Article

Monitoring human impact in show caves. A study of four Romanian caves

Silviu Constantin [1,2,3*], Oana Teodora Moldovan [2,3,4*], Ionuț Cornel Mirea [1,2], Alexandru Petculescu [1,2], Răzvan Adrian Arghir [1,2], Dragoș Ștefan Măntoiu [4], Marius Kenesz [2,4] and Marius Robu [1]

[1] Emil Racovita Institute of Speleology, Department of Geospeleology and Paleontology, Frumoasă 31, București, Romania; silviu.constantin@iser.ro
[2] Romanian Institute of Science and Technology, Saturn 24-26, Cluj-Napoca, Romania
[3] Centro Nacional de Investigacion sobre la Evolucion Humana, CENIEH, Paseo de Atapuerca s/n, Burgos, Spain
[4] Emil Racovita Institute of Speleology, Department of Cluj, Clinicilor 5, Cluj-Napoca, Romania, oanamol35@gmail.com

* Correspondence: silviu.constantin@iser.ro, oanamol35@gmail.com ;

Abstract: (1) Background: Show caves are unique natural attractions and touristic traffic can trigger their degradation within a very short time. There are no universal solutions to counter the effects of the touristic impact upon 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 physico-chemical parameters of the air and water (CO_2, temperature, humidity, drip rate, conductivity, and pH) was implemented; (3) Results and Conclusions: The results of the study has: (i) established a monitoring protocol to be applied to each of the four show caves; (ii) established a set of basic principles to be enforced by the management of show caves; (iii) 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

1. Introduction

Karst regions are a spectacular but sensitive environment 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, karst regions 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 very 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 (troglobionts), 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 surfaces 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 deep 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 very old drawings in Coliboaia cave (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 beauty following a decrease in air relative humidity (RH), and an increase in temperature and partial CO_2 pressure in cave's air as a result 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. 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 [10].

In theory, the environment of a cave should have only a negligible contact with the external environment. Heaton [11] 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 touristic traffic in caves upon biodiversity was also documented [13]. The deep sections of the caves host a troglobitic 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 troglobitic invertebrates and (if any) of bat colonies, without forcing the later to move to new places where they could cause damage to mineralogical attractions.

In addition to the above, there is a large body of evidence that the lint (hair, dry-flaking skin, dust, spores) carried on by 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. 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.

Besides the conservation issues, the development of a show caves 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 [14-16]. 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 [17-21] have shown that radon concentration in show caves do not pose a health problem for the visitors but they may be of concern for professional workers such as the cave guides or cave researchers. 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 outmost importance to: (i) preserve caves' natural environment while (ii) monitor radon levels on a regular basis in order to assess the risks for visitors and professionals involved.

Table 1: Principal threats for the environment of show caves, their possible causes and effects.

Threat	**Cause**	**Effects**
Changes of natural air circulation	Opening of artificial entrances, changes in cave passage geometry	- 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	- development of heterotrophic films; lampenflora growth
	- Periodic temperature fluctuations from visitors' flux	- 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	- 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.)	- 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.)	- pollution of the cave environment affecting troglobitic fauna
Noise	ultrasonic noise from electrical equipment (e.g. transformers) or visitors noise	- 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. Monitoring programs have been enforced for both old show caves [6] and newly discovered caves [22]. 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 [23].

In Romania, before 2010, only 9 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, Urșilor Cave (Chișcău, Apuseni Mountains, north-western Romania), 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 Cetății, Farcu, Meziad). While they appear so far to be successful as tourist attractions and are fitted with modern pathways and LED lighting systems, their development was done in the absence of any previous 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. [24-27]).

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 on developing new caves as touristic attractions; (ii) uncontrolled development and unmonitored touristic traffic 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.

2. Materials and Methods

2.1. Studied caves

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

1. Peștera Muierilor (peștera = cave in Romanian) is located in the Southern Carpathians. It consists of a maze of passages totaling more than 8 km in length, spread across 4 levels. The cave is famous for the discovery of early modern human remains c. 35 ka old [28], Paleolithic artifacts and a large deposit of fossil remains of cave bears (*Ursus spelaeus*), cave lions, hyaenas, wolves and also herbivores and small mammals [29]. 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 (uni-directional), 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 located in the vicinity of Muierilor Cave. It is a multi-level cave with a total length of ~10 km. The touristic sector is ~500 m long and was opened in the '960s 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 for the next future. Both, Muierilor and Polovragi caves are sheltering bat colonies and are part of the ROSCI 0128 Natura 2000 protected area.

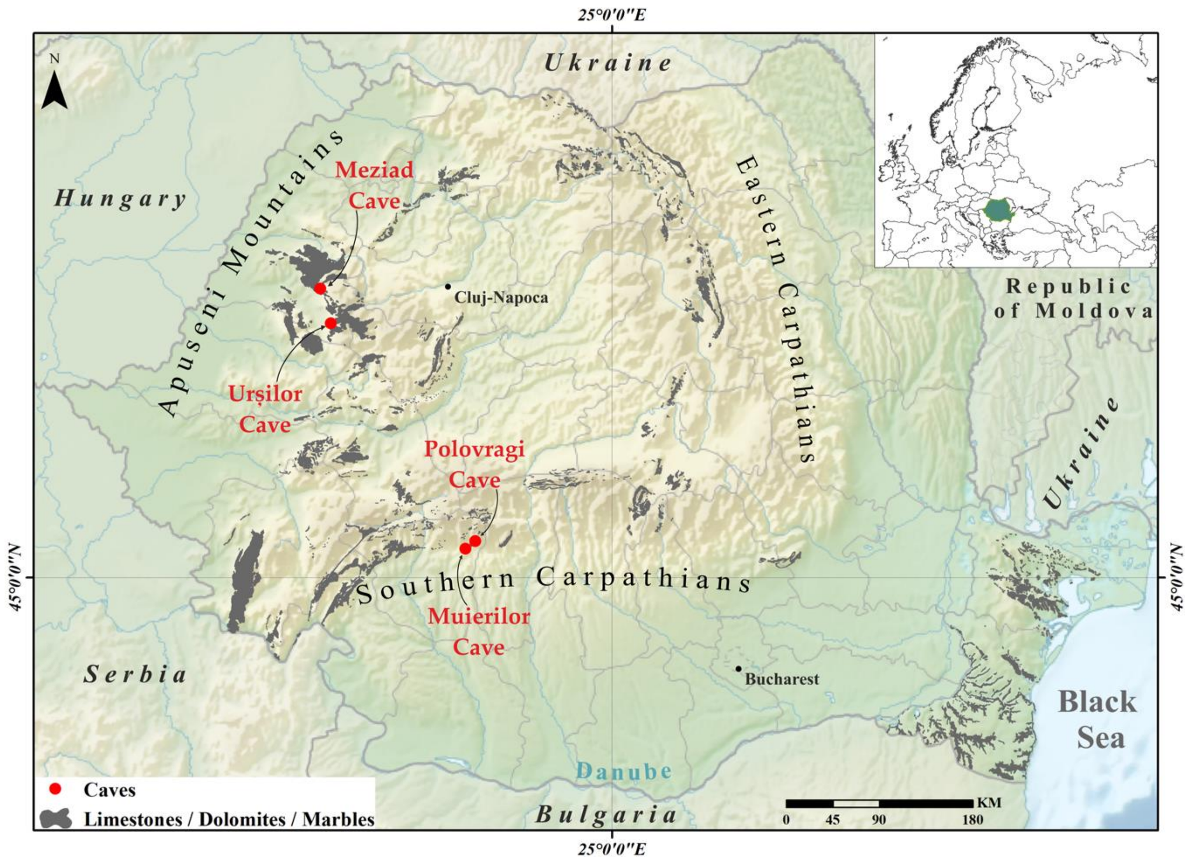

Figure 1. The location of the four studied show caves in Romania.

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 trail is walked through twice by the groups. This cave is a typical example of a show cave where artificial entrances have been caused a change in microclimate despite the airlocks. 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 yearly more than 120,000 visitors.

4. Peștera Meziad is located in Pădurea Craiului Mountains (Apuseni Mountains). It is one of the oldest show caves of Romania important for its large passages and chambers, massive speleothems and fossil remains. It is a natural monument and part of the ROSCI0062 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 troglobitic invertebrate species have been described [30]. After decades of reckless tourism, the cave was partially rehabilitated in 2012. However, the successful rehabilitation is poorly known so far and the cave attracts yearly only ~20,000 visitors. 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 by (see also Table 2):

- 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 minutes 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 2 months using portable equipment. The measured parameters were: air temperature, relative air humidity, CO_2 concentration, air speed and direction. The concentration of CO_2 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 and isotopic analysis, as well as freshly precipitated calcite samples for isotopic analysis. Water saturation index (SI) was also calculated for it provides an image of 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/langelier/index/langelier.htm).
- biological and microbiological monitoring was performed at intervals of 2 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 [31-33].
- 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 3 months, resulting in complete sets of measurements for each season. Radon measurements were reported by Burghele et al. [34-35].
- the outdoor 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 villages (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).

Table 2. Characteristics of measurements in the four studied show-caves (2015-2017).

Cave/Protocol		Muierilor	Polovragi	Urşilor	Meziad
Number of stations: touristic passages/non-touristic passages		5/3	2/1	3/2	4/1
Tourist traffic		continuous	continuous	continuous	continuous
Temperature (°C)	continuous	Hobo Pendant UA-002-64 Tinytag	Hobo Pendant UA-002-64	Microstep MIS (Slovakia)	Hobo Pendant UA-002-64
	spot	Every 2nd month			
Combined temperature + Light		Hobo Pendant UA-002-64			

Relative air humidity (RH; %)	continuous	Tinytag		Microstep MIS (Slovakia)	
	spot	Vaisala GMP222			
Air CO_2	continuous	CO_2 meter	CO_2 meter	Vaisala GMP222	CO_2 meter
	spot (Vaisala GM70+ GMP222 probe)	Every 2nd month			
Air speed and direction – spot		Every 2nd month			
Drip rate (Stalagmate Mark3)		5 stations	2 stations	4 stations	2 stations
Conductivity, pH		Every 2nd month; 2 stations			
Biological monitoring: Troglobiont invertebrates		Every 2nd month			
Microbiological monitoring: Total heterotrophic, pathogenic groups		Every 2nd month			
Radon		continuous			

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

2.3. *Vulnerability maps*

For modeling the maps with the seasonal vulnerabilities of the four caves we used the following indicators: temperature variation, humidity variation, CO_2 variation, dripping flow variation, dripping water chemistry, abundance of bat colonies (not published), abundance of pathogenic microorganisms (from [31]) 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 3). The algorithm for vulnerability calculations applied for each station in the caves was:

*Vulnerability score = sum of indicators value * weight / no. validated indicators,*

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

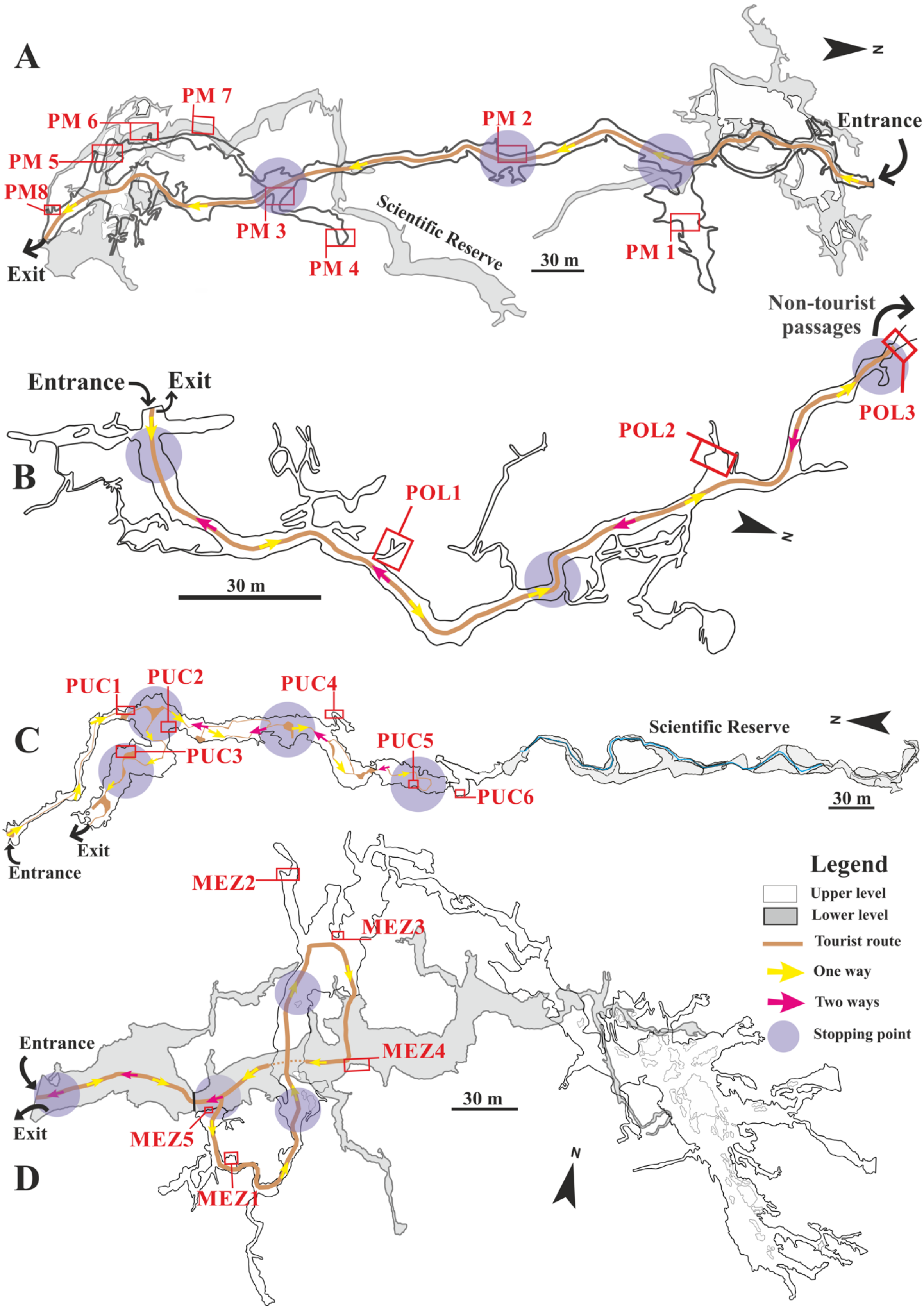

Figure 2. The four studied show caves and the location of the monitoring stations in Muierilor (A; modified after Mirea et al. [29]), Polovragi (B; modified after Ponta and Aldica [37]), Urșilor (C; modified after Constantin et al. [38]) and Meziad (modified after Rusu et al. [39]).

