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Sustainable Tourism and Conservation of Underground Ecosystems through Airflow and Particle Distribution Modeling

Rosangela Addesso [1], Stefano Pingaro [1], Bruno Bisceglia [2] and Daniela Baldantoni [1,*]

[1] Department of Chemistry and Biology "Adolfo Zambelli", University of Salerno, Via Giovanni Paolo II, 132, 84084 Fisciano, SA, Italy; raddesso@unisa.it (R.A.); stepingaro@gmail.com (S.P.)
[2] Department of Industrial Engineering, University of Salerno, Via Giovanni Paolo II, 132, 84084 Fisciano, SA, Italy; bbisceglia@unisa.it
* Correspondence: dbaldantoni@unisa.it; Tel.: +39-089-969542; Fax: +39-089-969603

Abstract: Underground ecosystems are often of interest for the tourism industry due to their important naturalistic and cultural heritage. Since these underground ecosystems are almost completely isolated, external agents (such as human presence) can easily disrupt their chemico-physical and biological processes, which can affect, sometimes irrevocably, their natural equilibrium, placing the preservation of such sites at risk. The most sensible managers of caves, catacombs, mines, and all the accessible cultural sites are searching for methods to control these dynamics and the modeling appears to be effective in preventing scenarios of the known impacts as well as suggesting strategies for their mitigation. In this study, by employing finite element analysis by the COMSOL Multiphysics software and reproducing, in a simplified way, a section of the tourist trail of the Pertosa-Auletta Cave (Italy), for the first time we provided a fact-finding survey of the airflow and the scattering and subsequent deposition of particles transported by tourists. Taking into account discontinuities in the pathway, the simulations rebuilt the possible natural airflow line, reproducing the particle movements induced by different tourist loads, whose high numbers increase the swirling movement of air masses, promoting a higher dispersion of particles, even in the remote cave areas. Performed simulations clearly indicated both the speed and direction followed by particles, as well as deposition sites, highlighting potential hotspots of damage, and demonstrating that the employed approach can be an excellent tool for planning the management of these extraordinary ecosystems, foretelling anthropogenic impacts, and supporting managers in decision-making processes.

Keywords: atmosphere modeling; anthropogenic impacts; caves; naturalistic and cultural heritage; finite element analysis; COMSOL Multiphysics

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1. Introduction

Naturalistic and cultural heritage sites of interest for tourism represent an important opportunity to preserve the local historical identity as well as the naturalistic features of a focus area, diffusing their knowledge worldwide and promoting the economic development of the territory [1]. Among them, a number of natural and artificial underground environments, including caves, catacombs, mines, and hypogeum holy places, hold high appeal for tourists due to their environmental and cultural value [2]. However, thousands of visitors every year can create modifications in the environmental conditions, affecting (sometimes irreversibly) such confined ecosystems and compromising their integrity and conservation. Therefore, probing the human impacts in such places is necessary to safeguard the heritage sites and to properly manage their use [1,3–6].

In addition to the indoor climatic changes caused by human breathing, with temperature, relative humidity, and CO_2 concentrations increasing in atmosphere and often activating chemico-physical degradation processes of the lithic surfaces [7–11], tourists are carriers of allochthonous particles, such as dust, micro-plastics, fibers, hair, and also fungi, bacteria, spores, and seeds [12–14]. These constitute inorganic and organic inputs in the ecosystem, altering its natural ecological equilibrium [2,4,11,15–17], as well as activating forms of wall bio-deterioration, including mural paintings and speleothem surfaces [2,18,19].

The degree of vulnerability can be variable among systems. It may depend on the type of the ecosystem (dimensions, opening, connection with external environments, etc.) and on tourism load and associated inputs closely related to its use (visit duration, group size, breaks between and during tours, etc.), but also, especially in the case of natural caves, on their energy and mass flow [5,9,16,20]. For instance, underground systems with high energetic level, or rather with recurring natural air or water supplies from external sources, are more resilient than those with a medium-low energy flow [15,21]. Moreover, morphological and structural cave features can create several spatial and temporal indoor climatic zonation, affecting the system response to the changes [16,22].

