

Article

Monitoring Human Impact in Show Caves. A Study of Four Romanian Caves

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Abstract: (1) Background: Show caves are unique natural attractions and touristic traffic can trigger their degradation within a short time. There are no universal solutions to counter the effects of the touristic impact upon the cave environment and both protection protocols and management plans have to be established on a case-by-case basis. (2) Methods: The study includes four show caves from the Romanian Carpathians, where monitoring of the number of visitors, paralleled by the monitoring of the main physicochemical parameters of the air and water (CO₂, temperature, humidity, drip rate, conductivity, and pH) was implemented. (3) Results and Conclusions: The results of the study have established a set of basic principles to be enforced by the management of show caves and issued a set of preventive measures and instructions to be followed by the personnel and stakeholders of the caves.

Keywords: cave; microclimate; monitoring; sustainable management; Carpathians; Romania



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1. Introduction

Karst regions are spectacular but sensitive environments present in many regions of the world. With only a few exceptions, they are included within natural protected areas as they preserve biodiversity and valuable groundwater resources. At the same time, they are extremely vulnerable to human impact because aquifers are highly transmissive and prone to rapid pollutant transfer. Air pollution would reach karst underground by means of rainfall and percolating water or as aerosols [1]. Direct water pollution would reach karst springs after short transit times and with almost no filtration. Either way, both subterranean biodiversity and public health may be affected. In regions where karst landscape (surface and underground) is valued as a touristic asset, even minute pollutions may spoil its value and require costly remediation measures.

Caves are also recognized as valuable “natural laboratories”, which preserve climate archives such as speleothems (calcite formations such as stalactites, stalagmites, etc.), sediments, fauna with peculiar adaptations, and fossil remains. All of them are relevant for the reconstruction of past climate and past surface environments, but speleothems have the advantage of being able to record climate changes at remarkably high resolution—from centennial to annual. In the last 20 years, they became invaluable tools that help climate scientists to assess past climate changes and possibly forecast future ones [2].

In karst regions, caves are natural attractions that bring millions of visitors every year. The main assets that would transform a wild cave into a touristic attraction are related

to: (i) cave formations (speleothems); (ii) cave fauna, either current fauna, such as bats colonies and cave adapted invertebrates (troglonites), and other vertebrates or fossil fauna (e.g., remains of cave bears or other large mammals); (iii) past human activity such as prehistoric paintings, drawings, engravings, or burial sites. In many cases, successful touristic caves present a combination of these attractions and 128 natural caves are listed on the UNESCO World Heritage List [3]. However, opening a cave as a public attraction implies the disturbance of the natural habitat by construction of infrastructure elements such as walking trails and lighting systems and by the very presence of large numbers of visitors in a formerly pristine environment. The development of a wild cave into a show cave is especially complicated by the fact that each cave has its own climate, which depends both on its geographical location and internal morphology.

The aesthetic and scientific values of caves are preserved in the subterranean environment especially because of the remarkable constancy of the cave microclimate. Even minute changes of this microclimate may trigger irreversible effects that may destroy the attractions of a given show cave. It has been shown that uncontrolled visitor traffic may lead to degradation of cave paintings or drawings. The Paleolithic paintings of the UNESCO sites of Altamira (Spain) and Lascaux (France) have had to be closed due to rapid degradation of the paintings caused by biodegradation induced by aerosolization of the fine particles from the floor, including bacterial and fungal spores [4]. The recent discovery of old drawings in the Coliboaia cave (cca. 35,000 years BP; Western Carpathians, [5]) calls for a robust protocol of cave-monitoring even before the start of any research campaign.

In many caves, where the main attraction is represented by speleothems, these calcite formations have lost their aesthetic value following a decrease in air relative humidity (RH), and an increase in temperature and partial CO₂ pressure in the cave's air because of touristic activity [6,7]. In other show caves, the distribution and density of cave animals was affected—the most visible effect being recorded on the populations of bats [8]. In the United States, the fungal infection of bats with *Geomyces destructans* was first documented in 2006 in a commercial cave from the state of New York and has spread rapidly to more than 100 caves in North America leading to the near extinction of several bat species and immeasurable consequences on agriculture [9].

One of the best documented effect of touristic activity in show caves is the appearance of the so-called “lampenflora” (i.e., communities of microbes, algae, ferns, mosses) that develop on cave walls or speleothems in the proximity of light sources [10]. The lampenflora has proven to be difficult to eliminate and the simple installation of LED lamps was proven to be insufficient to stop its development [11].

In theory, the environment of a cave should have only a negligible contact with the external environment. Heaton [12] has reviewed the concept of energy levels and applied it to caves. Accordingly, he classified the caves into three categories of high, moderate, and low energy, respectively. The high-energy caves are those that experience important inputs of energy on a regular basis, such as periodic flooding or seasonal climatic events. Moderate-energy caves would normally undergo regular changes about one order of magnitude lower than the high-energy caves (e.g., caves with permanent streams or air current). Low-energy caves are those where the microclimate is extremely stable and often the highest energy event may be related to something as trivial as the falling of a single water drop [12]. When show caves are fit into the moderate- and low- energy categories, the energetic equilibrium can be very easily unbalanced especially in the deep areas of the caves, where the stable climate can be easily disturbed.

The effect of the visitors in caves on biodiversity was also documented [13]. The deep sections of the caves host a troglitic fauna, which is highly specialized and highly dependent on even small changes of the microclimatic parameters. Bats colonies were sometimes shown to be disturbed by touristic traffic in show caves [8]. In short, the touristic traffic in a cave should be kept to a level that would allow both the preservation of troglitic invertebrates and (if any) of bats colonies, without forcing the later to move to new places where they could cause damage to speleothems, caused by guano.

In addition to the above, there is a large body of evidence that the lint (hair, dry-flaking skin, dust, spores) carried on by a cave's visitors may deteriorate speleothems and create a favorable medium for the development of fungi and algae onto speleothems and fossil remains. Such effects are well known from many touristic caves where originally white speleothems are now covered by a dark layer or where fossil vertebrate remains (e.g., *Ursus spelaeus* bones) are covered by lampenflora (for example in Urșilor Cave, Chișcău, Romania) [14]. In the Lascaux Cave, attempts to remove the green alga *Bracteacoccus minor* by using biocides proved to be inefficient since they resulted in a selection of Gram-negative bacterial species adapted to the respective biocide [4]. A synthesis of potential touristic-induced threats to a deep-cave environment is presented in Table 1.

Table 1. Principal threats for the environment of show caves, their possible causes and effects (modified after [15]).

Threat	Cause	Effects
Changes of natural air circulation	Opening of artificial entrances, changes in cave passage geometry	<ul style="list-style-type: none"> - relative humidity (RH) lowering, “dull” (dry) speleothems - airborne particles (spores, etc.) creating nucleation medium for lampenflora - speleothem growth prevented or equilibrium deposition regime changed
Changes of cave temperature	Local warming due to electric lights Periodic temperature fluctuations from visitors' flux	<ul style="list-style-type: none"> - development of heterotrophic films; lampenflora growth - alteration of the stable cave microclimate; troglobionts migration with potential replacement by invading surface species
Changes of cave air CO ₂ concentrations	CO ₂ from visitors CO ₂ from other sources	<ul style="list-style-type: none"> - changes in calcite deposition rates - corrosion of speleothems due to aggressive condensation - lampenflora development
Organic matter input	Organic matter carried by visitors (dust, lints, spores, microbes, etc.)	<ul style="list-style-type: none"> - microbial films development on walls, speleothems, soil, and fossil remains that destroy local microflora and form a base for new trophic chains - potential spreading of diseases to cave animals (e.g., bats)
Chemical pollutants	Detergents input during maintenance work (e.g., washing paths, maintenance, etc.)	<ul style="list-style-type: none"> - pollution of the cave environment affecting troglobitic fauna
Noise	ultrasonic noise from electrical equipment (e.g., transformers) or visitors' noise	<ul style="list-style-type: none"> - may affect bats colonies triggering their relocation in other caves or in deeper, pristine sectors of a cave

Throughout the world, at least some of these problems are recognized and sometimes carefully dealt with [16–25]. Monitoring programs have been enforced for both old show caves [6] and newly discovered caves [26]. The role of microorganisms was recognized not only as a modifying agent for cave biota (e.g., by supporting formation of lampenflora) but also as a triggering agent for speleothem deposition [27].

Besides the conservation issues, the development of a show cave also requires an assessment of the radiological hazards to visitors and cave personnel. The main hazard concerns the potential accumulation of radon, as this gas is known to be one of the causes for lung cancer and bronchial tissue damage and underground cavities are especially prone to radon accumulation [28–30]. Radon levels in caves depend on different internal and external factors such as outside–inside temperature differences, wind velocity, variations in atmospheric pressure and humidity, local geomorphology, etc. Numerous studies [31–35] have shown that radon concentration in show caves do not pose a health problem for the visitors, during their short visit, but they may be of concern for professional workers such

as the cave guides or cave researchers, due to accumulation rates in time. Depending on specific microclimate of a cave or cave sector, emissions of radon and its short-lived progeny may be higher than the EU-established reference level of 1000 Bq/m³. In the case of most show caves, ensuring an artificial ventilation system is not an option, as any disturbance of the natural microclimate would rapidly compromise the cave assets. It is, therefore, of utmost importance to: (i) preserve caves' natural environment while (ii) monitoring radon levels on a regular basis to assess the risks for visitors and professionals involved.

In Romania, before 2010, only nine caves were developed for tourism and most of them had only rudimentary touristic fittings such as electric light based on incandescent bulbs, rudimentary tourist trails and infrastructure, poor guidance, and even prolonged periods when caves were virtually abandoned by administrators and subjected to uncontrolled tourism that resulted in vandalism. To date, there are no legal restrictions whatsoever concerning the touristic carrying capacity, nor any systematic monitoring of the microclimate to control the degradation of their environment. In fact, many old show caves have already lost part of their touristic value due to the uncontrolled touristic flow. The most famous show cave of Romania, Urşilor Cave (Chişcău, Apuseni Mountains), already shows significant lampenflora occurrences despite of it being fitted with air locks and despite several attempts of cleaning the speleothems or the fossil remains of cave bear (*Ursus spelaeus*) on display—one of the main cave's attractions. Other touristic caves show even greater signs of degradation as a result of the intense visitation despite some of them being slightly renovated. However, in the last six years only, three new show caves were opened (e.g., Valea Cetăţii, Farcu, Meziad). While they appear so far to be successful as tourist attractions and are fitted with modern pathways and LED lighting systems, their conversion into show caves was done without any previous basic microclimate monitoring and, unless a consistent monitoring program is carried out soon, it is hard to assess whether and when these caves may start to lose their aesthetic values and interest for tourists as well. On the other hand, the "Emil Racovita" Institute of Speleology (ERIS) has developed, in the last ten years, several continuous monitoring programs of both cave physical and microclimatic parameters and the ecology and dynamics of cave fauna. Numerous other cave monitoring studies have been performed in the past (e.g., [36–39]).

