Flooding in epiphreatic passages

Analysis of the 4-5 Nov. 2011 flood in the Chamois Cave (Alpes-de-Haute-Provence, France)

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Abstract: The Chamois Cave (Alpes-de-Haute-Provence, France) gives access to one of the largest underground river in France, the « Underground Coulomp », which catchment corresponds to the Grand Coyer massif between the upper Var and Verdon valleys. Together with exploration, we carry out hydrological studies with gauging and temperature-pressure data loggers setup at the spring and in the most significant places in the cave. This analysis focuses on data from the data logger located in the 3rd sump (S3) of the Entrance passage, which has to be pumped to give access to the cave. The 4-5 November 2011, heavy rainfall (270 mm during 5 days with a daily maximum of 124 mm), produced a flood with a peak at 27 m^3/s and a flooding of the Entrance passage. Reaction time to rainfall is ≈ 9 h for the beginning of the spring response and ≈ 21 h for the beginning of the flooding, in conditions corresponding to long recession after summertime. The flooding immediately closed S3 with a mean discharge of 60 L/s, rose up to 7 m in less than 1 h, poured during 1 week, and eventually flooded most of the Entrance series except the upper loops. When rain stopped, S3 returned to its normal level within 1.5 day, thanks to successive *soutirages* of 1.5 L/s and 0.5 L/mn. These data quantify the velocity and duration of floods in the Entrance series. It also confirms observations and strengthens our approach of integrating meteorological and hydrological conditions to carry out cave exploration in the best safety conditions. Studies will go on to quantify reaction time when karst in saturated, which are obviously much shorter.

Key words – Chamois Cave, flooding, epiphreatic gallery, flood reaction time

Résumé : Mise en charge dans les conduits épinoyés. Analyse de la crue du 4-5 nov. 2011 dans la grotte des Chamois (Alpes-de-Haute-Provence, France). *La grotte des Chamois (Alpes-de-Haute-Provence, France) donne accès à l'une des plus importantes rivières souterraines de France, le Coulomp souterrain, qui draine le massif du Grand Coyer entre les hautes vallées du Var et du Verdon. En complément des explorations, l'étude hydrologique réalisée est basée sur des jaugeages et les enregistrements de sondes de pression-température disposées à l'émergence et aux points clefs du réseau. Cette analyse porte sur les données de la sonde disposée dans le 3e siphon (S3) du réseau d'entrée, qui doit être pompé pour ouvrir l'accès au réseau. Les 4-5 novembre 2011, d'importantes précipitations (270 mm sur 5 jours avec un maximum journalier de 124 mm), produisent une crue avec un pic à 27 m^3/s et une mise en charge du réseau d'entrée. Le temps de réaction aux pluies est ≈ 9 h pour le début de crue à la source, et ≈ 21 h pour la mise en charge, dans des conditions consécutives à un long tarissement estival. L'arrivée de la mise en charge réamorce instantanément le S3 avec un débit moyen estimé à 60 L/s, s'élève de 7 m en moins de 1 h, et déverse durant une semaine, ennoyant la majeure partie du réseau d'entrée, à l'exception des points hauts. Dès l'arrêt des pluies, le S3 retrouve son niveau habituel en un jour et demi, grâce à des soutirages successifs de 1,5 L/s et 0,5 L/mn. Ces données quantifiant les vitesses et durées des mises en charges dans le réseau d'entrée confirment les observations, renforcent notre démarche de prise en compte des conditions météorologiques et hydrologiques pour conduire les explorations avec le maximum de sécurité. Les études seront poursuivies pour quantifier les temps de réponse pour des conditions de karst saturé, assurément beaucoup plus courtes.*

Mots clefs *- Grotte des Chamois, mise en charge, conduit épinoyé, temps de réaction aux crues*

