PAPER

The source of rock moisture in a sandstone cave in arid northern China: rainfall infiltration or vapor condensation?

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Abstract

During summers with intensive rainfall, water droplets and/or rock moisture are observed in some of the ancient caves of the Yungang Grottoes, northern China. There is debate on whether the water is derived from infiltrating precipitation or from condensation of water vapor, and this restricts the choice of appropriate methods to alleviate weathering of the stone carvings. By monitoring soil water content at the top of the vadose zone and analyzing responses to rainfall events, it is found that the silt overlying the rock mass plays the role of barrier to rainfall infiltration. By monitoring rock moisture in a cave wall at shallow depth, using frequency domain reflectometry, it was found that variations in rock moisture are directly controlled by the fluctuating vapor concentration. Moreover, there is a significant linear relationship between the magnitude of rock wetting (moisture addition) and the cumulative difference in vapor concentration between the inside and outside of the cave. Thus, the condensation of water vapor, which leads to decreased vapor concentration in the cave atmosphere, is the source of the rock moisture. Also, the period associated with rapidly increasing rock moisture and the highest rock moisture corresponds to the period with occurrence of water droplets in some caves. This study confirms that the water vapor is an important source of water which is responsible for weathering in caves, and indicates that the approach of estimating groundwater recharge based on cave drip rates should be used with caution, especially in arid environments.

Keywords Condensation water · Soil moisture · Rock weathering · Vadose zone · Arid regions · China

Introduction

Many caves, either formed naturally or artificially, are sites of tourism. Because caves are free from direct exposure of rainfall, the causes leading to occurrence of water in caves are of interest to the public. As early as in the fourth century BC, Aristotle (384–322 BC), probably inspired by the widespread cavernous limestone terranes in Greece, hypothesized that atmospheric water vapor could penetrate into rocks and

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condense and gather into water drops owing to the low temperature inside the rock, and he thought that condensation water is the source of river water (after Meinzer 1934). In the latter part of the seventeenth century, with contributions from Pierre Perrault (1608–1680) and Edméand Mariotté (1620–1684), rainfall was widely recognized to be the source of river water and groundwater (after Meinzer 1934), which is the cornerstone of modern hydrology. If there is plenty of rainfall, precipitation would infiltrate through unsaturated zones and arrive at caves, which would constitute seepage in caves. In the latter half of the twentieth century, the occurrence of condensation water in caves in the warm season was revealed in caves in Russia (after Dublyansky and Dublyansky 2000), Spain (Quindos et al. 1987), Romania (Sarbu and Lascu 1997) and New Zealand (De Freitas and Littlejohn 1987). The physics of condensation in the surface of caves controlled by microclimate has been established (Dublyansky and Dublyansky 1998; Gabrovšek et al. 2010). Moreover, adsorption and capillary condensation could lead to increased water content inside rocks even if the condition

of condensation is not satisfied at the rock surface (Lu and Likos 2004; Gregg and Sing 1982; Fisher et al. 1981). However, a clear understanding of condensation water in caves is still restricted by the difficulty of observing condensation water inside rocks in the field. Moreover, it is difficult to differentiate whether water that occurs in caves is derived from condensation of water vapor or infiltration of precipitation.

Because cave water from either seepage or condensation would deteriorate cave features, identifying the source of water is the precondition to develop protocols for minimizing the side-effect of water (Gázquez et al. 2022). If sufficient seepage or condensation water in caves can be collected, physical and chemical methods can be used to establish its relationship with precipitation or vapor. The relationship between discharge rate of seepage water and precipitation has been used to infer the hydrogeological conditions of the unsaturated zone overlying the cave (Baker et al. 1997), and the discharge rate has also been used to estimate the rate of groundwater recharge (Baker et al. 2020; Mahmud et al. 2015, 2016, 2018; Nathan et al. 2011). Hydrochemical and isotopic methods have also been widely used to establish the relationship between precipitation and seepage water (Wu et al. 2022), and to identify the sources of condensation water (Gázquez et al. 2022). However, physical and chemical methods are hardly applicable in arid regions due to the difficulty of collecting the limited seepage water or condensation water. In fact, as long as seepage water and condensation water occasionally occur in caves, they can be absorbed by the rock and their amounts can be reflected in rock moisture, which is termed a 'hidden component' of the hydrological cycle (Rempe and Dietrich 2018). Although a few studies have monitored rock moisture and identified its response to precipitation (Rempe and Dietrich 2018; Schmidt and Rempe 2020; Sass 2005), to the authors' knowledge, there has been no study on the monitoring of rock moisture inside caves. The available techniques for measuring rock moisture provide an alternative approach for differentiating the source of water from seepage or condensation.

The Yungang Grottoes in northern China, which have 252 caves and 51,000 statues (Fig. 1), were declared a World Heritage Site by the UNESCO in 2001. Unfortunately, most of the statues carved in the sandstone caves have suffered severe weathering and deterioration (Fig. 1b-d). Water droplets occasionally occur in some of the caves, and water may also occur in the form of rock moisture because water can be easily adsorbed by sandstone. It was long believed that seepage from precipitation is the main source of water droplets in these caves (Wang et al. 2012). However, a recent geophysical study using time-lapse electrical resistivity tomography revealed that infiltrating water cannot recharge local groundwater and is not the source of water responsible for the weathering (Mao et al. 2022). Some researchers

speculated that condensation water could be the source of water droplets in the summer (Huang 2010; Cao et al. 2005; Wan et al. 2012), and a recent laboratory study demonstrates that the formation of condensation water inside the rock is earlier than that at the rock surface (Huang et al. 2022). However, there is no field evidence to support the control of adsorption and condensation of rock moisture inside rocks and water droplets on rock surfaces. The uncertainty of the water sources in the caves restricts the choice of appropriate methods to protect the stone carving art in the Yungang Grottoes.

In this study, to identify the source of water droplets and rock moisture in caves, the frequency domain reflectometry (FDR) technique is chosen to continuously monitor rock moisture in a shallow part of the cave wall. Soil moisture at different depths of the topsoil overlying the caves were also monitored for comparison. By examining the responses of rock moisture to vapor concentration and the responses of soil moisture to rainfall, and by observing occurrence of water droplets in the rock walls, the source of water droplets and rock moisture in the caves is found to be derived from condensation of vapor.

Study area and field monitoring

Study area

The Yungang Grottoes (40°07' N, 113°08' E) site is located in Datong City, Shanxi Province, in northern China (Fig. 2). It is one of the greatest ancient stone-carving art treasures in the world. As shown in Fig. 1b-d, many of the statues carved in the caves that are free from direct exposure to sun and rainfall have suffered strong weathering. Identifying the sources of water responsible for the weathering is one of the challenges facing the protectors of the stone carving art in the Yungang Grottoes.

