rate within the cave system, acoustic signals capture the relative intensity and timing of water movement, with particular sensitivity to the slower recession phase. This demonstrates the potential of acoustics as a non-invasive tool to characterise cave water dynamics during flood events, complementing conventional hydrological monitoring approaches.

As a further possible use of the information presented in this article, the idea of an automated early-warning framework is proposed. The recurrent occurrence of low-frequency acoustic peaks during the rising phase of the event, systematically preceding the onset of flood discharge, indicates that specific acoustic patterns may be associated with distinct stages of flood development. Although the present analysis is based on a single case study and does not aim at defining a quantitative predictive relationship, such a framework would rely on the recognition of characteristic sequences of acoustic peaks rather than on linear correlations, and would require site-specific calibration and validation before any operational implementation. Nonetheless, the results highlight the potential of passive acoustic monitoring as a complementary tool for anticipating flood events in karst systems.

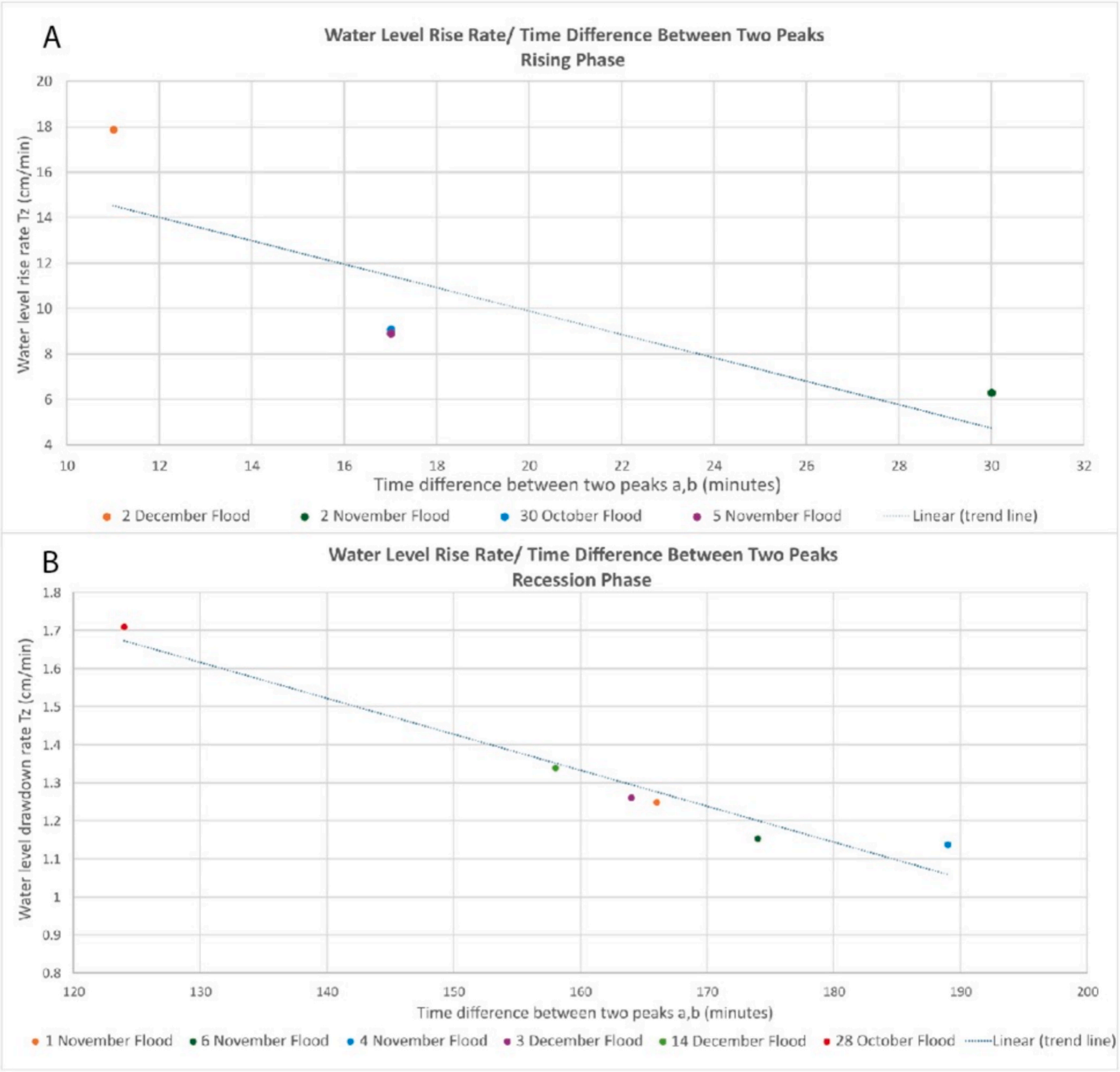

Fig. 10. A) Plot of the temporal difference between peaks a and b (as identified in Fig. 7) versus the water level rise rate during the rising phase of different flood events. The linear correlation among the plotted points is also shown. B) Plot of the temporal difference between peaks a and b (as identified in Fig. 8) versus the water level decrease rate during the recession phase of different flood events. The linear correlation among the plotted points is also shown.

5.3. *The origin of sound peaks*