The recent raise in number of show caves in Romania indicates the real need for such touristic attractions in Romania. According to the Romanian Show Caves Association (RoSCA), 10 out of the 13 show caves in the country have attracted more than 500,000 visitors in 2011 only. Little or no data is available concerning the visitor numbers for the other caves but it is clear that: (i) there is a growing demand for developing new caves as touristic attractions; (ii) uncontrolled development and unmonitored touristic exploitation will lead to irreversible damage to cave mineral attractions and subterranean biodiversity; (iii) the pressure for developing new show cave sites will grow as Romania is a country rich in spectacular caves and tourism is considered a valuable asset of future economic growth.

The opening of new caves for tourism without previous microclimatic monitoring and without the implementation of continuous climatic monitoring after their opening was the trigger for starting a monitoring program in Romanian show caves. The four most visited show caves of the country were selected for this program to: (i) understand the interplay between natural behavior of the cave microclimate and tourism, (ii) establish the vulnerabilities of cave visitations caused by the intensity of tourist traffic, and (iii) propose management measures for each of the studied caves, measures to be implemented by the cave administrators. The originality of our study lies in the parallel study of four different caves, each with particular morphology, number of entrances, size of passages, number of tourists, and visitation patterns.

2. Materials and Methods

2.1. Studied Caves

Four Romanian show-caves were considered in the present study (Figure 1, Table 2), each of them with different visitation patterns:

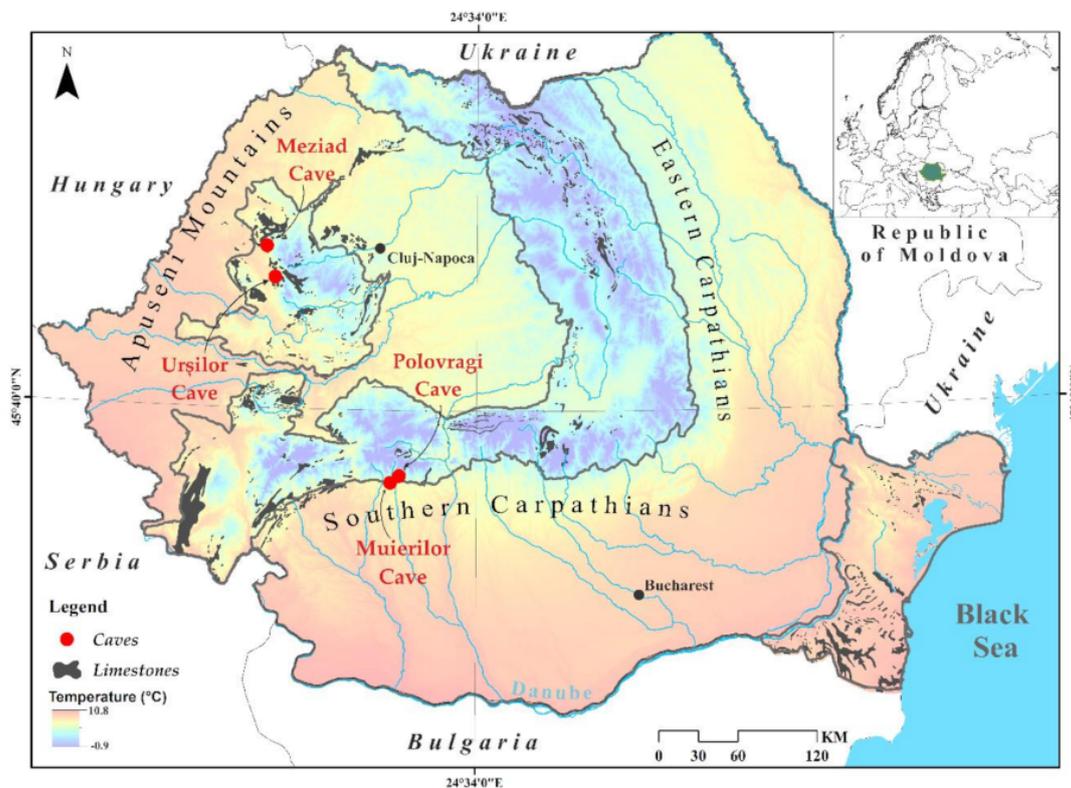


Figure 1. The location of the four studied show caves in Romania, with the position of the country in Europe. Karstic areas and mean annual temperatures are also shown.

Table 2. General information on the studied show caves.

Cave	No. Entrances	Type	Elevation (m a.s.l.)	Rock Thickness Above (m)	Lighting System	Tourist Path Length (m)	Visit Time (Mean Min.)
Muierilor	3	2 naturals 1 artificial	650	100	Switched off after each visited sector	800	30–55
Polovragi	6	1 artificial 5 naturals	645	250	Switched off after each visit	500	25–50
Urşilor	2	2 artificials	490	100	Switched off after each visited sector	450	30–45
Meziad	3	3 naturals	435	80	Switched off after each visited sector	1000	30–60

1. Peștera Muierilor (peștera = cave in Romanian) is in the Southern Carpathians. It consists of a maze of passages totaling more than 8 km in length, spread across four levels. The cave is famous for the discovery of early modern human remains c. 35 ka old [40], Paleolithic artifacts and a large deposit of fossil remains of cave bears (*Ursus spelaeus*), cave lions, hyaenas, wolves, and also herbivores and small mammals [41]. It was the first cave of Romania fitted with electric light (1963) and it typically has more than 100,000 visitors/year. The visitation flow is one-way (unidirectional), i.e., tourists enter the cave through the northern entrance and exit it through the southern one. Cave lighting still uses incandescent bulbs, which led to the development of abundant lampenflora on cave walls, speleothems, and fossil remains.

2. Peștera Polovragi is in the vicinity of the Muierilor Cave. It is a multilevel cave with a total length of ~10 km. The touristic sector is ~500 m long and was opened in the 1960s by blasting. This sector has suffered serious degradations following occasionally uncontrolled visits that led to vandalism and the usage of incandescent bulbs that favored the formation of lampenflora. However, the cave still attracts ~30,000 visitors/year. Polovragi is a

typical example of a show cave where the original environment has been disturbed by the enlargement of the entrance, the inappropriate lighting, and the bidirectional visitor flow (tourists enter and exit the cave through the same point). However, the cave has still pristine passages that may be developed for tourism and a renovation and extension project is planned. Both Muierilor and Polovragi caves are sheltering bat colonies and are part of the ROSCI 0128 Natura 2000 protected area.

3. Peștera Urșilor (Bears' Cave) is the most famous show cave in Romania owing to both the abundance of spectacular speleothems and the large number of fossils of cave bears. It is located in Chișcău village in the Bihor Mountains (Apuseni Mountains) and was discovered in 1975 by blasting in a local quarry. Two artificial entrances were excavated and fitted with airlocks. Visitors use different accesses for entrance and exit but in the deeper part of the cave the traffic is bidirectional. This cave is a typical example of a show cave where artificial entrances has caused a change in microclimate despite the airlocks. The cave is developed on two major levels, one fossil with the touristic path, and the base level with the subterranean river that represents a Scientific Reserve. The lighting system uses LED illumination and lampenflora is forming on walls and speleothems in smaller-sized passages and over the displayed fossil remains. The cave attracts more than 120,000 visitors/year.

4. Peștera Meziad is in Pădurea Craiului Mountains (Apuseni Mountains). It is one of the oldest show caves of Romania important for its large passages and chambers, developed on two levels, massive speleothems, and fossil remains. It is a natural monument and part of the ROSCI 0062 Natura 2000 site. It is a maze-like cave ~6.3 km long. Owing to its large entrance the cave is well ventilated in its first 300 m of passages. It shelters a large colony of bats, estimated to as many as 20,000 individuals and rare troglomorphic invertebrate species have been described [42]. After decades of uncontrolled tourism, the cave was partially rehabilitated in 2012. However, the successful rehabilitation is poorly advertised so far, and the cave attracts only ~20,000 visitors/year. The visitation flow is circuit-type, with tourists entering and exiting through the same porch but following a one-way trail inside.

2.2. Monitoring Protocol

Considering both the topography of each cave and the length of the tourist route, the study was carried out between December 2015 and December 2017 (see also Table 3).

Table 3. Characteristics of measurements in the four studied show caves (December 2015–December 2017).

No.	Cave/Protocol	Muierilor	Polovragi	Urșilor	Meziad
1	Number of stations: touristic/non-touristic passages	5/3	2/1	3/2	4/1
2	Tourist traffic continuous	Long Range Infrared (LIR) people counter (Chambers Electronics)			
3	Temperature (°C)	Hobo Pendant UA-002-64 Tinytag	Hobo Pendant UA-002-64	Microstep MIS (Slovakia)	Hobo Pendant UA-002-64
4	Combined temperature + Light			Every 2nd month Hobo Pendant UA-002-64	
5	Relative air humidity (RH; %)	Tinytag		Microstep MIS (Slovakia) Vaisala GMP222	
6	Air CO ₂ (ppm)	iSense (CO ₂ m)	iSense (CO ₂ m)	Vaisala GMP222 Vaisala GM70 + GMP222 probe every 2nd month	iSense (CO ₂ m)
7	Air speed and direction (m/s); spot			PCE-423 Hot Wire Anemometer every 2nd month Stalagmate Mark3	
8	Drip rate (L/h)	5 stations	2 stations	4 stations	2 stations
9	Conductivity (μS/cm), pH			WTW ph/conductivity meter every 2nd month; 2 stations	
10 *	Microbiological monitoring: Enterobacteriaceae			Every 2nd month	
11 *	Radon			Continuous	

* Result of these parameters are not discussed in this paper, but they were considered for the vulnerability maps and are mentioned in the Discussion [43,44].