Therefore, the complexity of underground ecosystems makes the complete understanding of their ecological processes, as well as of the consequences activated by potential disturber factors, difficult to achieve. Models, by representing in a simplified way the reality of these ecosystems, analyzing key factors and their behavior in different contexts (natural or artificial), predicting alternative scenarios of management, suggesting mitigation strategies of the anthropogenic impacts, supporting decision-making and giving the visitors an increasingly sustainable offer, may be an effective tool in managing natural resources [23,24]. With the view to proposing a predictive tool on the possible impacts created by tourism use of underground ecosystems which would be helpful for their sustainable management, we employed a finite element analysis approach based on physical models of the airflow and particle dispersion and deposition processes. The useful predictive potential of the tool for exact and in-depth planning of sustainable tourism management of underground ecosystems, facilitates the identification of the most vulnerable areas exposed to potential disturbance drivers and the implementation of effective prevention measures limiting harmful consequences that can jeopardize the integrity and the safety of such extraordinary natural heritage.

2. Materials and Methods

To simulate and model the airflow and the particle dispersions and depositions, the application Cylinder flow in COMSOL Multiphysics® (v4.3, COMSOL, Inc., Burlington, MA, USA) software was employed, modeling tourism sections of the Pertosa-Auletta Cave (in total, ~3 km long; Figure 1), located in the Alburni Massif, one of the most important limestone karst areas in Southern Italy [25]. This allowed the examination of the propagation of a variable and compressible flow within 2D geometry. The software uses preset physical notions based on the drag and lift coefficients of the fluid [26]; Application Library path: COMSOL_Multiphysics/Fluid_Dynamics/cylinder_flow:

$$C_D = \frac{2F_D}{\rho U_{mean}^2 A}$$

$$C_L = \frac{2F_L}{\rho U_{mean}^2 A}$$

where

- C_D: drag coefficient, a dimensionless coefficient used to quantify the drag of an object in a fluid environment, such as air or water. The lower the coefficient, the lower the aerodynamic or hydrodynamic resistance of the object
- C_L: lift coefficient, a dimensionless coefficient that relates the lift generated by a lifting body to the density of the fluid around the object, the fluid speed and an associated reference area
- F_D: drag force, the force component parallel to the flow direction
- F_L: lift force, the force component perpendicular to the flow direction

