Natural and anthropogenic influences on the year-round temperature dynamics of air and water in Postojna show cave, Slovenia

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HIGHLIGHTS

- Postojna Cave is one of the World’s most-visited show caves, attracting around 500,000 visitors per year.
- The potential impact of mass tourism on the cave air and water temperature was studied.
- The susceptibility of cave water temperature to anthropogenic influences is higher than the susceptibility of cave air.
- Higher visitor numbers during winter represent a greater disturbance to the cave microclimate than in summer.

ABSTRACT

Air and groundwater temperatures were measured in a rimstone pool in Postojna Cave, to advise evaluation of the impact of natural and anthropogenic influences related to heat being initially transmitted into cave air by visitors. Such heat can accumulate both in the rock mass and in water. Results show that attention must be paid to temperature changes of rimstone pool water rather than those of cave air, especially during the winter. Thanks to good ventilation deep inside the cave, short-term air temperature increases related to higher visitor numbers have not influenced flowstone precipitation or the cave fauna. However, this situation might change if winter visitor numbers increased greatly. This study does not support a suggested increase in winter visits (currently the tourism low-season) and reduction of summer visits (currently the tourism high-season).

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1. Introduction

Since 1819 Postojna Cave has welcomed 36 million visitors and is now Slovenia’s premier tourist attraction, with slightly more than 500,000 visitors in 2012. Environmental (climatological, microbiological and biological) monitoring within the cave supports development of guidelines for its sustainable management as a crucial part of Slovenia’s natural heritage, not only locally but also regionally among the Karst areas as a whole (Gabrovšek et al., 2011; Šebela, Prelovšek, & Turk, 2013).

Routine climatological monitoring carried out in several parts of the cave since 2009 includes measurement of air temperature, air pressure (Šebela & Turk, 2011a), CO2 levels and wind speed and direction. Water temperature was measured in a rimstone pool in Lepe Jame (Fig. 1) from 01 April 2010 to 06 June 2011, to investigate the effects of natural and anthropogenic influences on temperature variation. Lying 0.5 m from a footpath used by visitors passing through the cave (Fig. 2), the pool is fed by seepage water from the overlying land surface, penetrating some 60 m of limestone beds. As there are no surface streams above the cave, seepage derives exclusively from rainfall and snow-melt (in winter and early spring).

Whereas the study set out to evaluate possible impacts of mass tourism on the cave’s air and water temperatures, the potential involvement of other influences, such as surface-derived seepage water entering through the cave roof and internal air currents affected by external weather conditions, had to be acknowledged and evaluated. In Postojna Cave (Šebela & Turk, 2011b), and elsewhere, air currents impact strongly on cave air temperature, and might also affect water temperatures. Anthropogenic influences linked to mass tourism can also affect cave climate noticeably (Calaforra, Fernández-Cortés, Sánchez-Martos, Gisbert, & Pulido-Bosch, 2003; Santos Lobo et al., 2013) because human body heat...
is brought into the cave. Air temperatures also rise if warm (heat-producing) lamps are installed to facilitate cave tourism but, because cool lighting is used in selected parts of Postojna Cave, such effects are considered negligible in the study area. Air, water and rock temperatures within the cave tend towards equilibrium, such that heat can accumulate in the rock mass and also in water (Stoeva & Stoev, 2005).

As well as several known entrances, Postojna Cave presumably has many currently unrecognised surface connections (Sebela, 2010), so it was considered impracticable to apply realistic calculations to the cave system as a whole. Thus, Lepe Jame passage (Fig. 3) was chosen as a representative site to study the above factors, to help evaluate natural and anthropogenic influences on air and water temperatures. Because Postojna Cave is one of the world’s most-visited show caves, the results are valuable, and will inform future studies, especially those in other show caves displaying meteorological conditions related to cave morphology (Faimon, Lichinská, Zajíček, & Sracek, 2012a; Faimon, Troppová, Baldík, & Novotný, 2012b; Peršoň, Onac, & Peršoň, 2011; Pflichtsch, Wiles, Horrock, Piascekl, & Ringeis, 2010).

