

Article

Geospatial Tool Development for the Management of Historical Hiking Trails—The Case of the Holy Site of Meteora

Chryssy Potsiou *, Charalabos Ioannidis, Sofia Soile , Argyro-Maria Boutsi, Regina Chliverou, Konstantinos Apostolopoulos, Maria Gkeli and Fotis Bourexis

School of Rural, Surveying and Geoinformatics Engineering, National Technical University of Athens, 15780 Athens, Greece; cioannid@survey.ntua.gr (C.I.); ssoile@survey.ntua.gr (S.S.); iboutsi@mail.ntua.gr (A.-M.B.); regina@survey.ntua.gr (R.C.); apostolk@central.ntua.gr (K.A.); gkelimaria@mail.ntua.gr (M.G.); fotis.bourexis@gmail.com (F.B.)

* Correspondence: chryssyp@survey.ntua.gr

Abstract: This paper presents a holistic guiding methodology for the development of a geospatial tool to be used for the documentation, planning, smart management and dissemination of a country's network of historic hiking trails. To deal with the challenges and to ensure the sustainability of a historic site, geospatial documentation merging authoritative and crowdsourced data and a WebGIS-based spatial analysis is necessary. Geospatial data collection should include professional field surveys, professional and crowdsourced photographic documentation and video recording of the existing historic walking/hiking trails. A geodatabase, structured using relational model technology, including vector spatial entities (feature classes), mosaics (raster) and tabulated data (geodatabase tables), should be developed on a commercial or open platform; in this case, the ArcGIS Pro is used. Entities with embedded descriptive information and metadata for the technical, legal, historical, and administrative context may then be created. An object-oriented data model is needed to connect spatial and descriptive information. Spatial and descriptive queries or correlations between attribute fields of spatial entities must be enabled for specialized information retrieval by either experts or users. Next, a web GIS application to present the developed geodatabase in a visually appealing and informative way is created. It should integrate 2D maps with built-in tools and should support advanced functionalities, such as: (i) pop-ups that display brief information and images about specific spots along the trails; (ii) dynamic visualization of the vertical profile of each trail; (iii) multimedia information about landmarks, natural features and scenic viewpoints. Finally, the tool includes a feedback service and continuous efficiency monitoring and assessment, and enables adjustments, if and where needed. The tool is tested and used for 10 historical walking/hiking trails of the archaeological and Holy Site of Meteora, Central Greece. This is a UNESCO World Heritage site. The network, with a total length of 35 km, leads to six monasteries, still active since the 12th century, passing by gigantic rocks and beautiful natural landscapes. The site is famous globally and the greater area is continuously overcrowded with visitors. The tool is anticipated to be used for the documentation and management of the whole walking/hiking historic trail network of Greece in the future.

Keywords: GIS; cultural heritage; trail hiking; geodatabase; surveying documentation



Citation: Potsiou, C.; Ioannidis, C.; Soile, S.; Boutsi, A.-M.; Chliverou, R.; Apostolopoulos, K.; Gkeli, M.; Bourexis, F. Geospatial Tool Development for the Management of Historical Hiking Trails—The Case of the Holy Site of Meteora. *Land* **2023**, *12*, 1530. <https://doi.org/10.3390/land12081530>

Academic Editor: Maria Fe Schmitz

Received: 5 July 2023

Revised: 27 July 2023

Accepted: 31 July 2023

Published: 2 August 2023



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1. Introduction

Cultural Heritage (CH) sustainability has been recently introduced to the SDG 11 “Sustainable cities and communities” of the UN Sustainable Development Agenda 2030 to describe the significant relationship between conservation and sustainable development [1]. Target 11.4 aims to “strengthen efforts to protect and safeguard the world’s cultural and natural heritage”. Conservation of CH plays a significant role in sustaining local communities, not only reinforcing local identity and traditions, but also, in maximizing economic

benefits through well-managed tourism. Heritage trails are CH assets of significant historical and cultural value that are worth being preserved. A heritage trail typically refers to a designated route or path that showcases and highlights the historical and cultural heritage of a particular region or community. Depending on the types of features and landmarks it may include along the designated route, it can be characterized as historical, cultural, foot trail or bikeway, interpretive/natural trail, multi-use trail, etc. A historical hiking trail entails sites of significant historical importance or showcases events that have shaped the region's past, such as battlefields, monuments or statues commemorating historical figures, or museums showcasing artifacts and exhibits from a particular time period. The protection and expansion of linear CH sites has received an increasing amount of attention, as it allows for the possibility of resolving contradictions between the economic and market values of tourism and sustainability [2]. Heritage trails may also combine cultural heritage interest with sites of significant biodiversity and natural beauty. SDG 15 "Life on Land" and the more specific Targets 15.2, 15.4 and 15.9 emphasize the need for sustainable management of all types of forests, for conservation of mountain ecosystems, including their biodiversity, and for integrating ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts. For the successful implementation of the above-mentioned goals, the role of geospatial infrastructure is highly appreciated. Geospatial infrastructure ensures evidence-based, sustainable planning and smart management of trail networks and the greater area; it provides updated and reliable information for decision-makers, local authorities and planners but also for visitors who may easily retrieve information about the historic and biocultural data, but also about the difficulty of the trails, the type of trail, the marked trail designations, social trails, as well as information about hazards, dangerous conditions, if any, and guidelines on how to hike smartly and stay safe.

This paper presents the creation of an innovative geospatial tool dedicated to the redevelopment, rehabilitation and sustainable management of historic trails of various levels of difficulty and thematic categories. Its innovative features contribute to effective planning, decision-making, and user engagement in the context of eco-tourism and regional development. It supports any kind of data that derive from topographic surveying, photographic documentation, video recording of walking tours, metadata and extensive archival research. Different groups, such as local communities, urban and regional planners, government authorities and policy makers, etc., can contribute through crowdsourcing. The managers of the tool could review the contributions, validate the information provided, and incorporate it into a unique geodatabase as appropriate. This collaborative approach leverages the collective knowledge, experiences, and expertise of diverse stakeholders, to ensure that the tool's functionalities align with the needs and aspirations of the wider community. The enriched geodatabase serves as a repository for the historic routes, where the GIS reference points trace them. The tool utilizes an object-oriented GIS-based model to integrate descriptive information into the corresponding vector spatial entities, mosaics and tabulated data. The geodatabase is enriched with multimedia content, such as text, images, videos, links, and charts related to landmarks, natural features, and points of interest along the trails. This integration allows for a seamless connection between spatial data (recorded routes) and descriptive data, such as historical or cultural information, enhancing the overall understanding and management of the trails. By performing map algebra operations, various geometric information related to the trails, such as path length and distances between points of interest, can be calculated. Moreover, the tool can identify and spatially locate issues along the trails, such as damaged sections, overgrown vegetation, and lack of amenities, such as signage or seating areas. Analyzing and mapping these issues facilitates targeted interventions and maintenance activities. Finally, the tool leverages ArcGIS Online (or any other web-based service) to disseminate the developed geodatabase. Its web application provides interactive 2D maps with features such as bookmarks, measurement tools, and search bars. It also includes pop-ups that display information and images about specific points of interest, as well as dynamic visualization of the vertical

profile of each trail in 3D. The publication enables wide accessibility and engagement, provides comprehensive information for visitors or stakeholders, and effective planning and analysis of the trail network.