- ρ: fluid density
- U_{mean}: average fluid speed
- A: projected area

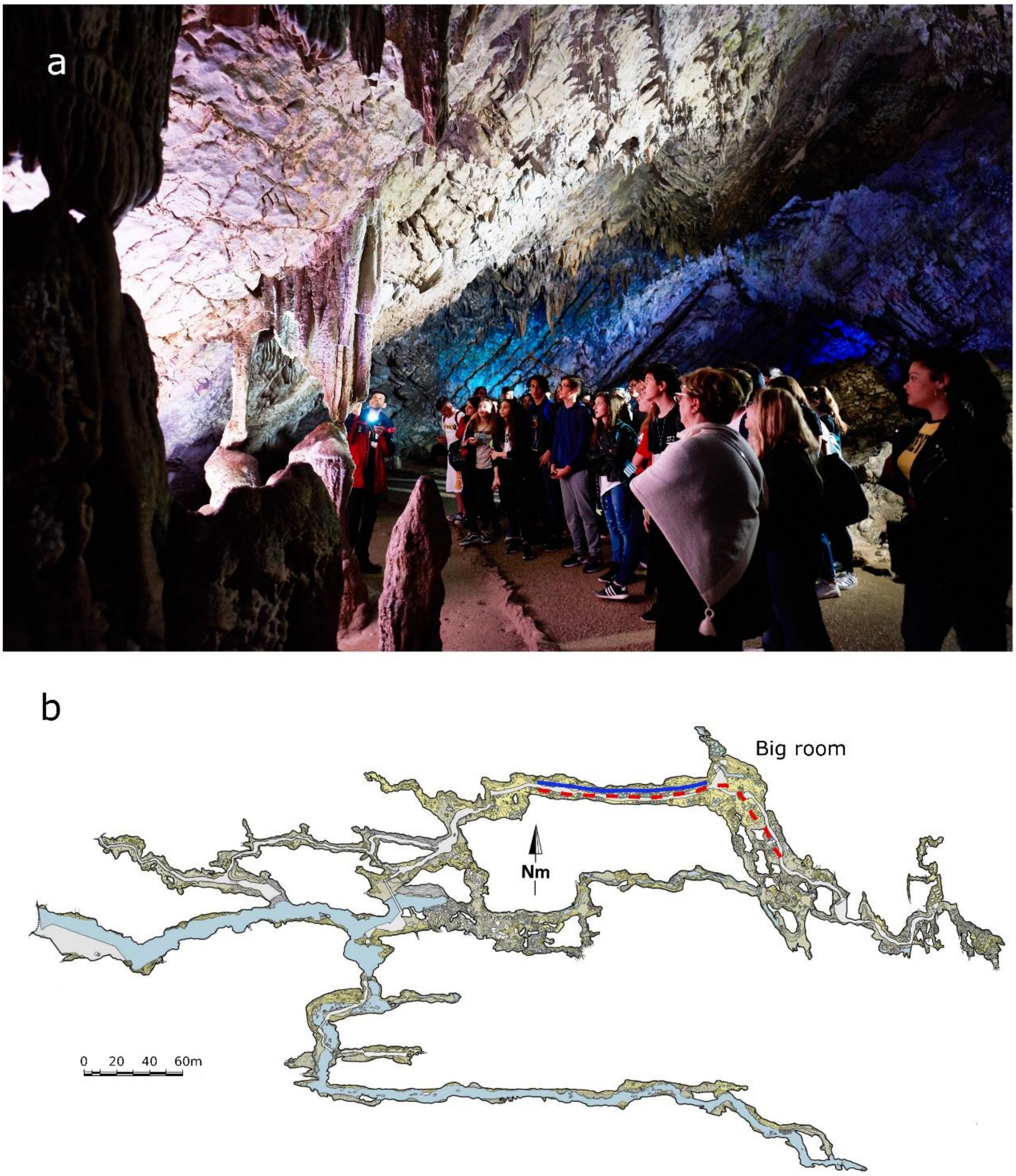

Figure 1. Tourists in the Pertosa-Auletta Cave (ph. Giuseppe Natalino) (**a**). Pertosa-Auletta Cave map with the indication of the linear conduct considered for the first simulation (blue line) and that one articulated with the big room considered for the second simulation (red line) (**b**).

The model examines a flow in a cylinder, working in two-dimensional geometry, and results are reported in the longitudinal section. Simplified geometries of two cavity sections of the Pertosa-Auletta Cave (Figure 1), frequented by 60,000 tourists per year (Figure 1a), were built. The first one consisted of a 2D cylinder, simulating a linear conduct of the cavity (blue line in Figure 1b); the second one was more articulated, in an attempt to rebuild a larger circular room, with tunnels for tourist entrance and exit (red line in Figure 1b). Some of the values of the physical parameters characterizing the moving air mass simulations (Table S1) were derived from the real data recorded by two monitoring stations, installed in the cave to control key atmospheric factors, in particular, the temperature (286.15 K) and the pressure (101,325 Pa) [27]. The dimensional characteristics of the shapes are in scale with the real ones (Table S1). In addition, a discontinuity was added to the normal physical arrangement, representing a foreign body, which could be recognized as one person or a group of tourists visiting the trail, as well as a speleothem, such as a column, a stalactite, or a stalagmite.

To follow the particulate matter movement dragged by the airflow, the maximum particle tracking application provided by COMSOL Multiphysics® was also applied in both the sections analyzed. Not having data on the average wind speed inside the Pertosa-Auletta Cave, we based our study on information from the literature [28], reporting values around 1 m/s, which we set up at 3 m/s, facilitating the visualization of the processes.

In the outputs, the fluid speed is observable by a color palette, where red describes the most sudden air movement; particulate matter, indicated by dots, is represented in not-real size. Being a time-dependent study, the final outputs of the simulations are released by the software in the form of short animations. Only the frames considered most significant have been reported.