The study was envisaged primarily to support understanding of natural climate conditions inside the cave and secondarily to focus on human influences on cave climate. Continuous long-term monitoring of precise cave air, outside air and cave water temperature values represents a baseline approach to evaluation of the state of the underground environment. In passages remote from its entrances, annual temperature variations in Postojna Cave are less than 1 °C (Sebela & Turk, 2011a) — a markedly stable regime compared to nearby surface locations. Nevertheless, in a vulnerable environment such as a karst cave, even minuscule temperature differences can be a significant factor. Additional research (radon, CO₂, fauna, wind velocity and direction, airborne micro-organisms, percolation water chemistry, flowstone deposition/corrosion, tourist impact on the cave environment) must start from the temperature information, which is a baseline parameter for all studies related to evaluation of cave system vulnerability and for improvement of sustainable cave management.

Few climatic studies took place in Postojna Cave before 2009. Detailed meteorological studies were carried out by Crestani and Anelli (1939), who measured cave air temperature, rock temperature, humidity and cave ventilation. They described the characteristics of winter and summer ventilation regimes, and noted the inter-dependence of in-cave and external climatic factors. Research in Postojna Cave by Gams (1974) revealed that, thanks to active natural ventilation, tourism was not increasing CO₂ concentrations significantly. In those days the cave attracted about 700,000 visitors per year.

It is important that scientists and cave managers work together to evaluate proposed research projects and modify them to minimize damage and maximize benefit for all cave stakeholders (Gillieson, 2011). Choosing to begin modern research with detailed studies of temperature characteristics provides a clear directive for on-going complex scientific studies oriented towards sustainable use of the natural heritage.

2. Methods

To measure water temperature a Van Essen Instruments Diver® data logger, with a 24,000-measurement storage capacity, was sited...
in the rimstone pool. Claimed data logger accuracy is ±0.1 °C, with a resolution of 0.01 °C. Cave air temperature was measured a few metres from the pool, using the same data logger. External air temperature was recorded in the forest above the cave (Fig. 1). Cave air and external air temperatures were measured hourly, so data recording intervals were the same at all monitoring sites.

Precipitation was measured using a rain gauge connected to an Onset HOBO Event Logger RG2-M data logger, which records every 0.2 mm of precipitation (Kogovsek, 2010). Precipitation data were recorded every 24 h.

Visitor number data were obtained from the cave manager (Postojnska Jama d.d.).

Rimstone pool water temperature was compared with cave air temperature by means of scatter plot analysis. 3-D surface plot analysis was also applied, whereby a surface function is fitted to a 3-D scatter plot. Such analyses help to reveal hidden data patterns and can detect relationships between the three plotted variables. Algorithms smooth the data and approximate a surface at a given level of rigorosity — distance — weighted least squares. Influences of external temperature on cave water and cave air temperatures were studied in this way, and relationships with visitor numbers were also examined.

Spectral analyses of time-series data were used to determine the cave’s thermal behaviour over time.

Calculations of seasonal energy balance within the cave enabled rough comparisons between natural and anthropogenic influences on rimstone pool water temperature.

3. Site description

Postojna Cave lies within the Classical Karst region of southwestern Slovenia. The nearby town of Postojna has a transitional climate, somewhere between continental and Mediterranean, with an average annual precipitation of 1600 mm/m² (Fridl, 1998). According to Environmental Agency of Slovenia measurements, between 1961 and 1990 Postojna town’s mean annual air temperature was 8.4 °C but it has risen in recent years, reaching 9 °C in 2010.

Developed in limestone of Late Cretaceous age (Sebela, 2012), Postojna Cave, one of the earliest show caves to be developed anywhere in the world, has been a celebrated tourist attraction since 1818. Previously visits occurred as long ago as Palaeolithic times, and stone artefacts attributed to the Mousterian culture were found in the cave (Brodar, 1966, 2009). Signatures dating back to the 13th century are inscribed on the cave walls (Cuk, 2008). A railway constructed through part of the cave in 1872 facilitated tourism. Visitors now enter the cave by train (Fig. 3) and travel to the Velika Gora chamber before continuing through the cave on foot for about 45 min. In 1866 the cave’s principal entrance

![Fig. 3. Tourist attractions in Postojna Cave. A – Flowstone column and stalagmite, B – Proteus Anguinus, 20 cm-long cave invertebrate, C – tourist train, D – Lepe Jame passage.](image-url)
about 12 m of rock (Fig. 4), is only a few metres below the pool epiphreatic (water-table position). The karst aquifer, which is about 20 m below pool level, is recharged percolating surface precipitation. The upper limit of the aquifer lies 18.5 m below the surface precipitation, which percolates through the soil (0.2 m) and bedrock (60 m) above the cave to reach Lepe Jame. Only slowly percolating water (so-called film-water) enters the pool, following low-permeability fissures and bedding planes within the limestone so that recharge is fairly constant throughout most of the year (Kogovšek, 2007; Kogovšek & Sebela, 2004). Annual fluctuations of the pool’s water level are around 0.2 m.