Thus, through data integration, spatial analysis, issue identification, and web-based dissemination, the tool contributes to effective planning, maintenance, monitoring, accessibility and user engagement for visitors, stakeholders, and decision-makers. Potential users of the geospatial tool for historic trails encompass tourists and visitors, local communities, heritage organizations, environmental and conservation agencies, urban and regional planners, as well as government authorities and policy makers. The proposed geospatial tool is tested and implemented on a network of ten historical walking trails of the UNESCO, archaeological and Holy site of Meteora, Greece [3]. In this site, it is essential to manage the natural and cultural environment of the greater Holy area in parallel with safeguarding of the historical trails' authenticity in a sustainable manner. The trail network, of a total length of 35 km, leads the visitors from the two neighboring settlements of Kalampaka and Kastraki to the six active monasteries. These CH routes constitute part of a broader trail network of various levels of difficulty and thematic categories across the whole Trikala region. It is part of the regional strategy and local government management models and constitutes a Master Plan for sustainable redevelopment, improvement and management through eco-tourism (walking, bicycling, adventure, cultural and other alternative types of tourism).

The article is structured as follows. In the following section, a comprehensive review of the literature is performed to identify similar approaches in spatial analysis and GIS infrastructures in the field of linear CH. Section 3 concerns the requirements, concepts and methodology used for data collection, process, analysis and online visualization of the proposed geospatial tool. Section 4 concerns the implementation of the tool. It documents the current state and presents strategic planning, including the description of the historic walking trails of Meteora, the proposed treatment and maintenance measures, as well as the procedures and results of data collection, geodatabase creation and web publishing. Finally, Section 5 analyzes the significance of the proposed tool for sustainable monitoring and promotion for various stakeholders while Section 6 summarizes the findings and proposes future work.

2. Literature Review

In recent years, many debates have taken place regarding the role of CH in sustainable development [4]. The role of community in sustainable CH management has been highlighted at UNESCO conferences since the mid-1990s [5]. Public participation is an important approach for achieving CH sustainability. While conservation efforts and co-operation from major stakeholders are inevitably crucial factors for CH sustainability, the active effort and participation of local communities actually determine whether relevant preservation actions may be successfully implemented, being essential for the success of CH conservation, as discussed in [6]. However, CH sustainability is a complex issue that is rarely measured, mainly due to lack of universal CH sustainability indicators. Methods for measuring and evaluating CH sustainability are proposed in [7]. The link between sustainability and historic environments is addressed in [8], where the authors establish a framework for appraising sustainability in the CH sector, focusing on the available case study material.

However, interest in preservation of historical and cultural trails as opposed to urbanization and mass tourism has only emerged recently. While multiple similar quantitative method approaches have been conducted regarding the tourism value of linear CH in general [9–13], only a few works in the literature demonstrate their value and impact through extensive documentation and spatial analysis tools. The most common and long-established technology used is the Geographic Information System (GIS). The Tambunan site was recorded and megalithic stones were mapped. Then, least-cost path analysis (LCPA) in GIS was used to identify cost-effective and sloping routes to produce heritage

trails [14]. An integrated GIS system for the organization and planning of two cultural routes in Chios Island, Greece based on in-situ observations and the study of the corresponding spatial and legal framework is presented in [15]. Two GIS tools (Boolean algebra and logical operations) were exploited for comparative analysis among the descriptive characteristics of the elaborated thematic maps of the current state, the implemented interventions proposed in an older relevant study of 1999, and new proposals. GIS-based mapping techniques have been applied to evaluate two alternative itineraries for the Monks Route, that cross the agricultural landscape in southern Milan, with the aim to document their spatial features and rank them in relation to their spatial quality [16]. These techniques form the SQISR method (Spatial Quality Index of Slow Routes) that also allows comparison of alternative routes on the base of a set of heterogeneous indicators.

Regarding GIS applications for decision-making in trails' optimization, the variations in trail conditions, such as incisions caused by soil erosion, are related to their potential as influencing factors for the Nakahechi Heritage route by performing a series of multivariate regression analyses [17]. After evaluating route walkability for people with different needs, accessible pedestrian networks between touristic attractions were created in Lisbon [18] and in Faro [19] historic city cores, Portugal. The diagnoses validate that the physical characteristics of urban cultural routes do not always comply with the requirements of the National Law of Accessibility, being unsafe and inaccessible to people with limited mobility. Moreover, multi-criteria analysis, including clustering and classification, is employed to identify the different typologies of the surrounding landscapes of the Via Francigena path in Italy and to promote sustainable tourism through rural planning [20]. Three geo-routes in Santa Elena Province in South America were designed and generated as a result of SWOT analysis, revealing that geo-tourism development should be based on strategic planning [21]. In the context of urban heritage trails, Advanced Spatial Analysis (ASA) techniques were applied to obtain a diagnosis of the existing spatial problems of Seville city, as well as the opportunities offered by the context [22]. After recording pedestrian accessibility to assets and the concentration of tourist activity, mathematical, historical and sensory criteria were used to generate routes and balance the distribution of tourist flows. Compared to the aforementioned studies, this research studies multiple factors and incorporates both on foot and by bicycle metrics to serve as a reference for other tourist-centric historic cities. Finally, an operational GIS-based model for megaregional transportation planning has been developed analyzing the Texas Triangle (Austin, Dallas–Fort Worth, Houston, and San Antonio) [23]. It extends the spatial scale of a regional transportation model to the megaregion, which accommodates larger areas, more passenger and freight trips, and more complex transportation networks. Other GIS-based technologies for the investigation of the level of CH accessibility at territorial scale involve mobile applications [24] and open data in a semantic web [25].