3. Results and Discussion

Even if numerical modeling is a mature discipline and some procedures, such as the finite element method and others, are well known and documented in the literature, each application has its own specificities, which can be taken advantage of, in order to simplify the problem and reduce the associated computational size. An easy application of classical methods often may lead to computation times that are much longer than required [29]. In this work, we simulated a simple model that involves the significant variables of the physical process. The 2D geometry allows an easy analysis of the results and permits a 3D study of the physical model. Starting from a simplified model to a gradually more complex one, COMSOL Multiphysics® (through the Cylinder flow and the Maximum particle tracking applications) allowed the simulation of the airflow and the particle dispersions and depositions of tourism sections of the Pertosa-Auletta Cave. The approach is widely applicable in any subterranean system, considering that the system morphology can affect the cave microclimate (for instance, the gas concentrations, the temperature/relative humidity, as well as the spread and deposition of particles) and, consequently, a large part of the karst processes through several atmospheric variables [30–32].

Figure 2a shows a simple 2D construction of the straight duct leading to the large room of the cave, revealing the basic level of the physical model behavior considering a compressible flow. The laminar fluid is arranged in a section without any kind of discontinuity and, therefore, without any impediment to the fluid flow. In this case, the fluid is faster in the central part than in the areas in direct contact with the walls, where it proceeds slowly due to the friction. Adding a discontinuity (Figure 2b), representing for instance one person or a group of tourists, the initial laminar fluid course is modified, with interferences to the flow. The presence of an obstacle, characterized by Reynolds number equal to 100, causes an unstable wake, where the swirls alternately break away from the lateral regions forming a trail of laminar vortexes. It is interesting to note that, in the early phase of the simulation, the fluid impact with the obstacle produces strong turbulences traveling through the cylinder. The maximum speed reached by the fluid is 6.72 ms^{-1}, the gradient of which was obtained by computation as reported in the cited COMSOL library.

The tracking of massive particles is shown in Figure 2c, where the origin of the release is located just close to the discontinuity. Analyzing the animation, it is observable that, at the beginning, the particles follow the flow line in all its directions, but, once having picked up speed, they are no able to change direction quickly following the airflow, finally colliding with the domain walls. With a larger discontinuity (Figure 2d), due to an increased number of tourists, we can observe that the resulting air swirls are clearly larger than the previous simulation; this certainly causes a greater transport of particles by the fluid, because the speed reaches 9.06 ms^{-1}, as well as an evidently greater deposition on the cave walls. On this scenario, the tourists, together with natural air movements, can produce a significant contribution to the particulate matter scattering. They become vectors of additional substances carried on their body, facilitating their arrival even in remote and deeper areas of the karst system, as well as re-suspending the deposited particles on the ground and the walls while going through the pathway [11,32]. The arrival of allochthonous natural/anthropogenic inorganic/organic aerosols causes several consequent effects, such as the incorporation of dust or soot in speleothems or the proliferation of seed and spores in tourism cavities due to the artificial light, placing at risk the preservation of the underground ecosystem [11,19,32]. Moreover, high particulate concentrations can also affect air quality, causing problems for human health, especially for the respiratory apparatus [33]. Nevertheless, in general, particulate matter is largely cut back in caves, due to the high air relative humidity, close to the saturation, reducing considerably the hanging particles by abatement [33].