The four vulnerability classes, established from the analysis of the data 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 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 [36]. 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.

Table 3. The parameters, their weight and the respective categories, used to build vulnerability maps

	PARAMETER x WEIGHT	CATEGORY		
		0	10	20
1	Temperature (°C) x 2 (T)	Seasonal variation < 1	Seasonal variation 1-2	Seasonal variations> 2C
2	RH (%) x 2 (RH)	Variation <5	Variation 5-10	Variation >10%
3	CO_2 (ppm) x 2 (CO_2)	<5000	5000-10000	>10000
4	Saturation index x 1 (SI)	positive	negative	
5	Drip rate (%) x 1 (DR)	Constant flow <25	Short interruptions 25-50	Long interruptions >50%
6	Bats number x 1 (Bats)	None	Few dozens	Big colonies
7	Microorganisms (CFU/m^3) x 1 (Microorg.)	<50	50-500	>500
8	Tourist number /season x 2 (Tourists)	<2500	2500-5000	>5000

3. Results

3.1 Muierilor Cave

Eight stations were established in the cave (Table 4), of which five stations were set in the touristic sector and three in the Scientific Reserve (see also Figure 2).

Table 4. The stations in Muierilor Cave and the values of the measured parameters in air and water.

Stations/ Parameters	PM1	PM2	PM3	PM4	PM5	PM6	PM7	PM8
T ºC 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	

3.1.1. Temperature

Variations in air temperature decreased towards the interior of the cave (especially in the Scientific Reserve) where they become 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 has triggered a temperature increase by about 0.5 °C in a rather short time (1-2 days) in a medium-sized gallery (~6 x 1.5 m), after a working time of 6-8 hours 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.

3.1.2. Tourist traffic

An infrared traffic recorder was installed at the PM2 station in order to record the human presence. With a very large number of 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 closely 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 minutes 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 meters from the two entrances. Inside the cave the RH values are constantly higher than 95%.

3.1.4. Air CO_2 concentration

The touristic sector is relatively well ventilated with measured values of CO_2 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 and heavy rain, the tourist gallery becomes unvisitable due to the flooding of the floor.

3.1.7. Physico-chemical 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. As a general rule, 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 5), with all stations in the touristic sector (see also Figure 2).

Table 5. The stations in 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	

3.2.1. Temperature

As expected, variations in air temperature droped into the cave where the air temperature become 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 Pol 2 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 Pol 1 station. No direct correlation between the number of tourists and the variation of air temperature (Figure S6).

3.2.3. Influence of lighting sources

The data loggers were oriented towards two reflectors in the cave. In the station Pol 1 at about 1 m distance from the reflector and in the station Pol 2 at about 3 m distance from the reflector (Figure S6). The analysis of the data shows that the operation of the reflector in the Pol 1 station produces a heating of 0.3-0.4 °C at about 20 minutes 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 hours. If the visit regime is reduced the next day, the temperature can return to previous values. In the Pol 2 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 approximatively 100 m from the entrance. Towards the inside of the cave the RH values are constantly higher than 95%.

3.2.5. Air CO_2 concentration

In the touristic sector, Polovragi Cave is relatively well ventilated and the measured values of CO_2 vary between about 400 ppm, a normal value for atmospheric air measured in the entrance area, and 1300 ppm. The maximum values of the CO_2 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 during 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.

3.2.7. Drip rate

The two loggers installed in Pol 1 and Pol 2 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/hour 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. Physico-chemical 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 high in Pol1 (values up to -0.8) and moderate in Pol2 (<-0.5).

3.3. Urșilor Cave

Six stations were established in the cave (Table 6), 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).

Table 6. The stations in Urșilor 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
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

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 vs ~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.

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) in order 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 hours. 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 hours (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 Fig 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. CO_2 concentration in the air

In the touristic sector, the cave had high measured CO_2 concentrations that varied between about 1000 ppm and over 10,000 ppm (Figure S12). The CO_2 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. For reference, we specify that the value of 25,000 ppm is considered as a threshold beyond which the CO_2 concentration is dangerous for human health.

3.3.6. Air speed

Due to the airlocks system, the Ursilor 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 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. Physico-chemical parameters of drip water

The conductivity of the water was relatively constant, with slightly higher values during the winter. Lower values (~200-350 µS/cm) were measured in the non-touristic area at stations PUC4 and PUC 6. Higher values, constantly over 400 µS/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 valued 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 Meziad Cave five stations were established in the cave (Table 7), with stations Mez1, Mez3, Mez4 and Mez5 in the touristic sector and station Mez2 in a non-touristic passage (see also Figure 2).

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

Stations/Parameters	Mez1	Mez2	Mez3	Mez4	Mez5
T ºC 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 (µS/cm)		527-593		400-440	
pH (min-max)		7.6-8.1		7.5-8.2	

The lower level of the cave is strongly influenced by the surface temperature. The multiannual variability 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 Chamber. 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 disturbs 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. CO_2 concentration in the air

In the touristic sector, the Meziad Cave is well ventilated. In the upper tourist level (Mez1) CO_2 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 CO_2 concentration (1800 ppm) were recorded in Mez2. The maximum values of the CO_2 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 Ursilor 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 Ursilor 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. Physico-chemical 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.

The saturation index had positive throughout the year, with values ranging from 0 to 0.9.

4. Discussion

4.1. Muierilor Cave

The cave represents an important tourist objective that requires a radical redevelopment. Table 8 and Figure 4 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.

Table 8. The calculations of classes for the different stations in Muierilor Cave: W = winter (December-January-February); Sp = spring (March-April-May); S = summer (June-July-August); A = autumn (September-October-November).

STATION	PARAMETER								SCORE	CLASS
SEASON	Temp	RH	CO_2	SI	DR	Bats	Microorg.	Tourists		
PM1Sp	0	0	0			20	0	0	3	**1**
PM1S	20	0	0			0	10	0	5	**1**
PM1A	0	0	0			0	10	0	2	**1**
PM1W	20	0	0			20	0	0	7	**2**
PM2Sp	0	0	0			10	10	40	10	**2**
PM2S	0	0	0			0	20	40	10	**2**
PM2A	0	0	0			0	0	40	7	**2**
PM2W	20	0	0			10	0	40	12	**3**
PM3Sp	0	0	0	10	0	10	10	40	9	**2**
PM3S	0	0	0	0	20	10	20	40	11	**3**
PM3A	0	0	0	0	10	0	0	40	6	**2**
PM3W	20	0	0	10	0	0	0	40	9	**2**
PM4Sp	0	0	0	10	10	0	0	0	3	**1**
PM4S	0	0	0	0	20	0	10	0	4	**1**
PM4A	0	0	0	0	10	0	0	0	1	**1**
PM4W	0	0	0	10	20	0	0	0	4	**1**
PM5Sp	20	0	0	0	10	0	10	40	10	**2**
PM5S	0	0	0	0	20	0	10	40	9	**2**
PM5A	0	0	0	0	20	0	0	40	8	**2**
PM5W	20	0	0	10	20	0	10	40	13	**3**
PM6Sp	0			10	20	0		0	6	**2**
PM6S	0			0	20	0		0	4	**1**
PM6A	0			0	20	0		0	4	**1**
PM6W	0			10	20	0		0	**6**	**2**

The influences of the external temperature are felt in the Muierilor Cave up to about 50 meters from both entrances, especially from the southern entrance. At depth, the air temperature is relatively stable around 8.8-9.6 °C. There are three components that influence the variation of temperature: (a) the natural (seasonal) component, little felt in the deep zone; (b) the operation of light sources whose influence is felt to a distance of 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.

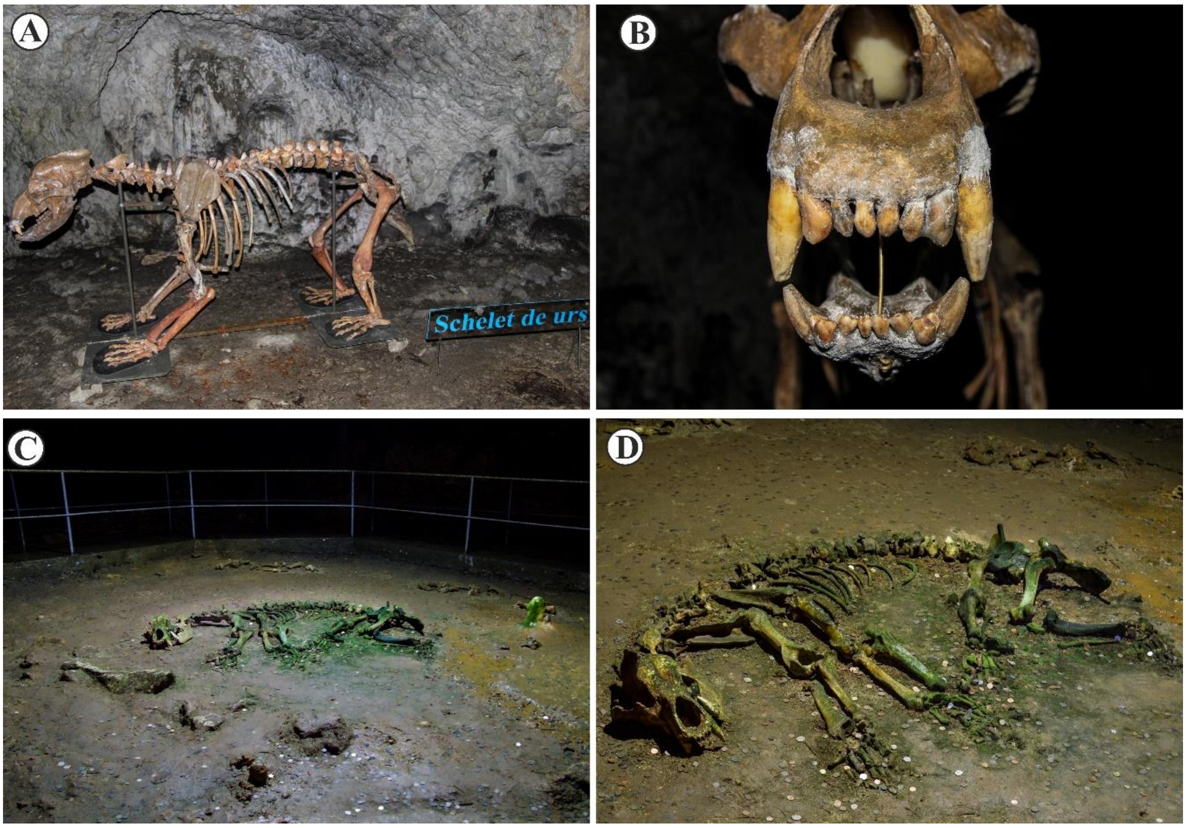

Figure 3. A. Lateral view of the cave bear from Muierilor Cave; B. Frontal view of the skull showing large areas of the maxilla and jaws extremely affected by lampenflora; C. Stopping point (approximately 10 minutes per group) for tourist in Urșilor Cave near the cave bear skeleton; D. Cave bear skeleton from Urșilor Cave extremely affected by lampenflora.

The current lighting installation has generated the appearance of lampenflora and it also affects the cave exhibits (the cave bear skeleton; Figure 3). 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 [33].

Measured Radon doses indicate that staff (guides) are at moderate occupational risk (category B). This risk should be monitored periodically using personal dosimeters. Measured Radon concentrations are not a danger to tourists [31-32].

In the case of the tourist redevelopment of the Muierilor Cave, the project will have to provide 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.