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Introduction

During high water, the lowest part of the vadose zone (i.e. the "epiphreatic zone") can be flooded by large amounts of water that cannot be drained by the conduits and the spring. The study of cave flooding allows a better understanding of the karst hydrodynamic situation. Such studies have been carried in a naturalist way describing the phenomenon (BÄTTIG & WILDBERGER, 2007), with a hydraulic modeling approach (JEANNIN, 2001; JEANNIN & WILDBERGER, 1997), or to assess the role of flooding as a speleogenetical process (AUDRA, 2007; AUDRA & PALMER, 2011; HÄUSELMANN et al., 2003). Flooding is also a hazard that any caver must take into account during exploration. From the beginning of the exploration of the Chamois Cave, we studied the dynamics of the cave system and particularly the flooding in the entrance series, a key issue for exploration security.
In this paper, we present the hydrogeological setting of the Chamois Cave, which contains the largest underground river in France and feeds the Coulomp spring, the largest of the Southern French Alps. The record of the flood of November 2011 provided discharge and flooding depth data. We discuss the reaction time, the modalities of flooding and draining.

Cave and context

The Chamois Cave (Castellet-lès-Sausses, Alpes de Haute-Provence, France) opens at 1360 m asl. in Grand Coyer massif, between the upper segments of the Var and Verdon valleys (AUDRA et al., 2009). The Chamois Cave develops more than 10 km for a depth of 326 m (+284 / -42) (fig. 1). It gives access to a 1 km segment of the Underground Coulomp, the largest underground river in France (1 m^3/s). This underground river gives origin to the Coulomp spring, the largest in the Southern Alps, which pours out below the cave in a scenery waterfall. Its discharge is about 1 m^3/s, with low water at 400 L/s in summer and winter, and high water up to 30 m^3/s during fall and spring snow melting. The watershed covers about 30-35 km² up to the summit of the Grand Coyer summit. A sequence of thick marly limestone from Upper Cretaceous (Turonian-Coniacian-Santonian) begins with bedded limestones, where the cave develops, at the top of black marls. Most of the catchment is covered by impervious layers or semi-permeable layers, mainly the cretaceous marly limestone. No karst feature is visible, and infiltration through Cretaceous marly limestone is mainly diffuse. Some discrete sinkhole occur at the bottom of some valleys, where marly limestone is thin and could provide some concentrated recharge to the Cretaceous limestone. In the cave, a temporary river is present in Valette-Hormones Galleries. It joins the Underground Coulomp. Small infiltrations gather in the entrance series. During flood, a 20 m backflooding occurs in the river. In the entrance (Shadoks Gallery), backflooding from entrance infiltration may reach several meters, and water pours out in the Shadoks Gallery towards the entrance.

At the beginning of November 2011, the south-east part of France was under a rain-stormy event, which was exceptional regarding its length and the cumulated amount of rain (SPC MÉDEST, 2011). Meteorological setting is strongly disturbed by a southern flux concerning the whole Mediterranean basin that provokes a rainy-stormy event from 3rd November onward. From 7th and till 10th of November, meteorological conditions evolve toward "warm center" depression stationary above the Mediterranean coast. Stormy rainfalls concentrate along the coast and in the Maures massif. This overload of precipitation, pouring down on still oversaturated soils caused numerous flooding along the French Riviera coast. In the triangle Fréjus-Draguignan-Annot, the 6-days total precipitation reach 200 mm, with a maximum of 400 mm in the Maures massif, where stormy rain were concentrated during the second event. The intensity peak occurred in the evening of 5th of November, especially in the triangle Fréjus-Grasse-Draguignan, with 150-180 mm / 24 h, and with intensities of 25 mm / h during 4 h. In this area, the rivers record peak discharges corresponding to a 50-years return period (that is a 1/50 probability of yearly occurrence). In the Upstream segment of the Var valley, Méailles station located 6 km away from the Chamois Cave, recorded 270 mm in 5 days (3-7 nov.), with a 124 mm peak on 5th of November (fig. 2). The flood at the Coulomp Spring is the largest recorded since the beginning of discharge measurements (2008-12).