To offer more than simple 2D mapping and geocoding, a complete study should be oriented to online solutions, for dissemination, remote access and collaboration purposes. The ISTER GIS-based Atlas of Roman Routes in the Danube Region is an open-source, online inventory and platform that provides a spatial representation of the Roman routes' legacy in Danube Region, developed in the context of the ISTER project [26]. The use of ArcGIS online is successfully established as web-based mapping software (version 3) for integrated visualization of trail networks [27]. The historical and cultural information material (text, maps, and photographs) of Kynouria's archaeological routes in Peloponnese, Greece, is organized into a spatial database and published in a web-GIS application with interactive access and retrieval services.

The work presented in this paper differs from the aforementioned examples in that it not only integrates, manages and analyzes data of heterogeneous origin and format into a unique geodatabase, but also translates and converts the findings into specific rehabilitation and enhancement measures with their spatial reference. The input of various stakeholders and experts and the participatory approach align the trails with sustainable urban development goals and with the needs and aspirations of the wider community. The

proposed web application that visualizes the historic trails into interactive 2D maps and spatially and logically correlates them with relevant multimedia information engages the public and advances planning for scientists and policy makers.

3. Methodology

3.1. Workflow of Sustainable Management

Data from various sources, including geospatial data, crowdsourced information, archival records, expert knowledge, and agency-provided data, are organized and structured within the geodatabase of the tool. The historic trails can be initially recorded with GPS tracking devices and surveying engineering methods. In addition, the current state, real-time and geometrically accurate data collection allows for efficient issue identification and maintenance prioritization. Field surveys and on-site inspections can be conducted to visually identify and document trail issues, such as damaged sections, overgrown vegetation, or missing amenities. Moreover, high-resolution orthophotos or aerial imagery can be used to detect changes in the trail environment. Crowdsourcing involves feedback, issue reports, and multimedia content by visitors, tourists and locals. Heritage organizations contribute archival data, expert knowledge, and conservation information through collaboration with the tool managers, while planners share land-use plans, infrastructure data, and visitor management insights through collaborative workshops, data sharing platforms, or dedicated channels. Local communities share historical and cultural information, personal anecdotes, and traditional practices through community engagement initiatives, workshops, or dedicated portals. The provided content can be images, text documents, video files, metadata, structured data, audio files, etc.

The managers of the tool review and assess the crowdsourced data for accuracy, relevance, and reliability. They validate the data, cross-reference it with existing information, and ensure it aligns with the goals of the geospatial tool and the respective trail network. Feedback loops are established with the data contributors to address any clarifications or follow-up questions. After quality, accuracy and relevance evaluation, the data are converted into compliant-with-GIS file formats, such as shapefile, geojson, Keyhole Markup Language (.kml), CSV (Comma-Separated Values) and DXF (Drawing Exchange Format). The validated crowdsourced data is integrated into the geodatabase of the geospatial tool. Object-oriented GIS-based models and spatial entities are used to incorporate descriptive information, multimedia content, and spatial references. Spatial analysis techniques are employed to diagnose and assess the trail network, as well as to identify issues such as damaged sections, vegetation encroachment, or lack of amenities. Additional geometric information and insights into the trails' characteristics and challenges can be generated by map algebra operations. Based on diagnosis and analysis, planning activities are conducted to address the identified issues and optimize the trail network. Urban and regional planners can utilize the geospatial tool and its findings to integrate the trails with urban infrastructure, develop land-use plans, and align the trails with sustainable development goals. Conservation measures, infrastructure improvements, and visitor management strategies are planned to enhance the sustainability and visitor experience of the trails. To depict the current state, impact, measurements or potential policies, the geospatial tool utilizes a web application interface to disseminate the developed geodatabase. Users, including tourists, local communities, heritage organizations, environmental agencies, planners, and government authorities, can access the web-app and provide feedback on their experiences, suggestions, or reports on trail conditions. Thus, the managers continuously monitor and evaluate the feedback, updating the geodatabase and the web-app as needed. Feedback loops are established with the data contributors, ensuring a continuous flow of information (Figure 1).

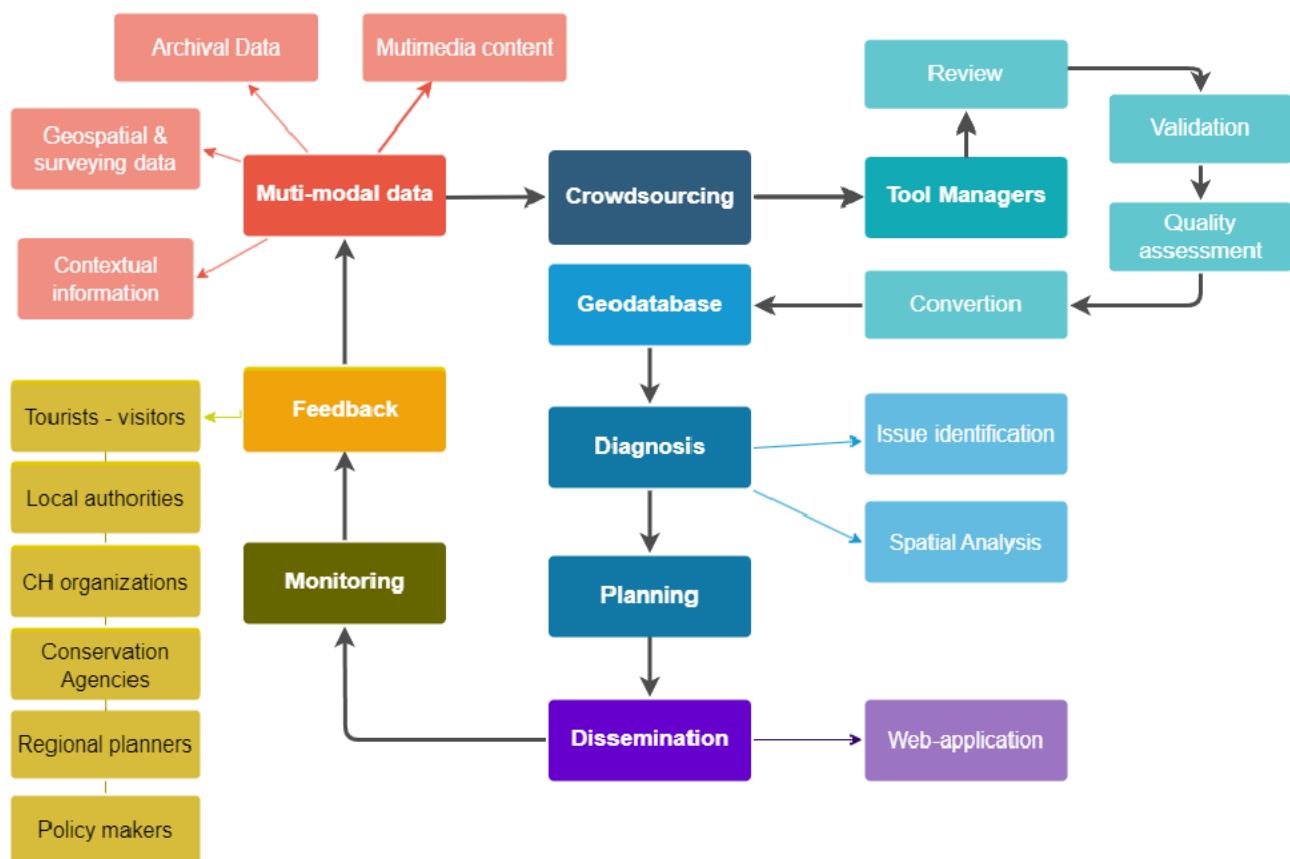


Figure 1. Workflow of the main processes and utilities of the proposed geospatial tool.