- Installing monitoring stations in the touristic and non-touristic sectors of each cave. In these stations, the physical and hydrological parameters were recorded continuously, using dataloggers. The measurements were performed at intervals ranging between 5 and 30 min depending on the type of datalogger, the monitored parameter, and the actual situation in the field.
- Periodic monitoring by spot measurements both in the fixed stations and in additional stations. Spot measurements were performed every two months using portable equipment. The measured parameters were: air temperature, relative air humidity, CO₂ concentration, air speed and direction. The concentration of CO₂ in the air is an important parameter both for the safety of visitors and staff, and especially because it can influence the process of precipitation or dissolution of calcium carbonate. In addition, water samples were collected for chemical analysis. Water saturation index (SI) was also calculated for it provides information on the ability of dripping water to precipitate or dissolve calcite. The SI was computed using the Langelier Saturation Index formula and the Lenntech online calculator (<https://www.lenntech.com/calculators/angelier/index/angelier.htm>).
- Biological and microbiological monitoring was performed at intervals of two months for water and air microorganisms and invertebrates and for bats the observations were at least seasonal. The results on air and water microorganisms sampled during the present study were published in [43,44].
- Radiological monitoring was performed by distributing 90 SSNTD/CR-39 radon detectors of RSKS type in 10 monitoring stations. The detectors have been installed since December 2014, and then replaced every three months, resulting in complete sets of measurements for each season. Radon measurements were reported by Burghela et al. [45,46].
- The surface climate monitoring was performed by using meteorological data recorded by automatic Vaisala weather station installed at Baia de Fier (for Muierilor and Polovragi) and Chişcău village (for Urşilor and Meziad). The purpose of climate monitoring was to anticipate the response time and amplitude of microclimate changes and hydrological parameters in the cave to meteorological phenomena (mainly temperature and precipitation).

The locations of the monitoring points within the four caves are shown in Figure 2.

2.3. Vulnerability Maps

We define here vulnerability maps of a cave as the projection on the cave map of the calculated algorithms (see below) based on the measured parameters in each station. Such maps can be useful in taking management decisions. Such decision can be modification of the touristic path, reducing the number of tourists/day or tourists/season, changes of the ventilation inside the cave by reducing or increasing the periods for gate openings, etc. For modeling the maps with the seasonal vulnerabilities of the four caves, we used the following indicators: temperature variation, humidity variation, CO₂ variation, drip rate variation, drip water chemistry, abundance of bat colonies (not published), abundance of pathogenic microorganisms (from [43]), and number of tourists. Four vulnerability classes were established for each indicator and then the vulnerability index was calculated according to the vulnerability class and the number of significant indicators (Table 4). The algorithm for vulnerability calculations applied for each station in the caves was:

$$\text{Vulnerability score} = \text{sum of indicators value} * \text{weight/no. validated indicators},$$

where validated indicators are those that were measured in every station.

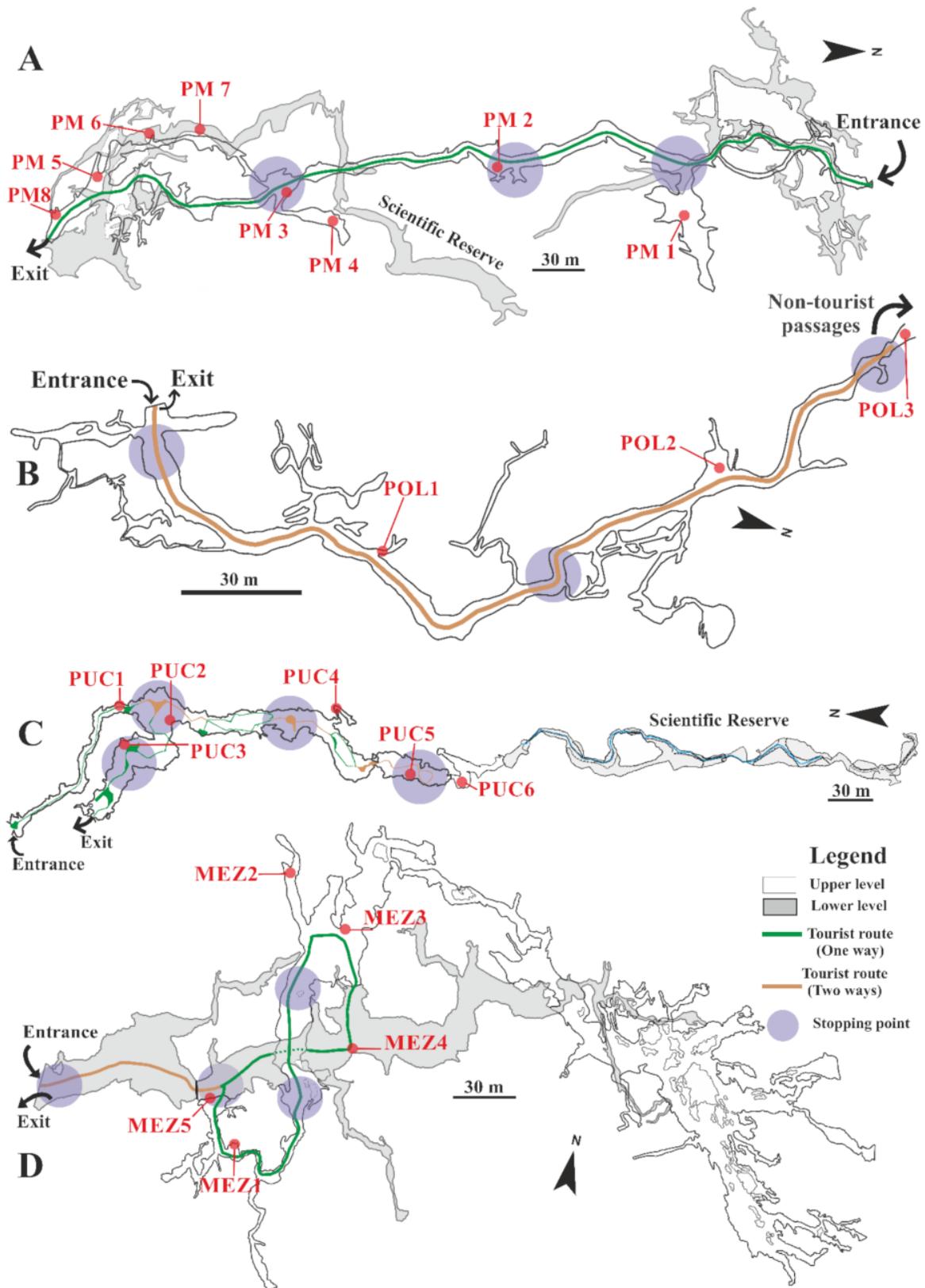


Figure 2. The four studied show caves and the location of the monitoring stations in Muierilor (A; modified after Mirea et al. [41]), Polovragi (B; modified after Ponta and Aldica [47]), Urșilor (C; modified after Constantin et al. [48]), and Meziad (modified after Rusu et al. [49]).

Table 4. The parameters, their weight in the analysis (in italics), and the respective categories used to build vulnerability maps. Human induced (1–4 and 7–8) and natural (5 and 6) parameters were considered here.

	PARAMETER × WEIGHT (Abbreviation)	CATEGORY		
		0	10	20
1	Temperature (°C) × 2 (T)	Seasonal variation <1	Seasonal variation 1–2	Seasonal variations >2C
2	RH (%) × 2 (RH)	Variation <5	Variation 5–10	Variation >10%
3	CO ₂ (ppm) × 2 (CO ₂)	<5000	5000–10,000	>10,000
4	Saturation index × 1 (SI)	(−0.5)–0.5	±0.1	>±0.1
5	Drip rate (L/h) × 1 (DR)	Constant flow <25	Short interruptions 25–50	Long interruptions >50%
6	Bats number × 1 (Bats)	None	Few dozens	Big colonies
7	Microorganisms (CFU * /m ³) × 1 (Microorg.)	<50	50–500	>500
8	Tourist number/season × 2 (Tourists)	<2500	2500–5000	>5000

* CFU = colony forming-unit of Enterobacteriaceae (a family of bacteria including the familiar pathogens, such as *Salmonella*, *Escherichia coli*, *Klebsiella*, and *Shigella*), counted in 1 mL of water.

The four vulnerability classes, established from the analysis of the time series at the end of the monitoring program, are as described below:

1 = score 0–5—no/reduced vulnerability

2 = score 6–10—medium vulnerability

3 = score 11–15—high vulnerability

4 = score 16+—extreme vulnerability

The vulnerability classes, the weight, and category of each parameter (Table 4) were established relative to the obtained data from the four caves, the experience we have on the range of variation of different parameters in natural caves, and the observed modifications induced by the human presence.

The results on the obtained classes were added within an ArcGIS 10.3.1. ESRI environment. Multiple 0.5 m resolution surfaces were generated with the help of a deterministic interpolation (natural neighbor) that used barriers [50]. The method helped to constrain interpolated values within the cave boundary. Surfaces were generated for each season of interest considering the vulnerability class. Validating the surfaces was not possible, due to the limited amount of information. The surfaces did not consider various volumetric and morphological variations of the cave systems, having just one observation point per certain section of interest. This strongly constrained the obtained results, which were solely used as indicators of the general trend of the observed phenomenon.

3. Results

3.1. Muierilor Cave

Eight stations were installed in the cave (Table 5), of which five stations were set in the touristic sector and three in the Scientific Reserve (see also Figure 2 and Table 3).

3.1.1. Temperature

Variations in air temperature decreased towards the interior of the cave (especially in the Scientific Reserve) where it became almost constant. In Figures S1 and S2 the temperature variations recorded in the touristic (PM1, PM2, PM3, PM5, and PM8) and non-touristic (PM6, PM7) stations by comparison with the surface temperature recorded during the 2-year measurement cycle are presented.

Outside the tourist area, the temperatures are much more constant but there was a general trend of increasing temperature since the summer of 2015 followed by a stabilization in 2016. In Figure S3, a temperature increase pulses were measured during the paleontological excavations that were carried out in the Scientific Reserve. It is observed that a group of only 5–6 people triggered a temperature increase by about 0.5 °C in a rather short time (1–2 days) in a medium-sized gallery (~6 × 1.5 m), after a working time of 6–8 h

per day. The period of return to the initial state is usually 1–3 days, but it should be noted that after the second campaign, the temperature continued to rise, reaching a maximum in the summer of 2016, even in the absence of researchers.

