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Analysis on the mode of depletion of water reserves contained in the Locoli aquifer (Monte Albo - northeastern Sardinia).

Analisi sulle modalità di svuotamento delle riserve idriche contenute nell'acquifero Locoli (Monte Albo - Sardegna nord-orientale)

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Parole chiave:
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Abstract

This paper presents analytical insights based on hydrogeological monitoring data collected in a specific portion of Monte Albo, the Locoli aquifer, located in the Mesozoic limestones of north-eastern Sardinia: these analyses were carried out by processing the data of the variations in water level in the aquifer, acquired in collaboration with some Sardinian speleological groups. In particular, a first in-depth analysis concerned the water level measurements relating to the emptying phases of the karst aquifer that occurred between 2009 and 2024 in unaffected regime. The use of high-precision pressure (level) gauges and fixed monitoring stations allowed the processing of homogeneous data, the analysis of which made it possible the reconstruction of a curve that represents the typical trend of water level decreases in the karst aquifer during the low-water phase.
The reconstruction of the ways in which the aquifer empties over time was then compared to some flow rates measured in the underground stream that drains the same aquifer and transmits water towards the karst spring of Fruncu 'e Oche, the main perennial water resurgence in Monte Albo. Measurements of these flows were carried out by the cave divers of Phreatic Aps in the post-siphon environments of the Locoli cave, during a particularly dry period such as August 2024. Finally, the combined analysis of level decreases and flow rates of the underground stream made it possible to estimate, with good approximation, the water reserves stored in the Locoli aquifer during the low water phase. A planned and sustainable management of these water volumes, which correspond to approximately 3 Mm^3 contained in 0.5 m thick of the aquifer, could be very useful in mitigating the effects of the now recurring water crises that negatively impact the aqueduct system that supplies the Baronia region.

Riassunto

Si illustrano alcuni approfondimenti analitici eseguiti su dati di monitoraggio idrogeologico rilevati in una specifica porzione del Monte Albo, l'acquifero Locoli, localizzato nei calcari mesozoici della Sardegna nord-orientale: tali analisi sono state effettuate elaborando i dati delle variazioni di livello idrico nell'acquifero acquisiti in collaborazione con alcuni gruppi speleologici sardi. In particolare, un primo approfondimento ha riguardato le misurazioni di livello idrico relative alle fasi di svuotamento dell'acquifero carsico succedutesi tra il 2009 ed il 2024 in regime non influenzato. L'utilizzo di misuratori di pressione (livello) dotati di buona precisione e di stazioni fisse di monitoraggio hanno permesso di elaborare dati tra loro omogenei, la cui analisi ha consentito di ricostruire una curva che rappresenta la tendenza tipica dei decrementi di livello idrico nell'acquifero carsico durante la fase di magra.
La ricostruzione delle modalità attraverso le quali l'acquifero si svuota nel tempo è stata quindi confrontata con alcune portate misurate nel torrente sotterraneo che, drenando lo stesso acquifero, trasmette le acque verso la sorgente carsica di Fruncu 'e Oche, la principale emergenza idrica perenne presente nel Monte Albo. Le misure di questi deflussi sono state effettuate dagli speleosubacquei di Phreatic Aps negli ambienti post sifone della grotta Locoli in un periodo particolarmente siccitoso qual è stato il mese di agosto del 2024. L'analisi combinata dei decrementi di livello e delle misure di portata del torrente sotterraneo, infine, ha permesso di stimare, con buona approssimazione, le riserve idriche immagazzinate nell'acquifero Locoli in fase di magra.
Una gestione pianificata e sostenibile di questi volumi idrici, che corrispondono a circa 3 Mm^3 contenuti in uno spessore di 0.5 m di acquifero, potrebbe essere molto utile per mitigare gli effetti delle ormai ricorrenti crisi idriche che impattano negativamente sul sistema acquedottistico che approvvigiona il territorio della Baronia.

Introduction

The effects of ongoing climate change combined with an ever-increasing demand for good quality water contribute to increase the risks of overexploitation of groundwater. This issue has also been addressed in the recent EU Climate Change Adaptation Strategy (EC, 2021), which calls on Member States to plan their actions in order to ensure drinking water for communities in the long term. In order to mitigate the risks of degradation and effectively manage groundwater resources, it is therefore essential to deepen our understanding of how aquifers respond to climate change (Green et al., 2011). Almost 30 years ago, water resource assessments conducted by UNESCO and FAO in the Mediterranean area already estimated that about two-thirds of drinking water came from lowland wells and one-third from carbonate massifs (Forti, 1998). The same documents predicted that by 2025, that ratio would be reversed due to the pollution of alluvial aquifers caused by the growing anthropization of the lowlands. These estimates, therefore, have long attributed a strategic role to the water resources of karst aquifers, a role that is all the more appropriate to define in its operational aspects, also in the perspective of the most recent and unfortunate scenarios related to climate change. In this sense, the efficiency of the infiltration systems of limestones (Goldscheider N., 2015), capable of transferring even more than 50% of the precipitations that fall in the hydrogeological basins into the underground karst conduits, is a first very important insight: in fact, the values of the infiltration coefficient in karst limestones, which are much higher than the same coefficients that generally characterise other lithotypes, can attribute to carbonate aquifers a great recharge potential and, therefore, their strategic importance.