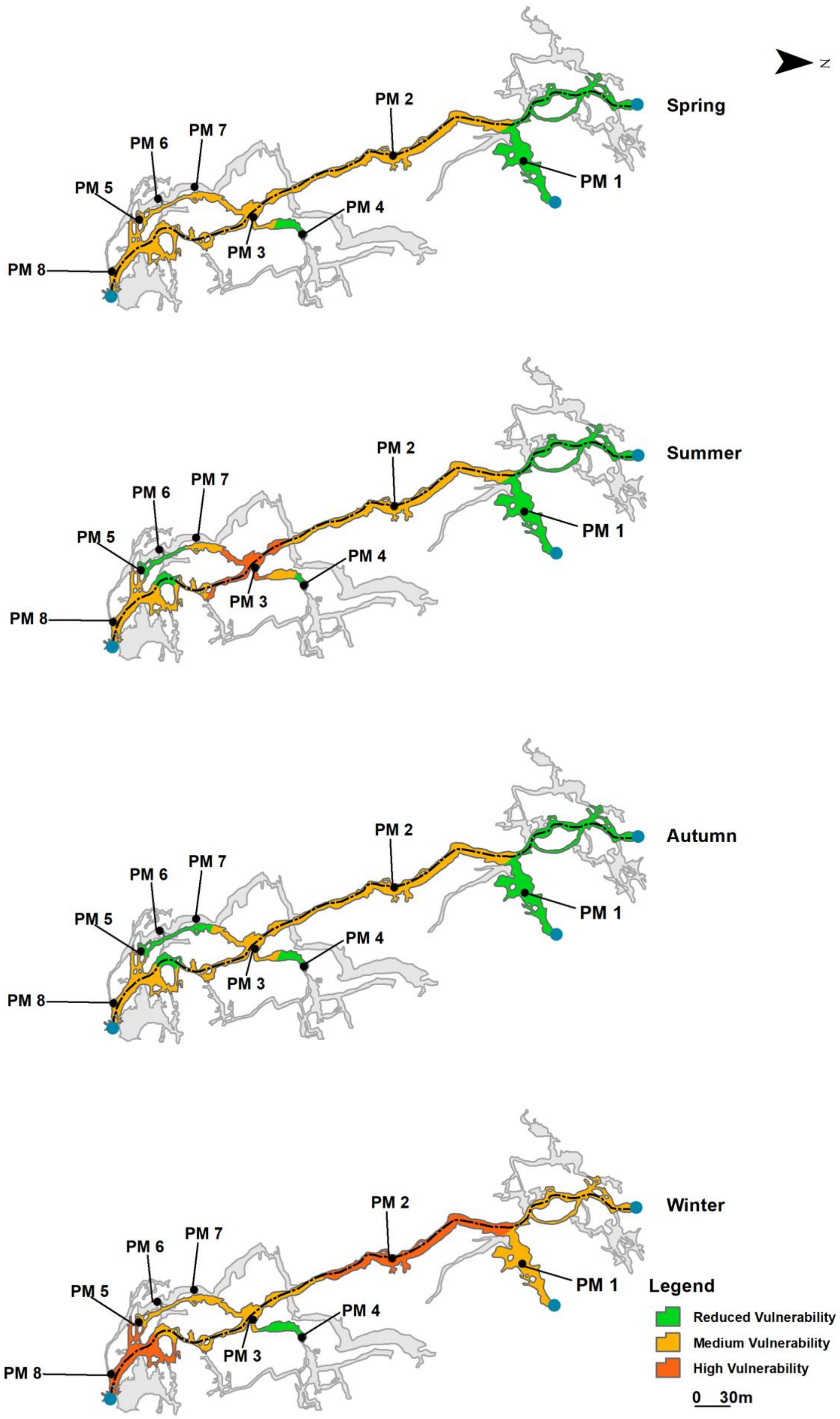

Figure 4. Muierilor Cave vulnerability maps by season.

4.2. Polovragi Cave

Polovragi Cave could attract a much higher number of tourists that requires a radical redevelopment. Table 9 and Figure 5 shows 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 which form hibernation colony.

Table 9. The calculations of classes for the different stations in Polovragi Cave: W = winter (December-January-February); Sp = spring (March-April-May); S = summer (June-July-August).

STATION SEASON	PARAMETER								SCORE	CLASS
	T	RH	CO_2	SI	DR	Bats	Microorg.	Tourists		
Pol1W	0	0	0	10	20	20	0	20	9	**2**
Pol1Sp	0	0	0	10	10	20	10	40	11	**3**
Pol1S	20	0	0	10	0	0	10	40	10	**2**
Pol2W	0	0	0	10	20	20	0	20	9	**2**
Pol2Sp	0	0	0	10	10	20	0	40	10	**2**
Pol2S	0	0	0	0	0	0	10	40	6	**2**
Pol3W	0	0	0			20	0	20	7	**2**
Pol3Sp	0	0	0			20	0	40	10	**2**
Pol3S	0	0	0			0	0	40	7	**2**

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 felt in the cave to about 50 meters 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 identified 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 1 m distance during their operation. A return time of about 40 hours is required to return to the initial temperature. The current lighting installation has generated the appearance of lampenflora. The current lighting installation 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.

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 [31-32].

Of interest for the vulnerability of the cave is the fact that during periods of heavy drip in some sectors there is flooding of the floor which affects both 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 absolutely necessary to dig a tunnel between the end of the tourist area and the slope of the Olteţ Gorges, that flows in front of the cave entrance. This tunnel (provided with at least two double doors) 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 minutes leaving through the final part, in the Olteţ 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.

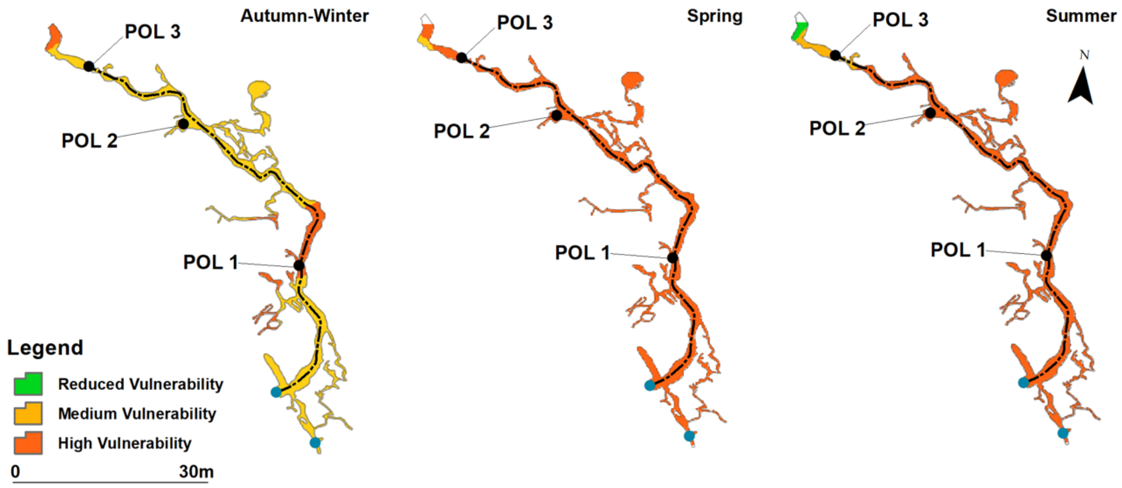

Figure 5. Maps of the seasonal vulnerability of Polovragi Cave.

4.3 Urșilor Cave

Ursilor Cave is a tourist objective of highest importance but which needs a different management approach. Table 10 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. Also, the vulnerability near the end of the touristic trail, where the dimensions of the gallery are reduced, and the tourists are stopping for a while.

Table 10. The calculations of classes for the different stations in Meziad Cave: W = winter (December-January-February); Sp = spring (March-April-May); S = summer (June-July-August); A = autumn (September-October-November).

STATION	PARAMETERS							SCORE	CLASS
SEASON	T	RH	CO_2	SI	DR	Microorg.	Tourists		
PU1Sp	0	0	0			0	40	8	**2**
PU1S	0	0	20			20	40	16	**4**
PU1A	0	0	0			10	40	10	**2**
PU1W	0	0	0			0	20	4	**1**
PU2Sp	0	0	0	0	20	10	40	10	**2**
PU2S	0	0	20	10	0	20	40	13	**3**
PU2A	0	0	0	0	20	10	40	10	**2**
PU2W	0	0	0	0	20	0	20	6	**2**
PU3Sp	0	0	0	0	0	0	40	6	**2**
PU3S	0	0	20	10	10	10	40	13	**3**
PU3A	0	0	0	0	20	10	40	10	**2**
PU3W	0	0	0	0	10	0	20	4	**1**

PU4Sp	0		0		0		0	0	**1**
PU4S	0		20	10	0		0	8	**2**
PU4A	0		0	0	0		0	0	**1**
PU4W	0		0	0	0		0	0	**1**
PU5Sp	0	0	0	0	0	10	40	7	**2**
PU5S	0	0	20	10	10	20	40	14	**3**
PU5A	0	0	0	0	20	10	40	10	**2**
PU5W	0	0	0	10	0	0	20	4	**1**
PU6Sp	0	0	0	10	0	10	0	3	**1**
PU6S	0	0	20	10	0	10	0	6	**2**
PU6A	0	0	0	10	10	10	0	4	**1**
PU6W	20	0	0	10	10	10	0	7	**2**

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.

CO_2 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 hours) to CO_2 varies between 5,000 and 10,000 ppm. In Romania, this limit is set at 9,000 ppm by the general labor protection norms. The high concentrations of CO_2 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 CO_2 we recommend the opening of the entrance doors to increase ventilation during the peak periods of July-September the doors of the entrance frame be left open. 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 CO_2, with maximum values during the summer, are normal in all caves, including non-tourist ones, as they are due to the contribution of additional CO_2 formed at the surface as a result of biotic activity and transported underground by water or percolation. In the case of the Ursilor Cave, however, it is clear that visitors are the most important source of CO_2 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 CO_2 level increases. The restoration to initial values was relatively long, of about 2 weeks (Figure 7).

The dripping behavior showed that the karst aquifer is of the "buffer" type, with a gradual filling of the aquifer and rapid release of water once it reaches a threshold.

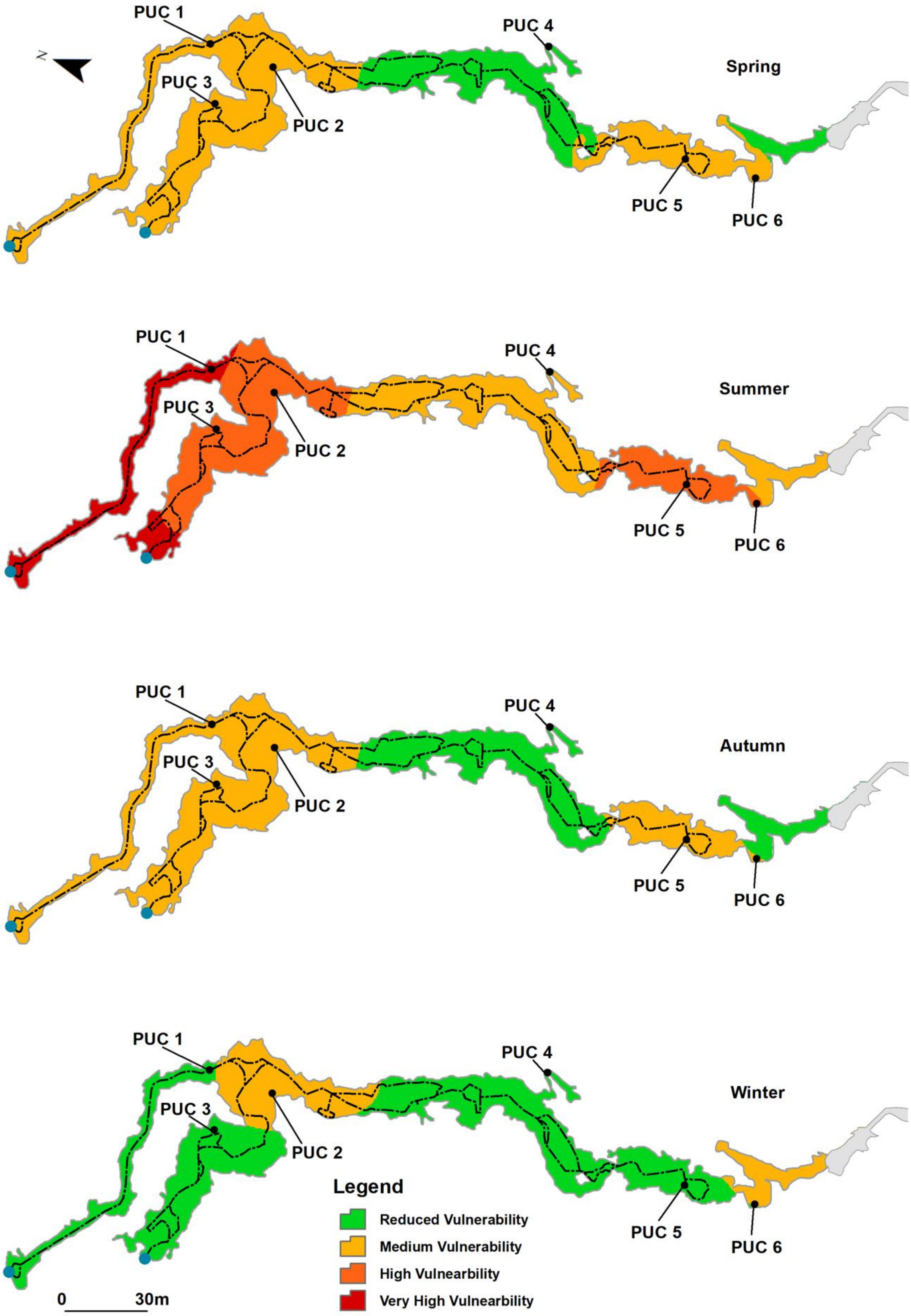

Figure 6. Maps of the seasonal vulnerability of the Urșilor Cave.