Table 5. The stations in the Muierilor Cave and the values of the measured parameters in air and water.

Stations/Parameters	PM1	PM2	PM3	PM4	PM5	PM6	PM7	PM8
T °C min-max	7.5–10.5	6.9–10.7	8.3–10.5	9.6–11.8	5.9–11.6	7.1–11.6		0.8–14.7
mean	9.1	8.5	9.2	10.9	11.2	9.7		8.4
Tourist traffic (no./h)		<250						
RH (%)	>90	>90	>90	>90	>90	>95		>40
CO ₂ (ppm)	400–1000	400–1000	400–1000	400–1000	400–1000			
Air speed (m/s; mean)	0.2	0	0	0	0	0		0
Drip rate (L/h; min-max)			0–1.15	0–1.38	0–0.28	0–20.46	0–14.79	
Conductivity (µS/cm)			336–368	355–382	432–453	360–406	305–396	
pH (min-max)			7.4–8.3	7.3–8.2	7.3–8.2	7.3–8.3	7.1–8.2	
SI (min-max)			(−0.46)–0.58	(−0.31)–0.53	(−0.24)–0.54	(−0.32)–0.51	(−0.31)–0.51	

3.1.2. Tourist Traffic

An infrared traffic recorder was installed at the PM2 station to record the human presence. With many visitors, the temperature rise can exceed 0.5–1 °C in a medium-sized room as is the PM2 station and with a tendency of thermal accumulation. This increase is linked to both the number of visitors per visit and the time spent at the given point. Stationing of the groups for more than 10 min in this station has the effect of rapidly increasing the temperature and at the same time lengthening the time to return to the initial situation.

3.1.3. Air Relative Humidity (RH)

RH has values higher than 90% throughout the year starting about 40–50 m from the two entrances. Inside the cave the RH values are constantly higher than 95%.

3.1.4. Air CO₂ Concentration

The touristic sector is relatively well ventilated with measured values of CO₂ between about 400 ppm (normal value for atmospheric air, measured in the entrance area) and 1000 ppm, the increases being recorded in the summer months.

3.1.5. Air Speed

The air currents show speeds of up to 0.2 m/s near the entrance area. Their direction varied depending on the air temperature at the surface. In the deep area or adjacent galleries (east and west branches and lower level), air circulation is imperceptible.

3.1.6. Drip Rate

Data obtained on the drip rates (Figure S4) show a good correlation both between the dripping points and between them and the rainfall regime recorded at the surface. Quantitatively, the recorded flows vary between 0.1 L/h in the PM7 station and 1.4 L/h in the PM4 station, respectively. Response time to precipitation events shows a dynamic related both to the amount of precipitation infiltrated and accumulated in the karst system and to their duration and intensity: as a result, response time intervals of the order of months (1–3 months) are identified, in the case of dry periods but also response time on the order of days, especially in constant and abundant rainy periods. In this sense, the PM3 and PM4 dripping points respond most quickly to high-flow events. During periods of heavy rain, the tourist gallery becomes unvisitable due to the flooding of the floor.

3.1.7. Physicochemical Parameters of Drip Water

The conductivity of the water is relatively constant, with slightly lower values during the winter. There is a clear difference between PM3, PM4, PM6, and PM7 stations, for which the average conductivity value was about 362 µS/cm, and the PM5 station where it was about 450 µS/cm. The pH values of the water oscillate between 7.2 and 8.7 in the five

measuring points, with average values of 7.8–7.9. Generally, the pH is lower in winter and higher in spring and summer. The total hardness of carbonates varies between 12.6 and 15.8 dH.

The calculated values of the saturation index (SI) showed that the drip water is more saturated in carbonate in summer and aggressive in winter. At PM3, the water is aggressive (corrosive) in winter, while at PM4 the water precipitates calcite throughout the year.

3.2. Polovragi Cave

Three stations were established in the cave (Table 6), with all stations in the touristic sector (see also Figure 2 and Table 3).

Table 6. The stations in the Polovragi Cave and the values of the measured parameters in air and water.

Stations/Parameters	Pol1	Pol2	Pol3
T air °C min-max	7.7–9.1	8.3–9.6	8–8.5
mean	8.4	8.4	8.2
Tourist traffic (no/h)	<120		
RH (%)	>90	>95	>99
CO ₂ (ppm)	<1260	<1040	<1000
Air speed (m/s)	0.02–0.11	0	0
Drip rate (L/h; min-max)	0–0.8	0–3.5	
Conductivity (µS/cm) min-max	223–270	342–396	
pH (min-max)	6.8–8.2	7.2–8.1	
SI (min-max)	(−0.74)–(−0.023)	(−0.04)–0.4	

3.2.1. Temperature

As expected, variations in air temperature decreased deeper inside the cave where the air temperature becomes quasi-constant all year round. Figure S5 shows the temperature variations recorded in Pol1 and Pol2 stations during the 2-year measurement cycle. One may notice that in the Pol1 station the air temperature is influenced by the variations of the surface temperature varying by about 1 °C between the minimums registered in January–February and the maximums registered in August–September. In the Pol2 station, the air temperature was practically constant, varying by only 0.3 °C around the average of 8.4 °C.

3.2.2. Tourist Traffic

An infrared traffic recorder was installed in Pol1 station. No direct correlation between the number of tourists and the variation of air temperature was observed (Figure S6).

3.2.3. Influence of Lighting Sources

The data loggers were oriented towards two reflectors in the cave. In the station Pol1, at about 1 m distance from the reflector and in the station Pol2 at about 3 m distance from the reflector (Figure S6). The analysis of the data shows that the operation of the reflector in the Pol1 station produces a heating of 0.3–0.4 °C at about 20 min from the lighting of the reflector, the effect being felt during the whole day of visiting. The temperature drops by about 0.2 °C after about 16 h. If the visit regime is reduced the next day, the temperature can return to previous values. In the Pol2 station, at 3 m distance from the reflector, no influence on the air temperature is observed.

3.2.4. Relative Humidity

RH has values higher than 90% throughout the year approximately 100 m from the entrance. Towards the inside of the cave, the RH values are constantly higher than 95%.

3.2.5. Air CO₂ Concentration

In the touristic sector, the Polovragi Cave is relatively well ventilated and the measured values of CO₂ vary between about 400 ppm, a normal value for atmospheric air measured in the entrance area, and 1300 ppm. The maximum values of the CO₂ concentration were measured inside the cave, in all fixed stations in the summer months (June–August) and can be considered normal.

3.2.6. Air Speed

Due to the large volume of the cave passages, the tourist sector is well ventilated, especially along the first 200 m. The air currents had speeds of 0.02–0.11 m/s in the entrance area, their direction varying depending on the air temperature at the surface. In the deep sector, the air circulation is imperceptible, except for the non-touristic zone where the gallery section is reduced and small air currents form.

3.2.7. Drip Rate

The two loggers installed in Pol1 and Pol2 stations show a very good correlation both between the two measuring points and between them and the precipitation regime (Figure S7). Quantitatively, the registered flows reached up to 3.5 L/h in the Pol2 station, and 0.8 L/hour in the Pol1 station, respectively. The response time to precipitation events has two periodicities: a relatively short one, about 3–4 days and a much longer one, which can reach 2–3 months and occurs after prolonged periods of drought. This can be seen by comparing the years 2015 (drier) and 2016.

3.2.8. Physicochemical Parameters of Drip Water

The conductivity of the water is relatively constant, with lower values during the winter. However, there is a clear difference between the two measuring stations. The average conductivity value in Pol1 was about 250 µS/cm, while in Pol2 it was about 384 µS/cm. The pH values of the water are similar in the two points and have average values of 7.63–7.64. The total hardness of carbonates is also much higher at the Pol2 point (11.4 dH) than at the Pol1 point (8.25 dH).

The water saturation index (SI) showed that the dripping water is more saturated in carbonate in summer and aggressive in winter, and in this case there is a difference between points Pol1 and Pol2; in Pol1 the water is aggressive (corrosive), while in Pol2 the water precipitates calcite in summer but dissolves in winter. Water aggressiveness can be considered moderate in Pol1 (values up to −0.8) and neutral in Pol2 (<−0.5).

3.3. Urşilor Cave

Six stations were established in the cave (Table 7), with stations PUC1, PUC2, PUC3, and PUC5 in the touristic sector and stations PUC4 and PUC6 in the non-touristic passages (see also Figure 2 and Table 3).

3.3.1. Air Temperature

The constant values registered outside the tourist path (PUC4, upper level) and PUC6 (Scientific Reserve) define the range of natural temperature variation. It is confirmed that under natural conditions, the temperature in the cave should be constant, with variations of maximum 0.1–0.2 °C. In the touristic sector, all the registered values show increases during the summer season, which also corresponds to the peak season for tourism (Figure S8). The registered seasonal variations are slightly higher in the PUC 5 station located in the deeper part of the cave, compared to the PUC2 and PUC3 stations (~1°C versus ~0.7 °C) but this is normal considering that in the PUC5 station the volume of the gallery is lower and tourist traffic in that sector is a round trip. There was no clear correlation between seasonal oscillations of outdoor temperature and those recorded in the cave.

Table 7. The stations in the Urşilor Cave and the values of the measured parameters in air and water.

Stations/ Parameters	PUC1	PUC2	PUC3	PUC4	PUC5	PUC6
T air °C min-max mean		10.2–11.1 10.4	10.3–11.1 10.4	10.5 (+0.1 in summer)	10.1–11.1 10.3	9.6 (constant)
Tourist traffic (no./h)	<500					
RH (%)		>98	>98	>98	>98	>98
CO ₂ (ppm)		>10000	<8000	<8140	<6500	<7800
Air speed (m/s)		<0.46	<0.42		<0.57	
Drip rate (L/h; min-max)		0.03–1.34	0.014–0.22	0–0.03	0.14–2.5	0.03–0.65
Conductivity (µS/cm)		419–441	304–445	228–384	407–431	331–392
pH (min–max)		7.3–8.0	7.4–8.1	7.6–8	7.3–8.2	7.3–8.3
SI (min–max)		(−0.069)–0.42	(−0.07)–0.2	(−0.29)–0.04	(−0.15)–0.1	(−0.32)–(−0.05)

3.3.2. The Influence of Tourist Traffic

Three infrared tourist traffic recorders were installed in stations PUC 1 (unidirectional), PUC 3 (unidirectional), and PUC 5 (bidirectional) to record the tourist transit at the respective points. From the data analysis a correlation is observed between the tourist traffic and the air temperature variations in the measured area (i.e., PUC 3 in Figure S9). The temperature increases are relatively small of 0.1–0.2 °C, but they accumulate in the peak season, when the temperature does not return to normal from one day to the next.