3.2. Geodatabase Design Principles

Geographic Information Systems (GIS) allow the documentation, organization, management, processing, analysis, visualization and dissemination of geographic information. In this study, a unique geodatabase is designed, developed and enriched with geographic and descriptive information concerning the Holy Site of Meteora. For the implementation of the geodatabase and its final products, the ESRI's ArcGIS Pro software package is utilized (version 3.0). The information is stored in the form of GIS layers and tables, and can be processed, analyzed and visualized. A variety of tools are provided for the easy search and management of this information, which can be easily selected and used. Not only the simple reading of digital data, but also the compilation of the application results with the appropriate administrative and analytical tools is possible.

All the available geospatial and descriptive data are integrated into a digital geodatabase, whose components can be visualized through the digital map environment of ArcGIS Pro, combined with multiple geographic base-maps providing a comprehensive visualization of the geospatial information. The derived digital map allows the input, storage, and easy retrieval of information related to the trails of the Holy Site of Meteora.

The database structuring process followed the architecture of the three levels (conceptual, logical, physical) that is commonly followed by modern database systems. During the conceptual design of the geodatabase, the following aspects are taken into account:

1. The study area concerns the archaeological and Holy Site of Meteora, where there is a network of walking trails with a total length of 35 km.
2. The representation of vector spatial entities is carried out using all forms of geospatial primitives (point, line, polygon).
3. The calculation of necessary geospatial information (e.g., length of trails, distances between points of interest) is performed by executing map algebra operations.

4. The visualization of specialized information is achieved through the execution of spatial, descriptive queries or correlations between the property fields (attributes) of the spatial entities.

Continuing with the logical design of the geodatabase, the requirements regarding the type of geodatabase and the relationship between its objects are specified. The logical design is based on the following:

- Developing a unique geodatabase based on relational model technology that includes vector spatial entities (feature classes), raster data, and tabular (geodatabase tables) data.
- Creating entities with embedded descriptive information. The connection between the spatial and descriptive information is made through an object-oriented data model, according to which the descriptive information is integrated into the corresponding spatial entities in the form of attribute fields.
- Selecting the Greek Geodetic Reference System (GGRS87) as the reference system for recording all vector spatial entities.
- Creating metadata to interconnect all entities stored in the database.

In the last phase of the physical design, the development of the geodatabase and its enrichment with all the available digital data is conducted, in the environment of ArcGIS Pro. Each spatial entity is stored as a separate thematic layer, allowing for visualization and presentation of geospatial information. Different symbols and labeling are selected for each thematic layer to differentiate spatial entities and visually convey necessary information. By overlaying multiple thematic layers, the possibility of map compilation and implementation of spatial operations and analysis is provided. Thus, the retrieval and study of information regarding the walking trails of the archaeological and Holy Site of Meteora is made available. It also provides the ability to produce embedded 2D maps with built-in tools and supports advanced functionalities, such as:

- pop-ups that display short pieces of information and images for specific points along the trail;
- dynamic visualization of the vertical profile of each trail, and;
- multimedia information relevant to landmarks, natural features and scenic viewpoints.

3.3. GIS Analysis Techniques

Spatial analysis for historic trails can involve several calculations and tools in the geodatabase in order to manage, diagnose, provide exact information, and finally, plan and depict sustainable policies. In the context of the geospatial tool, several analysis techniques that are tailored to the preservation and maintenance of historic trails are proposed and implemented. Firstly, slope analysis, elevation profiling, and contour analysis assess the terrain and identify challenging sections. Valuable information about the trail's difficulty, steepness, and changes in elevation can be extracted for visitors and regional planners. Then, viewshed analysis determines the areas visible from specific points along the trail, such as scenic viewpoints, viewpoints of cultural significance, or areas with obstructed views that may require vegetation management. The creation of buffer zones around specific trail features, points of interest or sensitive areas such as cultural heritage sites or environmentally sensitive habitats, helps assess the impact of development and encroachment. Buffer analysis can be combined with hotspot analysis. Hotspot analysis identifies clusters or concentrations of specific trail features or issues. High tourist density, high incidents of damage, or high levels of vegetation encroachment are spatially located and monitored. To enhance the trail network and the combined transport network, analysis tools are integrated into the tool, such as route analysis and connectivity analysis. Route analysis considers trail conditions, terrain, elevation, and visitors' preferences in order to assess accessibility and provide seamless navigation for visitors. The evaluation of the degree of connectivity within the trail network helps to identify gaps, bottlenecks, or disconnected segments that hinder accessibility or prevent the smooth flow of visitors.

By analyzing the connectivity, trail managers can identify areas where additional trails, connectors, or trailhead facilities may be needed to improve accessibility and promote sustainable use of the trail network. Sustainable trail networks may require integration with other modes of transportation, such as public transport or cycling routes, to access and distribute visitor traffic more evenly. The tool supports the determination of the best combination of transportation modes based on the existing transport infrastructure and by taking into consideration factors such as proximity to public transport, parking availability, and barrier-free access for individuals with disabilities. Further utilities of the tool concern spatial interpolation and land use analysis. Techniques, such as kriging or inverse distance weighting, estimate values at unsampled locations based on known data points. For example, if data on trail surface conditions (e.g., smoothness, roughness) or trail erosion levels are available at certain locations along the trail, these techniques can be employed to predict the conditions at other locations where data may be lacking. This information can help policy makers, local authorities and environmental agencies to assess maintenance needs, prioritize interventions, and allocate resources effectively to ensure safe and enjoyable trail experiences for visitors. Finally, analyzing land use patterns and overlaying them onto the trail network enable the recording of potential conflicts, zoning issues, or areas where land use changes may impact the historic trail.