The most comprehensive hydrogeological investigation of the Monte Albo karst aquifer—a Mesozoic limestone ridge covering over 50 km² in northeastern Sardinia—was conducted between 2008 and 2013. Data for the study were obtained through tracer tests, performed under varying hydrodynamic conditions across different sectors of the aquifer. Data was also collected by setting up point-in-time monitoring of water inflows and outflows within the recharge basin and at the Fruncu ‘e Oche spring, (the primary perennial discharge point of the system), which has an average annual flow rate of 0.57 m³/s. The analysis incorporated over 1,200,000 monitoring data points, enabling the identification of surface infiltration zones, delineation of principal subsurface runoff, estimation of hydrological balance parameters (Fig. 1), characterizing a geological reservoir with an estimated volume exceeding 25 Mm³ (F. Murgia, 2013).

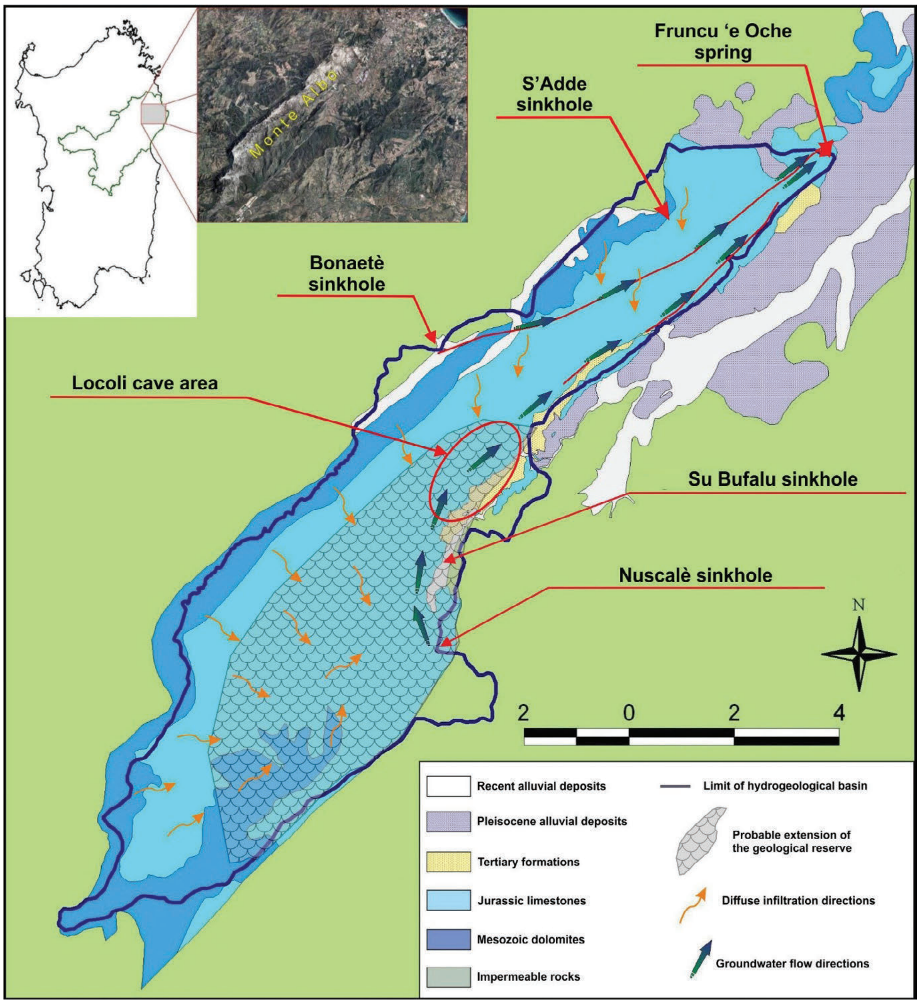

Fig. 1 - General hydrogeological scheme in the Monte Albo area.

Fig. 1 - Schema idrogeologico generale nell’area del Monte Albo.

That study identified a specific hydrogeological compartmentalization of the aquifer, which can be schematically described (Fig. 2) as follows: a large, deep groundwater storage basin located beneath the Locoli cave (referred to as Locoli aquifer); a drainage system (Siniscola Branch tunnels) that conveys water from this basin to the Fruncu 'e Oche spring; and a second hypogean water basin (Baronie aquifer), situated further north that laminates groundwater flow before it reaches the spring (F. Murgia & F. Stoch, 2023).

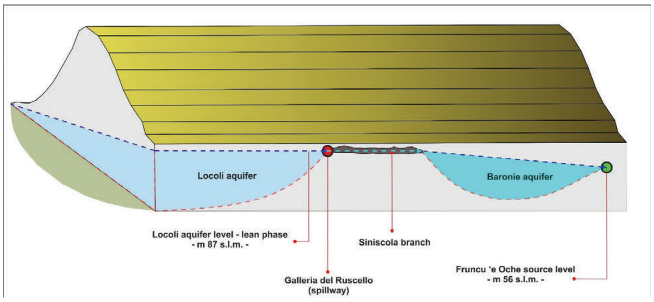

Fig. 2 - Diagram of the compartmentalization of the karst aquifer in Monte Albo.