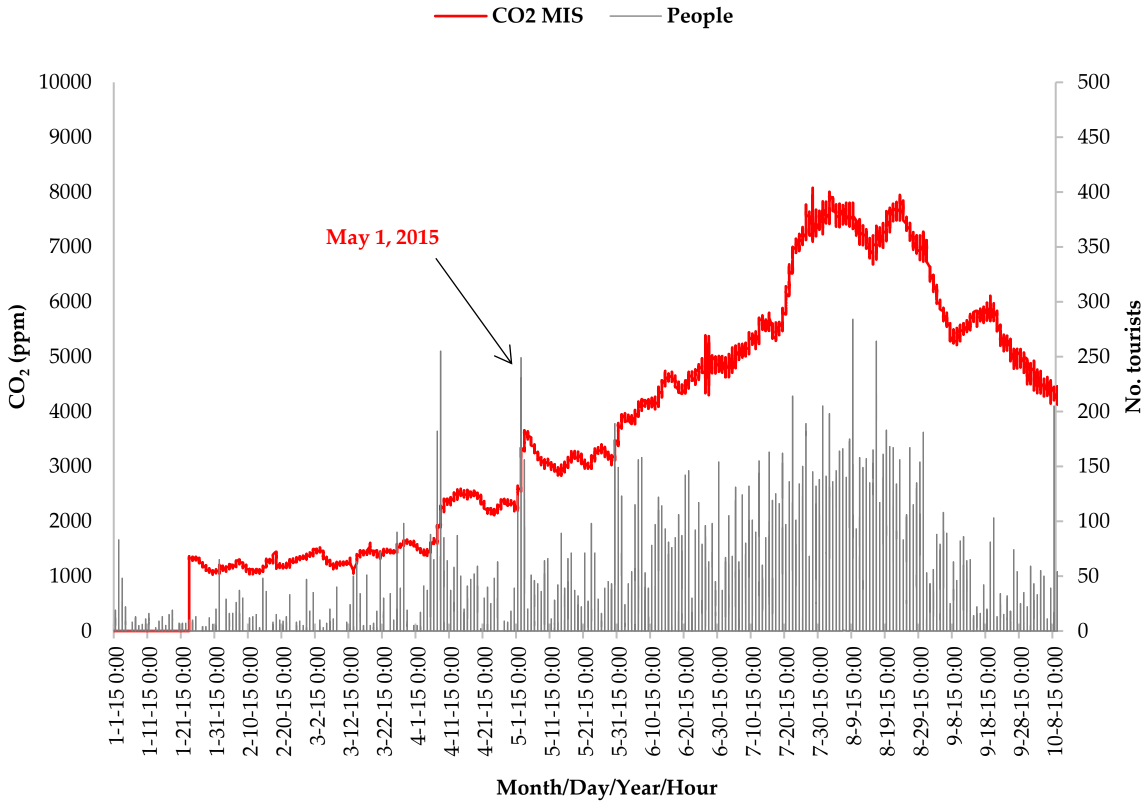

Figure 7. CO_2 concentration (ppm; blue) measured in the PUC2 station compared to tourist traffic (black). There is an immediate increase in CO_2 values in the periods corresponding to the national holidays.

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 [31-32]. Measured Radon concentrations are not a danger to tourists.

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 [31, 33]. We recommend ventilating it especially during periods with many tourists, heating it during the summer and antifungal hygiene as often as possible. We recommend the installation as soon as possible of systems for disinfecting the feet of tourists at the entrance to the cave.

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

4.4. Meziad Cave.

Meziad Cave an important and spectacular tourist attraction that could attract a much higher number of tourists than it currently does. Table 11 and Figure 8 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 in the cave and the corresponding increase in the number of pathogenic microorganisms.

Table 11. The calculations of classes for the different stations in Meziad Cave: W = winter (December-January-February); Sp = spring (March-April-May); S = summer (June-July-August).

STATION SEASON	PARAMETER								SCORE	**CLASS**
	T	RH	CO_2	SI	DR	Bats	Microorg.	Tourists		
Mez1Sp	0	0	0			0	10	20	5	**1**
Mez1S	20	20	0			0	20	40	17	**4**
Mez1A	20	0	0			0	0	20	7	**2**
Mez1W	0	0	0			0	20	0	3	**1**
Mez2Sp	0	0	0	0	0	20	10	20	6	**2**
Mez2S	0		0	0	10	10	10	40	10	**2**
Mez2A			0	0	20	0	0	20	7	**2**
Mez2W	0	0	0	0	0	20	0	0	3	**1**
Mez3Sp	0	0	0			10	0	20	5	**1**
Mez3S	20	20	0			10	10	40	17	**4**
Mez3A	20		0			0	0	20	8	**2**
Mez3W	0	0	0			10	0	0	2	**1**
Mez4Sp	40	0	0	0	10	0	10	0	8	**2**
Mez4S	0	0	0	0	0	0	10	0	1	**1**
Mez4A			0	0	20	0	10	0	5	**1**
Mez4W	0	0	0	0	0	0	0	0	0	**1**
Mez5Sp	40	40	0			10	10	20	20	**4**
Mez5S	0	0	0			10	20	40	12	**3**
Mez5A	40		0			0	10	20	14	**3**
Mez5W	40	20	0			0	0	0	10	**2**

No vulnerabilities were identified related to changes in the microclimate (temperature, RH, CO_2) 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.

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 H_2O_2 buffered solution [10].

From the previously published data [31, 33] measures were proposed for 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.

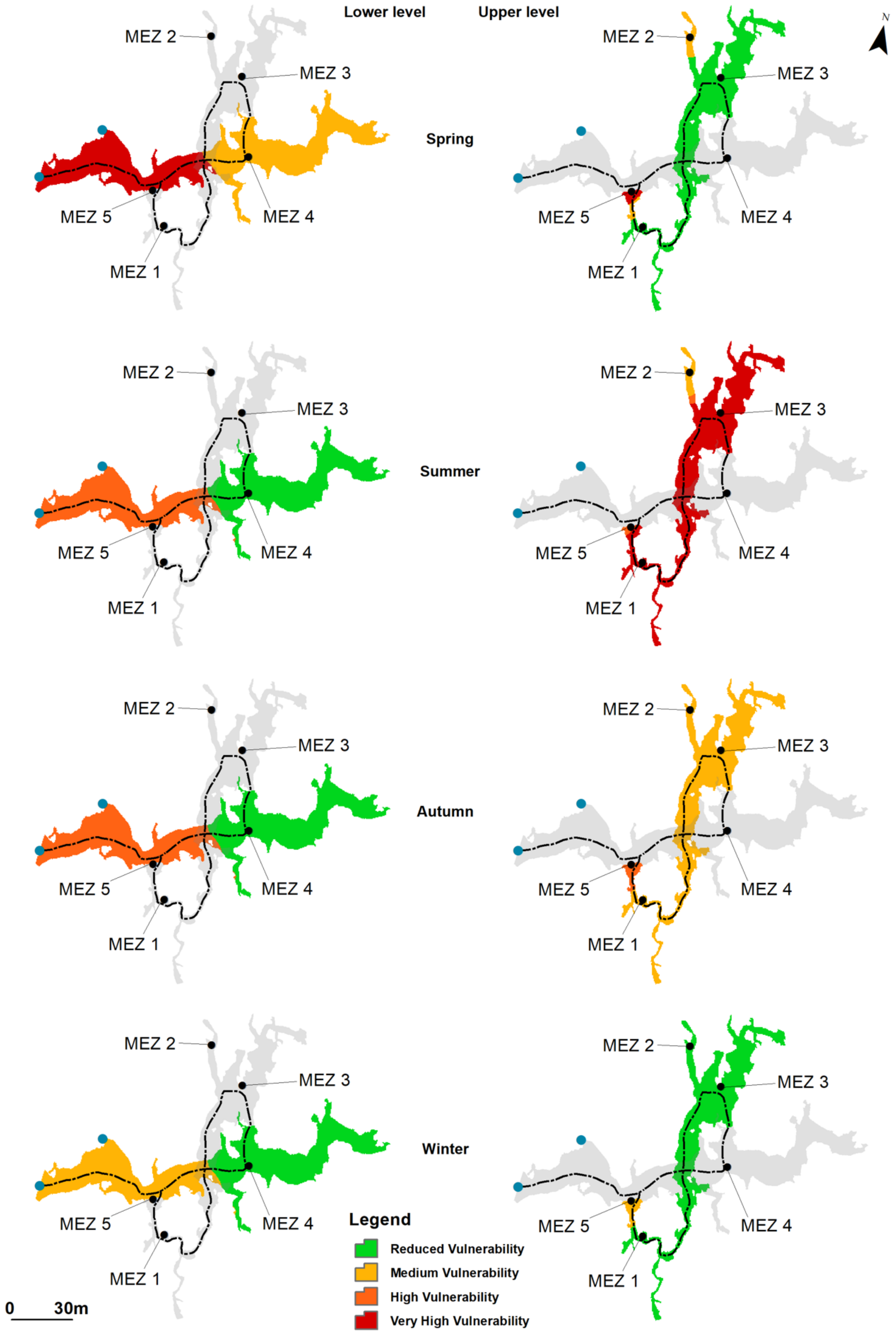

Figure 8. Meziad Cave vulnerability maps by season.

In general, the dripping is very low in the Meziad Cave, which is a 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 is of "buffer" type, with long-term storage and episodic discharge.

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 which was not influenced by the touristic traffic, all caves having normal values. In the non-ventilated caves, temperature and CO_2 concentration were the parameters most influenced by the human traffic and have shown large variations in the touristic high seasons. The CO_2 concentration remained low in Muierilor, Polovragi, and Meziad and did not endangered the health of visitors or tourists, while the values were high in Urșilor.

Several management measures for a sustainable use are common to all the four caves. Firstly, the lighting system caused problems by the development of lampenflora. Changing to LED lighting has no effect as long as the existing lampenflora is not totally removed. Controlling the lighting remains a long-term mitigation measure that has to be undertaken permanently through a combination of lampenflora early removal and adjusting of illuminance levels (both light intensity and lighting time).

In caves with no natural entrance(s), such as Urșilor a continuous monitoring of CO_2 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-CO_2 levels (those of low-season) are restored.

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.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Figure S1: title, Table S1: title, Video S1: title.

Author Contributions: Conceptualization, S.C. and O.T.M.; methodology, S.C.; validation, S.C. and O.T.M.; formal analysis, S.C., O.T.M., D.S.M.; investigation, S.C., O.T.M., I.C.M., A.P., R.A.A., D.S.M., M.K., M.R.; data curation, S.C.; writing—original draft preparation, S.C. and O.T.M.; funding acquisition, S.C. and O.T.M. All authors have read and agreed to the published version of the manuscript

Funding: This work was supported by an EEA Financial Mechanism 2009-2014 under the project contract no. 17SEE/2014, a grant of Ministry of Research and Innovation, CNCS - UEFISCDI, project number PN-III-P4-ID-PCCF-2016-0016 (DARKFOOD), within PNCDI III, and from the EEA Grants 2014-2021, under Project contract no. 3/2019 (KARSTHIVES).