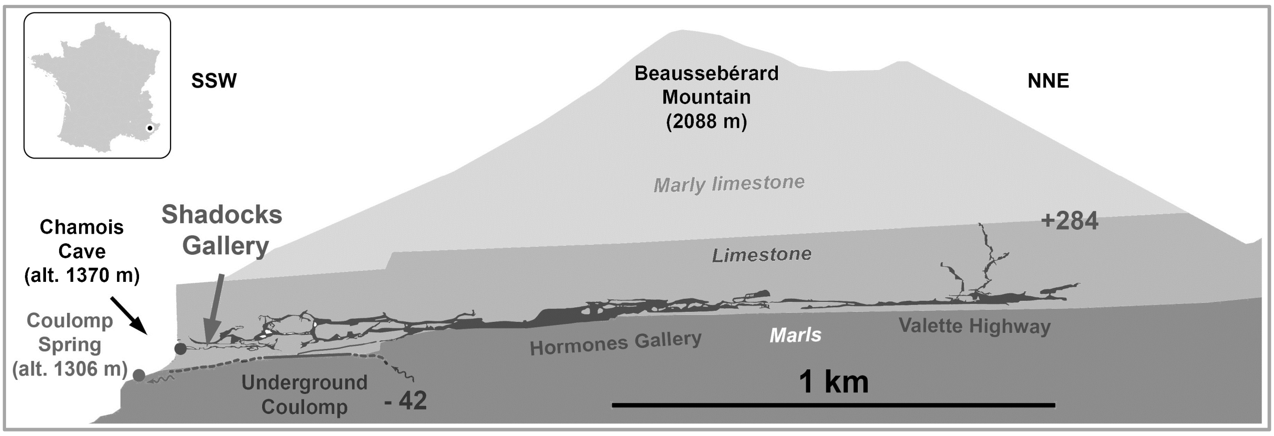

Fig. 1: Cross section of the Chamois Cave, showing its development at the contact of a marly basement and in a limestone covered with a thick sequence of marly limestones. In summer, strong draft entering at high altitude crosses the cave systems toward the entrance, as a simple wind tube.

Methodology

Discharge at Coulomp spring is measured since 3 years. To measure water depth at the spring pool, we use Schlumberger and Reefnet pressure data loggers that also record water temperature. Atmospheric pressure from an additional data logger is subtracted to the raw measure to obtain the true water depth curve. Water depth is converted to discharge by means of a rating curve, which is established by measuring discharges for various stages, using chemical gauging with salt dilution. For the moment, the rating curve is well defined up to 2 m^3 /s, higher discharge are extrapolated and consequently approximate. Additionally, to record flooding in the cave we use several Reefnet data loggers located in adequate places, which also record temperature of water when flooding occurs, otherwise temperature of air. Data are recorded every 30 min. In this study, we use data of the November flood, comprising spring discharge, water depth in third sump (S3) of the entrance gallery, the "Shadoks Gallery". Additionally, Météo-France provided hourly rainfall from the nearest station, located 6 km away in Méailles village. Volumes, cross sections, and profiles of the Shadoks Gallery are calculated from cave relief data, measured here with a Topofil. Finally, field observations during cave exploration brought precious indications, such as places prone to flooding, current features or slake water marks, relationships between rain event and flooding, reaction times, *etc*.

Results

Rain starts on 3 Nov. 09:00 in Méailles, with continuous downpours till 9 Nov. At the Coulomp spring, the flood begins on 3 Nov. 18:00 (Q = 750 L/s) and reaches a peak at 27.5 m^3/s on 5 Nov. 03:00. High discharge (>3 m^3/s) occurs till 11 Nov. (fig. 2). The flood fills the 3rd sump (S3) on 4 Nov. 06:10 (fig. 3), which pours out during 1 week till 11 Nov., where it drains to its stable low level (fig. 4).

Discussion

Reaction time (fig. 3).