Fig. 2 - Schema della compartimentazione dell'acquifero carsico nel Monte Albo.

Recent cave diving explorations in the Locoli cave (within the flooded sumps of the Siniscola Branch (Fig. 3), have documented the presence of residual patches of ancient speleothems (Fig. 4). This evidence indicates that groundwater circulation within the Locoli aquifer previously occurred at lower elevations than it does today. It also supports the interpretation of the current aquifer as a large flooded karst, that originated as a result of the geological and geomorphological events that affected northeastern Sardinia from the Tertiary period onward.

Fig. 4 - Residual concretions in the flooded galleries of Locoli cave (Photo: Sven Bertelmann).

Fig. 4 - Concrezionamenti residuali nelle gallerie allagate di grotta Locoli (Foto: Sven Bertelmann)

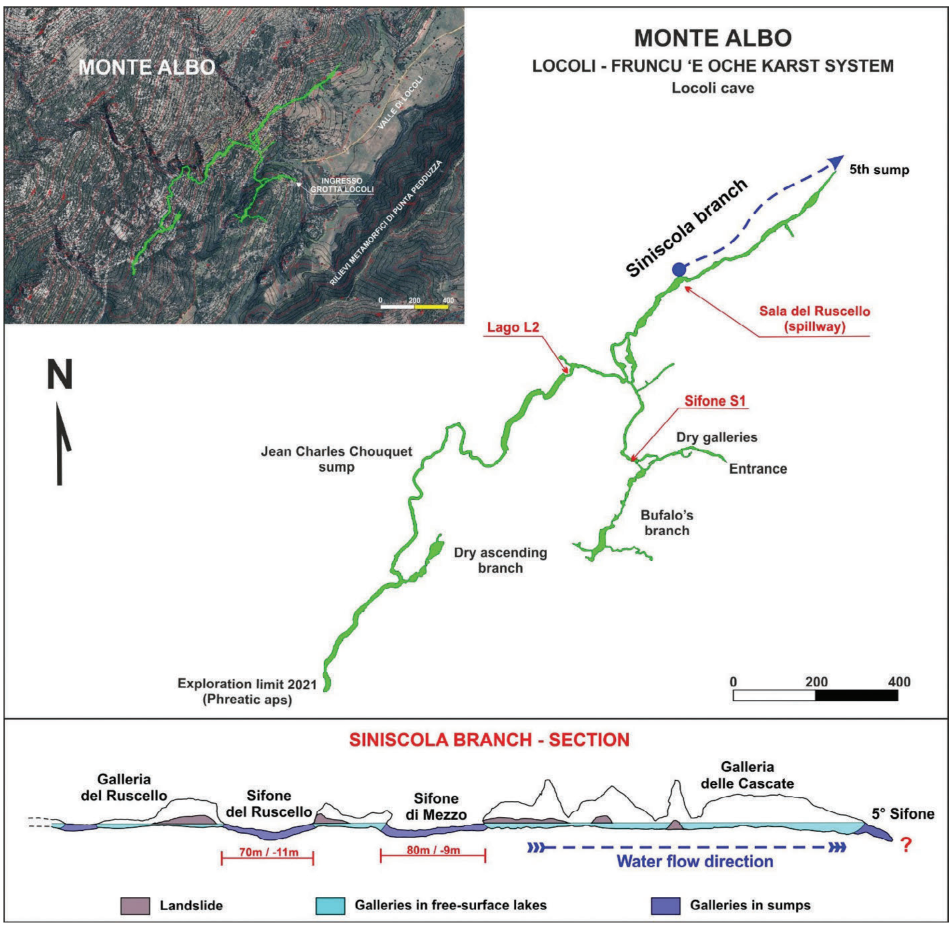

Fig. 3 - Chorography and topographic survey of Locoli cave (from REGIONE AUTONOMA DELLA SARDEGNA, 2018 - CSR 149 SA/NU – modified).

Fig. 3 - Corografia e rilievo topografico di grotta Locoli (da REGIONE AUTONOMA DELLA SARDEGNA, 2018 - CSR 149 SA/NU – modificato)

The presence of these aforementioned geomorphological features also supports the existence of a single-level hypogean water storage basin within Monte Albo, as previously described by F. Murgia and A. Marassich (2022). This basin extends into all the flooded conduits of the system. Notably, water level variations observed simultaneously across different portions of the Locoli aquifer exhibit consistent values throughout all hydrodynamic phases (Fig. 5), further confirming the hydraulic continuity of this unified storage structure.

The objectives of this study are twofold: to assess the mechanisms by which the underground stream in the Siniscola Branch transfers groundwater from the Locoli aquifer to the Fruncu 'e Oche spring, and to estimate the aquifer's stored water volume during the lean phase. These goals were pursued by analyzing four depletion curves recorded in the aquifer between 2009 and 2012 and in 2024. Each curve corresponds to a depletion event triggered at a peak water level exceeding 12 m, with minimal influence from infiltration processes that could alter the natural recession trend.