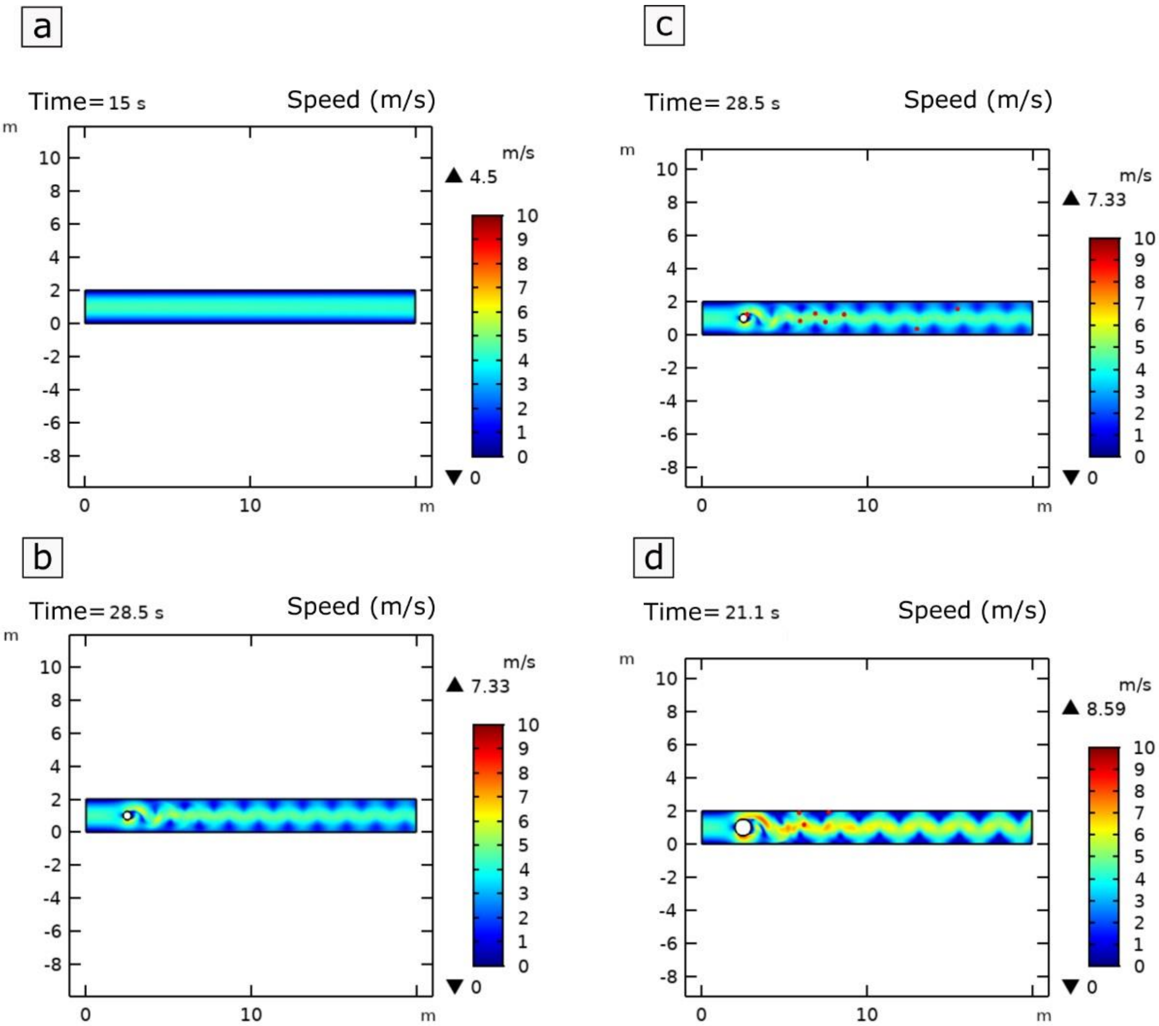

Figure 2. Simulations based on a simplified geometry of a linear conduct of the Pertosa-Auletta Cave, where the *Y*-axis represents the airflow speed (m/s) and the *X*-axis the cylinder dimension (m); in particular, the basic physical model behavior (**a**), with the addition of a discontinuity (white circle) (**b**), of the tracking of massive particles (red circles) (**c**) and of a larger discontinuity (white circle) (**d**) are reported.

Adding further discontinuities (Figure 3), such as speleothems, representing typical obstacles in caves, the linear airflow is perturbed (Figure 3a), also influencing the particle paths (Figure 3b,c) that follow the preferential flow lines. Introducing a number of tourists, 5 and 15 respectively in Figure 3b,c, causes a more chaotic movement of air masses, with a consequent deposition of the particles in the low-pressure zones. The animation of such simulation (Animation S1) was also reported. For a sustainable management of these ecosystems, managers can install active or passive particle trapping devices in such areas, in order to avoid damage to the structures.