The rain started on 3 Nov. 09:00 in Méailles. At 18:00, the discharge being at 750 L/s increases. A critical threshold of 2.5 m^3/s is reached 7 h later: during 6 h, the spring discharge oscillates, before restarting to increase. This plateau either mimics the pulses of rainfall events or reflects the flooding of some cave passages that intercept part of the discharge. Flood of the S3 begins on 4 Nov. 06:10, i.e. 21 h after the rain beginning, 12 h after the beginning of the Coulomp spring flood, and 5 h after beginning of the plateau. During this event, the reaction time between rain beginning and flooding is 21 h (or less if we take into account the time for soil saturation). Two weeks before, a flash storm occurred with 93 mm of downpours in 24 h, it was the first rain after summer drought. During this event, the reaction time before S3 flooding was reduced to 12-14 h, because of the storm intensity.

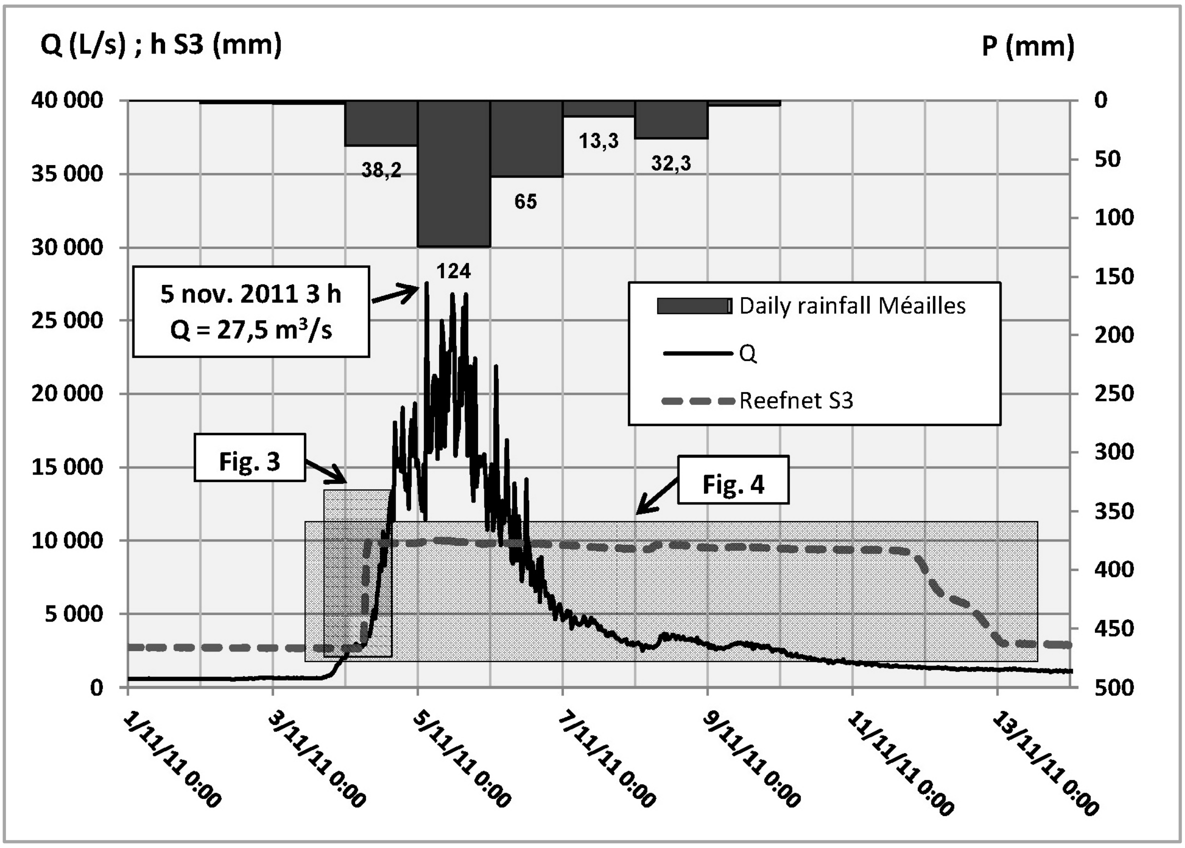

Fig. 2: Flood event of Nov. 2011 showing rainfall at the Méailles station, the Coulomp spring discharge, and the level on 3rd sump (S3) in Chamois Cave. The fluctuations correspond either to real discharge pulses or to turbulences in the pool.