A representative depletion curve was derived by assigning a common reference time (T_0) to the onset of each depletion event and averaging the water levels recorded at subsequent

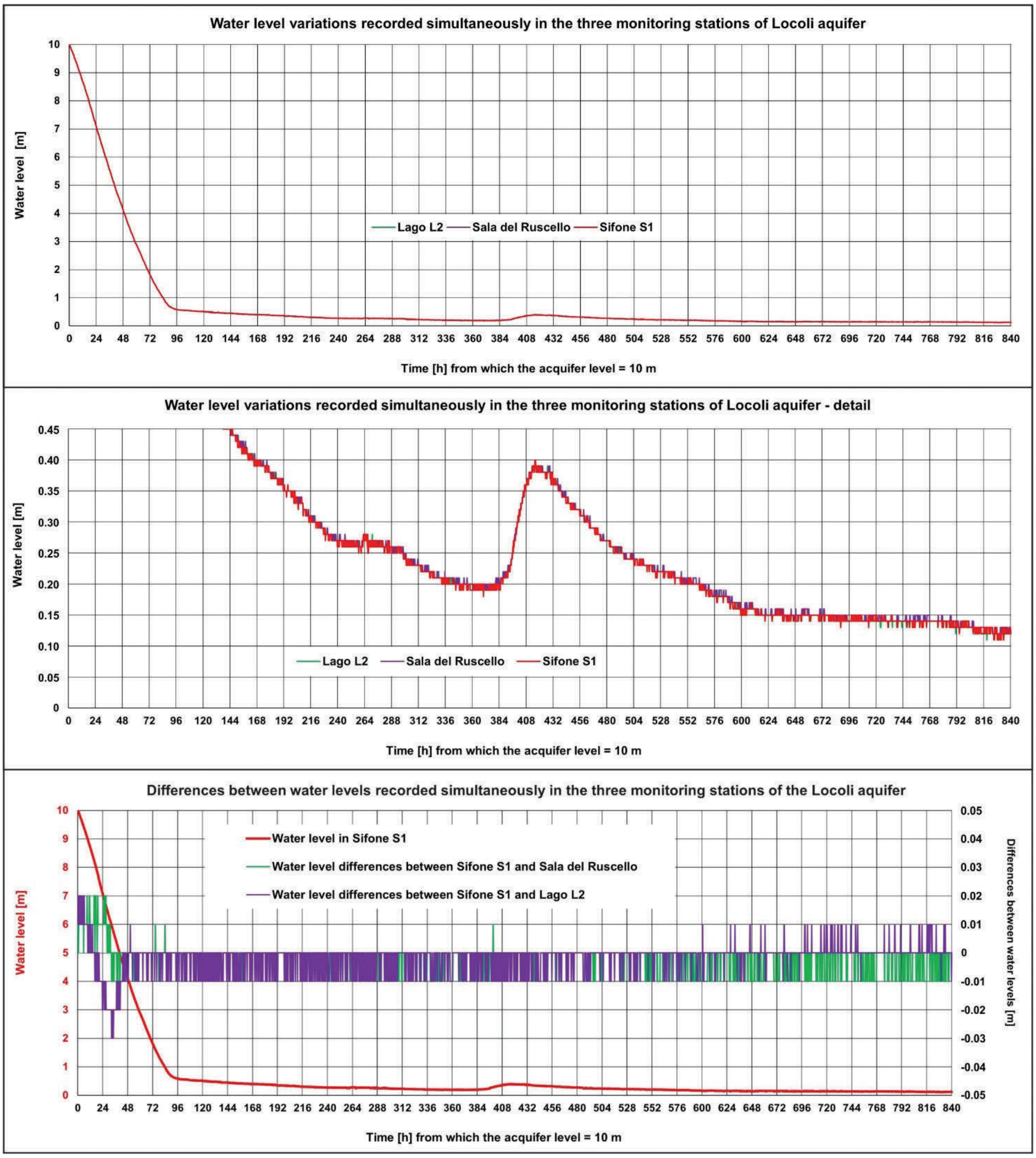

Fig. 5 - Simultaneous variations in water level recorded in different points of the Locoli aquifer.

Fig. 5 - variazioni simultanee di livello idrico registrate in punti diversi dell'acquifero Locoli.

DOI 10.7343/as-2025-876

15-minute monitoring intervals. Finally, the portion of the decreasing curve referable to the lean water levels was evaluated as a function of some underground stream flow measurements, performed by Phreatic APS in August 2024 during the maximum lean phase, to estimate the water reserves contained in the aquifer and laminated during depletion.

Materials and methods

A number of "DL/N70" multi-parameter sensors produced by Sensor Technik Simach (STS®), equipped with dataloggers capable of recording changes in water levels over time, were used to acquire data of water level variations in the Monte Albo karst aquifer between 2009 and 2012. The accuracy of these instruments in relation to pressure measurement is ± 0.1% of full scale while their resolution is < 0.01% of full scale. On the other hand, "TD Diver" and "Diver Baro" sensors produced by Van Essen®, which are equipped with dataloggers capable of recording changes in water headwaters over time, were used to acquire data of water level changes recorded in 2024. The accuracy of these instruments in relation to pressure measurement is ±0.01 m H_2O while their resolution is ± 0.004 m H_2O.