3.3.3. Influence of the Lighting Sources

The loggers in PUC 2, PUC 3, and PUC 5 stations were oriented towards the light sources. In PUC2 and PUC3 they measured the ambient lighting while in PUC 5 the sensor was placed at about 1 m distance from the light source. The analysis of the recorded data shows that the light sources generated in all stations an increase in temperature of 0.1–0.2 °C (Figure S10). In case of low traffic, when the lighting time is limited, the temperature returns to the initial values after a relatively short time, of about 1–2 h. The operation of the light sources in the PUC3 station in the absence of tourists produced a rapid response with a heating of 0.1–0.2 °C, the temperature returning to the initial level after a much longer time, of about 10 h (Figure S11).

As the increase in temperature in the cave is the cumulative effect of the presence of tourists and the operation of the lighting installation, it is difficult to determine how much of the temperature increase is due to the operation of light sources. The situation shown in Figure S10 suggests that the light sources alone can produce heating up to 0.2 °C even in a large space.

3.3.4. Relative Humidity

RH was 95–100% regardless of the registration point, season, or tourist traffic.

3.3.5. CO₂ Concentration in the Air

In the touristic sector, the cave had high measured CO₂ concentrations that varied between about 1000 ppm and over 10,000 ppm (Figure S12). The CO₂ concentrations recorded during the summer in the cave are among the highest measured. Due to sensor limitations, we could not measure values over 10,000 ppm, but point measurements performed with a portable Vaisala instrument, in August 2016, showed values exceeding 14,000 ppm at PUC2. For reference, we specify that the value of 25,000 ppm is considered as a threshold beyond which the CO₂ concentration is dangerous for human health [51].

3.3.6. Air Speed

Due to the airlocks system, the Urşilor Cave does not have a high level of ventilation. The most intense air movements were recorded in the PUC2 station, with velocities of maximum 0.46 m/s. The speed of the air currents is slightly higher during the warm

season and lower in winter, probably due to the frequency with which the access doors are opened. In stations furthest from the access area (PUC 5 and PUC 3), the average speed of air currents is much lower, up to 0.01 m/s.

3.3.7. Drip Rate

In the cave, the most active dripping point was PUC 5 where maximum flows of over 2.5 L/h were recorded (Figure S13). The drip rates recorded in the cave were not directly correlated with the rainfall events at the surface. The PUC5 station has a clear seasonal behavior, with extremely low flows during the summer (<0.5 L/h) and very high flows during periods of heavy rain or snow melting.

3.3.8. Physicochemical Parameters of Drip Water

The conductivity of the water was relatively constant, with slightly higher values during the winter. Lower values (~200–350 $\mu\text{S}/\text{cm}$) were measured in the non-touristic area at stations PUC4 and PUC 6. Higher values, constantly over 400 $\mu\text{S}/\text{cm}$ were recorded in the stations PUC2 and PUC3. The total hardness had the highest values (12–15 dH) in the touristic sector, in all the stations.

The calculated value of the water saturation index (SI) demonstrated that the dripping water was generally unsaturated (aggressive), especially during the summer. The maximum SI values are recorded in winter, only in PUC2 and PUC3 stations, but they are quite low anyway. This shows that dripping water was generally aggressive and calcite was deposited only in a few points in the touristic sector and only in winter.

3.4. Meziad Cave

In the Meziad Cave, five stations were established in the cave (Table 8), with stations Mez1, Mez3, Mez4, and Mez5 in the touristic sector and station Mez2 in a non-touristic passage (see also Figure 2 and Table 3).

Table 8. The stations in the Meziad Cave and the values of the measured parameters in air and water.

Stations/ Parameters	Mez1	Mez2	Mez3	Mez4	Mez5
T °C min-max	11.5–22.3	11.3–13.6	11.7–17.3	0.0–14.2	−3.8–15.3
mean	14.2	12.2	13.4	9.1	9.7
Tourist traffic (no./h)	<136				
RH (%)	60–100	>90	80–100	80–100	80–100
CO ₂ (ppm)	400–850	<1800 (June–September)		<1100	
Air speed (m/s; min-max)	0.02–0.2	0	0–0.04	0.01–0.2	0–0.24
Drip rate (L/h)		0.45		0.1	
Conductivity ($\mu\text{S}/\text{cm}$)		527–593		400–440	
pH (min-max)		7.6–8.1		7.5–8.2	
SI (min-max)		0.19–0.6		0.01–0.42	

3.4.1. Air Temperature

The lower level of the cave is strongly influenced by the surface temperature. The multiannual variability of the temperature is over 19 °C near the gate and decreases to about 14 °C deeper inside the cave. In the upper level, the temperature is much higher (on average about 4.5–5 °C). The multiannual temperature variability is about 11 °C in the Mez1, close to the entrance and about 5.5 °C in Mez3, close to the bats' colony. The most constant temperature is recorded in Mez2, located in the non-touristic area where the temperature recorded variations of maximum 2 °C during the monitoring cycle (Figure S14). The lower level is strongly influenced by variations of surface temperature in the cold season, and the upper level by the warm season, as the warm air remains "captive" on the top level in the cold season. During the summer, the warm air entering the cave portal influences

the microclimate of the upper level, registering even diurnal variations. Side passages are much less influenced by seasonal variations.

3.4.2. Tourist Traffic

An infrared traffic recorder was installed in the Mez1 station (Figure S15).

3.4.3. Influence of Lighting Sources

In the stations Mez1, Mez3, and Mez5 the light loggers were oriented towards the nearest lighting sources, located at distances of about 3–5 m. No heating effect could be detected in any of the stations due to the lighting sources, which is to be expected for the LED lighting system.

3.4.4. Relative Humidity

RH had values ranging from 60% to 100% in the upper-level entrance area and between 80% and 100% in the lower level and deep area. In Mez2, RH was constantly higher than 90%.

3.4.5. CO₂ Concentration in the Air

In the touristic sector, the Meziad Cave is well ventilated. In the upper tourist level (Mez1), CO₂ concentration varies between about 400 ppm (normal value in atmospheric air) and 850 ppm. In the lower level (Mez4), the maximum values reach about 1100 ppm. The highest values of CO₂ concentration (1800 ppm) were recorded in Mez2. The maximum values of the CO₂ concentration were measured in the summer months (June–September) and can be considered normal. There is no direct link between the higher number of visitors in the summer months or during various holidays and increases in the air temperature in the cave.

3.4.6. Air Speed

Due to the large volume of the galleries, the touristic sector of the Meziad Cave is well ventilated, especially in the entrance area and the lower level. The air currents have speeds of 0.02–0.2 m/s, their direction varying depending on the surface air temperature. In the upper level and the side galleries, the air circulation is imperceptible.

3.4.7. Drip Rate

In the Mez2 and Mez4 stations, the two loggers show a weak correlation between the dripping rate and the precipitation regime (Figure S16). It should be noted, however, that the data used for precipitation are those recorded at the Urşilor Cave. Under these conditions, the values used for precipitation may be different, although it is assumed that the major trends are the same.

Quantitatively, the flow rates recorded for the two drip points are low, with maximum values of 0.45 L/h in the Mez4, respectively 0.1 L/h in the Mez4. These values are about 5–10 times lower than the recorded values in stations in the Urşilor Cave, in the same interval. At both points, the peak flows are recorded in spring and autumn, but without being related to major episodes of precipitation. There is a response gap of 1–4 months between Mez2 (located closer to the surface) and Mez4 (lower level).

3.4.8. Physicochemical Parameters of Drip Water

Water conductivity is relatively constant throughout the year, with a difference between the two measuring stations. The average conductivity value in Mez2 was about 550 µS/cm, while in Mez4 it was about 440 µS/cm. Relatively high conductivity values indicate a high concentration of dissolved salts. This is also observed in the results of the total hardness of the carbonates, which is also high in absolute value (13–16 dH, compared to the usual values of 8–12 dH found in other caves). In Mez2 point, the average total hardness is higher (16.5 dH) compared to Mez 4 point (13.8 dH). The pH of the water had a similar variation over the measurement period in both stations, with an average value of 7.9.

4. Discussion

4.1. Muierilor Cave

The cave represents an important touristic objective that requires a radical redevelopment. Table S1 and Figure 3 shows that the vulnerability of the cave to tourist traffic is maximum during the summer due to the drastic increase in the number of tourists, the presence of bats (as source of pathogens; [33]) in the cave and the corresponding increase in the number of possible pathogenic microorganisms. Vulnerabilities related to temperature changes appear as a combined effect of human presence associated with the operation of incandescent bulbs. During the warm season, the accumulated changes led to an increase in temperature of up to 2 °C.

The influences of the external temperature are felt in the Muierilor Cave up to about 50 m from both entrances, especially from the southern entrance. There are three components that influence the variation of temperature: (a) the natural (seasonal) component, with low influence in the deep zone; (b) the operation of light sources whose influence was measured to up to about 2–3 m, corroborated with (c) the presence of groups of tourists. Temperature increases in the tourist gallery can reach about 1 °C during the visiting hours and do not return to previous values until the next day. These increases accumulate over time so that in the peak season (summer) the air temperature can be up to 2 °C higher than normal. The return is gradual during autumn and winter when the cave is less visited.

The current lighting installation has generated the appearance of lampenflora and it also affects the cave exhibits (the cave bear skeleton; Figure 4). They reappear shortly after cleaning, whether chemical or using ultraviolet light. The current lighting installation should be replaced as soon as possible with one based on low power LED sources, at the same time with an action of total eradication of the lampenflora.

The summer months also have an increased microbiological risk for tourists and guides. The microbial limits in the air are far exceeded by European standards and possible pathogenic bacteria have been identified. That is why it is necessary to limit the time spent by groups of tourists, especially in the summer season [44].