Acknowledgments: We thank the administrators and guides of the show caves for granting the access and help during the sampling.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Dredge, J.; Fairchild, I.J.; Harrison, R.M.; Fernandez-Cortés, A.; Sanchez-Moral, S.; Jurado, V.; Gunn, J.; et al. Cave aero-sols: distribution and contribution to speleothem geochemistry. *Quat. Sci Rev.* **2013**, *63*, 23–41.
2. Fairchild, I.J.; Smith, C.L.; Baker, A.; Fuller L.; Spötl, C.; Mattey, D.; McDermott, F.; E.I.M.F. Modification and preservation of environmental signals in speleothems. *Earth-Sci. Rev.* **2006**, *75*, 105–153.
3. UNESCO World Heritage List https://whc.unesco.org/en/list/. Last accessed 30 December 2020.
4. Saiz-Jimenez, C..; Cuezva, S.;, Jurado, V.; Fernandez-Cortes, A.; Porca, E.; Benavente, D.; Cañevaras, J.C.; Sanchez-Moral, S. Paleolithic Art in Peril: Policy and Science Collide at Altamira Cave. *Science* **2011**, *334*, 42-43.
5. Clottes, J.; Gély, B.; Ghemis, C.; Kaltnecker, E.; Lascu, V.-T.; Moreau, C.,;Philippe, M.; Prud'homme, F.; Valladas, H. Un art très ancien en Roumanie. Les dates de Coliboaia. *International Newsletter on Rock Art*, **2011**, *61*, 1-3.
6. Bourges, F.; Genthon, P.; Mangini, A.; D'Hulst, D. Microclimates of L'Aven d'Orgnac and other French limestone caves (Chauvet, Esparros, Marsoulas). *Int. J. Climatol*. **2006**, *26*, 1651-1670.
7. Fernandez-Cortes, A.; Calaforra, J.M.; Jiménez-Espinosa, R.; Sánchez-Martosa, F. Geostatistical spatiotemporal analysis of air temperature as an aid to delineating thermal stability zones in a potential show cave: Implications for environmental management. *J. Env. Managem.* **2006**, *81*, 371-383.
8. Fong, D. W. Management of subterranean fauna in karst. In: P.E. van Beynen (Ed.), *Karst management* Dordrecht: Springer **2011**, 201-224.
9. Lee, N.M.; Meisinger, D.B.; Aubrecht, R.; Kovacik, L.; Saiz-Jimenez, C.; Baskar, S.; Baskar, R.; Liebl, W.; Porter, M.L.; Engel, A.S. Caves and karst environments. In: *Life at Extremes: Environments, Organisms and Strategies for Survival* (Ed. E.M. Bell), CAB International, **2012**, 320-344.
10. Mulec, J. Human impact on underground cultural and natural heritage sites, biological parameters of monitoring and remediation actions for insensitive surfaces; case of Slovenian show caves. *Journal for Nature Conserv.* **2014**, *22*, 132-141.
11. Heaton, T.H.E. Isotopic studies of nitrogen pollution in the hydrosphere and atmosphere: A review, *Chemical Geology: Isotope Geoscience section*, **1986**, *59*, 87-102
12. Cigna, A.A. The problem of lampenflora in show caves. *6th ISCA Congress Proceedings*, Slovakia (P. Bella and P. Gazik, Eds.), **2011**, 201-205.
13. Moldovan O.; Racoviţă G.; Rajka G. The impact of tourism in Romanian show caves: the example of the beetle populations in the Urşilor Cave of Chişcău (Transylvania, Romania). *Subt. Biol.* **2003**, *1*, 73-78.
14. WHO (World Health Organization), 2009. *WHO handbook on indoor radon. A public health perspective* (http://www.who.int/ionizing_radiation/env/radon/en/index1.html).
15. UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation). Annex E: Sources-to-effects Assessment for Radon in Homes and Workplaces. United Nations, New York, **2006**.
16. ICRP (International Commission on Radiological Protection). Lung Cancer Risk From Radon and Progeny and Statement on Radon. *ICRP Publication 115* Ann. ICRP, **2010**, 40.
17. Lario, J.; Sanchez-Moral, S.; Canaveras, J.C.; Cuezva, S.; Soler, V. Radon continuous monitoring in Altamira Cave (northern Spain) to to assess user's annual effective dose. *J. Environ. Radioactiv.* **2005**, *80*, 161-174.
18. Vaupotic, J. Nanosize radon short-lived decay products in the air of the Postojna Cave. *Sci. Total Env.* **2008**, *393*, 27-38.
19. Kávási, N.; Somlai, J.; Szeiler, G.; Szabó, B.; Schafer, I.; Kovács, T. Estimation of effective doses to cavers based on radon measurements carried out in seven caves of the Bakony Mountains in Hungary. *Radiat. Meas.* **2010**, *45*, 1068-1071.
20. Tsvetkova, T.; Przylibski, T.A.; Nevinskaya, I.; Nevinskaya, V. Measurement of radon in the East Europe under the ground. *Radiat.Meas.* **2005**, *40*, 98-105.
21. Sainz, C.; Quindós, L.S.; Fuent, I.; Nicolás, J.; L., Q. Analysis of the main factors affecting the evaluation of the radon dose in workplaces: The case of tourist caves. *J. Hazar. Math.* **2007**, *145*, 368-371.
22. Bourges, F.; Genty, D.; Genthon, P.; Mangini, A.; D'Hulst, D. South-France caves monitoring: present day cave air dynamics characterization, paleoclimatic and archaeological interests. *Geophysical Research Abstracts* **2012**, *14*, EGU2012-5830.

23. Sanchez-Moral, S.; Portillo, M.C.; Jancies, I.,;Cuezva, S.; Fernandez-Cortes, A.; Canaveras, J.C.; Gonzales, J.M. The role of microorganisms in the formation of calcitic moonmilk deposits and speleothems in Altamira Cave. *Geomorphol.* **2012**, *139-140*, 285-292.
24. Racovita, G.; Boghean, V.; Petrescu, M. Le bilan topoclimatique de la grotte du Closani (Monts Mehedinti, Roumanie). *Theor. Appl. Karstol.* **1993**, *6*, 7-86.
25. Racovita, G.; Moldovan, O.; Rajka, G. Données préliminaires sur l'environement de la Grotte des Ours en régime d'exploitation touristique. *Theor. Apppl. Karstol.* **1999**, *11-12*, 61-74.
26. Borda, C.; Borda, D. Airborne microorganisms in show caves from Romania. *Trav. Inst. Spéol. "Emile Racovitza"* **2005**, *43-44*, 65-73.
27. Fejer, A.; Moldovan, O.T. Population size and dispersal patterns for a Drimeotus (Coleoptera, Leiodidae, Leptodirini) cave population. *Subt. Biol.* **2013**, *11*, 31–44.
28. Soficaru, A.; Dobos, A.; Trinkaus, E. Early modern humans from the Peştera Muierii, Baia de Fier, Romania. *Proc. Nat. Acad. Sci. USA* **2006**, *103*, 17196–17201.
29. Mirea, I.-C.; Robu, M.; Petculescu, A.; Kenesz, M.; Faur, L.; Arghir, R.; Tecsa, V.; Timar-Gabor, A.; Roban, R.-D.; Panaiotu, C.-G.; Sharifi, A.; Pourmand, A.; Codrea, V. A.; Constantin S. Last deglaciation flooding events in the South Carpathians as revealed by the study of cave deposits from Muierilor Cave, Romania. *Palaeogeogr. Palaeoclim. Palaeoecol.* **2020**, *562*, 110084.
30. Moldovan, O.T.; Iepure, S.; Brad, T.; Kenesz, M.; Mirea, I.C.; Năstase-Bucur, R. Database of Romanian cave invertebrates with a Red List of cave species and a list of hotspot/coldspot caves. *Biodiv. Data J.* **2020**, *8*, e53571.
31. Bercea, S.; Nastase-Bucur, R.; Mirea, I.C.; Mantoiu, D.S.; Kenesz, M.; Petculescu, A.; Baricz, A.; Andrei, A-S.; Banciu, H.L.; Papp, B.; Constantin, S.; Moldovan, O.T. Novel approach to microbiological air monitoring in show caves. *Aerobiol.* **2018**, *34*, 445-468.
32. Bercea, S.; Năstase-Bucur, R.; Moldovan, O.T.; Kenesz, M.; Constantin, S. Yearly microbial cycle of human exposed surfaces in show caves. *Subt. Biol.* **2019**, *31*, 1-14.
33. Moldovan, O-T.; Bercea, S.; Nastase-Bucur, R.; Constantin, S.; Kenesz, M.; Mirea, I.C.; Petculescu, A.; Robu, M.; Arghir, R.A. Management of water bodies in show caves - A microbial approach. *Tourism Managem.* **2020**, *78*, 104037.
34. Burghele, B. D.; Cucoș, A.; Papp, B.; Dicu, T.; Pressyanov, D.; Dimitrov, D.; Dimitrova, I.; Constantin, S. Comparative study of radon and thoron measurements in four Romanian show caves. *Radiat. Prot. Dosim.* **2017**, *177*, 181-185.
35. Burghele, B.D.; Cucos, A.; Papp, B.; Stetca, F.A.; Mirea, I.; Constantin, S. Distribution of Radon gas in Romanian show caves and radiation safety. *Radiat. Prot. Dosim.* **2018**, *181*, 1-5.
36. Sibson, R. A brief description of natural neighbor interpolation, interpolating multivariate data. In V. Barnett (Ed.), Multivariate data New York: Wiley **1981**, 21-36.
37. Ponta, G.; Aldica, G. Peşteri din Cheile Olteţului – Polovragi. Buletinul Speologic **1985**, *10*, 245–268.
38. Constantin, S.; Robu, M.; Munteanu, C.M.; Petculescu, A.; Vlaicu, M.; Mirea, I.; Kenesz, M.; Drăguşin, V.; Hoffmann, D.; Anechitei, V.; Timar-Gabor, A.; Roban, R.D.; Panaiotu, C.G. Reconstructing the evolution of cave systems as a key to understanding the taphonomy of fossil accumulations: The case of Urşilor Cave (Western Carpathians, Romania). *Quat. Internat.* **2014**, *339–340*, 25–40.
39. Rusu, T.; Racoviță, T.; Crăciun V. La grotte du Meziad. Aspects physico-géographiques, genèse et evolution de la cavité. *Trav. Instit. Spéol. E. Racovitza* **1974**, *13*, 147-173.

SUPPLEMENTAL

Monitoring human impact in show caves. A study of four Romanian caves

Silviu Constantin [1,2,3*], Oana Teodora Moldovan [2,3,4*], Ionuț Cornel Mirea [1,2], Alexandru Petculescu [1,2], Răzvan Adrian Arghir [1,2], Dragoș Ștefan Măntoiu [4], Marius Kenesz [2,4] and Marius Robu [1]

[1] Emil Racovita Institute of Speleology, Department of Geospeleology and Paleontology, Frumoasă 31, București, Romania; silviu.constantin@iser.ro
[2] Romanian Institute of Science and Technology, Saturn 24-26, Cluj-Napoca, Romania
[3] Centro Nacional de Investigacion sobre la Evolucion Humana, CENIEH, Paseo de Atapuerca s/n, Burgos, Spain
[4] Emil Racovita Institute of Speleology, Department of Cluj, Clinicilor 5, Cluj-Napoca, Romania, oanamol35@gmail.com

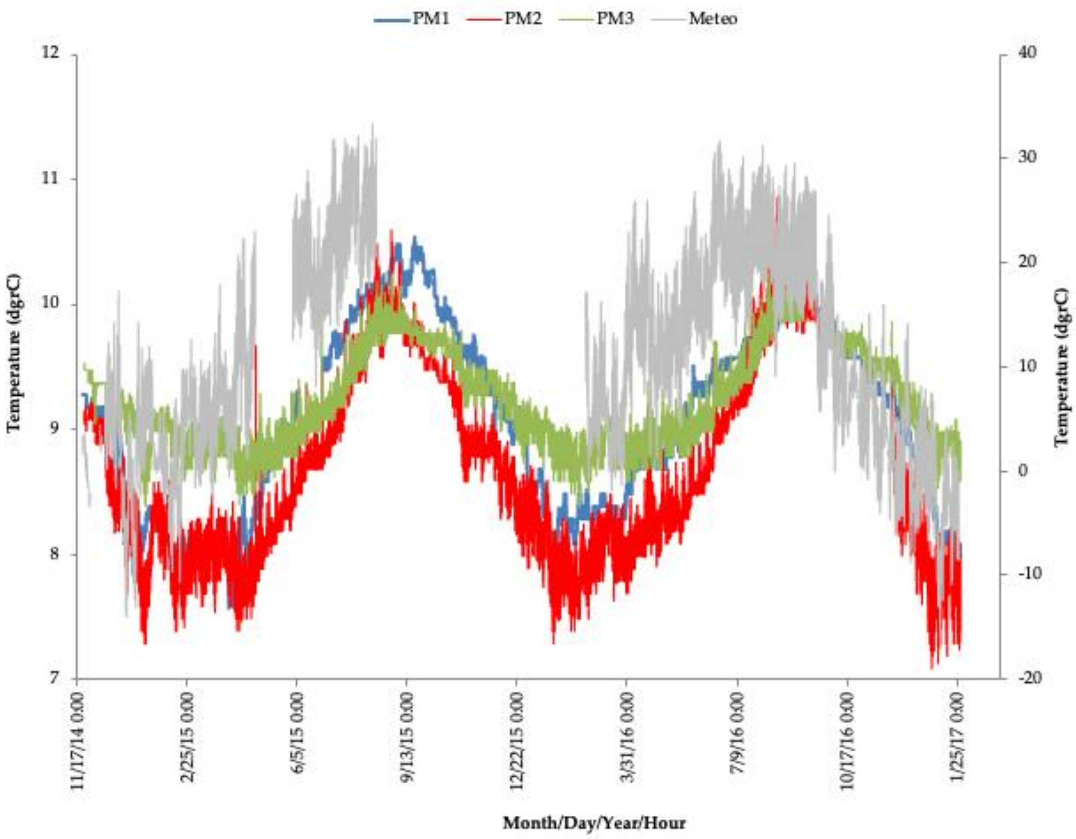

Figure S1. Temperature variation in the fixed monitoring stations PM1, PM2 and PM3, in comparison with the values recorded on the surface. The highest temperature variations are recorded in the PM2 station. Smaller variations are recorded in PM1, located in a side passage that is less frequently visited, as well as in PM3, located at the greatest distance from any of the two entrances.