The course of the underground Pivka River lies some 200 m from the pool (Figs. 1 and 4). However, the phreatic zone of the karst aquifer, which is about 20 m below pool level, is recharged both by the underground river (via fissure porosity) and by percolating surface precipitation. The upper limit of the aquifer’s epiphreatic (water-table fluctuation) zone, which varies through about 12 m of rock (Fig. 4), is only a few metres below the pool floor.

4. Results

Rimstone pool water temperatures and adjacent cave air temperatures in Lepe Jame exhibit comparable trends; moreover, analogous short-term (diurnal) temperature variations are apparent (Fig. 5).

For this reason, correlation between the two temperature curves is excellent ($r = 0.94$) throughout the monitored period (April 2010–June 2011; Fig. 6).

Good interdependence between external conditions and the cave climate of Postojna Cave had previously been recognized (Sebela & Turk, 2011a). Precipitation has no obvious direct influence on cave air temperature, but a delayed influence on rimstone pool water temperature is possible (Fig. 5); a high flood event on 19 September 2010 induced a significant thermal imprint in the pool (Fig. 5, event A). The start of the deviation between water temperatures and cave air temperatures occurred some time after monitoring began and coincided with the peak of a 100-years high flood event. A probable explanation is that measurements were affected by impurities that were washed into the pool from the vadose zone and deposited on the data logger.

Visitor influence on water temperature changes is also observed. Cave visitor numbers are greatest during August (more than 107,234 visitors) and July (83,329 visitors). Between July and September air temperature in the cave and water temperature in the Lepe Jame pool are also at their highest (Fig. 5). Body heat lost into the cave air by visitors has some influence on water temperatures because the air transfers heat to the surrounding rock mass, and directly into static water (Faimon, Troppová, et al., 2012b).

Visitor numbers are also relatively high during September (around 67,110 visitors), June and May (58,367 and 52,500 visitors). In winter visitor numbers are lower, with around 10,000 visitors per month from November to February. Exceptions occur during the Christmas and New Year holidays (Figs. 5B and 7). Between 25 and 29 December 2010 pool water temperature rose continuously in line with visitor numbers (Fig. 7), increasing by 0.1 °C per day for five days. Water temperature also rose by almost 0.1 °C per day on 01 and 02 January 2011 (Fig. 7, events F and G). It is clear that such temperature rises reflects anthropogenic influences related to high visitor numbers.

5. Discussion

5.1. Influence of external climate

The cave air and rimstone pool water temperatures are highly sensitive to cave climate dynamics. Temperature changes outside
the cave, especially seasonal changes, impose clear effects on pool water temperature and on the cave air temperature. Depending upon conditions, heat may transfer from the cave air into the adjacent rock mass and directly into the pool water, or heat may pass in the opposite direction from the water and rock into the cave air.

The Lepe Jame passage is some 1200 m from the cave's main entrances (Fig. 1). Air temperature in the passage exhibits several trend changes, reflecting surface climatic variations. Compared to timings outside the cave, inversion of seasonal trends in Lepe Jame lags by more than a month (about 45 days on average). Highest air temperatures in the cave are usually recorded in September,
whereas the highest external air temperatures occur in July and August (Fig. 5) (Sebela & Turk, 2011b). Taking the phase delay into account, the correlation coefficient is 0.77.

Water temperature changes in the Lepe Jame rimstone pool follow daily and annual trends that largely reflect changes in the passage’s air temperature. Both the diurnal and annual air temperature variations are related to external climate dynamics, as is also confirmed by spectral analysis. Both the cave air (Fig. 8) and water (rimstone pool, Fig. 9) temperatures show well-marked 24 h periodicity and less well-marked 12 h periodicity that indicate a clear interdependence and, more particularly, dependence upon external climatic factors (Figs. 10 and 11).