Measured radon doses indicate that staff (guides) is at moderate occupational risk (category B). This risk should be monitored periodically using personal dosimeters. Measured radon concentrations are not a danger to tourists [45,46].

In the case of the tourist redevelopment of the Muierilor Cave, the project will have to secure solutions for the limitation of the air circulation and the restoration of the natural conditions of relative humidity and the attenuation of temperature variations. This can be achieved by building a visitor center over the northern entrance that would allow for ventilation control and adjustment, limit the evaporation of percolating water and mitigation of the microbiological impact.

4.2. Polovragi Cave

The Polovragi Cave could attract a much higher number of tourists that requires a radical redevelopment. Table S2 and Figure 5 show that the cave's vulnerability to tourist traffic is maximum in summer–autumn, while in the winter season there is only a middle portion of the touristic path that is vulnerable, probably due to the presence of bats that form hibernation colony.

During the monitoring, no vulnerabilities were identified related to changes in the microclimate that could be associated with the presence of tourists. The influences of the surface temperature were detected in the cave to about 50 m from the entrance, after which the air temperature is relatively stable around 8.2–8.4 °C. There was no direct link between the high number of visitors in the summer months and the rising air temperature in the cave.

Significant temperature increases have been directly associated with the lighting installation and which do not return to normal values during a visit cycle. There was a direct influence of light sources, which translates into temperature increases ranging from about 2 °C in the immediate vicinity of the reflectors and about 0.4 °C at 1 m distance

during their operation. A return time of about 40 h is required for the temperature to return to the initial values. The current lighting installation has generated the appearance of lampenflora and should be replaced as soon as possible with one based on LED sources, at the same time with an action of total eradication of the lampenflora. However, the simple replacement with LED sources will not lead to the disappearance of the lampenflora.

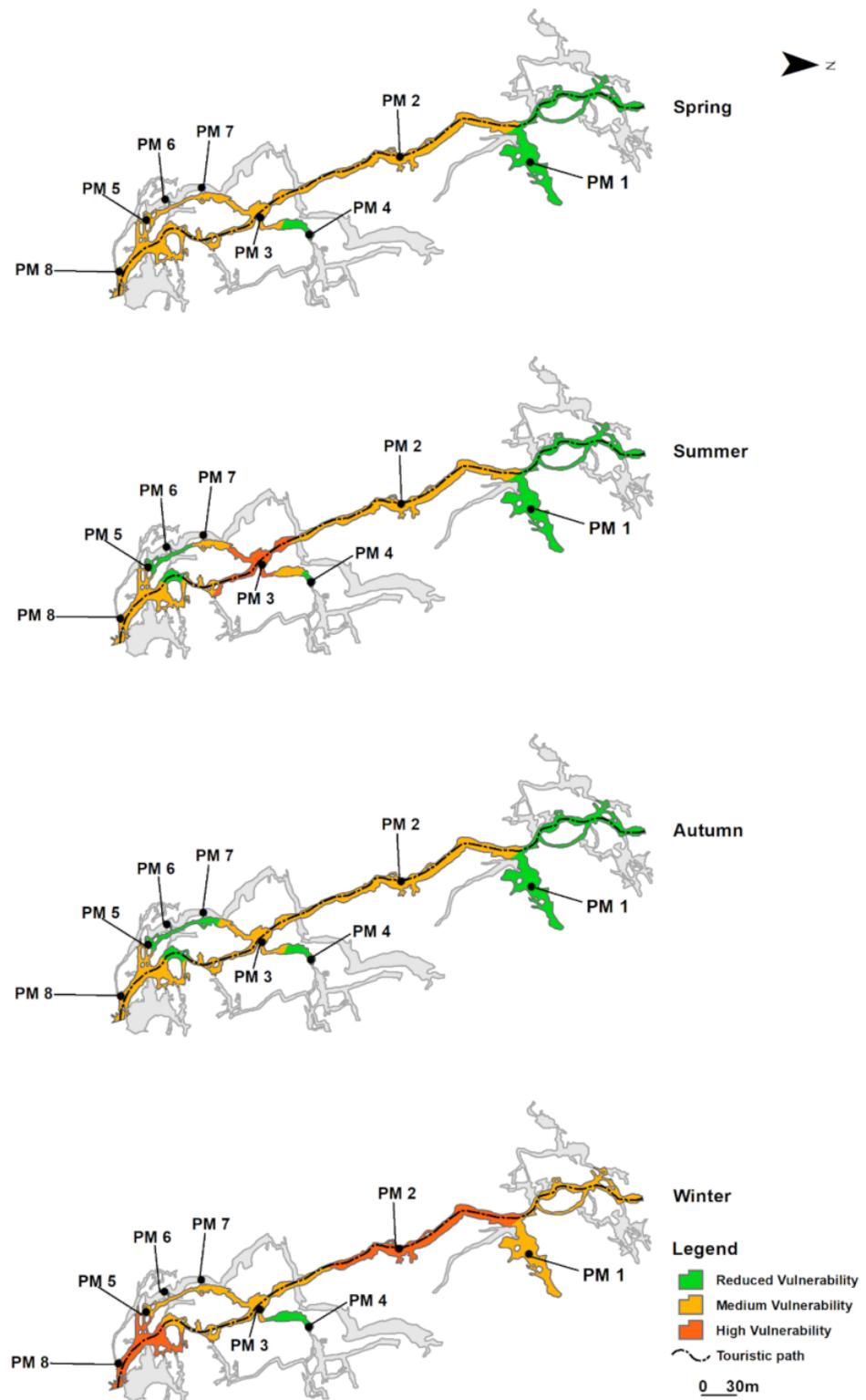


Figure 3. The Muierilor Cave vulnerability maps by season.

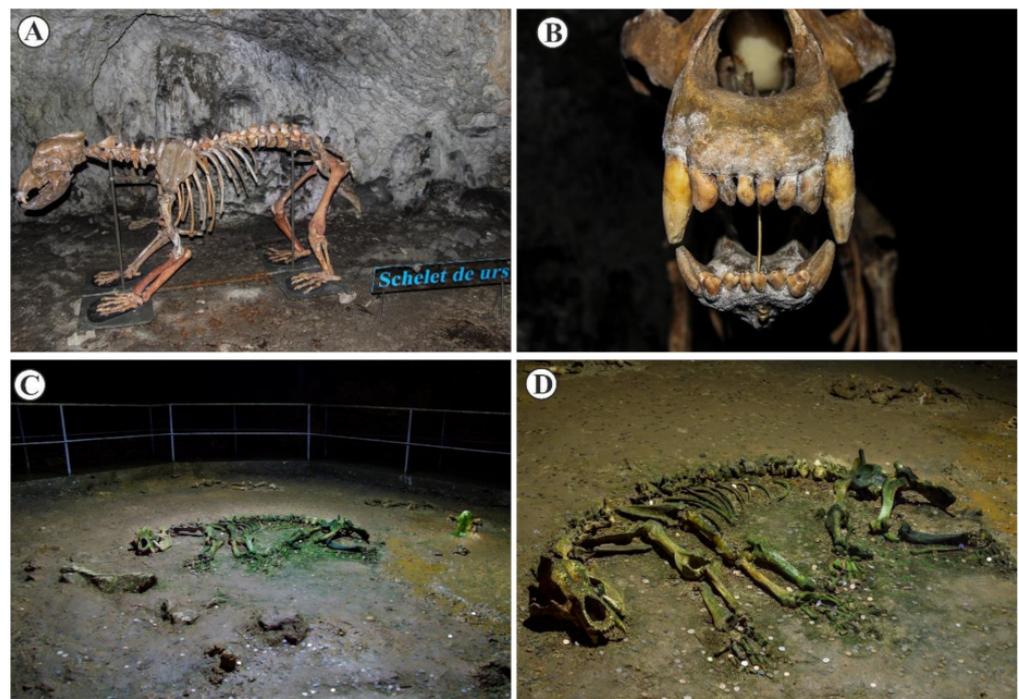


Figure 4. (A). Lateral view of the cave bear from the Muierilor Cave; (B). Frontal view of the skull showing large areas of the maxilla and jaws extremely affected by lampenflora; (C). Stopping point (approximately 10 min per group) for tourist in the Urşilor Cave near the cave bear skeleton; (D). Cave bear skeleton from the Urşilor Cave extremely affected by lampenflora.

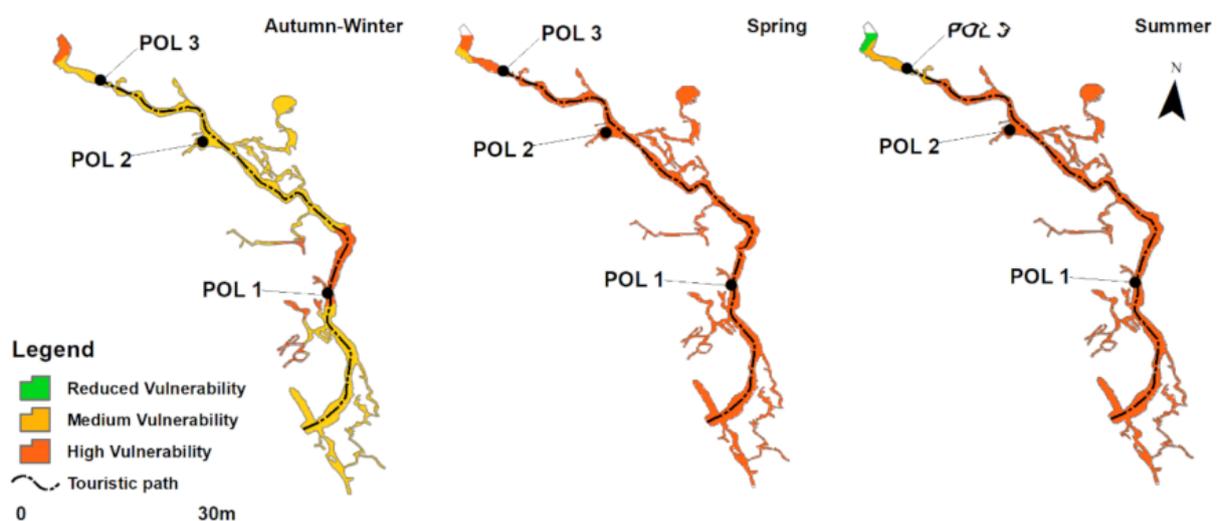


Figure 5. Maps of the seasonal vulnerability of the Polovragi Cave.