The sound intensity analysis produced unprecedented results, revealing the recurrence of the same low frequency sound peak pattern signature which is probably characteristic of this specific cave conduit.

As mentioned above, in all flood events, each sound intensity peak happens at a specific height reached by the water column, suggesting that the origin of the sounds is strictly related to the morphology of the conduit, which remains the same through the time of all flood events.

Moreover, it is observed that each peak recorded during the flood's rising and recession phases presents different durations. There are punctual peaks, lasting a few seconds, and peaks lasting more than 30 min. Fig. 11 shows that the most enduring peak, designated S and present in all recorded flood recession phases, coincides with a stabilisation of the atmospheric pressure data in the Hall of Wonders. During these flood recession phases, the atmospheric pressure is generally decreasing as a result of the lowering piezometric level in this chamber. However, when peak S appears, the atmospheric pressure curve levels off. This behaviour is interpreted as air being sucked into the Hall of Wonders through fractures that were previously flooded but become at that specific time permeable to air and connect this chamber with another pressurised compartment of the cave. The noise generated during peak S might thus be explained by air flowing rapidly through the small openings, thus the compressible flow of gas generates turbulent and irregular motion producing a low frequency sound. The reason for its repetitiveness across different episodes depends on the specific morphology of this area of the cave. For the other sharper peaks following S we have not enough time resolution in the pressure dataset