3.4. Online Dissemination

Planning, decision making, regulatory and standards development and knowledge transfer are mandatory, but inefficient if they are not accessible, visually perceived and participatory. Once published on the web, the geodatabase bridges the gap between stakeholders involved in CH management. Its visualization can be used as a cartographic basis to link geopolitical, economic and social operations with their spatial reference for a wide range of scientific specialties. The general public can explore the linked open data, plan their visit, walking and recreation activities and share any route or related information they are interested in on social media.

The integrated dataset comprises the proposed trail network, related multimedia files, exact location data and information regarding land cover, transport links, local touristic businesses, descriptions and statistics, as well as general information and level of heritage attractiveness. Images are pre-processed before being published on the web to ensure a qualitative consistent and uniform display across all devices. The selected JPEG quality ranges from 95–98% to maintain the original resolution. Finally, they are converted to the sRGB color space. Video files need to be already online in a social media platform such as YouTube. The URL of the uploaded video is used to embed it and show it to the framework via the built-in front-end media player. The data are stored in the ArcGIS Online software cloud for global access to the maps, both by members and non-members of the ArcGIS community. The application is implemented on top of ArcGIS Web AppBuilder software [28] and the Leaflet.js library [29]. Leaflet.js is an open-source client-side JavaScript library for creating online maps and services with interactive, responsive and mobile-friendly design. The Esri Leaflet open-source software development package is used to access ArcGIS location services and extend or customize the built-in functionalities of ArcGIS Web AppBuilder. Emphasis is given to the interaction of the application with the user through (i) sophisticated map navigation and real-time information retrieval mechanisms, and (ii) multiple levels of logical/semantic search depth and specialization.

The web application enables the depiction of measures for sustainable management and eco-tourism, addressing key aspects such as awareness raising and promotion of lesser-known monuments along the network. By highlighting these sites, the application can distribute visitor flows more evenly and reduce overcrowding at popular locations. It also addresses the redistribution of visitor flows by providing information on alternative routes and off-peak times, promoting a balanced visitor experience. Additionally, sustainable means of transportation and touristic activities throughout the site are introduced, encouraging eco-friendly travel options and minimizing environmental impacts. Lastly, it

fosters active collaboration between policy makers and cultural heritage authorities, facilitating dialogue and informed decision-making to ensure the preservation and sustainable development of historic trails.

4. Implementation

4.1. Case Study

A case where it is essential to determine the limits of natural and cultural environment and conserve historical trails authenticity is that of Meteora, Greece. It is designated as a UNESCO World Heritage Site, based on the cultural criteria of UNESCO (C 1-5), as well as on a criterion concerning the natural environment (N 7) [30]. It has also, been declared as a Holy Site (Law 2351/1995) and a “Historic Pre-served Monument” with decision no. 10977/16.5.1967 of the Minister of the Presidency of the Greek Government. It includes one of the most important complexes of Orthodox monasteries in Greece, with an active monastic community with a long history. At the same time, it is a special geological phenomenon with giant rocky formations that were created 23 million years ago. They are a unique example of the evolution of the earth, characterized as a natural monument and protected by the Greek legislation. Construction is either prohibited, or limited, and land exploitation and hiring is under control, thus the area is inhabited only by monks and nuns, as well as the inhabitants of the small village Kastraki. Two buffer zones that include all the remarkable monuments of the site are defined for the conservation of the natural and cultural heritage against interventions. Zone A (where building is prohibited) protects the monastery complex of Meteora and the surrounding area. Buffer Zone B sets conditions on the construction of buildings in Kastraki–Kalambaka in order to avert any change in the area surrounding the Meteora rocks.

On the top or in hollows of these rocks, several monasteries, churches and hermitages were built from the 12th century [3]. The first hermit monks came to the inaccessible peaks in the 11th century. In the mid-14th century, the monk Nilos gathered the monks who lived in isolation in caves in the rocks around the skete of Doupiani, thus organizing monasticism in Meteora. In the 14th century, Hosios Athanasios the Meteorite established the first organized monastic community in Great Meteoron rock. Twenty-four monasteries, many cells, hermitages and ascetics flourished, located all over the rocks, for more than 600 years. Today six monasteries are active and there are ruins of many others at the crown and in the caves of the great rocks [31]. Thus, the ICOMOS/IUCN evaluation concluded that Meteora site met the qualifications of a World Heritage monument, fulfilling the following criteria:

- Criterion I: The Meteora monasteries, meaning “Suspended in the air” in Greek, demonstrate an exceptional artistic accomplishment and exemplify how architecture can transform a site into a place for retreat, meditation, and prayer.
- Criterion II: The frescoes created in 1527 by Theophanes the Cretan became a fundamental reference for post-Byzantine painting, shaping its iconographic and stylistic features and leaving a profound and lasting influence.
- Criterion IV: The Meteora stands as an exceptional illustration of monastic construction from the 14th and 15th centuries, reflecting the revival of early Christian hermitic ideals held in high regard by monastic communities, both in the Western world and within the Orthodox church.
- Criterion V: Despite being built under challenging conditions without practical roads, the Meteora monasteries persist to this day as precarious human habitations. However, they have become vulnerable to the passage of time.

In the area of the archaeological and Holy site of Meteora, 10 existing hiking trails are identified, following the traces of the historical paths of the area. They cross the whole area, approach all the large rocks of the region and connect the active monasteries, ascetics and churches with the urban areas of Kalambaka and Kastraki. Specifically, the proposed network of 10 trails covers an area of 808 ha, which is 43% of the UNESCO buffer zone (1884.14 ha) (Figure 2). The trails have a rich history that dates back to the 10th century when the first hermit monks arrived in the area. They also cross beautiful forests with

unique natural habitats, wild fauna and flora, such as the area of Meteora along with the Antihasia Mountains, that are included in the European network of protected areas NATURA 2000 with code GR1440003. The particularity of the area and the impact of natural phenomena on the monuments expose monks and nuns to several risks that could bring about considerable damage. Over-tourism is translated into degradation of the natural and cultural environment as well as the quality of life of the monastic community. The area is characterized by stewardship conflicts of interest.