The park of the Yungang Grottoes has a semi-arid climate. The annual mean precipitation is 393 mm, and the annual mean evaporation is 1243 mm (Ouyang et al. 2023). The Shili River, with an elevation of around 1130 m above sea level (Fig. 2a), is the discharge area of groundwater. Because the river is less than 1 km away from the Yungang Grottoes, the elevation of the water table in the Yungang Grottoes approximates to 1130 m. The bottom of most caves, with elevations being around 1140 m above the sea level, is around 10 m above the water table, implying that water resulting from capillary rise from the water table can be excluded as a source of water in the caves.

Selected measurements of topography of the rock mass show that the elevation of the topography ranges from 1160.97 m to 1173.27 m. Therefore, the thickness
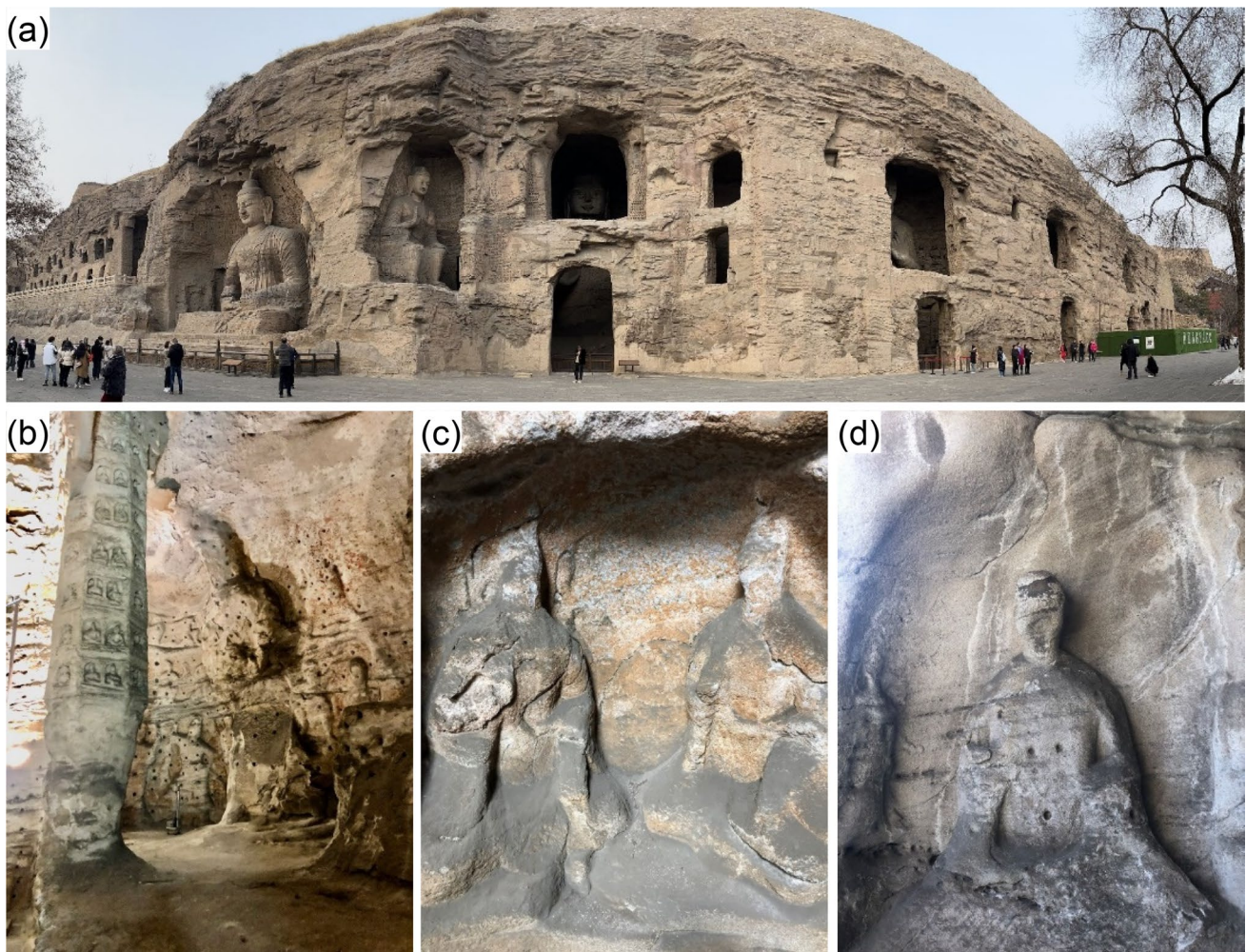
Fig. 1 (**a**) A photo showing some caves and statues in the Yungang Grottoes; (**b-d**) Photos showing the strong weathering of some statues in caves. Photo **a** also shows that the caves are overlain by a thick unsaturated zone. All photos were taken by Xiao-Wei Jiang

of unsaturated zone is generally more than 30 m. The unsaturated zone is mainly composed of sandstone interlayered with siltstone or mudstone, overlain by a layer of silt at the top with a thickness ranging from 0.2 m to 7.8 m. Several boreholes drilled into the unsaturated zone have revealed the occurrence of perched groundwater in the rock mass.

On the walls of some caves, water droplets can be occasionally observed in the summer (Fig. 3). For example, in the summer of 2021, water droplets flowed downward along the wall on 12 July (Fig. 3a) and could be observed until 28 July (Fig. 3b, c). The disappearance of water droplets on 2 August (Fig. 3d) did not guarantee that the wall was completely dry. Similarly, although most walls do not have water droplets throughout the year, there is still hidden water, i.e., rock moisture, inside the rock

wall. Note that the color of some sandstone walls would slightly change with the rock moisture.