After the alignment operations, the water level sensors were placed in the housings prepared in the Locoli aquifer. These sensors recorded the changes in total pressure (water head + atmospheric pressure) to which they were subjected during monitoring. Barometric sensors were installed in a protected location outside the cave to record atmospheric pressure variations, which were subtracted from the simultaneous pressure readings acquired by the submerged sensors in the aquifer. Given the initial depth of these sensors, the corrected data accurately reflect water level fluctuations within the Locoli aquifer throughout the monitoring period.

Subsurface stream flow measurements were conducted on August 20, 2024, in the post-sump environments of the Siniscola Branch using a non-instrumental approach, due to site constraints. Measurements were taken at two distinct points along the streambed. The cross sections were surveyed using a millimeter-precision metric bindel and subsequently modeled with Catia CAD software to reconstruct the channel geometry [identified sections]. A number of floating bodies released on the stream line were used to calculate the runoff velocity, the movement of which was filmed to estimate travel times, with an accuracy of 0.5 s, between previously assigned and surveyed milestones.

Analysis of water level decreases - lean phase

Water level decreases in the Locoli aquifer have been monitored several times in a discontinuous manner from April 10, 2009 until October 14, 2012 and continuously from November 01, 2023 to August 20, 2024. Among the numerous available depletion curves, four were selected (Fig. 5) based on comparable hydrological conditions in the Monte Albo karst system during both recharge and recession phases. Specifically, these curves were characterized by minimal influence from new water inflows during the depletion phases—either absent or already eliminated—ensuring that the observed declines reflect the natural discharge dynamics of the aquifer without external perturbations.

Graph 6(a) shows the decreases in water level recorded in the aquifer during the 10 days following the flood events. In the 120 hours following the maxima considered, the 4 curves are marked, between elevations +10 m and +2 m, by very high decreasing velocities, about 0.14 m/h in the 2009 to 2011 curves and about 0.21 m/h in the 2024 curve. The higher flow velocity recorded in the latter measurement can be attributed to a specific hydrogeological condition in which the Baronie aquifer—responsible for laminating water from the Locoli aquifer before it reaches the Fruncu 'e Oche spring—was already significantly depleted. This depletion was likely due to the prolonged drought affecting northeastern Sardinia since autumn 2023, which reduced the aquifer's buffering capacity at the time of the flood's arrival.

Graph 6(b) shows the water level decreases recorded in the aquifer in the months following the flood pulses and, therefore, referable to the depletion of the Locoli aquifer. More specifically, graph 6(c) shows the distributions of water levels referring to the times after 480 hours from T_0 for each of

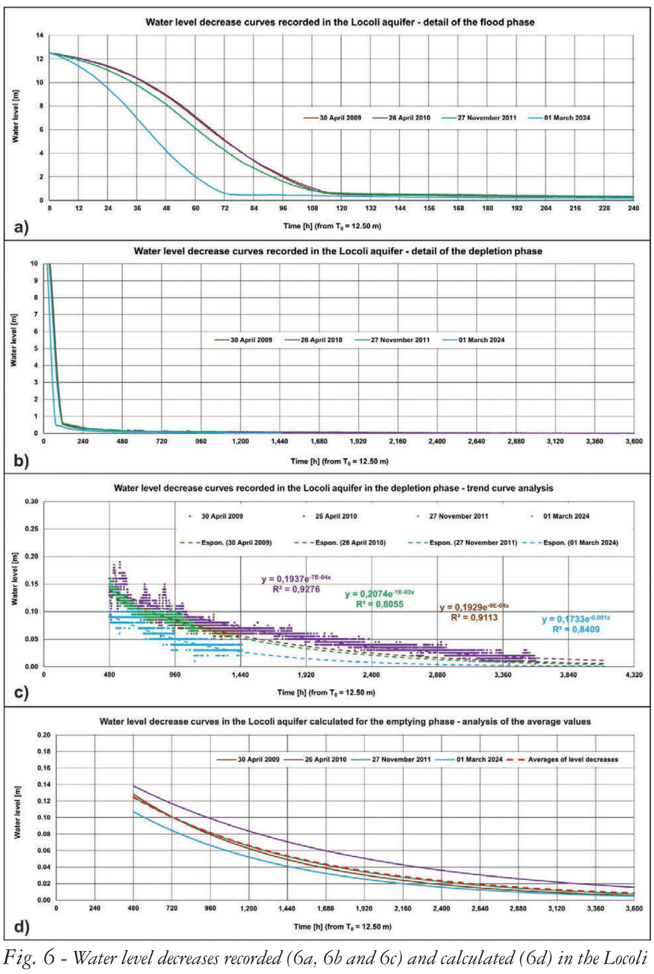

Fig. 6 - Water level decreases recorded (6a, 6b and 6c) and calculated (6d) in the Locoli aquifer during the emptying of the aquifer.