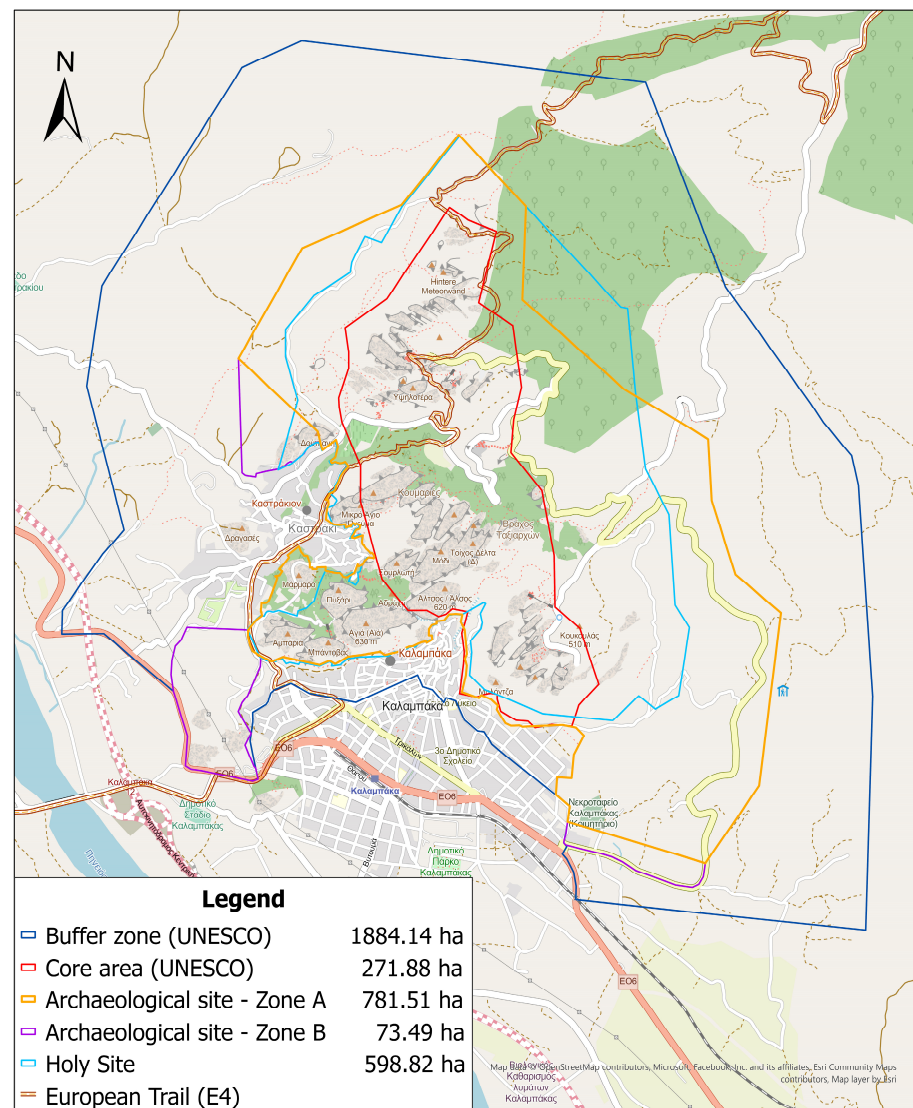


Figure 2. The Core area and the Buffer zone of UNESCO World Heritage Site of Meteora, the Holy Site boundaries and the archaeological site (Zones A and B) on OpenstreetMap's base-map.

Due to an increase in the population, private individuals submit requests for building activity in the settlements of Kastraki–Kalambaka on the foothills of Meteora, which would entail the reduction of buffer zone A and the extension of zone B. Meanwhile, there is no opportunity for the local residents to participate meaningfully in the decision-making process, and a lack of valid knowledge for sustainable mobility and alternative touristic activities.

4.2. Data Collection

By bringing together diverse sources of information into a centralized geodatabase, the tool creates a comprehensive repository for the historic trails. The data collection process

includes a detailed recording of the 10 walking trails that were discovered on the traces of the historical trails that served as access to the giant rocks and monasteries of Meteora. These trails run throughout the archaeological site of Meteora, but also extend beyond it to the northeast in a forest area. They connect the two nearby settlements with the six operational monasteries, as well as the monasteries among themselves. They move through a diverse landscape: urban outskirts, grazing areas, forests and forest expanses, at the foot or on top of giant rocks, with the degree of difficulty of the route usually being moderate or easy (Figure 3 left).