Field monitoring

In recent decades, such techniques as time domain reflectometry (TDR) (Sakaki and Rajaram 2006; Mollo and Greco 2011), frequency domain reflectometry (FDR) (Cooper 2016; Xie et al. 2021; Zhao et al. 2021), earth resistivity tomography (Sass 2005), and neutron probes (Rempe and Dietrich 2018) have been used to monitor soil moisture and rock moisture. In this study, FDR sensors are chosen to monitor soil moisture and rock moisture. Considering that calibration of rock moisture is difficult (Sass 2005) and calibration does not change the trend of temporal variations of soil moisture and rock moisture (Leite et al. 2021; Xu
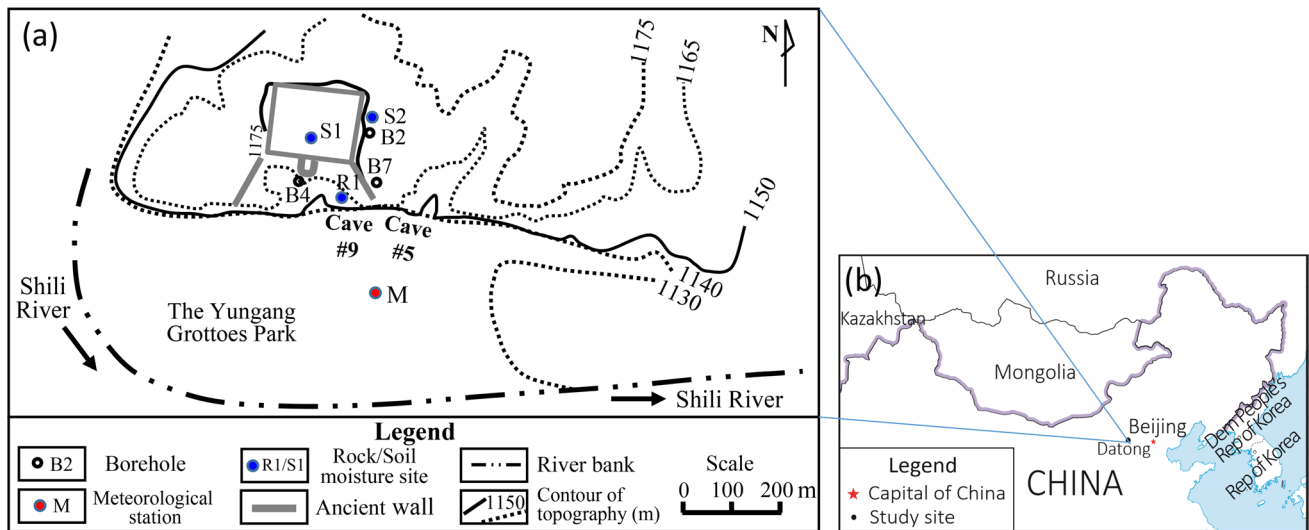
Fig. 2 (**a**) The locations of measurements of soil moisture, rock moisture, water level and meteorology in the Yungang Grottoes. (**b**) The location of the Yungang Grottoes in China. The contour of 1150 m corresponds to the cliff of the rock mass for rock carvings
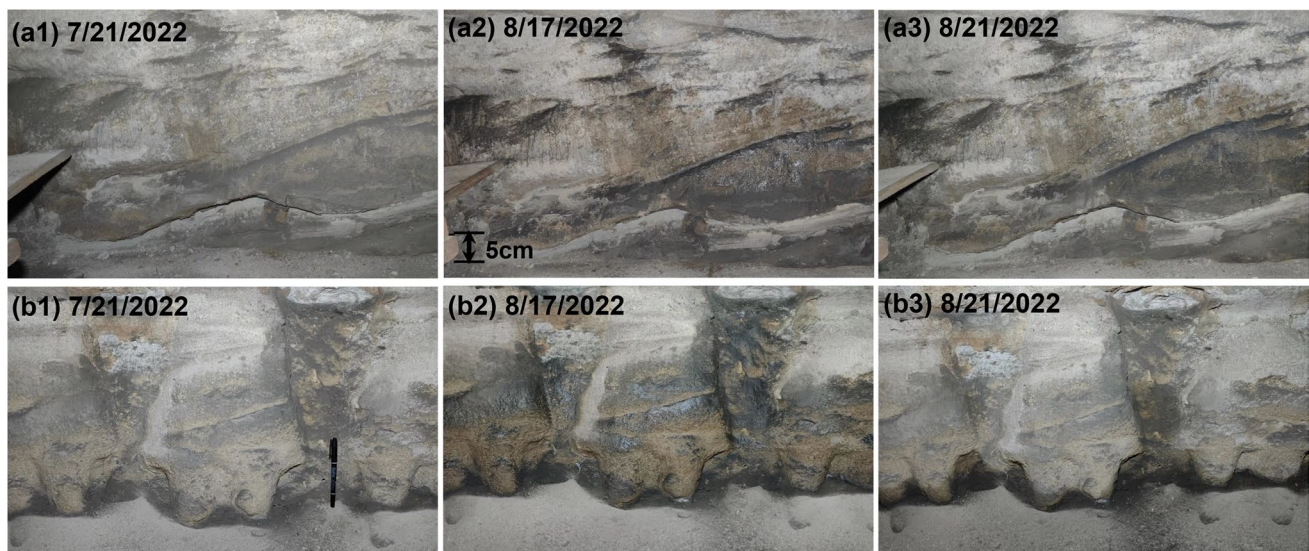
Fig. 3 The sandstone with different colors due to different amounts of rock moisture in (**a**) Cave #5 and (**b**) Cave #9. Among the three days shown, rock moisture was the highest on 17 August 2022 and the lowest on 21 July 2022

et al. 2012), the apparent soil moisture and apparent rock moisture measured by the FDR-based sensors are directly used to identify their responses to atmospheric conditions.

A FDR-based sensor (ECH, produced by DECAGON) was installed at a shallow horizontal depth (3–8 cm) of the north wall of the Cave #9 (R1 shown in Fig. 2a). To make sure that the FDR sensor is in close proximity to the rock, fine sand is used as infilling in the hole for installation. Two soil moisture measuring facilities (yielding profiles S1 and S2, shown in Fig. 2a) were installed in the silt overlying the sandstone on 31 May 2021. Specifically, 6 FDR-based

sensors (5TE, produced by DECAGON) were installed at profile S1 at six different depths (10 cm, 20 cm, 30 cm, 40 cm, 60 cm and 80 cm), and 6 FDR-based sensors were installed at profile S2 at six different depths (10 cm, 30 cm, 50 cm, 75 cm, 130 cm and 220 cm).

Several boreholes tap the perched groundwater in the unsaturated rock mass overlying the caves. To examine the responses of perched groundwater to precipitation events, the water levels are monitored in three boreholes (B2, B4 and B7, locations shown in Fig. 2a) penetrating the perched groundwater occurs at different elevations.

Data on precipitation, air temperature and relative humidity outside the caves are available from a meteorological station installed at the park. Moreover, air temperature and relative humidity are monitored inside the Cave #9, to examine their control on rock moisture.

Calculation of vapor concentration

Vapor concentration, which is the mass of water vapor per unit volume of air, is a function of air temperature and relative humidity. To determine vapor concentration, the first step is to obtain the saturated vapor pressure, $u_{v,sat}$ (kPa), at the corresponding temperature, T (K), and the second step is to calculate the actual vapor pressure, u_v (kPa), based on the measured relative humidity, RH. The formulae for calculating $u_{v,sat}$ and u_v for air with a temperature of T are (Lu and Likos 2004; Lawrence 2002):

$$u_{v,sat} = 0.611 \exp\left(17.27 \frac{T - 273.2}{T - 36}\right) \quad (1)$$

$$u_v = u_{v,sat} \cdot RH \quad (2)$$

The formula for calculating vapor concentration is:

$$C_v = 217 \cdot \frac{u_v}{T - 273.15} \quad (3)$$

where C_v is vapor concentration (g/m^3).