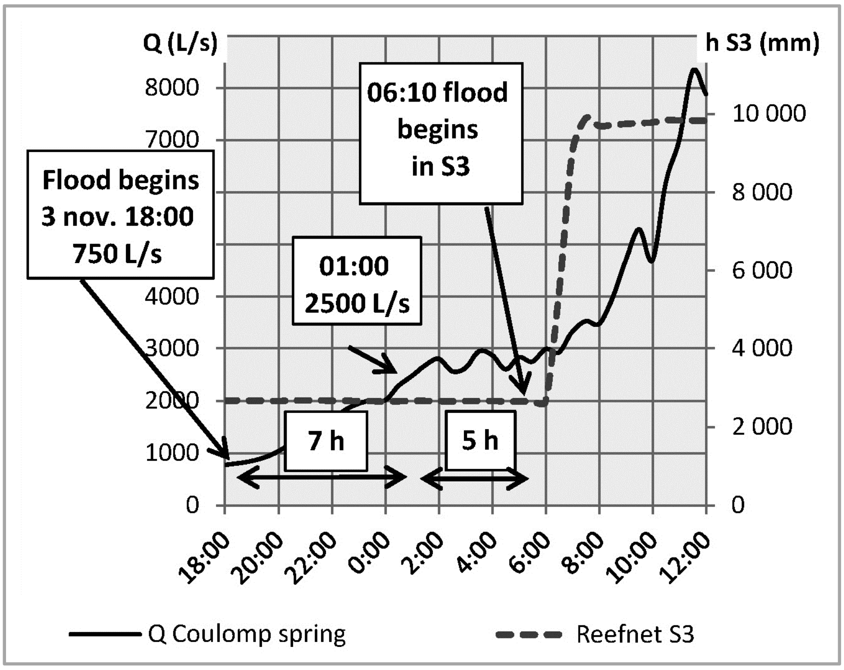

Fig. 3: Flood begins.

Rain started on 3 Nov. 09:00 in Méailles. 9 h later, at 18:00, the discharge increases, first from 750 L/s to a threshold of 2.5 m^3/s, which is reached 7 h later. Flood of the S3 begins on 4 Nov. 06:10, i.e. 21 h after the rain beginning and 12 h after the beginning of the Coulomp spring flood.