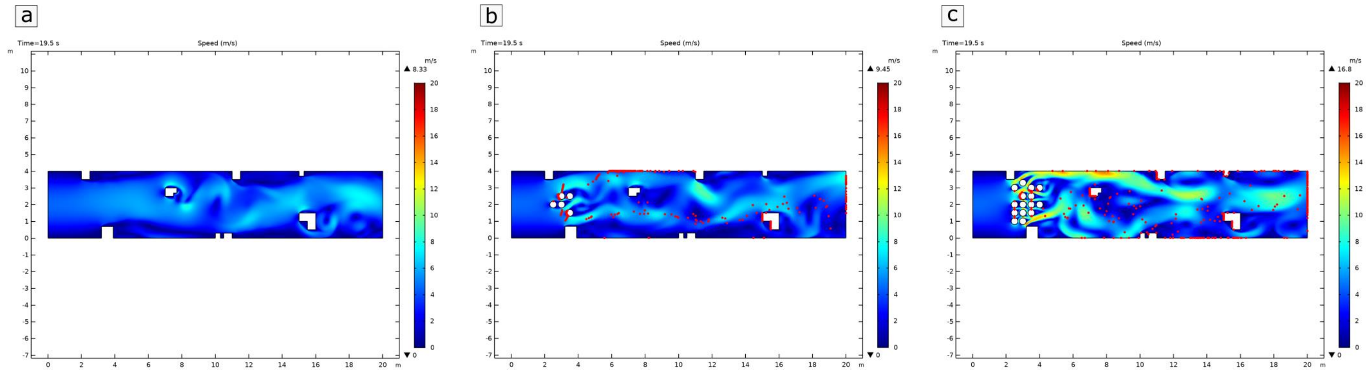

Figure 3. Simulations based on a simplified geometry of a linear conduct of the Pertosa-Auletta Cave, adding several discontinuities (white squares), where the *Y*-axis represents the airflow speed (m/s) and the *X*-axis the cylinder dimension (m). In particular, the basic physical model behavior (**a**) and the tracking of massive particles (red circles), considering a group of 5 (**b**) and 15 (**c**) visitors (white circles), are reported.

The simulation representing the path leading to the large room of the cave (Figure 4a) shows how the flow, coming from the initial straight section, bumps into the facing wall before flowing into the escape routes, especially in the wider one. This produces another flow traveling along the entire curvilinear perimeter of the big round section in a circular motion. The air speed quickly decreases in the straight section, remaining high in the center of the room, and then increasing again at the entrance of the flow escape routes. Tracking the massive particles from a discontinuity, representing one person or a tourist group, they do not deposit on the walls (Figure 4b), as in the first simulations, nor follow the entire path of the fluid, because the acquired speed determines an inertial force that pushes it towards the wall of the large room. This does not occur for the bigger particles, able to follow the sudden deviations of the wind, acquiring less velocity (Figure 4c).