Measured radon doses indicate that the guides are at high occupational risk. This risk should be monitored periodically using personal dosimeters. Measured radon concentrations are not a danger to tourists [45,46].

Of interest for the vulnerability of the cave is the fact that during periods of intense dripping in some sectors, there is flooding of the floor, which affects tourist traffic. In the event of a future redevelopment, these areas should be provided with stainless steel or other inert material decks raised above the floor level.

In the case of the tourist redevelopment of the cave, we consider it necessary to dig a tunnel between the end of the tourist area and the slope of the Olteț Gorges, Olteț being the river that flows in front of the cave entrance. This tunnel (provided with at least two airlocks) would fulfill the following functions: (1) it would increase the tourist flow as the groups of tourists could enter the cave at an interval of about 20 min leaving through the final part, in the Olteț Gorges; (2) it would minimize the impact of tourists on the cave as they would travel the cave in one direction only; (3) could function as an additional ventilation system during periods when high concentrations of radon are recorded.

4.3. Urșilor Cave

The Urșilor Cave is a tourist objective of highest importance that needs a different management approach. Table S3 and Figure 6 shows that the cave's vulnerability to tourist traffic is maximum during the summer–autumn period, especially in the entrance passages and in the touristic exit area. The vulnerability of the cave is also high in several points along the touristic trail, especially the platforms where tourists are stopping for explanations.

The identified vulnerabilities are related to temperature changes that may be associated with the presence of tourists. These changes appear as a combined effect of human presence associated with the operation of lighting. The outside temperature does not directly influence the microclimate of the cave. The average temperature measured on the tourist route registers seasonal variations, with increases of up to 0.7 °C in the warm season, which overlaps with the peak tourist season. In the non-touristic sector, the temperature has a remarkable constancy, both in the lower and in the upper levels. In the touristic sector, with much larger galleries, the temperature increases by up to 0.7–0.8 °C, with maximum values in August, and returns to the initial values only starting with December. From this increase, up to 0.2 °C is due to the operation of the lighting system.

CO₂ concentrations in the cave atmosphere are high during the summer (over 14,000 ppm) and, given the predictable increasing number of visitors in the future, could become potentially dangerous to the health of tourists and guides. The maximum limit for occupational exposure (8 h) to CO₂ varies between 5000 and 10,000 ppm. In Romania, this limit is set at 9000 ppm for an 8-h shift by the general labor protection norms [52]. The high concentrations of CO₂ were associated with increasing acidity of the dripping water and corrosion of speleothems, which are main attractions of the cave. To reduce the level of CO₂, we recommend the opening of the entrance doors to increase ventilation during the peak periods of July–September (the entrance is covered by a concrete building). The measures related to the ventilation of the cave by permanently opening the doors must be tested only under the conditions of a constant monitoring by specialists. Seasonal oscillations of CO₂, with maximum values during the summer, are normal in all caves, including non-tourist ones, as they are due to the contribution of additional CO₂ formed at the surface because of biotic activity and transported underground by water or percolation. In the case of the Urșilor Cave, however, visitors are the most important source of CO₂, as the maximum values measured in the non-tourist area did not exceed 7000 ppm, half of those measured in the touristic sector. In the touristic high season (summer), when the cave receives up to 200 visitors/hour, the CO₂ level increases. The restoration to initial values was relatively long, of about two weeks (Figure 7).

The dripping behavior showed that there is a gradual filling of the vadose zone above the cave and rapid release of water once it reaches a certain threshold.

The old lighting installation has generated the appearance of lampenflora, even on the fossil remains (the exposed cave bear skeleton). They reappear shortly after cleaning, whether it is done chemically or by using ultraviolet light. The replacement with LED sources did not lead to the disappearance of the lampenflora and we reinforce the need of using LED light of very low intensity.

We also recommend replacing the fossil cave bear remains at the end of the touristic path with a copy of a skeleton made of a chemically inert material.

Measured radon doses indicate that guides are at high occupational risk (category A). This risk should be monitored periodically using personal dosimeters [45,46]. Measured radon concentrations are not a danger to tourists.

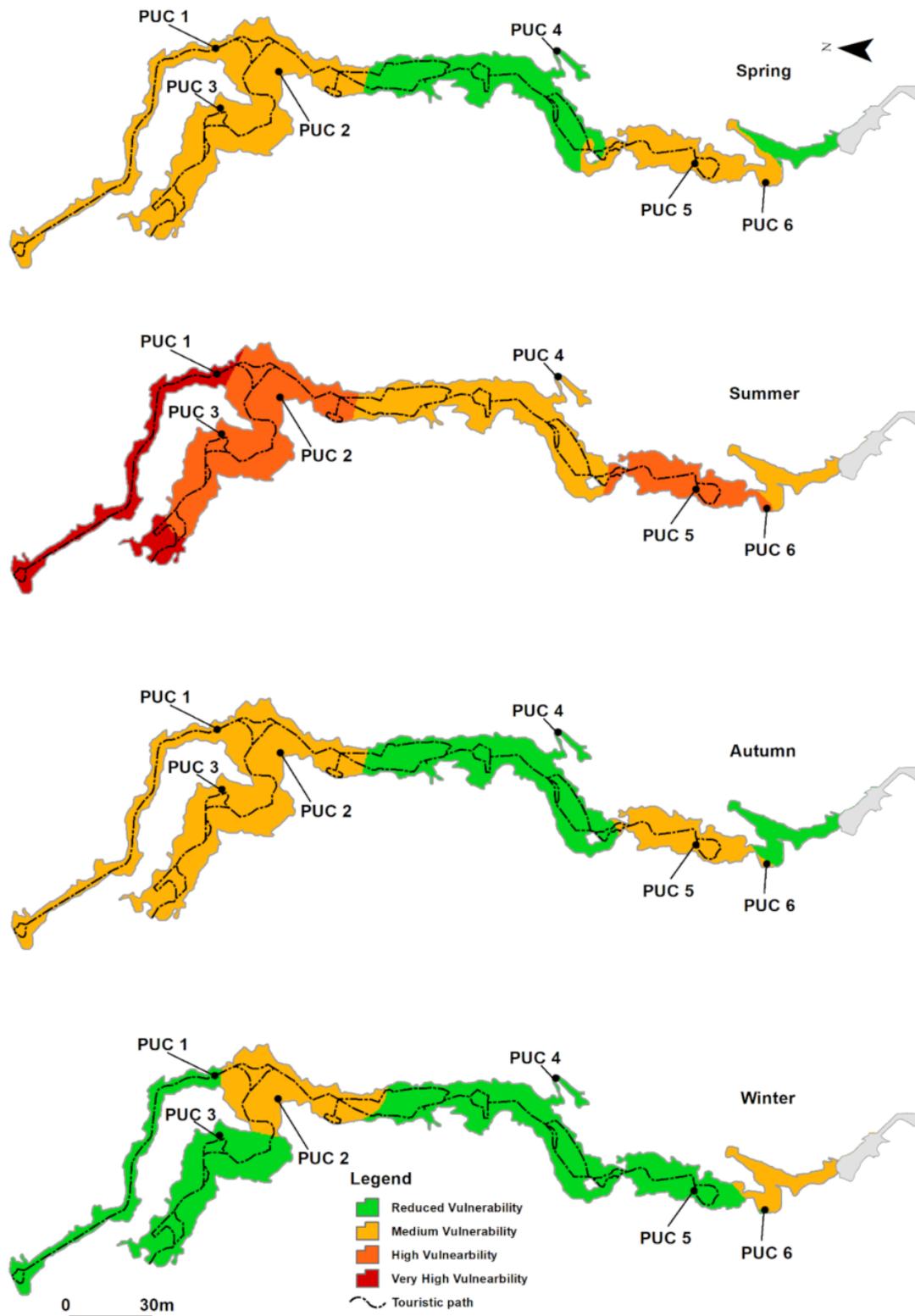


Figure 6. Maps of the seasonal vulnerability of the Urșilor Cave.

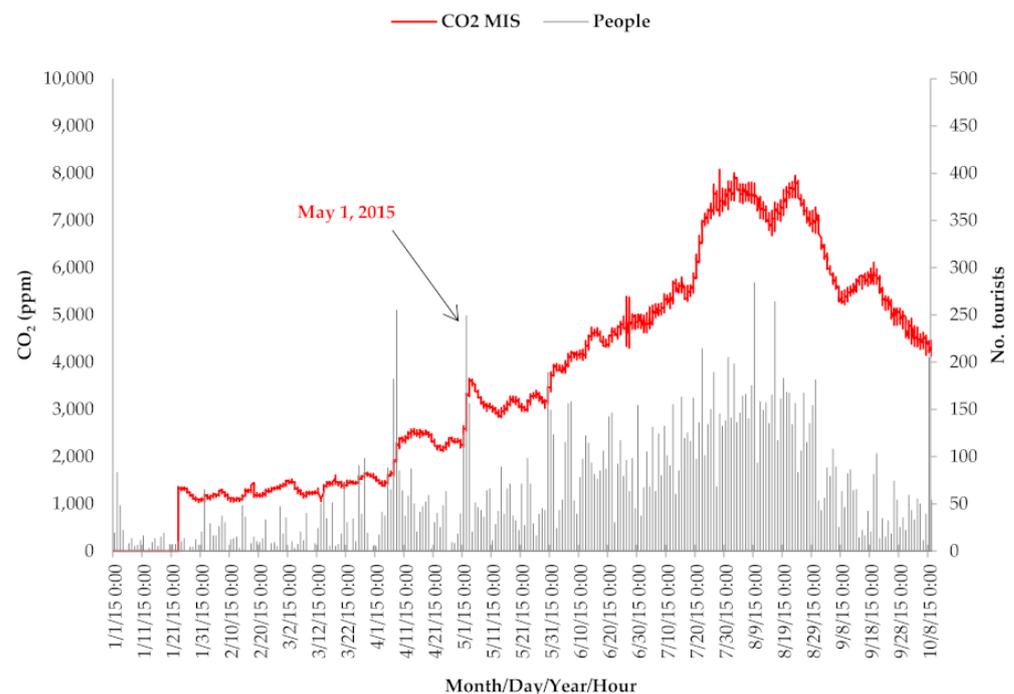


Figure 7. CO₂ concentration (ppm; red) in the Urșilor Cave measured in the PUC2 station compared to tourist traffic (black). There is an immediate increase in CO₂ values in the periods corresponding to the national holidays. MIS is the type of climatic station as indicated in Table 3.