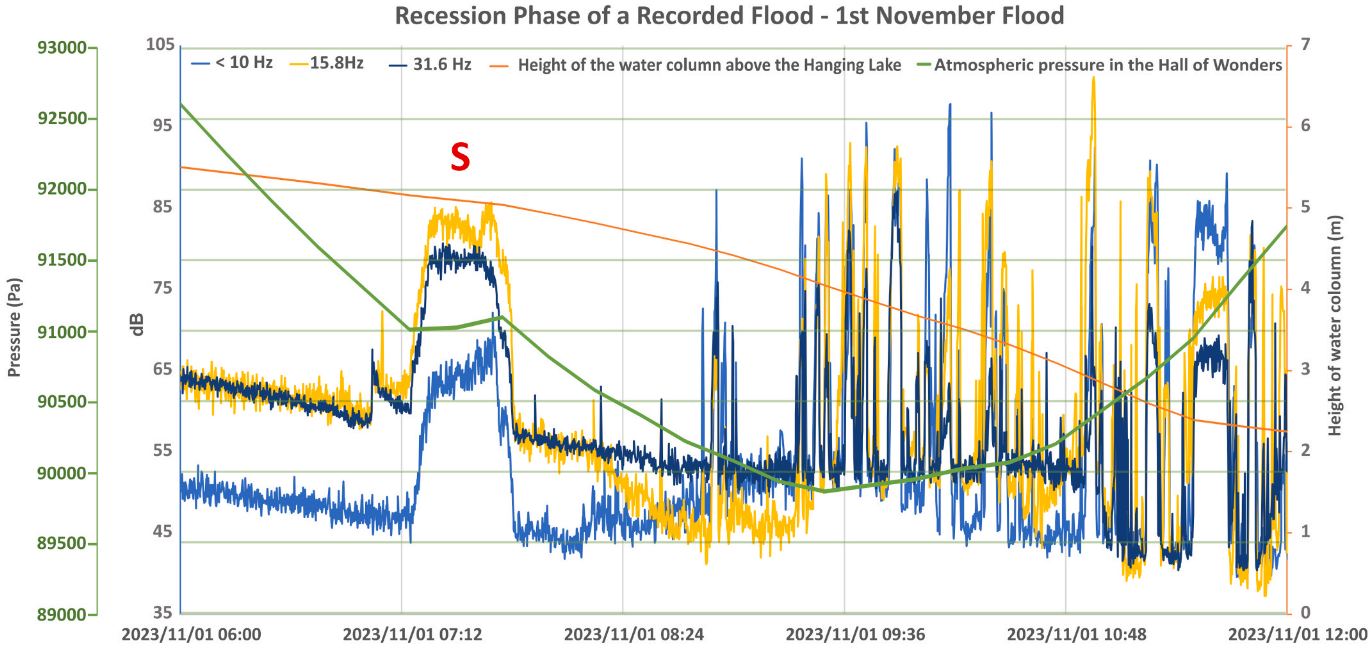

Fig. 11. Plot of atmospheric pressure, water column height, and recorded frequency intensity during the recession phase of the November 1, 2023 flood. A particularly long-lasting peak, labeled S, is highlighted.

to identify associated pressure releases (see Fig. 11 and Supplementary Materials). Nonetheless, while the sound peak train is happening the pressure is increasing again slowly reaching equilibrium levels. This correlation between the sound train and the pressure overall increase should again be related to air transfers between cave compartments. Turbulent air flow passing in thin spaces between the rock ceiling and the water are expected to produce low frequency sounds via turbulence, vortex shedding, and strong coupling with the duct's acoustic resonances. Geometry, flow speed, and fittings largely determine how intense and how low in frequency these sounds are (Chanson, 2009; Noh et al., 2019, Piana et al., 2022).

All these observations suggests that each peak occurs when the water level descends below a certain height allowing for a new connection between different pressurised cave compartments. These compartments can be significant voids with volumes of several m^3, like cupolas on the roof of the conduit and side chambers, or just small fractures where the air has been trapped during the flood. The duration of the peak is most probably related to the volumes of air that are freed by each new interconnection. Nonetheless, in order to better define this process, it would be necessary to obtain a higher frequency measurement of the atmospheric pressure in the Hall of Wonders in order to discern small variations lasting only few minutes or seconds.

The different rates at which the water level rises and falls could explain why fewer low frequenct sound peaks are observed during the rising phase than during the recession phase. The rising phase is characterised by a rapid increase in water level, which can be up to an order of magnitude faster than in the recession phase. Initially, the different cave chambers are in atmospheric equilibrium, so the increase in pressure is primarily driven by the rapid rise of the water column separating the different cave compartments. This produces relatively short, closely spaced acoustic peaks, which could be associated with air displacement through fractures and partially submerged conduits. During the recession phase, the water level decreases much more slowly. By this stage, the flood has often persisted for several hours or even days, allowing significant pressure differences to develop between cave compartments that have remained hydraulically isolated by water-filled passages. As the water progressively retreats, multiple communication pathways between chambers gradually reopen. Each newly re-established connection can generate a distinct airflow driven by these pressure gradients, producing individual acoustic peaks. As the water level decreases gradually, these events occur at slightly different times and can therefore be clearly distinguished in the recordings.

As observed in Spurga delle Cadene Cave, these air-transfer sound-generating processes should be common in all karst systems with complex geometries and alternating flooded passages with air filled chambers. We propose to call this previously unknown phenomenon "Cave Hydraulis", as a natural analogue of the water–air powered organ invented in ancient Greece by Ctesibius of Alexandria (Tannery and Carra de Vaux, 1908).