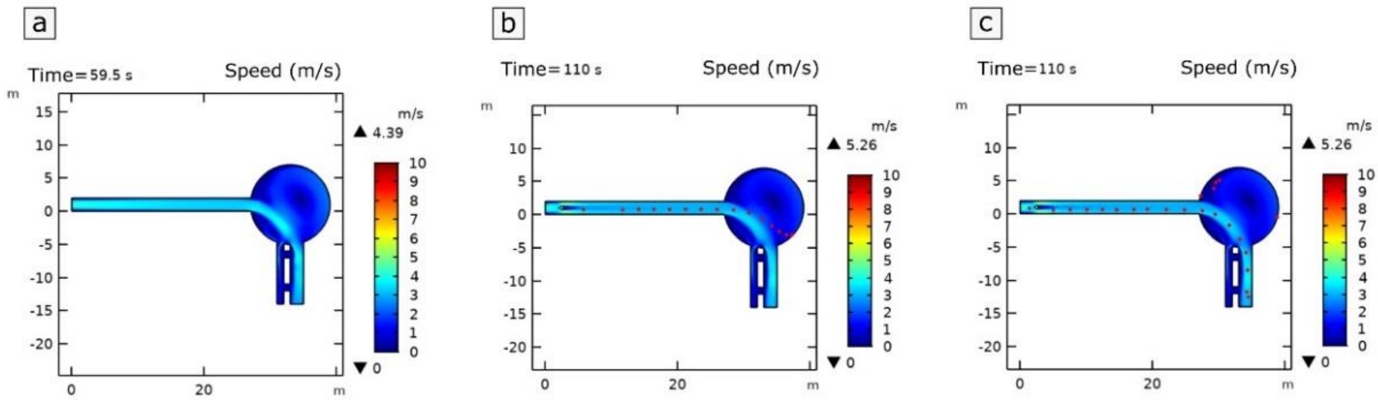

Figure 4. Simulations based on an articulated geometry, rebuilding the large circular room of the Pertosa-Auletta Cave, where the *Y*-axis represents the airflow speed (m/s) and the *X*-axis the linear dimension (m). In particular, the basic physical model behavior (**a**), the tracking of massive particles (red circles) from a discontinuity (white circle) (**b**), and the addition of heavier massive particles (**c**) are reported.

Rendering the system more complex with several obstacles and tourist groups (Figure 5), such discontinuities act as deposition sites, representing high-risk areas of damage. Moreover, in the first case (Figure 5a,b), where 5 and 15 visitors are at the beginning of the passage, the airflow pushes most of the particles on the walls due to the higher air speed developing along the extremities. The increase of tourists in the passage can cause the growth of the ventilation in the big room, while also promoting the dispersion in the deeper areas of the cave. When 5 and 15 visitors (Figure 5c,d) arrive in the large room, the particle deposition becomes more intense. In addition, as also shown in the Animation S2, the increase of the tourists in the big room distorts the airflow in a remarkable way, stimulating the formation of further vortexes, generating other arms of the airflow, with an increasing scattering of the particles in the space.