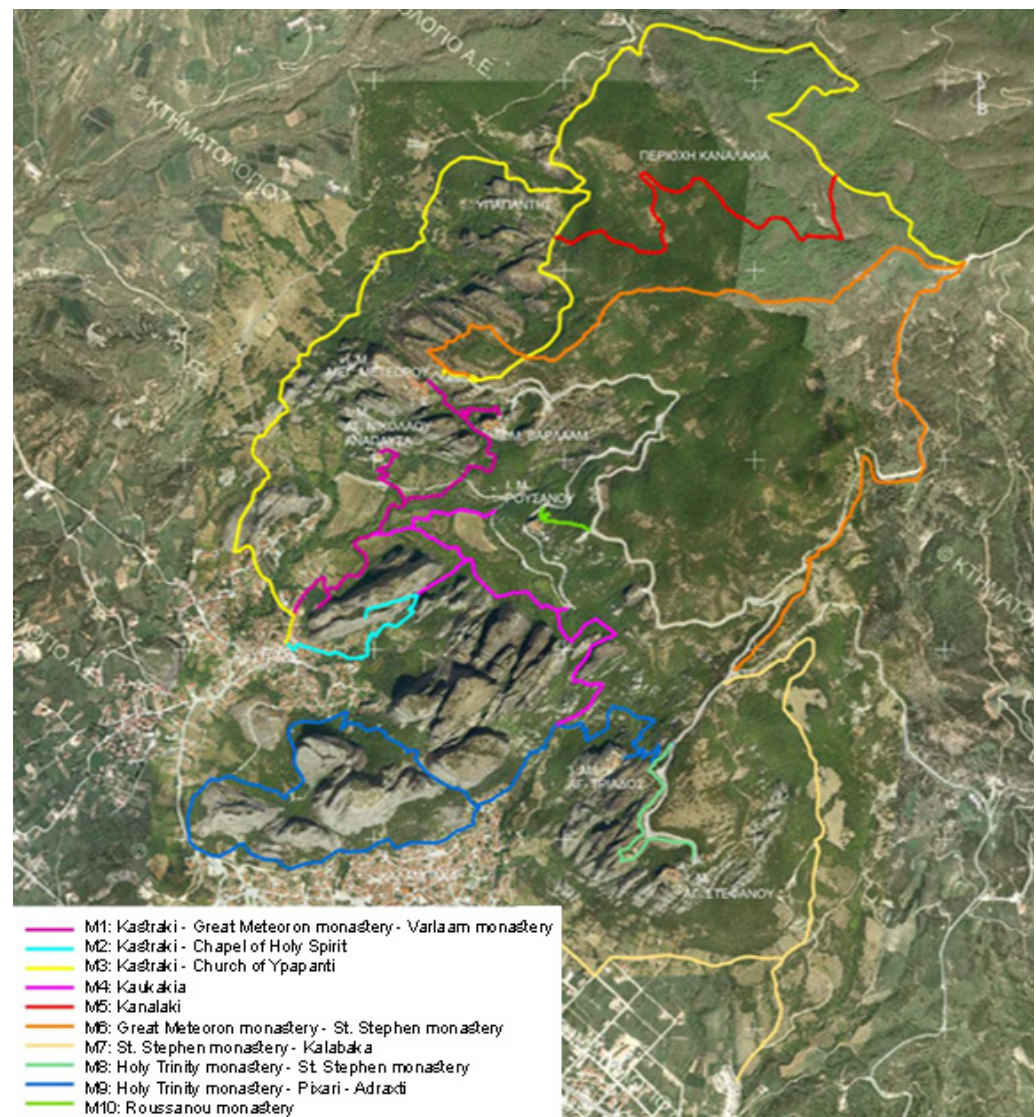


Figure 3. The 10 historic trails (M1–M10) of the proposed network in Meteora.

The documentation of the 10 trails was carried out through on-site surveying using a GPS receiver and a GoPro camera. The collected data is accompanied by digital files and videos in mp4 format, along with the itinerary of each trail, which includes characteristic photos (ground and aerial from a UAV) and 360-degree images from points of interest, and is accompanied by dynamic information regarding the altitude of the hiker's position and relative position on the trail. This process ensures the necessary accuracy of the measurements. Moreover, the recorded itinerary includes the possible hazards and the difficulty of the recorded trails.

The trails incorporate unique natural and cultural elements, such as landscapes, the archaeological site of the monastic complex of Meteora, chapels, sketes, etc. (Figure 3 right).

Given the area's particular geomorphology, each trail is also intended for the study of nature (plants, trees, reptiles, birds, geological formations, etc.) (Figure 4).

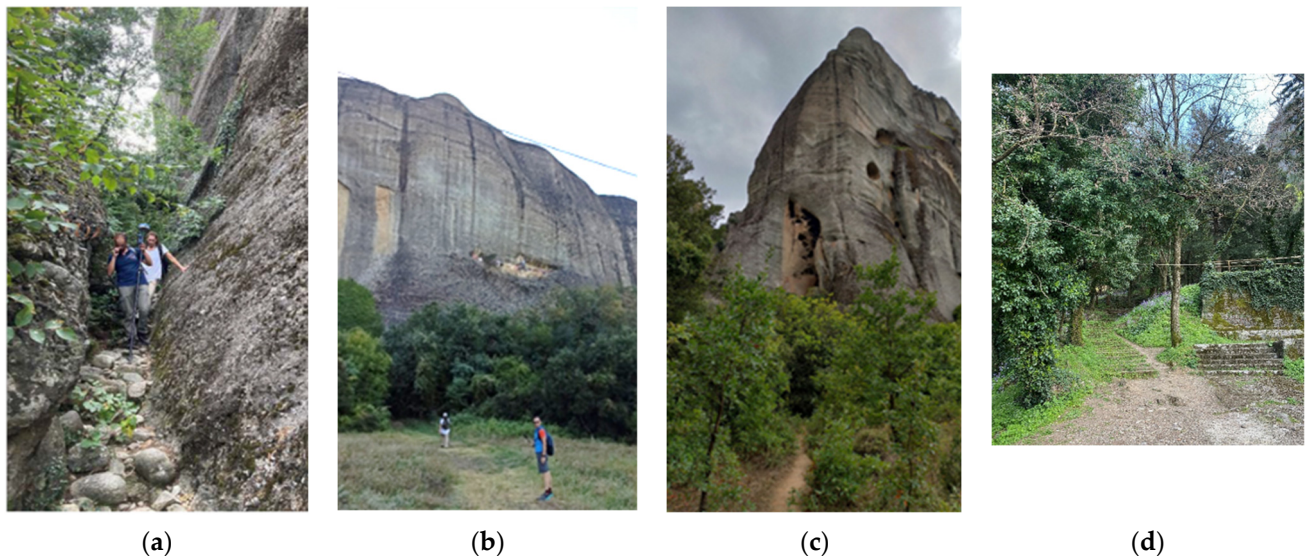


Figure 4. Photographic documentation from various locations along the trails: (a) rock of Holy Spirit (Agio Pnevma); (b) cave hermitage of St. George Mandilas; (c) hermit caves; (d) rest area in the forest before reaching the abandoned Monastery of Ypapanti.

4.3. Geodatabase

The geodatabase was implemented with ESRI's ArcGIS Pro software and includes valuable descriptive and geospatial information on the area of the Holy Site of Meteora, as well as information obtained through detailed data analysis and processing. The primary goal is to facilitate access to the natural environment, settlements and historical or cultural sites of Meteora. The geodatabase includes the following information:

- Five cartographic base-maps: OpenStreetMap; Esri's World Imagery; Esri's World Topographic Map; World Topographic Map (hill-shade); and high-precision orthophoto covering the Site of Meteora, compiled by the research team.
- The section of the European walking trail E4 that crosses the area.
- The settlements, categorized according to their population status (2011 census).
- Points of interest, appropriately categorized.
- The peaks and names of the rock formations at the Holy Site of Meteora.
- The most important tourist sites, archaeological sites, and museums at the Holy Site of Meteora.
- Land uses, classified according to Corine 2018.
- The hydrological and inland waters network.
- Protected areas (Natura 2000 areas, Special Protected Areas according to the Barcelona Convention, World Heritage Sites).
- The transportation network.

In addition, the geodatabase contains a comprehensive geometric and analytical description of the Meteora trails. Geometric and physiognomic characteristics (vegetation, terrain), attractiveness, service level, combined movements, correlation with other trails, and difficulties, such as slippery or steep terrain, steep slope, bad soil, and inaccessible points of interest, are analyzed. Each of the recorded historical trails is categorized according to the type of route (hiking, mountaineering, climbing), the mountain unit in which it is located, and the difficulty level (easy, moderate, difficult, very difficult). The length and the maximum or/and minimum elevation are also provided for those routes where such relevant information is available. Some trails are divided into sections, depending on the topography and distance, the necessary rest stops, the degree of difficulty and the

proximity to settlements, visitor gathering places or viewing points. For each section, a vertical profile of the trail section can be created exploiting the captured geometric data (Figure 5). Furthermore, analytical records regarding the location and type of necessary interventions along the trails are recorded in detail. The interventions concern:

- the establishment of marking signs (reception, location, information, warning and direction signs) (Figure 6);
- the maintenance of walking trails (regular cleaning positions, landscaping); and,
- necessary furniture (positions of litter bins, benches/seats, lighting, drinking water sources, parking spaces).