Results and discussion

The dynamics of soil moisture and the water level of perched groundwater

The response of soil moisture in the overlying silt to precipitation

If rainfall can shortly reach a specific depth below the land surface, there would be an abrupt rise in soil moisture, accompanying a peak in soil moisture. For profile S1 (Fig. 4a), there are clear soil moisture peaks induced by rainfall in the shallow part (10 cm and 20 cm), but no rainfall-induced fluctuations in soil moisture in the deep part (from 30 to 80 cm). Moreover, in the rainy season from June to mid-November, there is a trend of decreasing soil moisture in the vadose zone, indicating the dominant control of soil evaporation over rainfall infiltration on soil moisture. In the winter, soil freezing leads to decreased soil liquid water content at all depths. In the spring and early summer of 2022, soil thawing and rainfall infiltration lead to a trend of increasing soil moisture.

For profile S2 (Fig. 4b), only the sensor at 10 cm below the land surface is sensitive to the rainfall. Probably because of the low permeability of the silt at profile S2, all other sensors have trends of stable soil moisture. In the winter, soil freezing lead to decreases in soil liquid water content at 10, 30, 50 and 75 cm, but no changes in soil liquid water content at 130 cm, indicating that the freezing depth is less than 130 cm.

Fig. 4 The responses of soil moisture at different depths of the silt to precipitation, in profiles (**a**) S1 and (**b**) S2
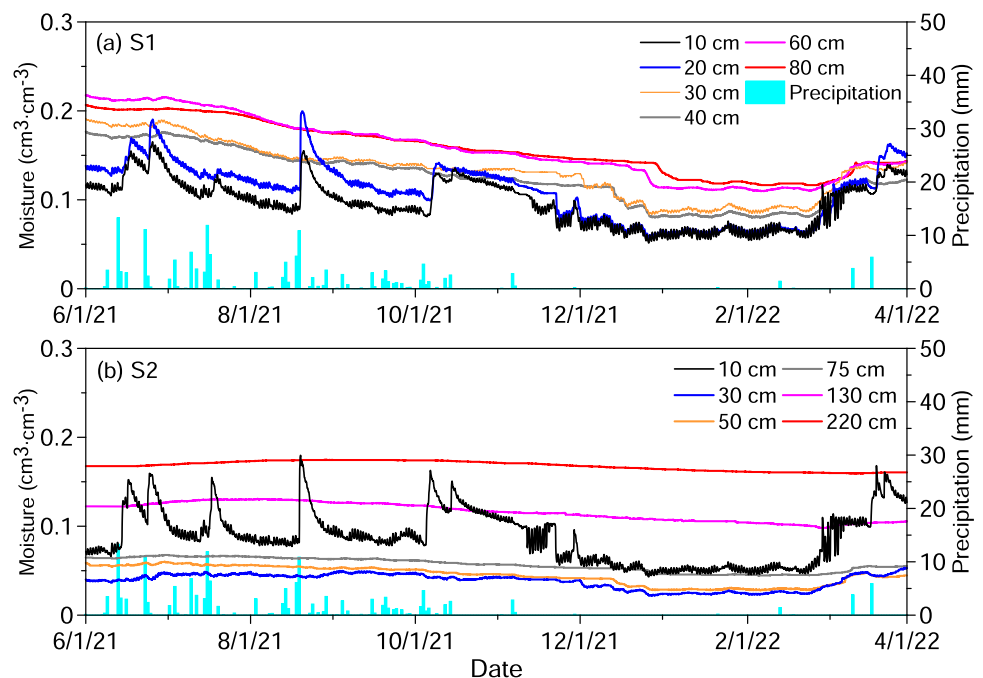
Table 1 The lag times of soil-moisture rise in response to precipitation at 10 cm below land surface in the two profiles

Date	Rainfall (mm/d)	Potential evaporation (mm/d)	Lag time, profile S1 (h)	Lag time, profile S2 (h)
6/13/2021	18	3.6	26	23
6/23/2021	14	4.0	20	6
7/16/2021	21	5.1	14	13
8/18/2021	13	3.4	18	11
10/5/2021	7	1.2	19	6

The lag time of soil-moisture rise can be used as an indicator of the time needed for precipitation infiltration. Table 1 lists the lag time of soil moisture rise to 5 rainfall events with rainfall intensity exceeding 7 mm/d in the warm season of the year 2021. The lag time ranges from 14 to 30 h at profile S1, and ranges from 6 to 23 h at profile S2, indicating that it is difficult for precipitation to infiltrate into the overlying silt due to such factors as low permeability and low preexisting soil water content.

To sum up, based on the limited responses of soil moisture at deep parts of the two profiles, it can be concluded that as long as the thickness of the overlying silt is large enough, the silt can be a barrier for precipitation infiltration.

### The stable water level of perched groundwater

Seasonal or multi-day scale water level fluctuations induced by infiltrating precipitation is a common phenomenon in the field (Healy and Cook 2002; Jiang et al. 2017). In the three boreholes tapping perched groundwater, as shown in Fig. 5, there are trends of continuous water level decline from 1 April 2021 to 1 June 2022, but no seasonal water-level rise induced by infiltrating precipitation. The absence of seasonal rises in water level and soil moisture is probably due to the low precipitation intensity (with a maximum of 13.05 mm/day, corresponding to a mean intensity of 0.544 mm/h) and low cumulative precipitation (189.01 mm) during the year 2021.

In borehole B7, accompanying the precipitation event with an amount of 19.6 mm on 14 June, there is a multi-day scale water-level rise from 11 June 2021 to 15 June 2021 (Fig. 6). In fact, it is the trend of decreasing atmospheric pressure that causes the rising water level. As shown in Fig. 6, daily and multi-day scale fluctuations in atmospheric pressure both lead to daily and multi-day scale fluctuations in water level.