Energy (heat) exchange occurs between the cave air and the rock surface, which is never in equilibrium with temperatures deeper within the rock mass; the dominant heat exchange process is conduction. In the case of daily variations the thickness of the limestone boundary layer that exchanges energy with the cave air is about 0.2 m; in the case of annual variations it is around 3–4 m (Badino, 2010).

5.2. Influence of precipitation (percolation water)

Isotopic analyses have confirmed that water can be retained within low-permeability cracks and fissures for several years before finally penetrating into underlying cave passages (Kogovšek, 2010; Vokal, Obecki, Genty, & Kobal, 1999). Consequently, when percolation water arrives at the Lepe Jame rimstone pool it is in equilibrium with the surrounding rock mass temperature.

However, extremely high precipitation levels seem to have at least an indirect thermal influence on the pool water. A major rainfall event occurred in Slovenia on 19 September 2010 (Fig. 5, event A) and related flooding caused the underground Pivka River in Tartarus Passage to rise from its average low-water level of around 506 m a.s.l. to 518 m a.s.l. (Sebela, 2011) (Figs. 1 and 4). The floor of the Lepe Jame pool is at 525 m a.s.l., so the water table in the epiphreatic zone was only about 7 m lower. Major fluctuations of the water table in flooded passages result both from the increased discharge of the Pivka River and from ponding caused by drainage obstructions. During flood episodes, the karst aquifer’s phreatic zone is recharged by the Pivka River and by rainfall (percolation water) (Gabrovšek & Turk, 2010).

The water table rose significantly after the studied storm event and it seems that groundwater (in the phreatic or epiphreatic zone) also left a thermal imprint on the monitored rimstone pool in the vadose zone (Fig. 5, event A). Considering the hypothesis that the water might be several metres deep because sub-vertical fissures are present in the pool floor, there is a strong possibility that groundwater and pool water could either mix or exchange heat via convection and/or conduction processes.

Also of relevance, the recharge of the underground Pivka River has no significant thermal influence on groundwater in the aquifer remote from the underground river channel. Thus, correlations of water temperature between the river and water in the karst aquifer phreatic zone (or in the Lepe Jame pool) are not possible.

5.3. Anthropogenic influence

Human visits also affect cave air temperature (Fig. 5, event B). The underground temperature peak in late December 2010 and early January 2011 is well marked in both the cave air and cave water, and it is the most distinct temperature peak recorded in the rimstone pool during the study, but it does not correlate with an external temperature increase (Figs. 5 and 7). Transfer of visitors’ body heat into the cave atmosphere probably led to the temperature increases when a Christmas Nativity play was performed in the immediate vicinity of the Lepe Jame monitoring locations during this period.

During the last 7 days of December (Fig. 7, A–E) when the Nativity play was performed in the cave there were 9889 visitors (maximum 2169 per day), compared to only 3528 in the previous...
three weeks (maximum 426 on 05 December). Likewise, in January there were 7,391 visitors between 01 and 08 January (maximum 2,731 on 02 January; Fig. 7G), compared to just 4,742 visitors between 09 and 31 January 2011 (maximum 389 on 30 January). This represents an enormous increase in cave visitor numbers during the Nativity play season compared to the periods before and after.

These data are taken to indicate that periodic abrupt increases in visitor numbers (Fig. 7, A–G) over several consecutive days (14–16 days in this case) have major impact on cave climate (temperature) in the studied area of the cave. Heat emitted into the cave air by the many visitors accumulates not only in the rock mass, but also in cave water such as the rimstone pool.

Water temperature in the rimstone pool is highest during the summer for two reasons. Firstly the cave air temperature is high at this time of the year, reflecting natural ventilation between the outside and the cave. Secondly this is the period during which visitor numbers are highest, leading to the accumulation of emitted anthropogenic (body) heat into the cave atmosphere and hence into the enclosing rock mass and bodies of static cave water.

Nevertheless, during some high visitor number episodes cave air temperatures remain relatively low with respect to the annual temperature cycle, and the thermal effect of cold airflow drawn from the surface prevails in the cave. At these times the anthropogenic influence on cave air temperature is somewhat less than the effects of natural ventilation. For example, there was a major boost in cave visits on 08 February 2011 (Preserener Day, Slovenia’s National Cultural Holiday). Rising from around 200 on the days leading up to the holiday, visitor numbers reached 3,562 on 08 February, before falling to less than 100 the following day. The duration of this event (one day) was, however, too short to produce a significant temperature change in the rimstone pool water (Fig. 5, event C).