Nonetheless, with the data available, we cannot exclude that the sound spectra recorded in Spurga delle Cadene could also contain information related to other air–water interaction processes. Luhmann et al. (2025) reported short-duration (<0.25 s), high-frequency seismic impulses resulting from the sudden collapse of compressed air pockets in flooded karst conduits. In our dataset, the dominant peaks are at lower frequencies and considerably longer, ranging from several seconds to tens of minutes, and arise during both flood rise and recession. Accordingly, the energetic framework based on critical air volume, radiated energy, and overpressure proposed by Luhmann et al. (2025) is not directly applicable to the phenomena observed here.

Nevertheless, we recognise that some of the short-duration acoustic peaks observed in our records, particularly within the 30–90 Hz frequency band, could correspond to small-scale air-pocket releases similar to those described by Luhmann et al. (2025). However, due to the type of acoustic analysis employed and the predominance of continuous flow-related noise, such impulsive events are strongly attenuated and embedded within background sound pressure levels generated by the flood turbulence. This makes them difficult to isolate and quantify. Further statistical studies are needed to better analyse the potential presence of characteristic repetitive peaks in higher frequencies.

Another aspect that is worthy of future investigation is the potential presence of Helmholtz-type resonances produced during or after air transfers in the rising and recession phases. These resonances could provide information on cavity source volumes (Perrier et al., 2023).

6. Conclusions

In the Spurga delle Cadene cave, the Plunger-Chamber Effect governs flood dynamics by temporarily isolating air-filled compartments, which are compressed as the water level rises, generating characteristic pressure differences that drive high-discharge flows through an overflow upper channel. Acoustic monitoring revealed that the recorded sounds are strongly controlled by the discharge onset and variations in the Upper Channel, while the spatial and temporal distribution of low frequency acoustic peaks systematically correlates with the rates of water level rise and fall. Faster water-level changes produce more compressed sound peak patterns, whereas slower variations result in more widely spaced peaks. This relationship demonstrates that acoustic signals can act as a sensitive proxy for hydrological dynamics.

These findings suggest that karst conduits with variable morphology and air-filled spaces may function as natural aerophones or "hydraulis", producing reproducible acoustic patterns during flood events. More broadly, similar sound-generating processes may occur in other caves and karst springs, implying that acoustic monitoring could become a non-invasive tool for characterising conduit geometry, tracking flood regimes, and inferring water flow dynamics in extreme hydrological events. By linking acoustic signatures to specific water-level thresholds and flood phases, this approach offers novel opportunities for real-time monitoring and potentially for early-warning systems in karst environments. Although the present observations are limited to this specific case study, the recurrent appearance of low-frequency acoustic peaks 25–50 min before the onset of each flood event suggests the potential for an automated early-warning framework. In principle, the recognition of a characteristic sequence of sound peaks could provide advance notice of flood arrival at karst springs, provided that site-specific calibration and validation are performed. This approach is applicable provided that the karst system is accessible during periods of low water levels and that its morphology includes environments (such as upper chambers or conduits) that remain unflooded during high-water events. These conditions are commonly encountered in epiphreatic, multi-level karst systems worldwide (De Waele & Gutiérrez, 2022). This suggests that sound monitoring could be a promising new way of understanding karst hydrological dynamics. In the future, coupling sound monitoring with additional environmental parameters like temperature, ventilation (wind speed and direction), or even changes in CO_2 concentrations, could also provide a better understanding of water–air interactions in cave systems during flood events.

Credit authorship contribution statement

Alessandro Mastella: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesco Sauro:** Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Michel André:** Validation, Methodology. **Mike van der Schaar:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis, Data curation. **Maria Filippini:** Writing – review & editing, Supervision, Resources, Methodology. **Guido Rossi:** Writing – review & editing, Investigation, Conceptualization. **Guido Gonzato:** Writing – review & editing, Investigation, Conceptualization. **Ennio Nicolini:** Investigation, Conceptualization. **Jo De Waele:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2026.135344.