The dynamics of rock moisture

The seasonal cycle of rock moisture addition and depletion

In the Yungang Grottoes, the sandstone walls and statues outside the caves are quite dry due to direct or indirect

Fig. 5 Temporal variations of precipitation and the water level of perched groundwater in three boreholes (B2, B4 and B7)
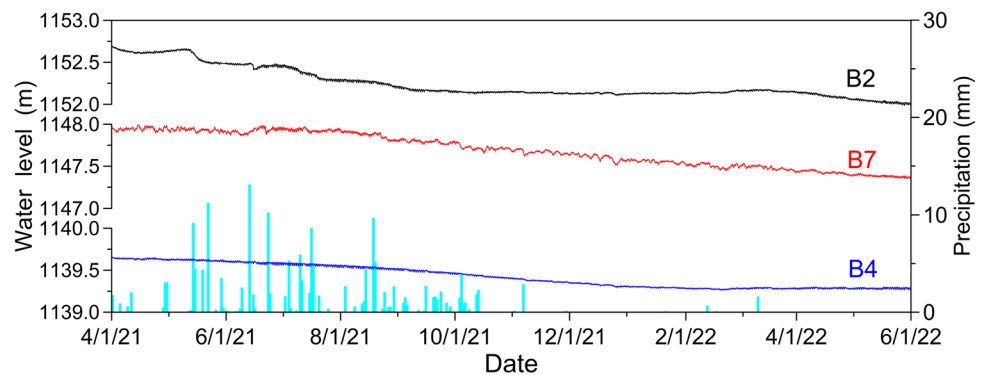
Fig. 6 The control of atmospheric pressure on water-level fluctuation from 1 June 2021 to 30 June 2021. The precipitation events on 13 June (16 mm) and 24 June (12 mm) correspond to periods with declining atmospheric pressure and rising water level
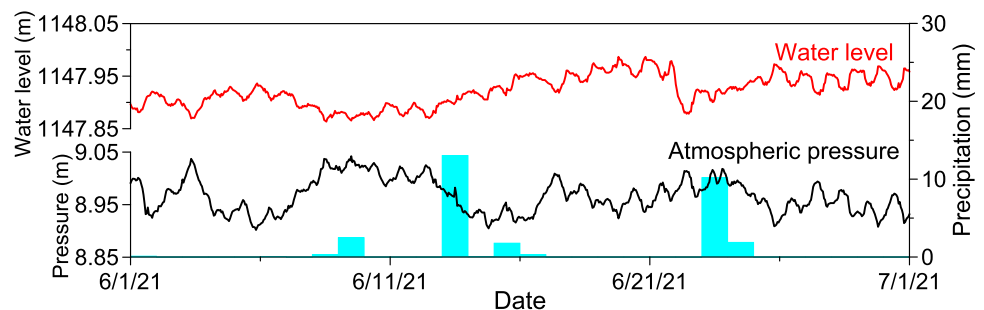
effects of sunshine. However, water droplets could occasionally occur on some walls of selected caves (Fig. 3). In the north wall of Cave #9, although there is no occasional occurrence of water droplets, the color of the sandstone walls would change slightly in the summer due to changes in rock moisture. As shown in Fig. 7, the apparent rock moisture maintains at around 0.013 cm^3/cm^3 in spring each year, and rises to 0.024 cm^3/ cm^3 on 8 August 2020 and 0.029 cm^3/ cm^3 on 17 July 2021, showing trends of rock moisture addition in the summer. From mid-summer to autumn each year, there is a trend of rock moisture depletion, and the apparent rock moisture returns to around 0.013 cm^3/cm^3 in December each year. The seasonal cycle of rock moisture addition (wetting) and depletion (drying) is responsible for both physical and chemical weathering (Hall and Hall 1996; Sumner and Loubser 2008; Turkington and Paradise 2005).

In the winter, the negative wall temperature leads to another cycle of rock moisture rise and fall. The rock moisture rise is a result of freezing-induced water migration, whereas the rock moisture fall is a result of transformation of liquid water into ice in pores. The freezing–thawing cycle is directly responsible for physical weathering (Deprez et al. 2020; Matsuoka and Murton 2008; Sun and Scherer 2010). Detailed analysis of these processes is beyond the scope of the current study. The freezing-induced water migration reflected in the rising apparent rock moisture also indicates that the low rock moisture stored in the sandstone in spring and winter belongs to mobile water, which is still responsible for chemical weathering.

The source of rock moisture in caves

The cycle of rock moisture addition and depletion in the warm season corresponds to the rainy season as well as the period with high vapor concentration (Fig. 7). In previous studies, rock moisture addition derived from infiltrating precipitation has been observed (Rempe and Dietrich 2018). In this subsection, the source of rock moisture in caves is identified by examining the direct controlling factor of rising rock moisture.

In the period from 1 June to 20 October, there are six peaks of precipitation-induced soil moisture at 10 cm below the land surface (Fig. 4). For each stage of soil moisture addition, there is also a trend of rock moisture addition, however, rock moisture measured at around 5 cm inside the wall rises much earlier than soil moisture measured at around 10 cm below the land surface (Fig. 8). The much earlier rises of rock moisture than soil moisture indicate that it is impossible for infiltrating precipitation to be the direct cause of rock moisture addition inside the cave.

Although precipitation is not the direct cause of rock moisture addition, the six stages of rock moisture rises are correspondent to precipitation events. In fact, as shown in Fig. 8, increases in rock moisture occur sooner after increases in vapor concentration, which are brought about by precipitation events. Therefore, condensation of vapor brought about by precipitation is the direct source of rock moisture in the studied cave.

Fig. 7 The temporal variations of apparent rock moisture, vapor concentration, wall temperature and rainfall. The two periods in yellow correspond to the warm season with cycles of increasing and decreasing temperature, humidity and rock moisture, whereas the two periods in green correspond to the cycle of freezing–thawing
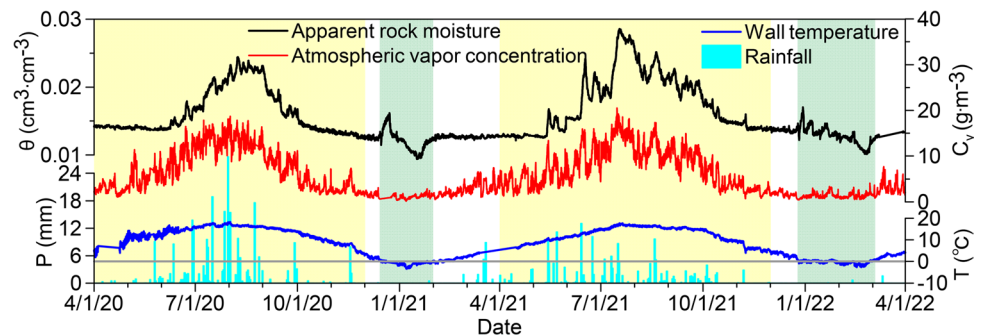
Fig. 8 The six stages with obvious signals of additions of both soil moisture and rock moisture in the warm season of the year 2021. The stages showing rising rock moisture are labeled with purple shades. Rock moisture has quick responses to rising vapor concentration, but soil moisture has slow responses to precipitation
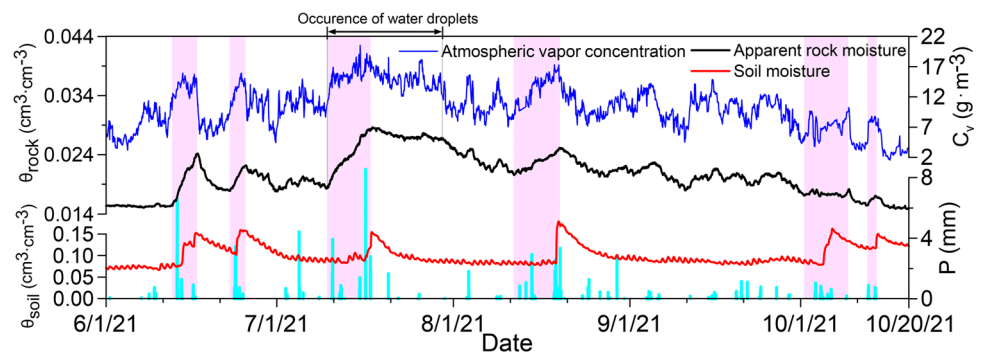
Table 2 Comparison of average apparent rock moisture, vapor concentration, and total rainfall in the period of the typical cycle of rock moisture addition and depletion between the warm season of 2020 and 2021