### 5.4. Energy balance

An estimation of heat exchange can be carried out at the Postojna Cave study site to provide a rough comparison between the effects of natural and anthropogenic influences on the water temperature in the rimstone pool. The energy balance is derived from the net flux and storage terms (modified after Luetscher et al., 2008):

\[
\Delta E_{\text{air}} + \Delta E_{\text{rock}} + \Delta E_{\text{percolating water}} + \Delta E_{\text{human body}} + \Delta E_{\text{lights}} + R = \Delta E_{\text{walls}} + \Delta E_{\text{rimstone pool}}
\]

Where:

- \( \Delta E_{\text{air}} \) is the sensible heat and latent heat advected by air circulation between the outside environment and the cave’s interior;
- \( \Delta E_{\text{rock}} \) is the ground heat flux;
- \( \Delta E_{\text{percolating water}} \) is the sensible heat advected by water circulation (percolation and seepage water);
- \( \Delta E_{\text{human body}} \) is the (body) heat emitted to the cave atmosphere by visitors;
- \( \Delta E_{\text{lights}} \) is the heat emitted to the cave atmosphere by the fixed cave lights;
- \( R \) is solar radiation;
Air circulation brings heat into the cave (in summer) or takes heat out of the cave (in winter). The heat gain or heat loss related to conduction is the difference in the specific enthalpy of the humid air that is exchanged at the system boundaries — 1000 J/kg.

\[
\Delta E_{\text{walls}} \text{ is the heat stored in the cave walls and ceiling (usually to a depth of a few cm) via conduction;}
\]

\[
\Delta E_{\text{rimstone pool}} \text{ is the heat stored in the rimstone pool water (via conduction).}
\]

Considering that \(\Delta E_{\text{rock}}, \Delta E_{\text{percolating water}}, \Delta E_{\text{lights}}, \text{ and } R\) are of minor significance, then the simplified energy balance for the discussed rimstone pool depends mainly upon \(\Delta E_{\text{air}}\) and \(\Delta E_{\text{human body}}\).

Air circulation brings heat into the cave (in summer) or takes heat out of the cave (in winter). The heat gain or heat loss related to advection by air circulation is (Luetscher & Jeannin, 2004):

\[
\Delta E_{\text{air}} = Q_{\text{air}} \cdot c \cdot (T_{\text{external}} - T_{\text{cave}}) \cdot t
\]

where:

\(Q_{\text{air}}\) is the flow of the air mass (kg/s) — estimated to 9 kg/s

\(c\) is the difference in the specific enthalpy of the humid air that is exchanged at the system boundaries — 1000 J/kg.

\(t\) is time (s) — each underground tour lasts for around 45 min; the supposition is that there are 10 tours per day on average (depending upon seasonal period, feast days, etc.).

The human body energy output consists of dry and evaporative heat transfer (thermal energy load) and of chemical energy load caused by water dispersion into the air (skin diffusion, air humidifying related to breathing and sweating) (Prek, 2006).

Heat flow emission from the human body can be described mathematically:

\[
\Delta E_{\text{Anthropogenic}} = k \cdot A \cdot (T_{\text{human}} - T_{\text{cave}}) \cdot t
\]

where:

\(k\) is the overall heat transfer coefficient — usually between 3.3 and 5 W/m², depending upon nature of clothing. For the current study a value of 4 W/m² is assumed.

\(A\) represents the approximate surface area of a conceptual “standard human”, taken as being c. 2 m²

\(T_{\text{cave}}\) is the temperature of the cave air — averaging 10.5 °C for Lepe Jame

\(T_{\text{human}}\) is human body temperature — 36.5 °C

\(t\) is time (on average each visitor spends about 45 min in the cave. The number of visitors should also be taken into consideration).

Calculations show that 3000 visitors emit \(1.7 \times 10^9\) J of heat in the studied part of the cave. Concurrently, natural ventilation (due to air convection) brings in \(3.5 - 4.7 \times 10^9\) J of heat on typical summer days (external temperature \(25\ °\text{C}\) or causes \(2.3 - 3.4 \times 10^9\) J of heat loss on typical winter days (external temperature \(0\ °\text{C}\)).

In the summer scenario typified by August, the amount of heat brought into the studied area of the cave by natural ventilation is about twice to 2.8 times the heat emitted by cave visitors. Thus, in summer, anthropogenic heat has no significant impact on cave climate (air and water temperature).