Data availability

All data is available in the supplementary file. Audio recordings are also available on http://lido.listentothedeep.com platform (Spurga di Peri dataset)

References

Anthony, R.E., Aster, R.C., Ryan, S., Rathburn, S., Baker, M.G., 2018. Measuring mountain river discharge using seismographs emplaced within the Hyporheic Zone. J. Geophys. Res.: Earth Surface 123 (2), 210–228.

Antonelli, R., Castellani, E., Consolaro, S., Peretti, A., Sauro, U., Sorbini, L., Zambrano, R., Zampieri, D., Zorzin, R., 1991. The springs of Montorio and the karst aquifer of the central-western Lessini Mountains (Verona-venetian Pre-Alps). Quaderni Del Dipartimento Di Geografia. Università Di Padova 13, 249–268.

Artoni, A., Rebesco, M., 1990. Deformazioni per thrusting nei Lessini nord occidentali (Verona-Italia settentrionale). In: Studi Geologici Camerti, Special Volume "neogene Thrust Tectonics", pp. 131–137.

Bassetti, M., Borsato, A., 2005. Evoluzione geomorfologica della Bassa Valle dell'Adige dall'Ultimo Massimo Glaciale: sintesi delle conoscenze e riferimenti ad aree limitrofe. Acta Geologica 82, 31–42.

Bonacci, O., Bojanić, D., 1991. Rhythmic karst springs. Hydrol. Sci. J. 36 (1), 35–47.

Braitenberg, C., Pivetta, T., Barbolla, D.F., Gabrovšek, F., Devoti, R., Nagy, I., 2019. Terrain uplift due to natural hydrologic overpressure in karstic conduits. Sci. Rep. 9 (1), 3934.

Chanson, H., 2009. The rumble sound generated by a tidal bore event in the Baie du Mont Saint Michel. J. Acoust. Soc. Am. 125 (6), 3561–3568.

Chanson, H., 2013. Hydraulics of aerated flows: Qui pro quo? J. Hydraul. Res. 51 (3), 223–243.

Crocker, M.J., 1998. Handbook of Acoustics. John Wiley & Sons.

De Waele, J., Gutiérrez, F., 2022. Karst Hydrogeology, Geomorphology and Caves. John Wiley & Sons, Chichester, p. 888.

Ervine, D.A., 1998. Air entrainment in hydraulic structures: A review. Proc. Inst. Civil Eng.-Water Maritime Energy 130 (3), 142–153.

Gabrovšek, F., Peric, B., Kaufmann, G., 2018. Hydraulics of epiphreatic flow of a karst aquifer. J. Hydrol. 560, 56–74.

Jakobs, H.E., Skibbe, Y., Mj, B., Makwiza, C., 2015. Correlating sound and flow rate at a tap. Procedia Eng. 119, 864–873.

Luhmann, A.J., Bilek, S.L., Grapenthin, R., Woo, H.B., Gochenour, J.A., 2025. Seismic observations from injection experiments and a recharge event in a karst aquifer: potential compressed air pocket release. Hydrgeol. J. 33, 1541–1561.

Mastella, A., 2024. Spurga delle Cadene: un approccio innovativo per l'analisi idrogeologica di una cavità carsica. University of Bologna, p. 160. Master Thesis.

Menichetti, M., Rossi, G., Zorzin, R., 2011. Idrogeologia dell'area della Spluga della Preta. Memorie Dell'istituto Italiano Di Speleologia 25 (2), 93–118.

Minnaert, M., 1933. On musical air-bubbles and the sounds of running water. Phil. Mag. 16 (104), 235–248.

Noh, E., Woo, S., Lee, D.J., Song, M.H., Lee, J.W., Lee, H., Seo, Y., 2019. Active control of low-frequency noise in bubbly water-filled pipes. J. Mech. Sci. Technol. 33 (7), 3127–3135.