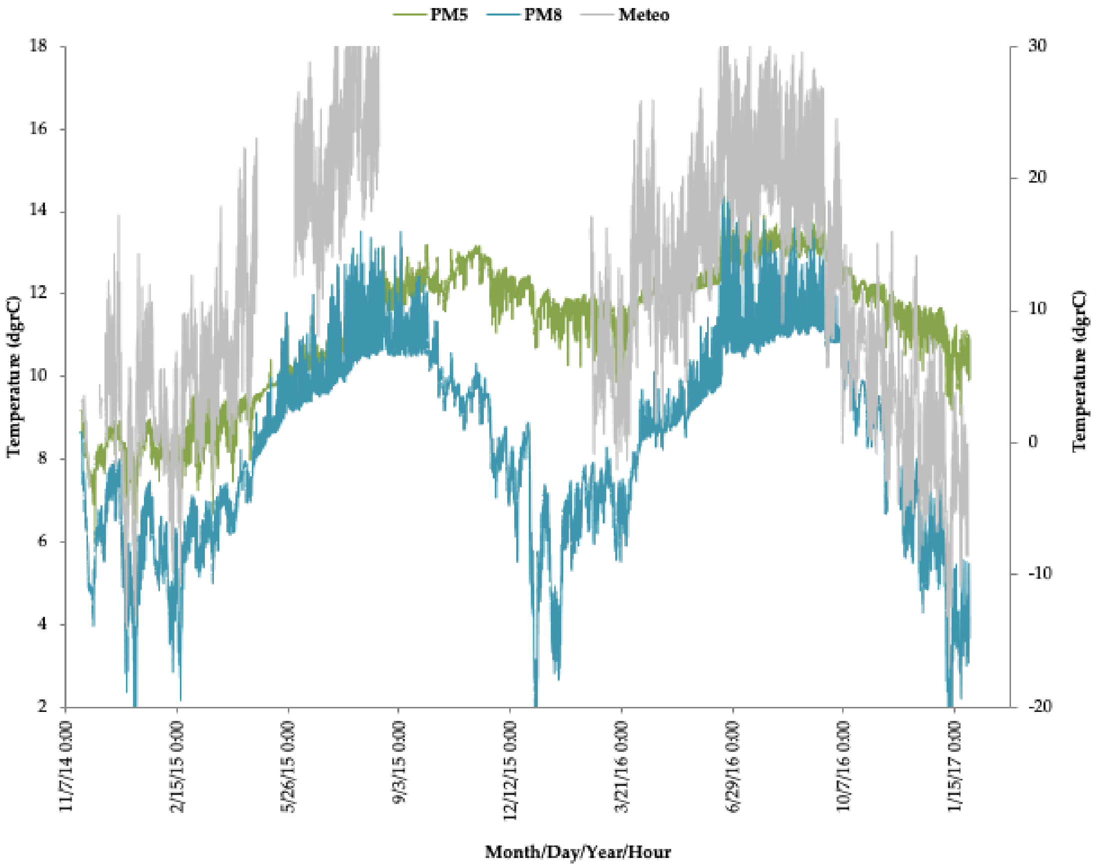

Figure S2. Temperature variation in the fixed monitoring stations, PM5 and PM8 and the temperature recorded by the surface weather station. In the PM8 station the air temperature is much influenced by the variations of the surface temperature varying by about 10 °C between the lows recorded in January-February and the highs recorded in August-September.

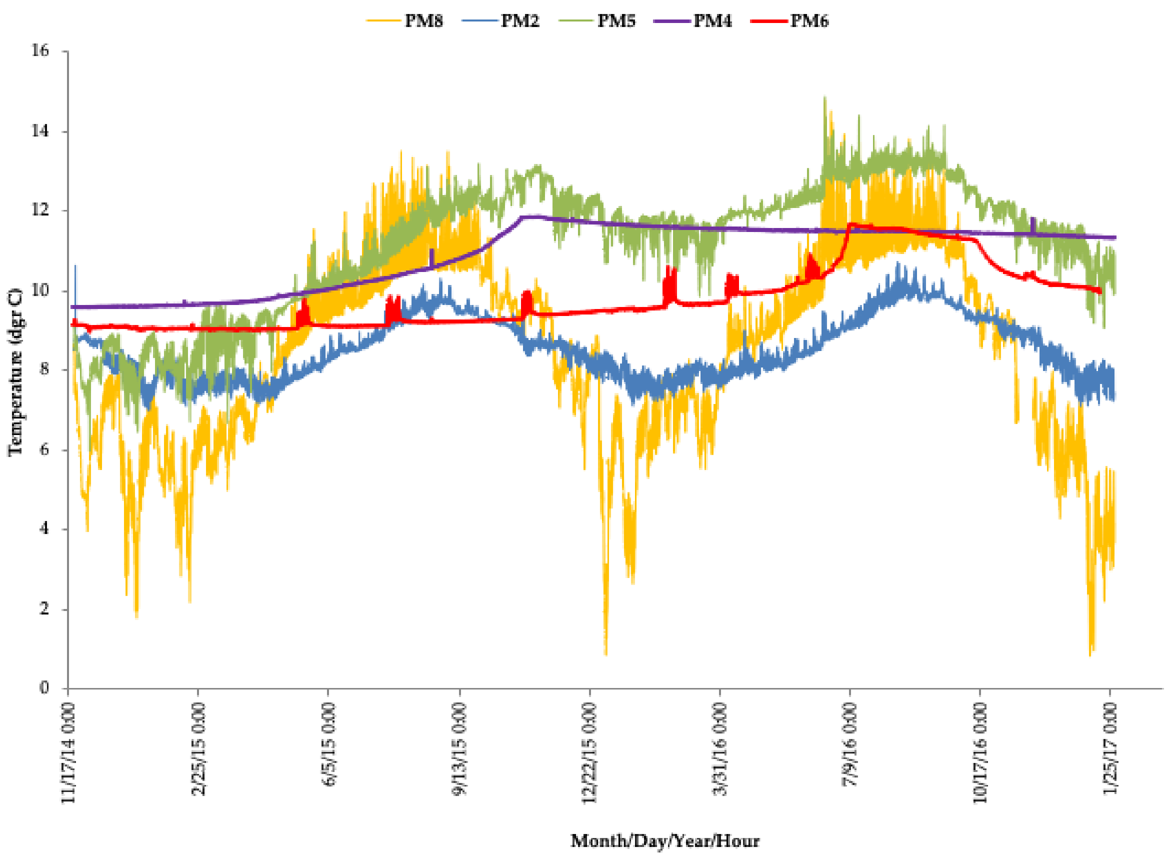

Figure S3. Temperature variation in stations PM2, PM4, PM5, PM6 (excavation place) and PM8 (exit gallery). The temperature increases recorded in point PM6 coincide with the 6 excavation campaigns carried out by ERIS researchers.

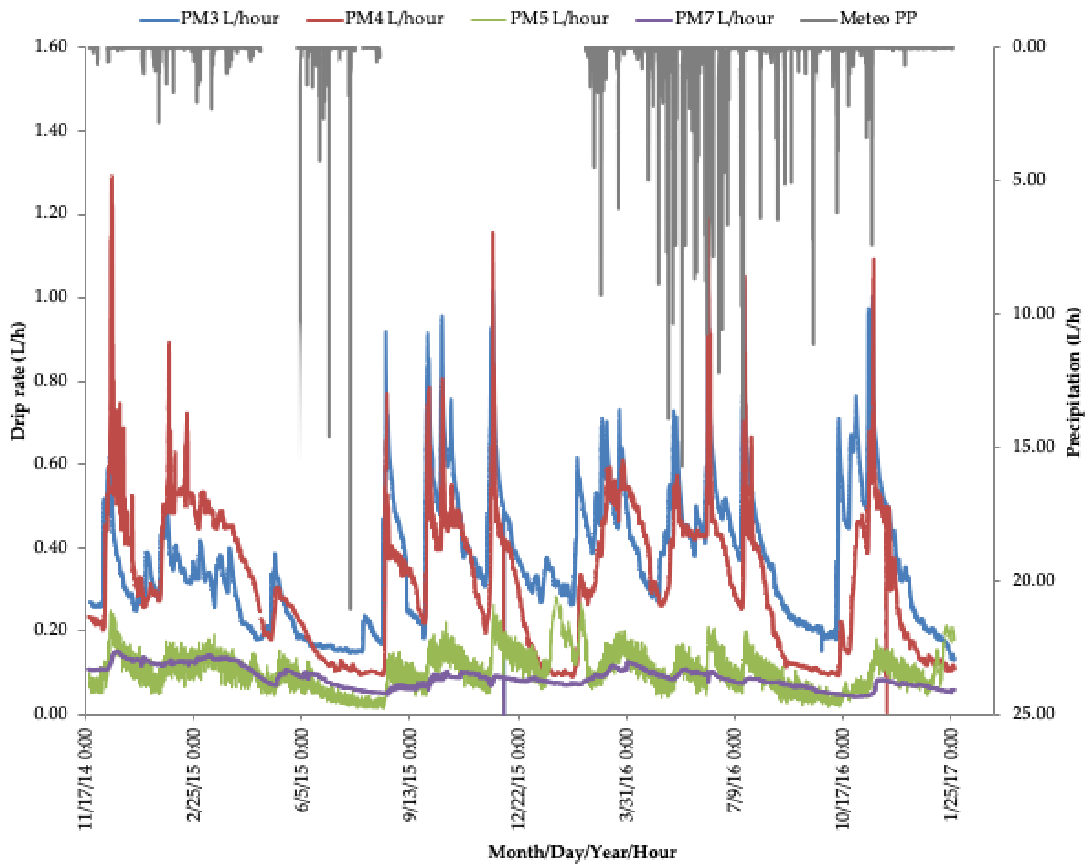

Figure S4. Variation of the drip rate in PM3, PM4, PM5 and PM7 stations compared to the precipitation values at Baia de Fier station.

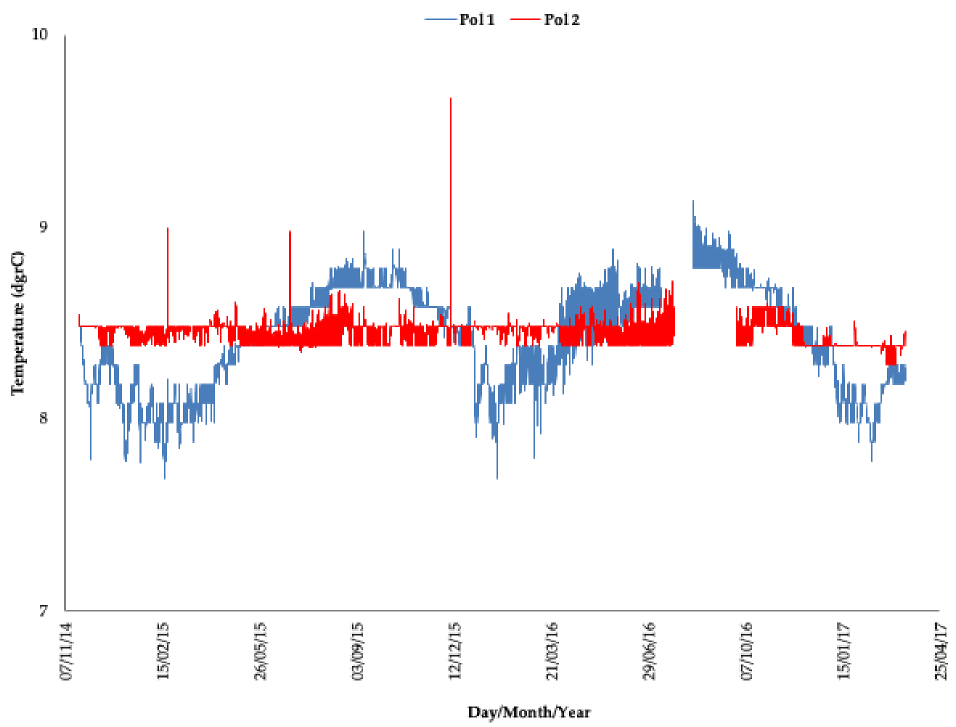

Figure S5. Temperature (°C) variation in the two monitoring stations in Polovragi Cave. The isolated temperature increases in the Pol2 station are due to the influence of the researchers during the monitoring visits.

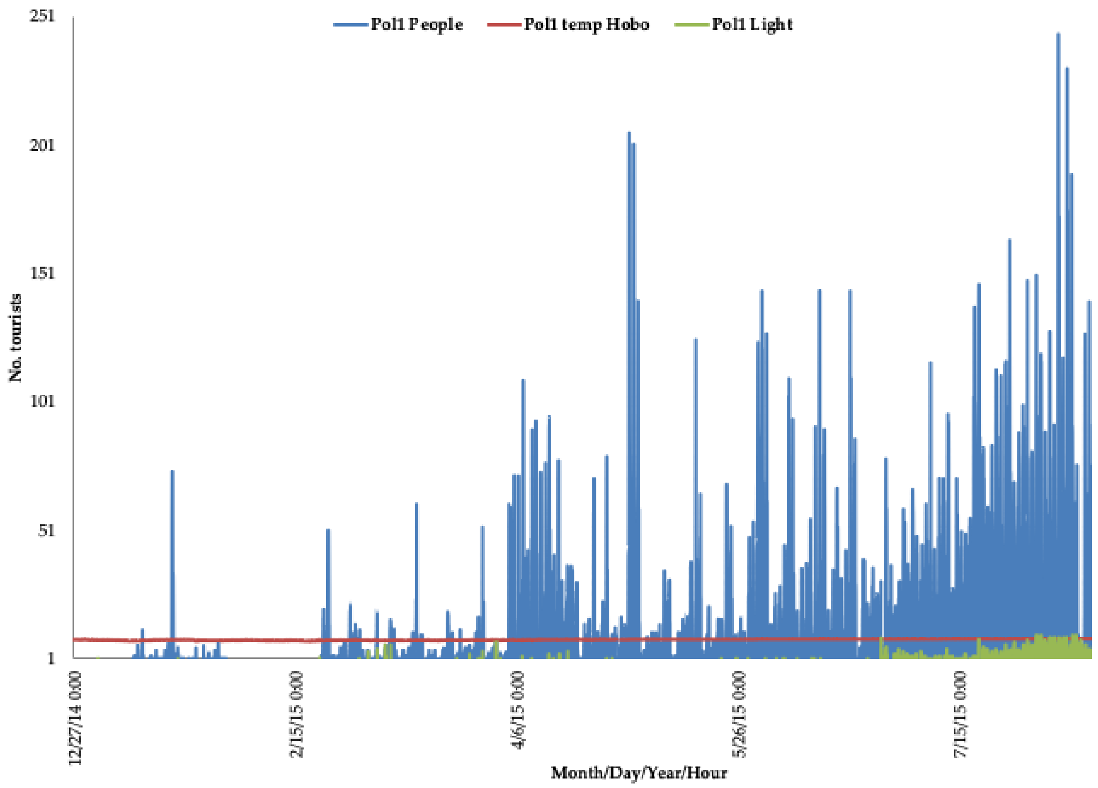

Figure S6. The variation of tourist traffic in Pol1 station (compared with that of luminosity and air temperature values between December 2014-August 2015.