Fig. 6 - Decrementi di livello idrico registrati (6a, 6b e 6c) e calcolati (6d) nell'acquifero Locoli durante lo svuotamento dell'acquifero.

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the curves considered, while graph 6(d) shows the exponential trend curves referring to each period of observed decrease - and that of the averages between the values of the calculated exponentials. The analysis of the latter curve makes it possible to determine the average rate of water level decrease recorded in the Locoli aquifer between elevations +0.8 m and +0.3 m, equal to about $4.5 \cdot 10^{-5}$ m/h, which corresponds to 0.05 m of piezometric level lowering in over 1,000 hours.

Flow rate measurements in the lean phase

On August 20, 2024, a team of cave divers from Phreatic aps consisting of Sven Bertelmann and Marcello Iacca, assisted by Dorota Czerny, Bartek Trzcinski, and Olga Martinelli, made some flow measurements at two separate points of the stream flowing in the Siniscola Branch of Locoli cave, referred to as "Waterfall" and "River."

Flow measurements in "Waterfall" area:

The area is characterized by a riverbed incised into solid rock and speleothem formations, feeding a small waterfall located immediately downstream, which, at the time of the survey, had a vertical drop of approximately 0.4 m.

- **Step 1**: Selected sections in this area were marked with a line to identify their location for subsequent measurements;
- **Step 2**: At each section, water depths from the surface to the riverbed were measured at regular intervals to estimate cross-sectional areas (Fig. 7). The calculated surface areas were: Section 1 - 0.116 m²; Section 2 - 0.104 m²; Section 3 - 0.060 m². The average surface area between Sections 1 and 2 was 0.11 m², and between Sections 2 and 3, 0.082 m².
- **Step 3:** The water flow path was measured along a multi-section line processed using a CAD system, designed to define a guide curve connecting the measured cross sections. To trace the flow path, a floating body was released into the stream, and its movement was recorded on video. From the footage, multiple positions of the floating body were extracted to accurately reconstruct the streamline. An interpolation curve was then generated based on these positions (Fig. 8), with a total length of approximately 3.188 m. Finally, in order to have more detail on the changes in runoff velocity, the entire curve was decomposed into a number of sections delimited by progressive transit times of the floating body, evaluated using the same video footage. The data collected are shown in Table 1.

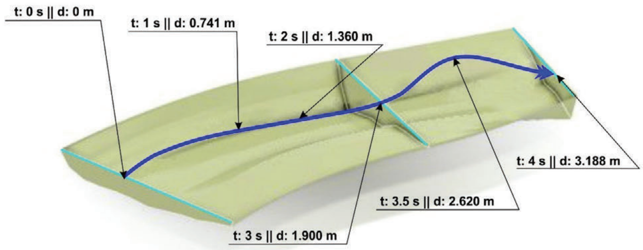

Fig. 8 - Flow line and related runoff times measured between measurement sections in the "Waterfall" area.

Fig. 8 - Linea di scorrimento e relativi tempi di deflusso rilevati tra le sezioni di misura nell'area "Waterfall".

Flow measurements in the "River" area:

Using the same data acquisition and calculation method as described above, water flow rates were evaluated in the second section of the underground stream, which is characterized by a gravel bottom and a shallower slope than that observed in the "Waterfall" zone (Fig. 9).

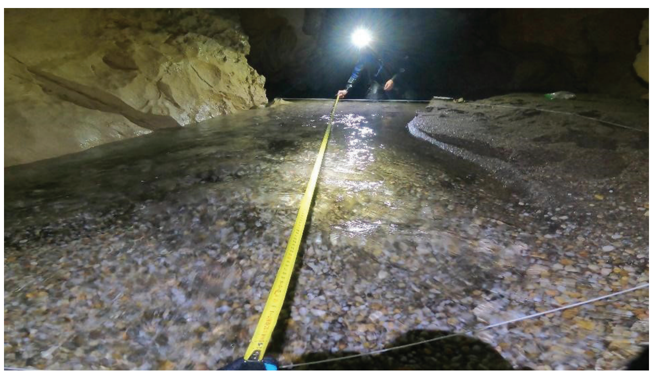

Fig. 9 - Measurement operations in the sections of the "River" area (Photo Marcello Iacca).

Fig. 9 - Operazioni di misura nelle sezioni di misura nell'area "River" (Foto Marcello Iacca).

Fig. 7 - Measurement sections in the "Waterfall" area and detail of measurements in section 3 (photo: Marcello Iacca).

Fig. 7 - Sezioni di misura nell'area "Waterfall" e particolare delle misure nella Stazione 3 (foto: Marcello Iacca).

These measurements were acquired to provide an additional dataset corresponding to a different hydrodynamic context, allowing for cross-validation of the previous results. The surface areas of the measured sections were as follows: Section 1 — 0.105 m^2; Section 2 — 0.118 m^2; Section 3 — 0.099 m^2. The average area between Sections 1 and 2 was 0.1115 m^2, and between Sections 2 and 3, 0.1085 m^2.