The winter scenario, with the same visitor numbers and an external temperature of \(0\ °\text{C}\) might correspond to the Christmas event discussed above. Here the cool air entering the cave due to natural ventilation is between 1.5 times and twice that emanating from cave visitors. Calculations indicate that the emitted heat linked to high levels of tourist visits has relatively higher impact on cave microclimate in winter than in summer. Its influence on cave air and water temperatures can be substantial in winter, when air convection gradually cools the cave environment.

5.5. Application of monitoring results for cave management

Capacity for a damaged cave system to regenerate in anything like human generational timescales is limited to non-existent. The most pronounced impacts that might result from human activity in caves are: alteration of the cave’s physical structure, modification of microclimate, installation of artificial light, damage to speleothems, destruction of fauna and introduction of alien organisms or materials (Gillieson, 2011).

Operators of heavily used caves should undertake monitoring that includes counting cave species, measuring CO₂ concentrations, watching for lampenflora, and observing the condition of speleothems. Implementation and enforcement of environmental regulations allied to these indicators would help government agencies meet their targets and reduce environmental degradation (van Beynen, Brinkmann, & van Beynen, 2012).

Diverse approaches are adopted for cave protection (Marín, Andrés, Jiménez-Sánchez, Domínguez-Cuesta, & Meléndez-Asesio, 2012).
2012), relating mainly to the speleo-morphological characteristics of the cave and the pressure of tourism development.

In Candamo Cave (Spain), which contains an important group of Palaeolithic paintings that deteriorated seriously due to the effects of mass tourism, the critical parameter limiting visitor capacity is air temperature (Hoyos, Soler, Cañaveras, Sánchez-Moral, & Sanz-Rubio, 1998). A maximum increase of 0.13 °C was observed during typical visits, so a maximum visitor capacity was calculated as an essential factor in providing future sustainable cave management (Hoyos et al., 1998).

Similar studies in Australia’s Jenolan Caves showed that temperatures at well-ventilated sites return to base levels within a few hours (Gillieson, 2011), as was also recognized in Postojna Cave (Sebela & Turk, 2011a).

Analysis of microclimatic variables in King Solomons Cave (Tasmania) showed significant differences in air temperature within sites and between sites. Where noted, such differences were as great as 4 °C. Strategies for future management included the requirement to construct an airtight double-door system at the cave’s entrance (Russell & MacLean, 2008).

Anthropogenically induced peaks in CO₂ concentration were detected in Nerja Cave, a well-known show cave in southern Spain that receives about 500,000 visitors per year (Benavente, Vadillo, Liñan, Carrasco, & Soler, 2011); similar peaks are recorded in Postojna Cave (Sebela et al., 2013). Microclimatic studies in parts of the Cueva del Agua (Spain) showed that the potential for condensation, together with likely elevated of CO₂ levels, if tourist visits to the study zone were allowed, would increase the risk of speleothem corrosion (Fernandez-Cortes et al., 2006).

The Postojna Cave management is making strenuous efforts to recover and retain the natural state of the cave. Since the beginning of modern tourism in 1819, the cave has received 36 million visitors, peaking at 940,000 visitors in 1985. Recently, LED lights have been installed in flowstone-decorated parts of the cave to help diminish lampenflora growth.

One of the Cave Management’s plans was to limit the number of visits during the summer peak and thus spread anthropogenic effects on the cave climate across the entire year. One clear outcome of the present study is that human heat emissions impact on cave climate more strongly in winter (when the cave cools gradually) than in summer (when the cave gradually becomes warmer). In view of this, apportioning visitor numbers equally throughout the year does not seem appropriate.

During the warmer part of the year, when temperatures in the cave are lower than those outside, the cave temperature rises gradually as warmer air enters from the surface. Additional heat emitted by up to 5000 tourists per day also contributes to raising the temperature of the cave environment (air, rock mass and water pools). However, this thermal disturbance is relatively minor, because natural air circulation brings in 2 or 3 times more heat per day. Increased and heavy visitor rates should be avoided in winter to moderate the most significant anthropogenic influences on cave climate. Especially problematical are heavy concentrations of winter visits on successive days, as shown by the 2010 Christmas Nativity play (10 successive days of heavy visits). Heat emitted by visitors accumulates in the cave environment, especially in the rock mass and in standing water, as is the case of the Lepe Jame rimstone pool. Over Christmas and New Year 2010—2011 the water temperature rose by about 0.15 °C in the pool, providing the highest recorded water temperature change (Fig. 7). Around 60—70% of this temperature rise can be attributed to anthropogenic forcing and only some 20—30% to the effects of natural ventilation.