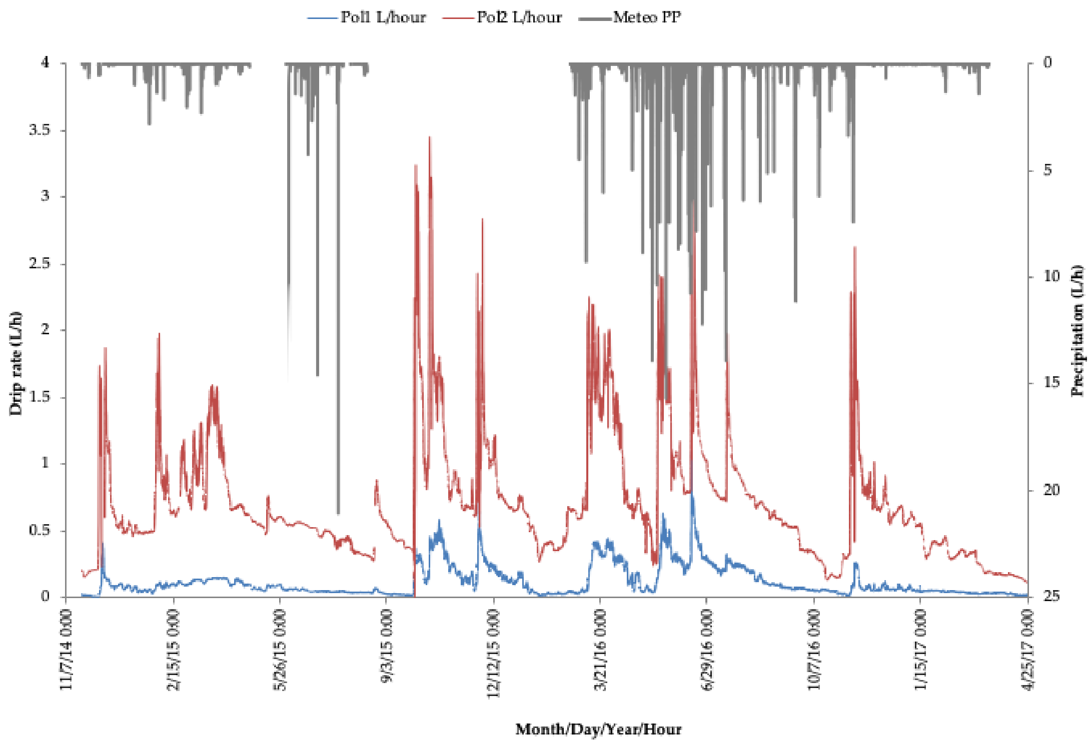

Figure S7. Variation of the drip rate in Pol 1 and Pol 2 stations compared to the precipitation values at Baia de Fier climatic station. All values in L/m2 (hourly amounts).

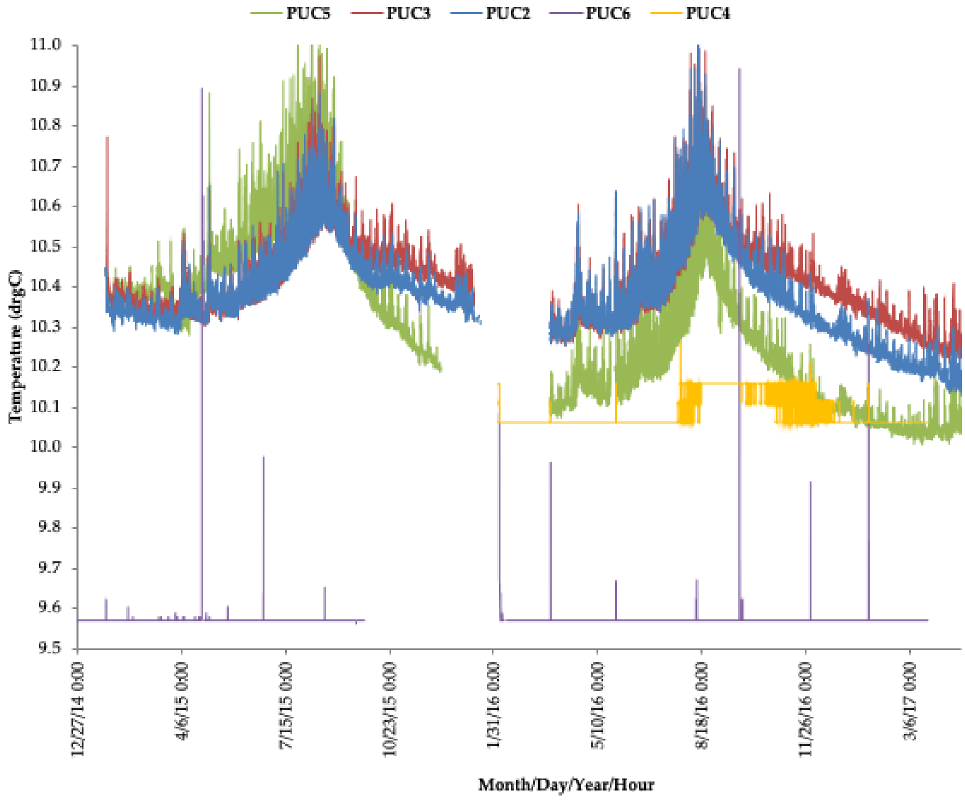

Figure S8. Temperature variation (°C) in the fixed monitoring stations PUC2, PUC3, PUC4, PUC5 and PUC6. The isolated peaks in PUC6 and PUC4 stations in some days are due to the presence of the operator during the monitoring visits.

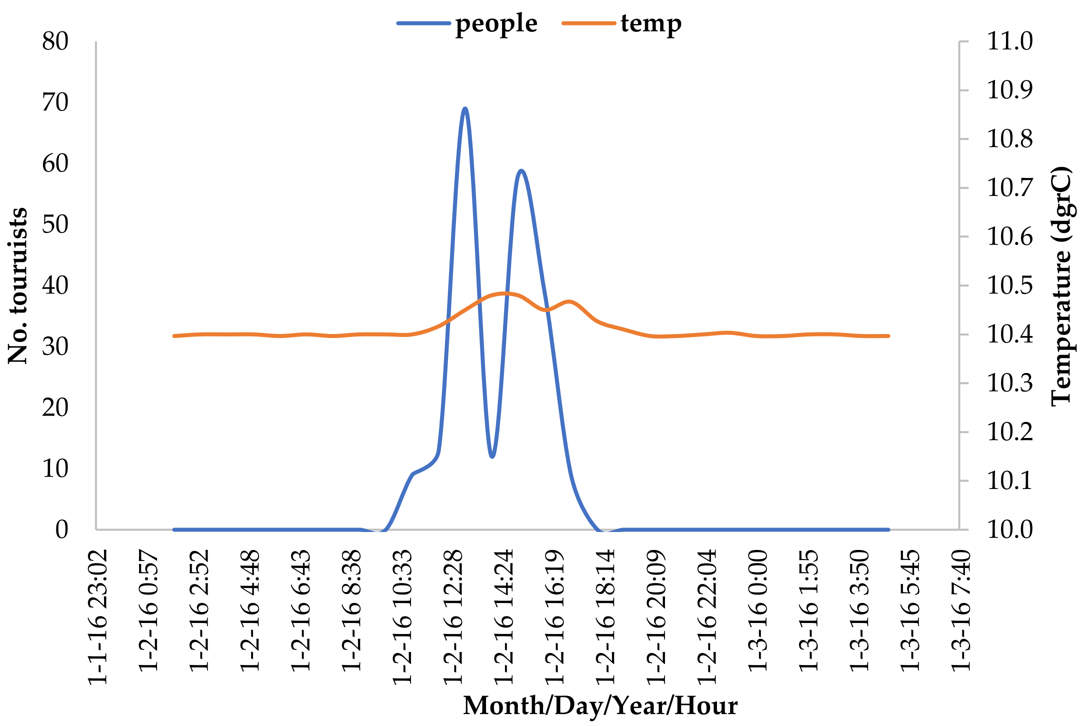

Figure S9. The variations of the air temperature in the PUC3 station in the presence of two groups (50-60 people/hour) on January 21st 2016.

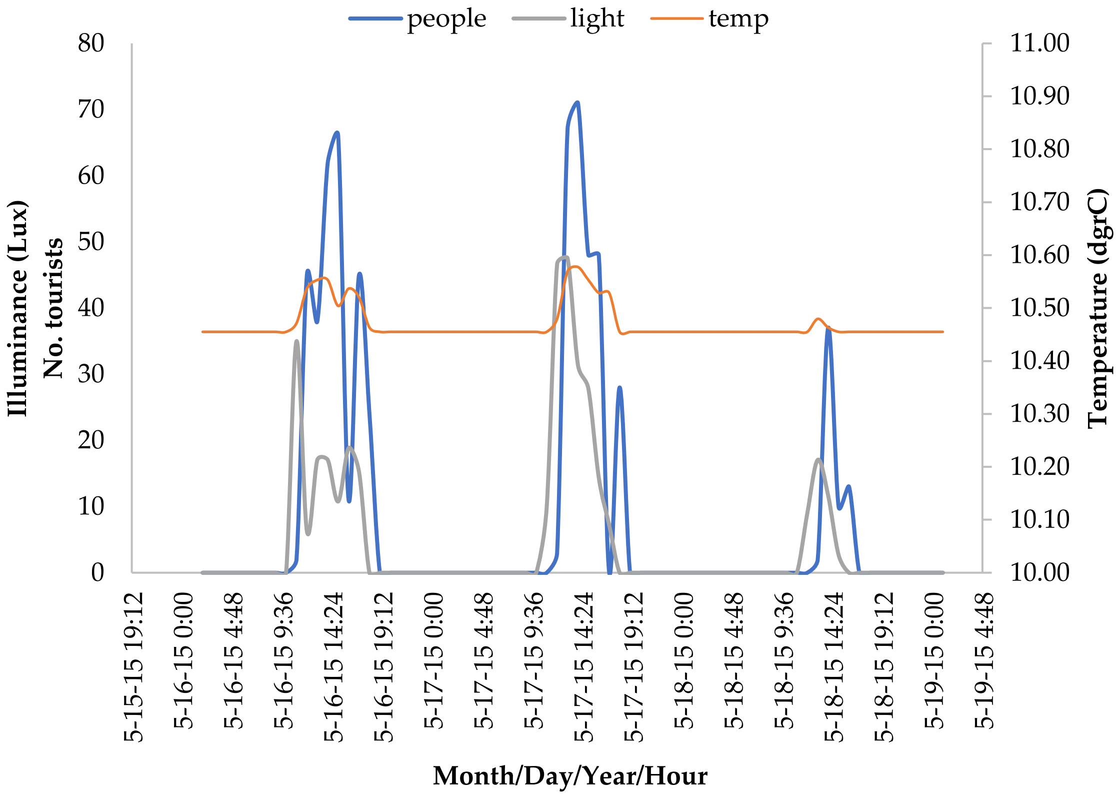

Figure S10. Temperature variation related to the registered traffic, respectively light intensity, in PUC2 station, in the interval 16-18 May 2015.

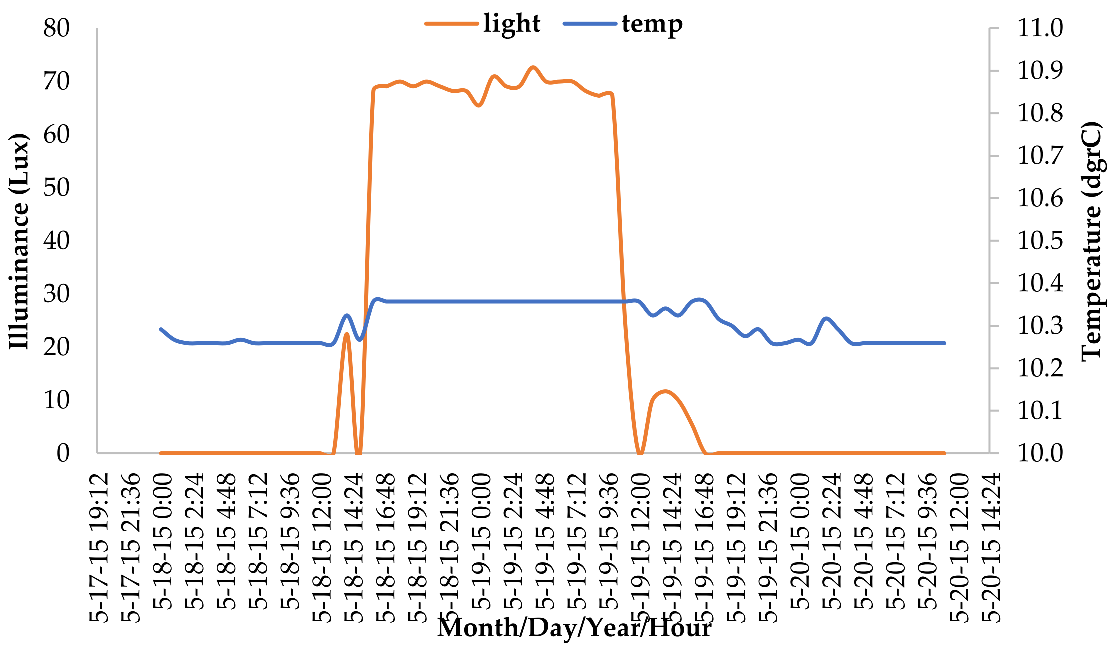

Figure S11. Temperature variation in the PUC2 station correlated with the light in the absence of tourists. The light was allowed to operate on the night of May 18th to 19th 2015.