In this case, after evaluating the movement of water fillets in the stream, the entire runoff line was broken down into two straight sections; the distance between Section 1 and Section 2 is 1.700 m while that between Section 2 and Section 3 is 3.240 m. Runoff velocities, again, were measured using some video footage in which the transit times of a moving floating body along the path between the identified cross sections were estimated. This is illustrated in Figure 10 and described in the following Tab. 2.

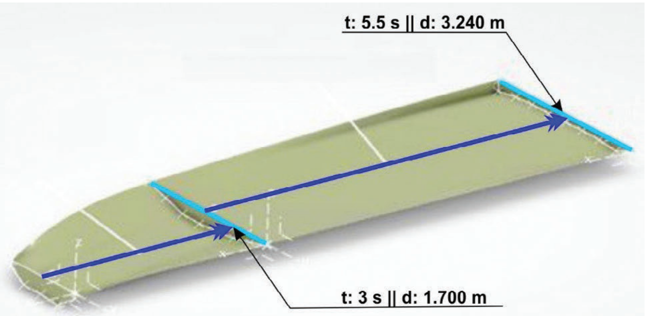

Fig. 10 - Flow line and related runoff times measured between measurement sections in the "River" area.

Fig. 10 - Linea di scorrimento e relativi tempi di deflusso rilevati tra le sezioni di misura nell'area "River".

Results and discussion

The following Table 1 shows the monitoring data acquired in the "Waterfall" area.

Tab. 1 - Distances and related runoff times measured between measurement sections in the "Waterfall" area.

Tab. 1 - Distanze e relativi tempi di deflusso misurati tra le sezioni di misura nell'area "Waterfall".

Section	Lenght (m)	Time (s)	Speed in each section (m/s)	Average speed between sections (m/s)
1	0	0		0.685
	0.741	1	0.741	
	1.360	2	0.680	
2	1.900	3	0.633	0.773
	2.620	3.5	0.749	
3	3.188	4	0.797	

Based on the collected data, the water flows in the "Waterfall" sections were calculated as follows:

- average area between Sections 1 and 2 = 0.11 m^2
- average velocity between Sections 1 and 2 = 0.685 m/s

$Q1 = S \times v = 0.11\ m^2 \times 0.685\ m/s = 0.0753\ m^3/s$

- average area between Sections 2 and 3 = 0.082 m^2
- average velocity between Sections 2 and 3 = 0.773 m/s

$Q2 = S \times v = 0.082\ m^2 \times 0.773\ m/s = 0.0634\ m^3/s$

The following Table 2 shows the monitoring data acquired in the "River" area.

Tab. 2 - Distances and related runoff times measured between measurement sections in the River" area.

Tab. 2 - Distanze e relativi tempi di deflusso misurati tra le sezioni di misura nell'area "River".

Section	Lenght (m)	Time (s)	Speed in each section (m/s)	Average speed between sections (m/s)
1	0	0		0.567
2	1.700	3	0.567	0.574
3	4.940	8.5	0.581	

Based on the data collected, the flow rates in the "River" zone sections were calculated as follows:

- average area between Sections 1 and 2 = 0.1115 m^2
- average velocity between Sections 1 and 2 = 0.567 m/s

$Q3 = S \times v = 0.1115\ m^2 \times 0.567\ m/s = 0.0632\ m^3/s$

- average area between Sections 2 and 3 = 0.1085 m^2
- average velocity between Sections 2 and 3 = 0.574 m/s

$Q4 = S \times v = 0.1085\ m^2 \times 0.574\ m/s = 0.0623\ m^3/s$

The 4 flow rate measurements taken in the two areas and their respective measuring sections are homogeneous with each other and 3 out of 4 of them are almost congruent, reflecting the accuracy of the measurements taken. The average flow rate can be estimated at approximately 66 L/s.

The availability of the average decline curve of water levels in the aquifer, along with a reliable estimate of the low-flow rate of the underground stream feeding the Fruncu 'e Oche spring, makes it possible to develop scenarios that help estimate the water volume in the Locoli aquifer during the low-flow phase (with reasonable accuracy). Considering the time it takes for the aquifer's water level to drop from +0.08 to +0.03 m —1,110 h (Fig. 11)— and the average groundwater outflow during this period, estimated between 70 and 80 L/s, the calculations shown in Table 3 were developed. Assuming an average underground stream flow rate of 75 L/s over this time period, the groundwater volume stored in just 0.5 m of the aquifer is estimated to be approximately 3 Mm^3.

Conclusion

The availability of multiple sets of monitoring data related to the times with which the Locoli karst aquifer empties has allowed the elaboration of the typical curve of water level decreases in the unaffected regime; this curve reproduces the ways in which the Locoli aquifer discharges to naturally feed the Fruncu 'e Oche spring, - the most important source in the northeastern portion of Sardinia - during the low water phase. The comparative analysis of this curve and some flow measurement carried out on the underground water outflows

Tab. 3 - Estimate of the volumes of water contained in 0.50 m of aquifer evaluated by varying between 70 and 80 L/s the average flow rates emitted by the same aquifer between the levels +0.08 m and +0.03 m.