Year	Mean apparent rock moisture (cm³/ cm³)	Max. apparent rock moisture (cm³/ cm³)	Cumulative rainfall (mm)	Mean C_v in the cave (g/m³)	Mean atmospheric C_v (g/ m³)
2020	0.0163	0.0245	252.41	7.32	7.87
2021	0.0185	0.0287	166.03	9.36	8.91

As shown in Fig. 3, water droplets could be observed in Cave #5 during the period from 9 to 28 July. Figure 8 shows that the apparent rock moisture rises significantly from 9 July, reaches a peak on 15 July, and maintains at high values until 28 July. Therefore, the rising rock moisture and the high rock moisture measured in Cave #9 during the period from 9 to 28 July demonstrate that water droplets observed in some caves are derived from condensation of water vapor. The physics of adsorption and condensation of water vapor, which leads to increasing rock moisture, can be found in the literature (Gabrovšek et al 2010; De Freitas and Schmekal 2003, 2006; Camuffo 1998). How vapor concentration difference between inside and outside of caves reflects condensation of water vapor is to be examined in section 3.3.

The yearly difference in rock moisture

As shown in Fig. 7, the precipitation intensity in the year 2021 is much lower than that in 2020, but the apparent rock moisture in the year 2021 is higher than that in 2020. For convenience of statistical comparison, the period from 1 April to 1 December (with a duration of 244 days) of each year is selected to calculate mean apparent rock moisture,

cumulative precipitation, and mean and maximum vapor concentrations in the atmosphere and inside caves.

As shown in Table 2, the precipitation intensity in the year 2021 is much lower than that in the year 2020, and the cumulative precipitation in the typical period of 2021 is only around two thirds of that in the year 2020. However, the maximum and mean apparent rock moisture in 2021 are both higher than that in 2020. The negative correlation between rock moisture and precipitation in the two years also indicates that it is impossible for precipitation infiltration to be the direct control factor of rock moisture.

The relationship between vapor concentration difference and rock moisture addition

Dublyansky and Dublyansky (1998) pointed out that whether vapor condensation has occurred in the cave can be estimated by measuring the vapor concentration difference between the wall and the atmosphere. The vapor concentration difference, ΔC_v, is defined as C_v in the atmosphere minus C_v near the cave wall. As shown in Fig. 9, as long as ΔC_v is maintained at positive values for a specific duration of time, the apparent rock moisture begins to rise; when

Fig. 9 The relationship between rock moisture and vapor concentration difference (ΔC_v) in summer of 2021. The periods in yellow represent that ΔC_v maintains at positive values for a specific duration of time and the cumulative ΔC_v in the period exceeds 10 g/m³. The precipitation is also shown for reference. For convenience, the monitoring periods are displayed as (**a**) 1 June to 16 August 2021, and (**b**) 16 August to 1 November 2021
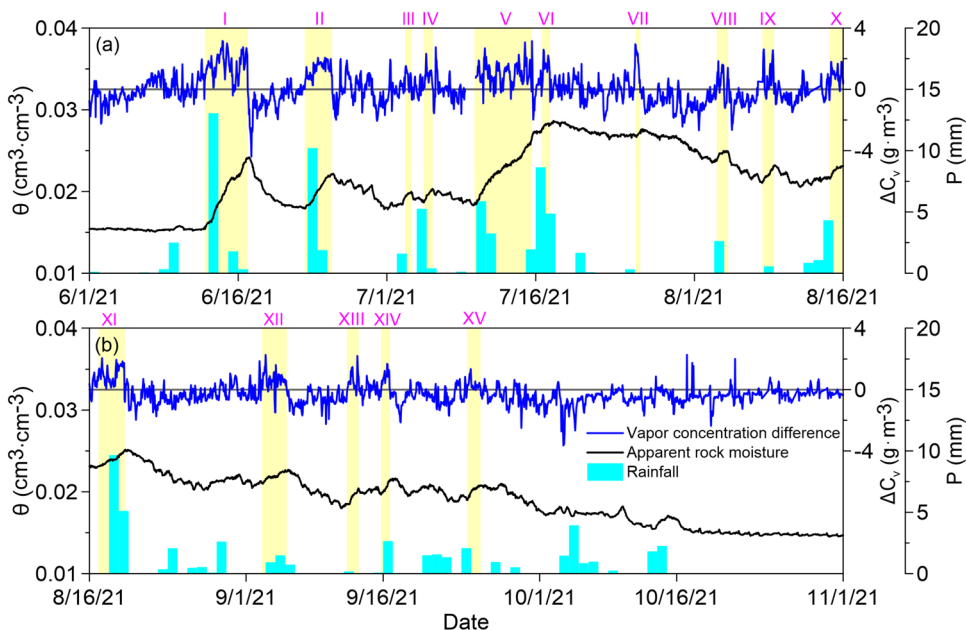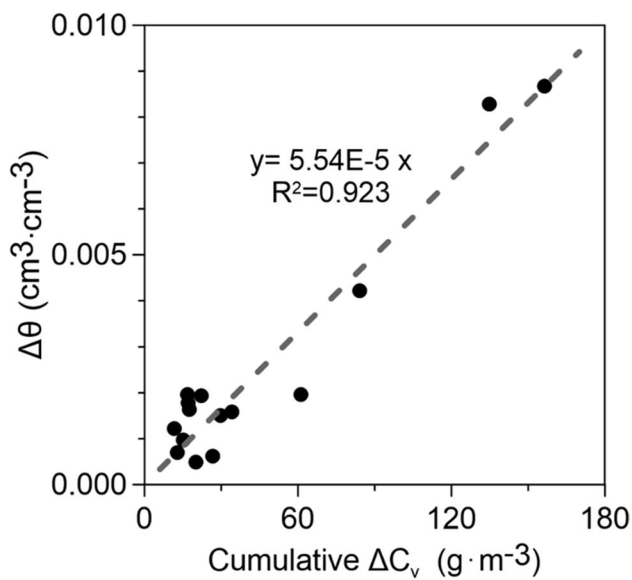
Fig. 10 The linear relationship between $\Delta\theta$ of shallow rock surface and cumulative ΔC_v during the 15 typical stages of apparent rock moisture addition

ΔC_v changes from positive to negative, the apparent rock moisture begins to decline. The coincidence of positive ΔC_v and rock moisture addition indicates that water condensed from vapor can be adsorbed by sandstone instantaneously.