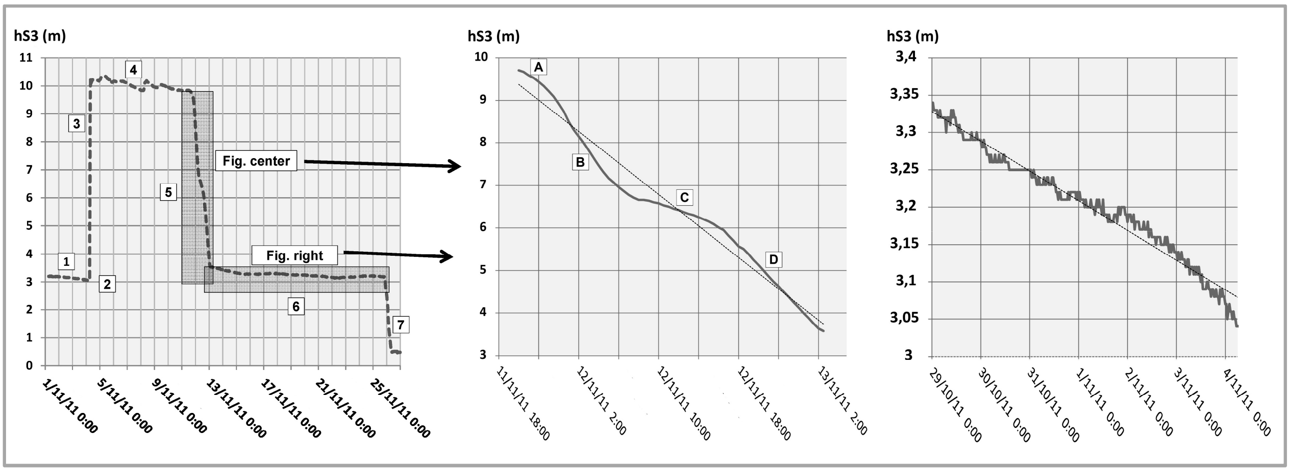

Fig.4: Flooding record in the S3 of Chamois Cave. (1) Low stable level of the sump, with very slow depletion from the last flood; (2): Rain starts on 3 Nov. 09:00 in Méailles, the flood in S3 begins on 4 Nov. 06:10; (3) S3 fills up over 7 m in 55 min. and pours out in Shadoks Gallery; (4) S3 remains active during 1 week till 11 nov., rains having stopped 60 h before; (5) fast depletion in 34 h of S3 level down to its low stable level (detail on central figure; letters correspond to the inclination changes of the emptying passage, see fig. 5); (6) very slow depletion similar to (1). Small peaks are electronic device artifacts (detail on right figure); (7) pumping of the S3 to reopen the access to the cave.

Flooding of S3 and pouring into Shadoks Gallery

When flooding starts, the water rises and floods the P7 (downstream part of S3) in 55 min with a rising velocity of 13 cm / min. From the survey, the corresponding volume of flooded conduit is estimated to 200 m^3 (fig. 5), thus corresponding to an average discharge of 60 L/s. When the S3 is pumped to allow access for exploration, the air space reaches 30 cm at the maximum in the lower part of the sump. It means that when flood arrives, the way out might be close within a few minutes!

Flooding of the Shadoks Gallery

When S3 is full, water reaches the top of the P7 and pours down into the Shadoks Gallery (fig. 5). This pouring-out lasted 1 week, with irregular discharge marked by secondary peaks and stopped about 60 h after the end of the rain (fig. 4). Water depth and temperature peaks are perfectly correlated and show their relationship to the successive lukewarm downpours that were characteristic of this storm event. While pouring-out from the S3, water flows in the Shadoks gallery, fills the low loops till the top of the spillway and eventually pours-out to fill the next loop. About half of the gallery gets flooded, only upper loops remain as air bells. Such a dynamic is typical of epiphreatic looping passages (HÄUSELMANN et al., 2003; AUDRA, 2007; AUDRA & PALMER, 2011). The cross section of the gallery shows that the flooding is controlled by 5 spillways ranging from +7.5 m above entrance upstream of S3 to +2.5 m between S2 and S1 (fig. 5). Several observations after flood event confirm this, with places washed down to the spillways, fine sediment accumulations in the bottom of the flooded loops, and ropes brushed backwards indicating rather strong flow velocity. Other observations inside the cave systems show that main part of the cave (Valette-Hormones) flows toward the Underground Coulomp but flood height cannot reach the entrance passages. The water responsible of the flooding of Shadoks Gallery comes from small tributaries along Anapophysis Gallery that flood the lower part of the passage and eventually pours out through Shadoks Gallery toward the cave entrance.

Fast lowering of S3 to the bottom of the P7 shaft

After rainfall, when flow stops, water lowers in 34 h down to the bottom of the P7 with an average velocity of 18 cm/h (fig. 4, center). The emptying of 200 m^3 / 34 h corresponds to a discharge of about 1.5 L/s. Since emptying occurs through a small hole, and since the progressive reducing of the head during emptying does not affect significantly the discharge, we consider the emptying discharge to be constant. Consequently, the observed changes of emptying velocity result of section changes, the largest a given section at a given level is, and the slowest the emptying is. Since the P7 section at the downstream side of S3 is constant, it is the irregular profile of the upstream side of S3 that influences the emptying velocity. Horizontal segments (1 and 3 on fig. 5) require longer emptying time than vertical segments (2 and 4 on fig. 5).

Slow lowering of S3 to the low stable level

One week after, the water still lowers of about 30 cm during an additional week (fig. 4, right). The corresponding volume, deduced from the pumping time, is about 4.5 m^3 giving an emptying discharge of about 0.5 L/min. Since the discharge through a smaller emptying hole is constant, the small changes of velocity emptying also correspond to small section changes.