During the same period, heat accumulation in the cave air was far less, due to the mediation of forced ventilation. Human heat emissions raised air temperatures by around 0.15 °C, but the increases were short-lived and linked directly to the visitors’ presence in the cave (Fig. 7). Daily variations of cave air temperature reached about 0.3 °C during the Christmas Nativity play season, meaning that around 50% of the temperature change can be attributed to anthropogenic forcing and about 50% to natural ventilation.

In contrast, single days with heavy visitor rates in winter do not impact significantly upon cave air or water temperatures because there is no accumulation effect. During the example of very high visitor numbers on Slovenia’s National Cultural Holiday (08 February 2011), only a minor impact on temperature was recorded (Fig. 5).

An important outcome of the study is recognition that more attention must be paid to temperature changes of rimstone pool waters due to their relatively higher thermal susceptibility to anthropogenic influences compared to the cave air. Such changes might result in alteration of flowstone precipitation in pool waters. Water temperature rises related to increased visitor numbers has not yet influenced flowstone precipitation, but the situation might change if temperature rises were more long-lasting due to increased winter visitor numbers. To evaluate the potential impacts of increased visitor numbers on flowstone precipitation, additional speleological, geochemical and hydrological surveys should be carried out.

Similar reasoning can be applied to the evaluation of impacts on the cave biota. About 35% of the cave passages are currently used for tourism and the cave fauna is especially rich in parts of the cave not regularly visited by tourists. It appears that up to now the air temperature rises related to human impact in highly visited parts of the cave have not been detrimental to the high diversity habitat of the subterranean community.

Based on the results of this study it is recommended that tourist visits to Postojna Cave in winter should not be increased, because the anthropogenic influence on cave temperature is much higher in winter than in summer.

The survey may serve as a recommendation for Cave Managers to distinguish between natural and anthropogenic impacts on cave climate (temperature) and to minimize or even prevent the most characteristic anthropogenic impacts in the future.

6. Conclusions

Results presented here from Postojna Cave demonstrate aspects of the natural and anthropogenic influences on cave air and rimstone pool water temperature in the most heavily frequented part (Lepe Jame passage) of the most visited tourist cave in Slovenia.

1. Natural influences, especially air ventilation, have a far greater long-term impact on cave air temperature than on anthropogenic influences. However, the situation with respect to water temperature is different. Anthropogenic effects have a relatively great impact on the water temperature in the Lepe Jame rimstone pool, especially in winter. The susceptibility of water temperature to anthropogenic influences is far higher than that of cave air. In Postojna Cave heat absorption by pools and the rock mass is relatively greater than into the cave air.

2. During warm seasons the amount of heat entering Postojna Cave due to natural ventilation is about twice to 2.8 times that transferred to the cave environment by visitors. In winter the amount of cool air brought into the cave by natural ventilation can be only 1.5 times to twice as great as the heat passed to the cave environment by visitors. Thus the ratio is relatively more similar in winter when the cave is gradually cooling. This means that higher visitor numbers during the winter represent a greater threat to the cave microclimate than posed by visitors in the summer months, and represent a potentially higher impact on the natural cave environment.
Thus, the study results indicate that reduction of high peak visitor numbers in summer (currently the tourism high season) should not be compensated by increasing visitor numbers in winter (currently the tourism low season) in an attempt to maintain total annual visitor numbers. The study confirmed that anthropogenic influence on cave temperature is far greater in winter than in summer.

3. Results obtained in Postojna Cave are considered applicable to other cave systems that are richly decorated with flowstone deposits and whose morphology enables good ventilation between the cave and the surface all year round. Because the main passages in Postojna Cave are well ventilated even deep inside the cave (Sebela & Turk, 2011a), short-term temperature rises due to increased visitor numbers have not yet influenced flowstone precipitation. Nevertheless the situation could change if winter visitor numbers increased significantly. As calculations showed, more attention must be paid to monitoring changes of rimstone pool water temperature due to high tourist numbers and to any consequential effects upon flowstone precipitation in cave waters.

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References

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