Osborne, W.A., Hodge, R.A., Love, G.D., Hawkin, P., Hawkin, R.E., 2021. Babbling brook to thunderous torrent: using sound to monitor river stage. Earth Surf. Proc. Land. 46 (13), 2656–2670.

Osborne, W.A., 2022. Listening to Rivers: Using Sound to Monitor Rivers. Doctoral thesis. Department of Geography, Durham University.

Pantiga, A., Allègre, V., Lastennet, R., Houillon, N., Naessens, F., Mateo, S., Denis, A., 2025. Estimating flow dynamics in a karst conduit from ambient noise monitoring. Environ. Proc. 12 (1), 11.

Pellet, H., Arfib, B., Henry, P., Touron, S., Gassier, G., 2024. Mesoscale permeability variations estimated from natural airflows in the decorated Cosquer Cave (southeastern France). Hydrol. Earth Syst. Sci. 28 (17), 4035–4057.

Perrier, F., Bourges, F., Girault, F., Le Mouël, J.L., Genty, D., Lartiges, B., Losno, R., Bonnet, S., 2023. Temperature variations in caves induced by atmospheric pressure variations—part 2: Unveiling hidden thermal signals. Geosyst. Geoenviron. 2 (2), 100146.

Piana, E.A., Carlsson, U.E., Lezzi, A.M., Paderno, D., Boij, S., 2022. Silencer design for the control of low frequency noise in ventilation ducts. Designs 6 (2), 37.

Piechowicz, J., Czopek, D., Malecki, P., Wiciak, J., 2018. Acoustic studies of glacier, Karst and Lava Caves. In: INTER-NOISE and NOISE-CON Congress and Conference Proceedings. Institute of Noise Control Engineering, pp. 1110–1116.

Rossi, G., 1987. Risultati dei test idrogeologici in relazione ai fenomeni di inquinamento della Spurga delle Cadene. Special Report. Archive of Commissione Gruppi Grotte Veronesi.

Rossi, G., Zorzin, R., 2011. Lo studio idrogeologico della Spurga delle Cadene. Memorie Dell'istituto Italiano Di Speleologia, Serie II 25, 119–128.

Sanz Pérez, E., Rosas Rodrigo, P., Pidal, M., de Navascués, I., 2016. Drainage and siphoning of a karstic spring: a case study. J. Cave Karst Studies 78 (3), 183–197.

Sauro, F., Piccini, L., Menichetti, M., Artoni, A., Migliorini, E., 2012. Lithological and structural guidance on speleogenesis in Spluga della Preta cave, Lessini Mountains (Veneto, Italy). Geogr. Fis. Din. Quat. 35 (2), 167–176.

Sauro, F., 2023. Der verborgene Kontinent: Expeditionen in die unterirdische Welt der Höhlen. Knesebeck Verlag.

Spellman, F.R., Whiting, N.E., 2004. Environmental Engineer's Mathematics Handbook. CRC Press.

Stroj, A., Paar, D., 2019. Water and air dynamics within a deep vadose zone of a karst massif: Observations from the Lukina Jama–Trojama cave system (− 1,431 m) in Dinaric karst (Croatia). Hydrol. Process. 33 (4), 551–561.

Tannery, P., Carra de Vaux, B., 1908. L'invention de l'hydraulis. Revue Des Etudes Grecques 21 (93/94), 326–340.

Wright, S.J., Vasconcelos, J.G., Lewis, J.W., 2017. Air–water interactions in urban drainage systems. Proc. Inst. Civil Eng.-Eng. Comput. Mech. 170 (3), 91–106.

Vasconcelos, J.G., Geller, V.G., Triboni, C.V., Wright, D.B., Hodges, B.R., 2024. Evolution and characterization of pressurized flow conditions in stormwater collection networks. J. Hydraul. Eng. 150 (2), 04024001.

Zorzin, R., 1996. Idrogeologia del Corno d'Aquilio e delle aree limitrofe (Monti Lessini-Verona-Italia). Atti del Congresso "Alpine Caves: alpine karst systems and their environmental context". Asiago, 1992. Tipografia Lanaro, Malo (VI) 385–389.