Tab. 3 - Stima dei volumi d'acqua contenuti in 0,50 m di acquifero valutati variando tra 70 e 80 L/s le portate medie emesse dallo stesso acquifero tra i livelli +0.08 m e +0.03 m.

Time elapsed between L = 0.08 m and L = 0.03 m [h]	1.110						Average
Q_m (estimated) emitted from Locoli aquifer between L = 0.08 and L = 0.03 m [L/s]	80	78	76	74	72	70	75
Estimated water reserve volumes in 0.50 m of Locoli aquifer [Mm^3]	3.20	3.12	3.04	2.96	2.88	2.80	3.00

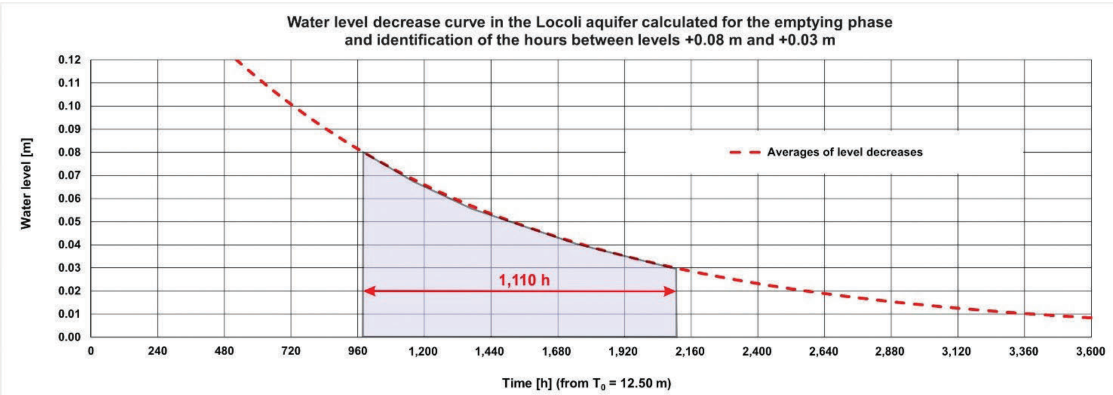

Fig. 11 - Graph showing the time intervals associated with groundwater flow between levels +0.08 m and +0.03 m, based on the average water level decline curve.

Fig. 11 - Grafico illustrativo dei tempi relativi ai deflussi idrici sotterranei tra i livelli +0.08 m e +0.03 m identificati sulla curva delle medie calcolate dei decrementi di livello idrico.

of the Locoli Cave in the low water phase has made it possible to estimate the volumes of water resources stored in the first 0.5 m of the aquifer at approximately 3 Mm^3. These assessments allow the operators of the regional aqueduct system to rely to hitherto unknown groundwater volumes, of good quality. The use of these resources might help both to cope with local water emergencies caused by the now recurring drought periods and, possibly, to optimise aqueduct withdrawals by intervening with artificial regulation of groundwater outflows that naturally propagate in the aquifer.

The same results, moreover, confirm what has long been established, namely. that the underground water resources contained in the karst aquifer of Mount Albo are substantial and that their use for drinking purposes, under well-defined withdrawal conditions established according to the necessary recharge of the aquifer, can be sustainable from a hydrogeological point of view. The outcomes of the ongoing biological study of the hypogean ecosystem of Monte Albo, funded by the UNESCO MaB Reserve "Tepilora, Rio Posada, Montalbo" and carried out by the University of Brussels, will help to define the limits of environmental sustainability within which, eventually, karst waters can be used to meet the needs of local communities.

A significant novelty that emerged in the course of the speleological exploration is the finding of the perennial character attributable to the hypogeous stream subjected to measurements: in fact, the water flows measured in August 2024 give evidence that they are important even during the maximum low water phase and that, most likely, they constitute the largest percentage of the water flows emitted by the Fruncu 'e Oche spring. To this new geographical object, the first cave divers who reached the point of overflow from the aquifer to the underground river in 2008 wanted to give the name "Baronie Stream." This novelty, together with the documentation of a flooded karst extending deep into the aquifer, highlights highlights the importance of the collaboration between the world of scientific research and the one of speleological exploration in fact, hypogean karst environments, often home to important aquifers, given the particular resilience of the morphologies contained within them, can be considered as true "archives of time", capable of preserving important traces which are fundamental for the reconstruction of the paleoenvironmental conditions that contributed to generating underground aquifers.

Competing interest
The authors declare no competing interest.

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Author contributions
Francesco Murgia: Methodology, Conceptualization, Formal analysis, Data curation, Visualization, Writing-original draft preparation, Writing-review and editing. Andrea Marassich: General organization and supervision of monitoring in post-sump environment, Conceptualization, Writing-review; Sven Bertelmann: Conceptualization, Video and monitoring operator in post-sump environments, Data curation, Visualization, Writing-original draft preparation; Marcello Iacca; Conceptualization, Video and monitoring operator in post-sump environments, Data curation; Dorota Czerny: Support in monitoring activities in post-sump environment; Olga Martinelli: Support in monitoring activities in post-sump environment. All authors read and approved the final version of the manuscript.

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