There are 15 stages with clear trends of rock moisture addition; each is dominated by positive ΔC_v and has cumulative ΔC_v being higher than 10 g/m³. As shown in Fig. 10, among the 15 stages, there is a good linear relationship between the magnitude of rock moisture addition, $\Delta\theta$, and the cumulative ΔC_v (p-value $= 2.6E-11$, significance $F = 8.6E-11$, $R^2 = 0.923$). This supports that water vapor is the source of rock moisture in the cave. In a subsequent study (Ouyang et al. 2023), the relationship between rock moisture and C_v has been established by using a machine learning method, which quantitatively reveals that water vapor is the source of rock moisture in the cave.

Conclusions

Whether the source of water in the caves in the Yungang Grottoes responsible for physical and chemical weathering is derived from rainfall infiltration or vapor condensation is a long-standing controversial issue. In this study, soil moisture measurements confirm that rainfall infiltration through the silt is a slow process and rainfall infiltration can only reach the very shallow part of the silt, whereas rock moisture measurements inside a cave indicate that the rising vapor concentration in the summer is the direct source of rock moisture. Moreover, the duration with occurrence of water droplets in some caves (like Caves #5) coincides with the time with increasing or high rock moisture.

To the authors' knowledge, this study is the first successful monitoring of rock moisture in caves and enhances understanding of condensation water in caves. Since some studies have tried to use measured cave drip rates to estimate groundwater recharge, the findings in the current study reveal that if condensation water is not correctly identified, groundwater recharge would be easily overestimated. The findings of this study indicates that measures controlling vapor condensation, instead of controlling seepage through the sandstone rock mass, should be proposed to alleviate weathering in caves.

Declarations

Conflict of 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.

References

Baker A, Barnes WL, Smart PL (1997) Variations in the discharge and organic matter content of stalagmite drip waters in lower cave. Bristol Hydrol Process 11(11):1541–1555. https://doi.org/10.1002/(SICI)1099-1085(199709)11:11%3c1541::AID-HYP484%3e3.0.CO;2-Z

Baker A, Berthelin R, Cuthbert MO, Treble PC, Hartmann A, the KSS Cave Studies Team (2020) Rainfall recharge thresholds in a subtropical climate determined using a regional cave drip water monitoring network. J Hydrol 587:125001. https://doi.org/10.1016/j.jhydrol.2020.125001

Camuffo D (1998) Microclimate for cultural heritage. Elsevier, Amsterdam

Camuffo D, Giorio R (2003) Quantitative evaluation of water deposited by dew on monuments. Bound-Lay Meteorol 107(3):655–672. https://doi.org/10.1023/A:1022893012277

Cao WB, Wan L, Zeng YJ, Gan XM, Jiang XW, Huang JZ, Yan HB, Zhang L (2005) Study on formation mechanism and prevention of condensation water in Yungang Grottoes. In: Collection of Papers of the 2005 Yungang International Academic Seminar (Protection Volume). Cultural Relics Publishing House, Beijing, pp 191–198 (in Chinese)

Cooper JD (2016) Soil water measurement: a practical handbook. John Wiely and Sons Ltd, Oxford

De Freitas CR, Littlejohn RN (1987) Cave climate: assessment of heat and moisture exchange. Int J Climatol 7(6):553–569. https://doi.org/10.1002/joc.3370070604

De Freitas CR, Schmekal A (2003) Condensation as a microclimate process: measurement, numerical simulation and prediction in the glowworm cave, New Zealand. Int J Climatol 23:557–575. https://doi.org/10.1002/joc.898

De Freitas CR, Schmekal A (2006) Studies of condensation/evaporation processes in the Glowworm Cave, New Zealand. Int J Speleol 35(2):75–81. https://doi.org/10.5038/1827-806X.35.2.3

Deprez M, De Kock T, De Schutterc G, Cnudde V (2020) A review on freeze–thaw action and weathering of rocks. Earth Sci Rev 203:103143. https://doi.org/10.1016/j.earscirev.2020.103143

Dublyansky VN, Dublyansky YV (1998) The problem of condensation in karst studies. J Cave Karst Stud 60(1):3–17

Dublyansky VN, Dublyansky YV (2000) The role of condensation in karst hydrogeology and speleogenesis. In: Klimchouk AB, Ford DC, Palmer AN, Wolfgang D (eds) Speleogenesis, evolution of karst aquifers. National Speleological Society, Huntsville, pp 100–111

Fisher LR, Gamble RA, Middlehurst J (1981) The Kelvin equation and the capillary condensation of water. Nature 290:575–576. https://doi.org/10.1038/290575a0

Gabrovšek F, Dreybrodt W, Perne M (2010) Physics of condensation corrosion in caves. In: Andreo B, Carrasco F, Durán JJ, LaMoreaux JW (eds) Advances in research in karst media. Environmental Earth Sciences, Springer, Berlin, pp 491–496. https://doi.org/10.1007/978-3-642-12486-0_75

Gázquez F, Quindós L, Rábago D, Fuente I, Celaya S, Sainz C (2022) The role of cave ventilation in the triple oxygen and hydrogen isotope composition of condensation waters in Altamira Cave, northern Spain. J Hydrol 606:127416. https://doi.org/10.1016/j.jhydrol.2021.127416

Gregg SJ, Sing KSW (1982) Adsorption, surface area, & porosity, 2nd edn. Academic Press, London

Hall K, Hall A (1996) Weathering by wetting and drying: some experimental results Earth Surface Processes and Landforms. Earth Surf Proc Land 21(4):365–376. https://doi.org/10.1002/(SICI)1096-9837(199604)21:4%3c365::AID-ESP571%3e3.0.CO;2-L

Healy RW, Cook PG (2002) Using groundwater levels to estimate recharge. Hydrogeol J 10:91–109. https://doi.org/10.1007/s10040-001-0178-0

Huang JZ, Wan L, Peng T, Cao WB, Wang XS (2012) Survey on water sources in Yungang Grottoes and some results. Geotech Invest Survey 40(11):1–5 (11 (in Chinese))

Huang JZ, Zheng Y, Li H (2022) Study of internal moisture condensation for the conservation of stone. J Cult Herit 56:1–9. https://doi.org/10.1016/j.culher.2022.05.003