The amounts of bacteria and pathogenic fungi in the air and water exceeded the European standards in many stations during April–August. However, the largest amounts of pathogenic bacteria and fungi appeared in the building at the entrance of tourists [43]. We recommend ventilating it especially during periods with many tourists and perform antifungal hygiene as often as possible. We recommend the immediate installation of systems for disinfecting the feet of tourists at the entrance to the cave.

Considering the summer vulnerability of the Urșilor Cave, we recommend reducing the visiting time and the stopping in the final area, at the cave bear skeleton.

4.4. Meziad Cave

The Meziad Cave is an important and spectacular tourist attraction that could attract a much higher number of tourists than it currently does. Table S4 and Figure 8 show that the vulnerability of the cave to tourist traffic is maximum during the summer due to the drastic increase in the number of tourists, the presence of the bats in the cave, and the corresponding increase in the number of pathogenic microorganisms.

No vulnerabilities were identified related to changes in the microclimate (temperature, RH, CO₂) that could be associated with the presence of tourists. The spatial modeling of the seasonal evolution of the temperature in the touristic sector shows the strong influence of the temperature from the surface on the first ~ 100 m of the cave in all seasons. There was no direct correlation between the registered traffic and the variation of the air temperature. In the cold season, changes in the outside temperature cause significant temperature variations especially in the lower level. In the warm season, temperature variations are felt predominantly on the upper level. Due to the large spaces, the Meziad Cave has an atypical thermal regime presenting an important thermal variability even in sectors located a few hundred meters away from the entrance. The exception is the side galleries, which are not subject to tourists' traffic.

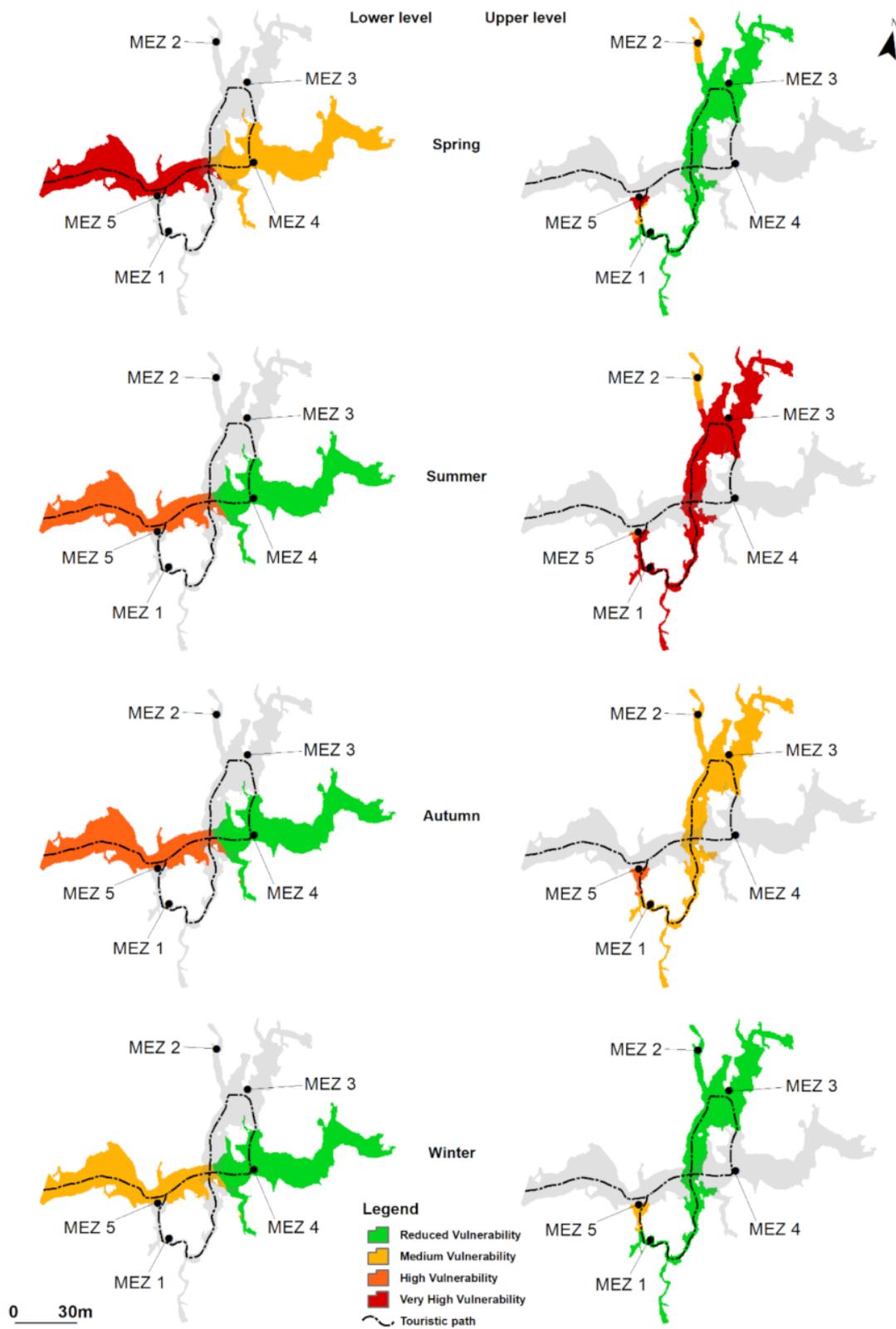


Figure 8. The Meziad Cave vulnerability maps by season.

No thermal influence of the lighting sources on the air temperature was observed. However, the current lighting installation, although based on LED lights, does not avoid the proliferation of the lampenflora. The lampenflora should be eradicated periodically;

either by using mobile UV lamps (local exposure for several hours) or by washing with a H₂O₂ buffered solution [11].

From the previously published data [43,44] measures were proposed against the presence of pathogenic bacteria in the cave, both in the air and in the water, such as reducing the duration of a visit by avoiding long stay throughout the tourism sector and avoiding winter visits in the southern part of the upper sector.

In general, the dripping is very low in the Meziad Cave, which is a point of vulnerability for the cave as the precipitation of new calcite is also reduced. The absence of a clear response of the dripping points in the cave to surface precipitation events indicates that the karst aquifer had long-term storage and episodic discharges.

5. Conclusions Concerning the Protection and Management Measures

Each of the four monitored show caves in this study represent a different situation due to their morphological characteristics, gating system, and management measures.

Air relative humidity was one of the characteristics that was not influenced by the touristic traffic, all caves having normal values, near the saturation. In the non-ventilated caves, temperature and CO₂ concentration were the parameters most influenced by the human traffic and have shown large variations in the touristic high seasons. The CO₂ concentration remained low in Muierilor, Polovragi, and Meziad caves and did not endanger the health of visitors or tourists, while the values were high in Urşilor. It is unclear whether there is a direct link between the CO₂ levels at Urşilor and drip water aggressiveness, but the SI levels are generally low in the summer when the CO₂ levels are also higher. In all caves where speleothems are an attraction, monitoring the SI remains important since it may trigger alerts concerning the anthropically-induced water aggressiveness and potential calcite dissolution.

However, several management measures for a sustainable use of show caves are common to all the four studied caves:

- (i) Firstly, the lighting system caused problems by the development of lampenflora. Changing to LED lighting has no effect if the existing lampenflora is not totally removed. Controlling the lighting remains a long-term mitigation measure that must be undertaken permanently through a combination of lampenflora early removal and adjusting of illuminance levels (both light intensity and lighting time).
- (ii) In caves with no natural entrance(s), such as Urşilor, a continuous monitoring of CO₂ levels should be complemented by occasional ventilation through the airlocks during the high season. However, such measures should be taken on a case-by-case basis and only until low-CO₂ levels (those of low-season) are restored.
- (iii) In caves such as Meziad, where vulnerability shows a seasonal variability, seasonal changes of the touristic circuits may be applied with benefits to both cave environment and visitors' health. Finally, microbiological monitoring of surfaces should be routinely done to counter both pathogens introduced by visitors and cave fauna such as bats.

Such a study, on several show caves in parallel and by using different devices and methods for monitoring was an excellent opportunity to establish future protocols for show cave monitoring and suggest measures to improve the management of the caves that were already affected by tourism.

Supplementary Materials: The following are available online at <https://www.mdpi.com/2071-1050/13/4/1619/s1>, Figure S1: Temperature variation in the fixed monitoring stations of Muierilor Cave, PM1, PM2 and PM3, Figure S2: Temperature variation in the fixed monitoring stations of Muierilor Cave, PM5 and PM8, Figure S3: Temperature variation in Muierilor Cave stations PM2, PM4, PM5, PM6 and PM8, Figure S4: Variation of the drip rate in Muierilor Cave, Figure S5: Temperature variation in the two monitoring stations in Polovragi Cave, Figure S6: The variation of tourists' number in Pol1 station of Polovragi Cave, Figure S7: Variation of the drip rate in Pol 1 and Pol 2 stations of Polovragi Cave, Figure S8: Temperature variation in the fixed monitoring stations of

Ursilor Cave, Figure S9: The variations of the air temperature in the PUC3 station of Ursilor Cave, Figure S10: Temperature variation related to the registered traffic, respectively light intensity, in PUC2 station in Ursilor Cave, Figure S11: Temperature variation in the PUC2 station of Ursilor Cave correlated with the light in the absence of tourists, Figure S12: CO₂ concentrations measured continuously in Ursilor Cave, at PUC2, PUC3 and PUC5 stations, Figure S13: The variation of the drip rate in the stations PUC2, PUC3, PUC5 and PUC6 compared to the precipitation values at the Ursilor Cave weather station, Figure S14: The temperature variation in the five monitoring stations from the Meziad Cave, Figure S15: The variation of the tourist traffic in Meziad Cave, Figure S16: Variation of the drip rate in Meziad Cave, Table S1: The calculations of classes for the different stations in Muierilor Cave, Table S2: The calculations of classes for the different stations in Polovragi Cave, Table S3: The calculations of classes for the different stations in Ursilor Cave, Table S4: The calculations of classes for the different stations in Meziad Cave.

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