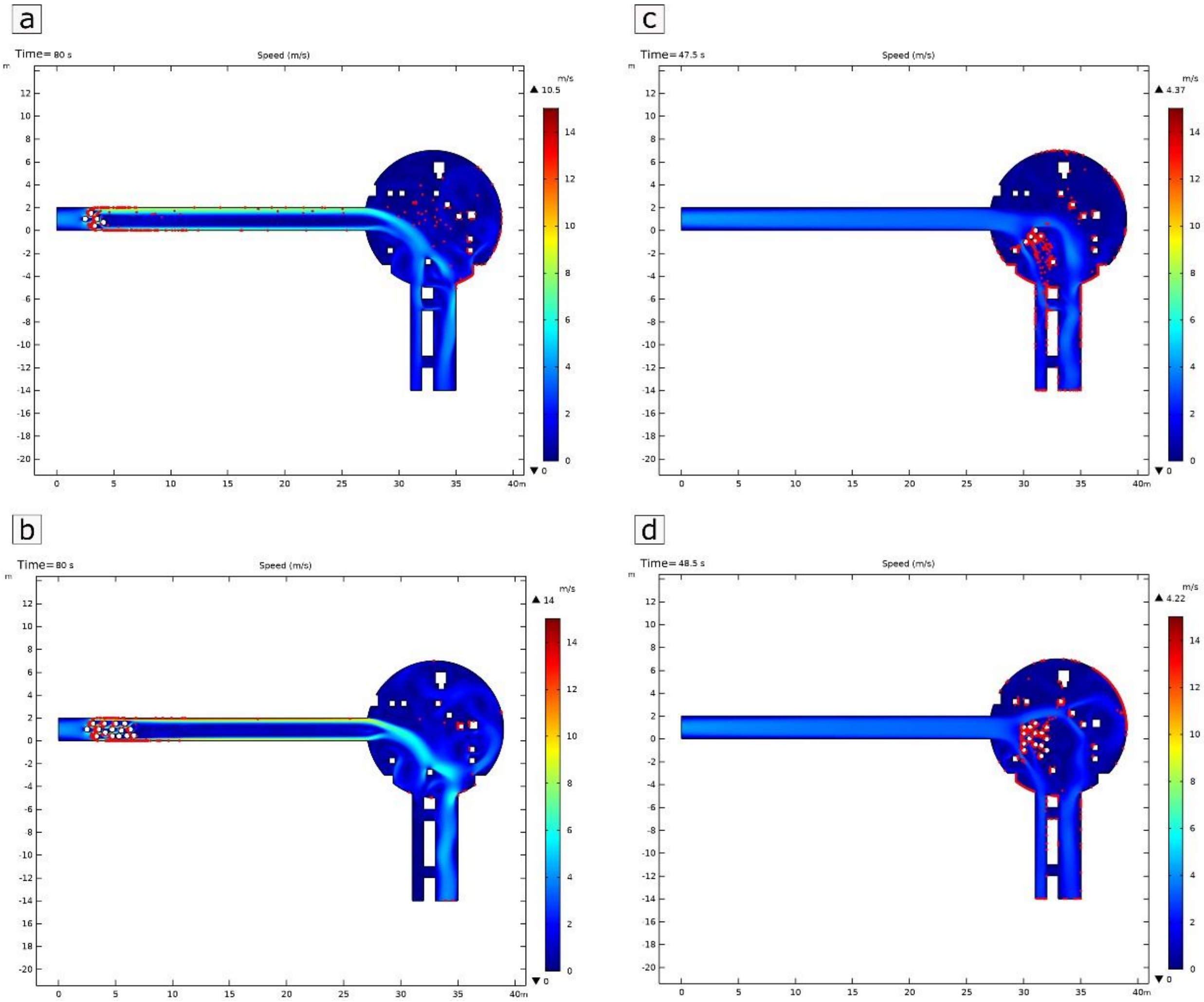

Figure 5. Simulations based on an articulated geometry, rebuilding the large circular room of the Pertosa-Auletta Cave, adding several discontinuities (white squares) and the tracking of massive particles (red circles), where the *Y*-axis represents the airflow speed (m/s) and the *X*-axis the linear dimension (m). In particular, a group of 5 (**a**,**c**) and 15 visitors (**b**,**d**) (white circles), positioned at the beginning of the long conduct (**a**,**b**) and in the large room (**c**,**d**), have been considered.

Overall, the obtained results provided an exhaustive description of the physical processes related to the airflow and the particle dispersions and depositions in underground ecosystems; however, further studies could take into account physical characteristics of the materials, as well as the exact shape of the study system. Moreover, the validation of coarse airborne particle simulations may be obtained by monitoring real cases (in terms of number of visitors per group, transit time, etc.) combined with a comprehensive and time-accurate monitoring of the key environmental parameters. Finally, it should be possible to create a graphic interface of the COMSOL Multiphysics® software, readily operable for managers of the sites to plan the tourist activities.

4. Conclusions

COMSOL Multiphysics® was found to be a suitable device to support the sustainable management of underground ecosystems in relation to tourism planning, such as in the choice of visit-break locations and time duration of tours, avoiding the most vulnerable sections or suggesting the installation of mitigation systems where anthropogenic impacts may be more intense. Indeed, this application is of general validity, being adaptable and implementable in relation to the different environments needing sustainable choices. In the case of the two simulated sections of the Pertosa-Auletta Cave, tourism load determines variations in both airflow and particle fates, influencing different areas, deeper and farther from the place of origin, to different extents, according to the system morphology. Further implementations of such simulations in underground tourist sites such as caves (as well as in other underground ecosystems) may be obtained, reproducing accurately the cave geometry (and also adding the several discontinuities represented by speleothems), and considering other physical features of the substrate. This goal may be easily achieved, in order to obtain a model as close as possible to the reality of the processes and help managers in decision-making to conserve these unique ecosystems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14137979/s1, Table S1: Values (units of measurement in brackets) of physical parameters characterizing the two moving air mass simulations; a. Parameters of the first simulation, considering a linear cave conduct, reproduced by a 2D cylinder. b. Parameters of the second simulation, considering a big room of the cavity, with tunnels for tourist entrance and exit.; Animation S1: Video animation of the simulation about massive particle (red circles) tracking, in presence of a group of 15 visitors (white circles) in a linear conduct of an underground system; Animation S2: Video animation of the simulation about massive particle (red circles) tracking, in presence of a group of 15 visitors (white circles) in a linear conduct of an underground system, with the addition of a large circular room.

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