Huang KZ (2010) Harm and prevention of water in Yungang Grottoes. In: Cultural relics protection technology (1981–1991), China Science Publishing & Media Ltd, Beijing, pp 284–290 (in Chinese)

Jiang XW, Sun ZC, Zhao KY, Shi FS, Wan L, Wang XS, Shi ZM (2017) A method for simultaneous estimation of groundwater evapotranspiration and inflow rates in the discharge area using seasonal water table fluctuations. J Hydrol 548:498–507. https://doi.org/10.1016/j.jhydrol.2017.03.026

Lawrence DS (2002) Physical hydrology. Prentice Hall, Upper Saddle River

Leite PA, Wilcox BP, McInnes K, Walker JW (2021) Applicability of soil moisture sensors for monitoring water dynamics in rock: A field test in weathered limestone. Vadose Zone J 20:e20164. https://doi.org/10.1002/vzj2.20164

Lu N, Likos WJ (2004) Unsaturated soil mechanics. John Wiley, Hoboken

Mahmud K, Mariethoz G, Treble PC, Baker A (2015) Terrestrial LiDAR survey and morphological analysis to identify infiltration properties in the Tamala limestone. Western Australia IEEE J-STARS 8(10):4871–4881. https://doi.org/10.1109/JSTARS.2015.2451088

Mahmud K, Mariethoz G, Baker A, Treble PC, Markowska M, McGuire L (2016) Estimation of deep infiltration in unsaturated limestone environments using cave LiDAR and drip count data. Hydrol Earth Syst Sci 20:359–373. https://doi.org/10.5194/hess-20-359-2016

Mahmud K, Mariethoz G, Baker A, Treble PC (2018) Hydrological characterization of cave drip waters in a porous limestone: Golgotha Cave, Western Australia. Hydrol Earth Syst Sci 22:977–988. https://doi.org/10.5194/hess-22-977-2018

Mao DQ, Wang XD, Meng J, Ma XM, Jiang XW, Wan L, Yan HB, Fan Y (2022) Infiltration assessments on top of Yungang Grottoes by time–lapse electrical resistivity tomography. Hydrology 9(5):77. https://doi.org/10.3390/hydrology9050077

Matsuoka N, Murton J (2008) Frost weathering: recent advances and future directions. Permafrost Periglac 19(2):195–210. https://doi.org/10.1002/ppp.620

Meinzer OE (1934) The history and development of ground–water hydrology. J Washington Acad Sci 24(1):6–32. http://www.jstor.org/stable/24532897

Mollo L, Greco R (2011) Moisture measurements in masonry materials by time domain reflectometry. J Mater Civil Eng 23(4):441–444. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000188

Nathan A, Sheffer NA, Cohen M, Efrat Morin E, Grodek T, Gimburg A, Magal E, Gvirtzman H, Nied M, Isele D, Frumkin A (2011) Integrated cave drip monitoring for epikarst recharge estimation in a dry Mediterranean area, Sif Cave, Israel. Hydrol Process 25:2837–2845. https://doi.org/10.1002/hyp.8046

Ouyang KG, Jiang XW, Mei G, Yan HB, Niu R, Wan L, Zeng Y (2023) Physics-informed machine learning for understanding rock moisture dynamics in a sandstone cave. Hydrol Earth Syst Sci 27(14):2579–2590. https://doi.org/10.5194/hess-27-2579-2023

Quindos LS, Bonet A, Diaz-Caneja N, Fernandez PL, Gutierrez I, Solana JR, Soto J, Villar E (1987) Study of the environmental variables affecting the natural preservation of the Altamira Cave paintings located at Santillana del Mar, Spain. Atmos Environ 21(3):551–560. https://doi.org/10.1016/0004-6981(87)90037-0

Rempe DM, Dietrich WE (2018) Direct observations of rock moisture, a hidden component of the hydrologic cycle. Proc Natl Acad Sci USA 115(11):2664–2669. https://doi.org/10.1073/pnas.1800141115

Sakaki T, Rajaram H (2006) Performance of different types of time domain reflectometry probes for water content measurement in partially saturated rocks. Water Resour Res 42(7):W07404. https://doi.org/10.1029/2005WR004643

Sarbu S, Lascu C (1997) Condensation corrosion in Movile Cave, Romania. J Cave Karst Stud 59(3):99–102

Sass O (2005) Rock moisture measurements: techniques, results, and implications for weathering. Earth Surf Proc Land 30(3):359–374. https://doi.org/10.1002/esp.1214

Schmidt L, Rempe D (2020) Quantifying dynamic water storage in unsaturated bedrock with borehole nuclear magnetic resonance. Geophys Res Lett 47(22):e2020GL089600. https://doi.org/10.1029/2020GL089600

Sumner PD, Loubser MJ (2008) Experimental sandstone weathering using different wetting and drying moisture amplitudes. Earth Surf Proc Land 33(6):985–990. https://doi.org/10.1002/esp.1586

Sun ZH, Scherer GW (2010) Effect of air voids on salt scaling and internal freezing. Cement Concrete Res 40(2):260–270. https://doi.org/10.1016/j.cemconres.2009.09.027

Turkington AV, Paradise TR (2005) Sandstone weathering: a century of research and innovation. Geomorphology 67(1–2):229–253. https://doi.org/10.1016/j.geomorph.2004.09.028

Wan L, Cao WB, Wang XS, Huang JZ, Xu F (2012) Preliminary investigation on water–vapor transfer in Yungang Grottoes. Geotech Invest Survey 40(11):6–11 ((in Chinese))

Wang XS, Wan L, Peng T, Dong P, Qian J (2012) Infiltration water in Yungang Grottoes and its movement. Geotech Invest Survey 40(11):12–16 ((in Chinese))

Wu X, Pan MC, Yin JJ, Zhang ML, Cao JH (2022) Hydrogeochemical responses of cave drip water to the local climate in the Liangfeng Cave. Southwest China Hydrol Res 53(7):945. https://doi.org/10.2166/nh.2022.015

Xie HY, Jiang XW, Tan SC, Wan L, Wang XS, Liang SH, Zeng YJ (2021) Interaction of soil water and groundwater during the freezing–thawing cycle: field observations and numerical modeling. Hydrol Earth Syst Sci 25:4243–4257. https://doi.org/10.5194/hess-25-4243-2021

Xu JH, Xiao YM, Sally DL, Robert H (2012) Short, multineedle frequency domain reflectometry sensor suitable for measuring soil water content. Soil Sci Soc Am J 76(6):1929–1937. https://doi.org/10.2136/sssaj2011.0361

Zhao KY, Jiang XW, Xu-Sheng Wang XS, Wan L (2021) Restriction of groundwater recharge and evapotranspiration due to a fluctuating water table: a study in the Ordos Plateau, China Hydrogeology Journal. Hydrogeol J 29:567–577. https://doi.org/10.1007/s10040-020-02208-9