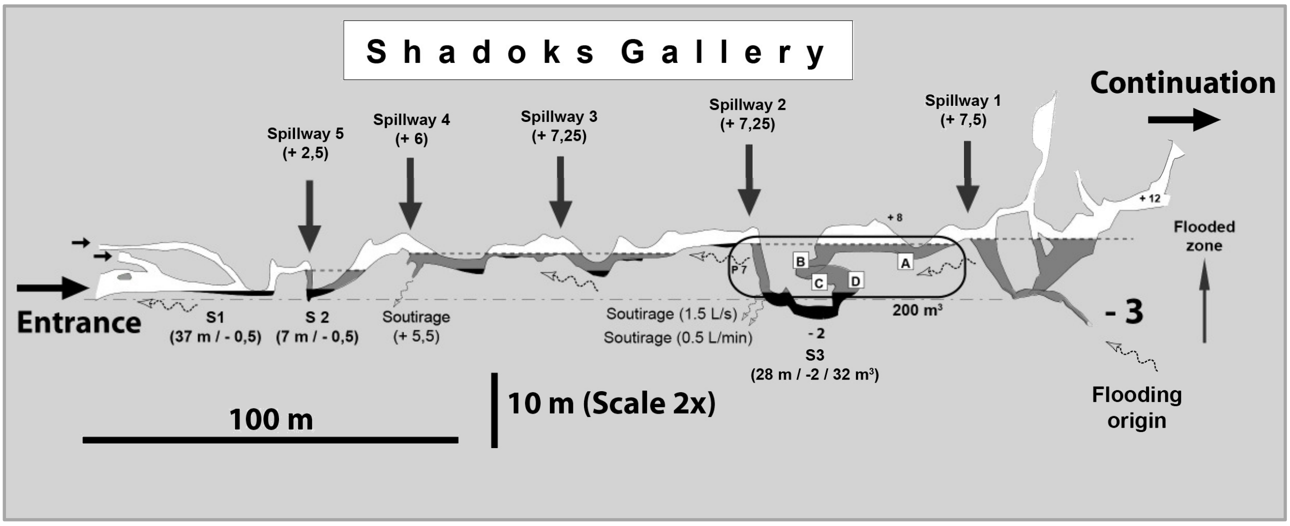

Fig. 5: Flooding of the Shadoks Gallery. Water rises from the right, and fills the S3 sump. During large floods, water rises in the S3, pours over spillway 2, and successively pours over the 3 next spillways. Volume flooded in S3 is about 200 m^3; letters [A], [B], [C], [D] correspond to the first stage of fast emptying of S3 (see fig. 4 center and text).

Conclusion

During the flood event of November 2011, the Coulomp spring reached a maximal discharge estimated to ≈27 m^3/s, and the entrance gallery (Shadoks Gallery) of the Chamois Cave got flooded.

Reaction time after beginning of the rain is 9 h for the spring and 21 h for the flooding of the S3. Since the epikarst was not saturated at the beginning of the event, one might expect much shorter reaction time in case of the situation where epikarst is saturated by previous rain events or in case of more intense storms. We quantified the emptying of S3, having a constant discharge of 1.5 L/s during the first 34 h and 0.5 L/min during the following week. Exploration of Chamois Cave requires the crossing of 3 pumped sumps in the Shadoks Gallery. Thanks to the data logger left in S3, we confirm that flooding closes the S3 sump within a few minutes. If flood is strong enough, in less than 1 h it pours into the Shadoks Gallery and soon closes the lower loops, only upper loops remain "dry". In November 2011, the flood of Shadoks Gallery lasted 1 week, stopping 60 h after the end of the rain. The return to the level of S3 at the bottom of the P7 required an additional 34 h, and the emptying of the lower loops probably required some additional days. The velocity and the duration of flooding must be taken into account and cave exploration must only happen when meteorological conditions are favorable. This study confirms the potential of data loggers for a better knowledge of the cave hydrodynamic and especially in a safety perspective during flooding. Study of time reaction when karst is saturated is ongoing.

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