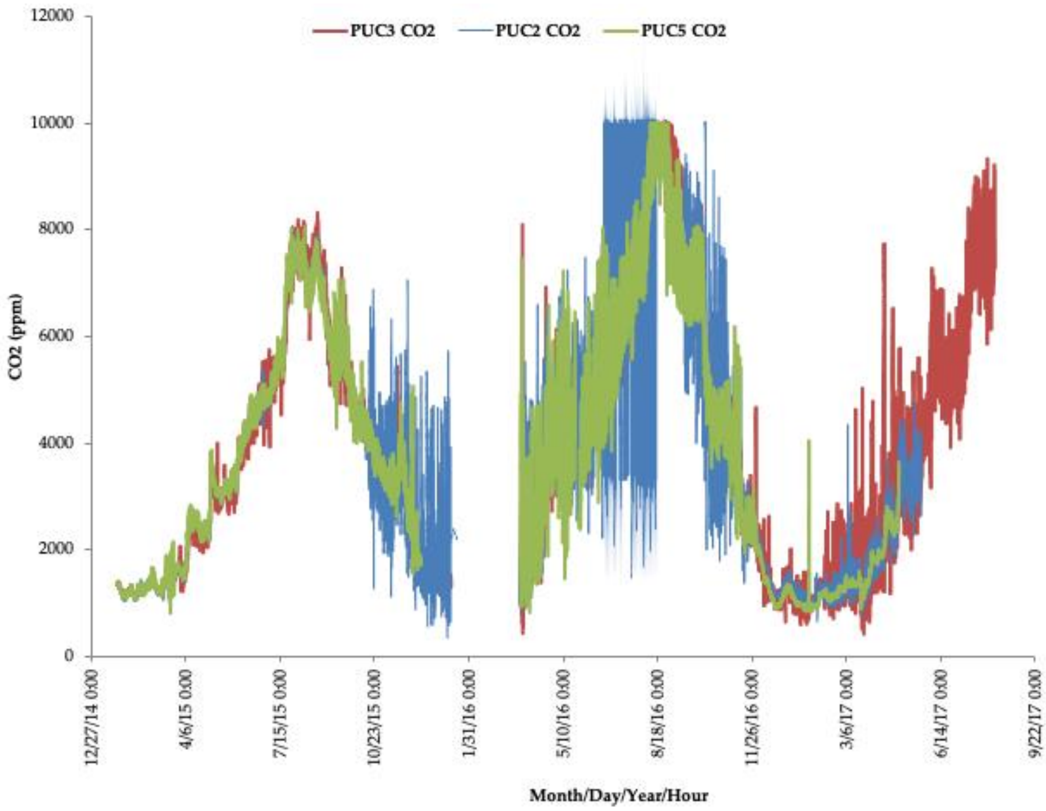

Figure S12. CO_2 concentrations measured at PUC2, PUC3 and PUC5 stations in the Ursilor Cave. Values exceeding 10,000 ppm could not be measured accurately as they exceed the limits of the sensor.

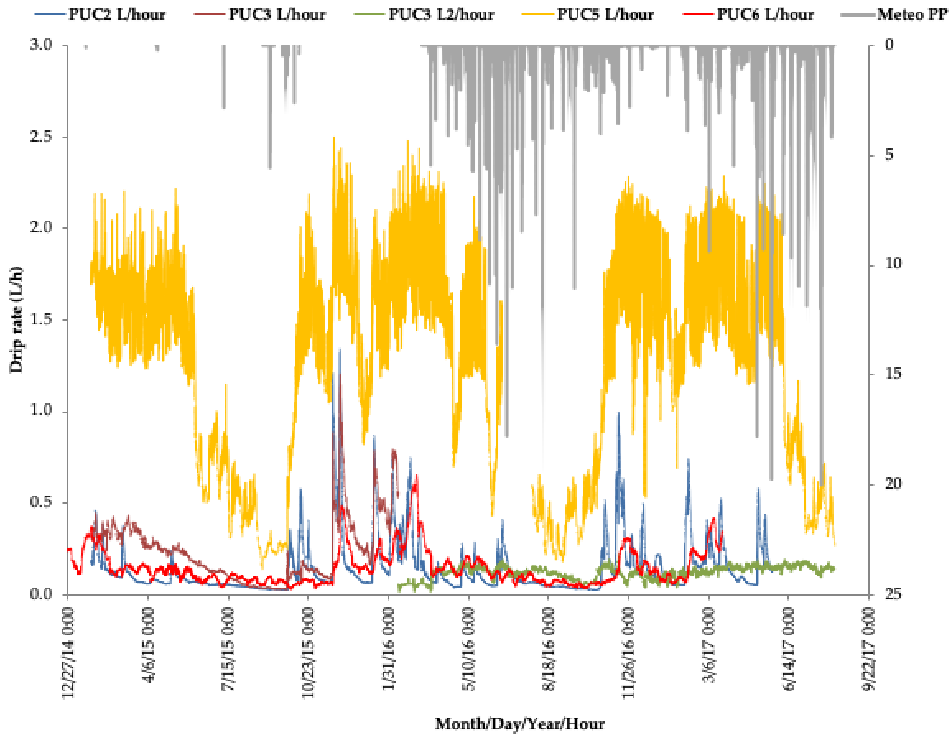

Figure S13. The variation of the drip rate in the stations PUC2, PUC3, PUC5 and PUC6 compared to the precipitation values at the Urşilor Cave weather station.

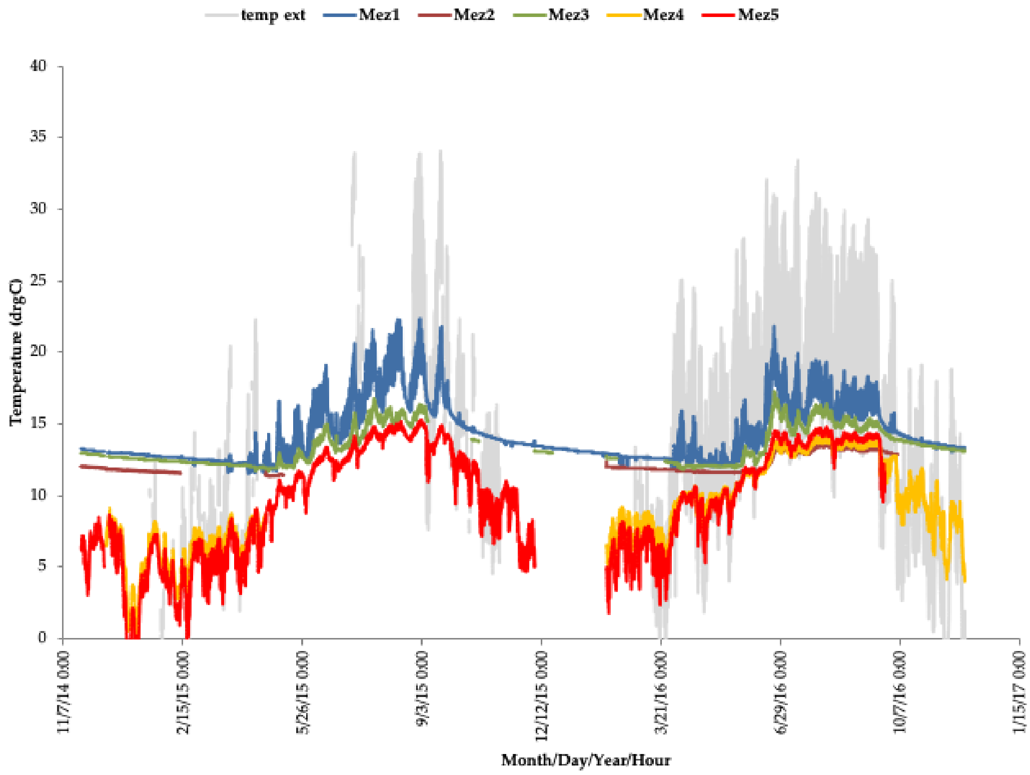

Figure S14. The temperature (°C) variation in the five monitoring stations from the Meziad Cave compared to the variation of the outdoor temperature registered at the Ursilor Cave weather station.

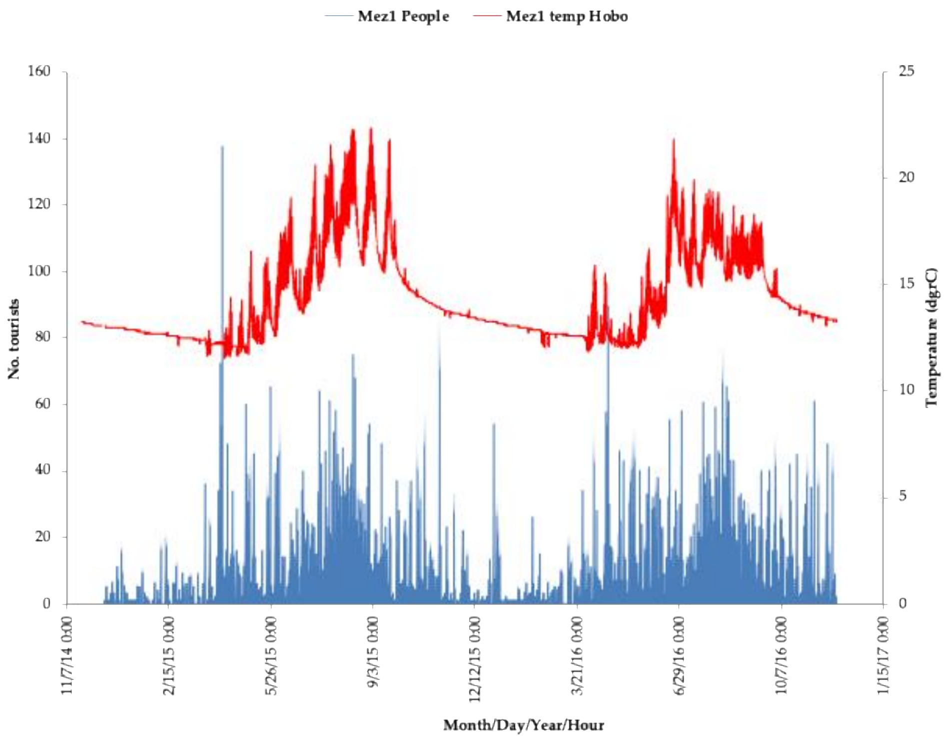

Figure S15. The variation of the traffic in Mez1 station in parallel with that of the air temperature between December 2014-December 2017. No correlation can be observed between the two variables, the temperature values reflecting the seasonal variations.

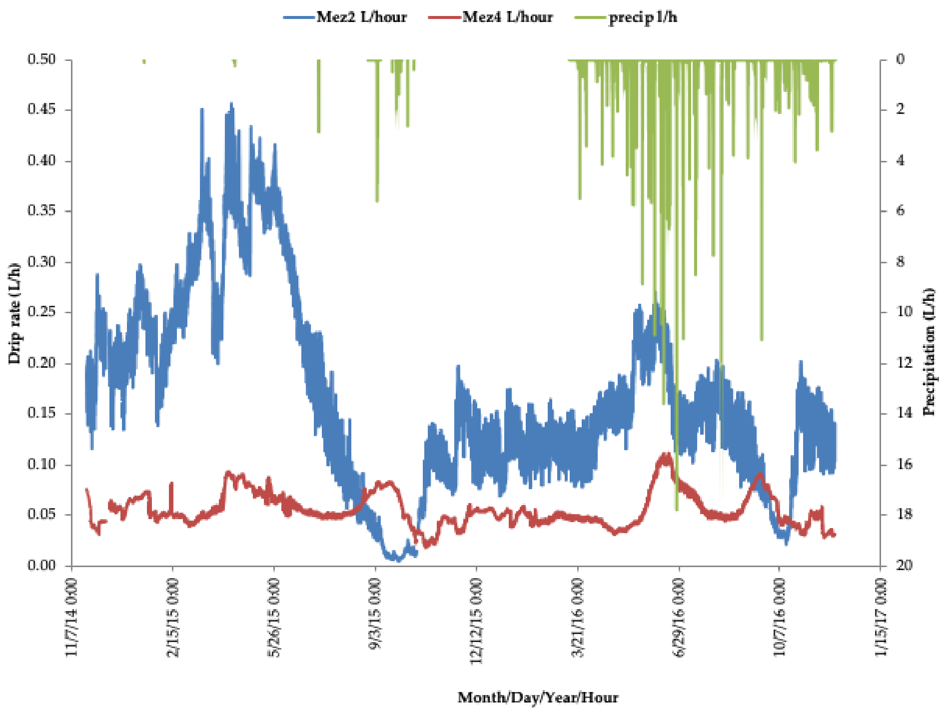

Figure S16. Variation of the drip rate in Mez2 and Mez4 stations compared to precipitation values.