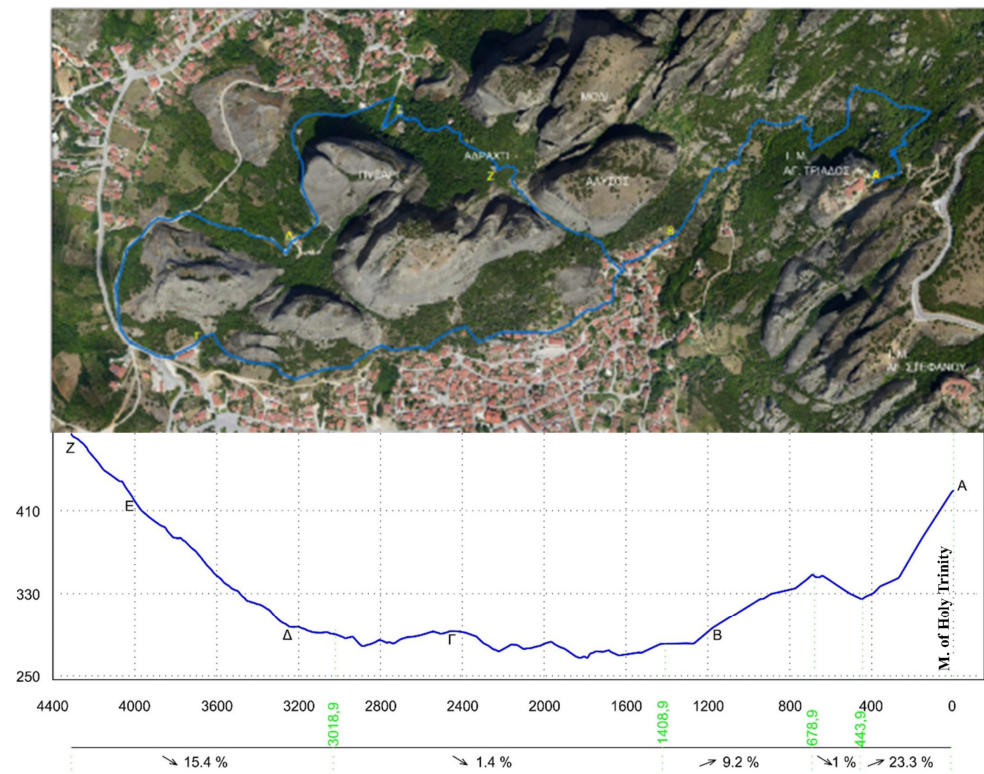


Figure 5. The horizontal (**up**) and vertical (**bottom**) profile of the trail M9.

Finally, in addition to the description of the trail with extensive text, digital image collections and video files are also included in the geodatabase.

4.4. Web GIS Application

The web-GIS application includes map API services and intuitive tools for spatial and contextual analysis. The goal of the user interface (UI) design is a user-friendly and stylish graphical environment, while maintaining a simple and consistent structure, and achieving a sense of predictability, i.e., making the user able to assess the location of each element of the website and the way each element works. The developed app presents the historical.

The Meteora trail network integrates a map of the ten trails of the archaeological area of Meteora, the European path E4, and two groups of point symbols, i.e., road junctions and points of interest. Besides the navigation utilities, the legends and the distance measurement offered by a simple map viewer, geoprocessing and analysis tools to perform operations on the visualized trails are integrated into the cartographic display. These enable data transformation, data conversion, proximity analysis and suitability estimation. The points of interest are clickable and activate the display of a pop-up modal window with the name of the feature for identification purposes, associated attributes, and photographic documentation. A powerful visualization tool that dynamically generates the cross-sectional view of the elevation along a selected path is the Vertical Profile tool (Figure 7). The profile

graph displays elevation changes along the trail, helping users to visualize the steepness of the trail, and any hills, valleys or other changes in the terrain. It offers the following features: (i) dynamic creation of the profile graph of the selected trail or path; (ii) display of the elevation along the trail in feet or meters; (iii) display of the slope of the trail as a percentage or in degrees; (iv) highlighting specific points along the trail such as trailheads and, (v) analyzing the trails' characteristics such as maximum and minimum elevation, length, etc. It is particularly useful in route planning for hikers, as well as for the evaluation of the suitability of a trail and the identification of potential safety concerns for land managers. Below the map, detailed and short descriptions, image collections of the route and videos of the recorded trekking are dynamically presented (Figure 8).

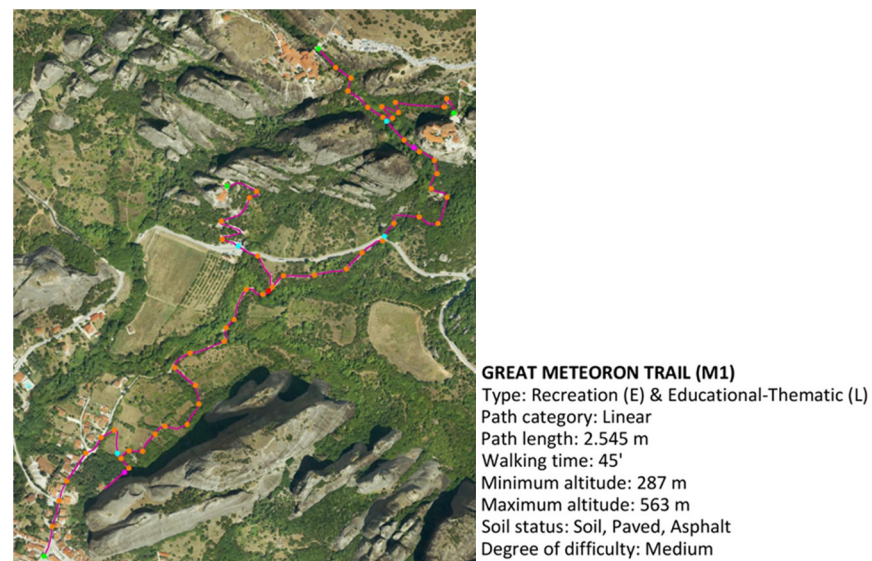


Figure 6. (Left): The proposed positions of the marking signs along the trail M1: reception sign (green); position sign (cyan); warning sign (red); information sign (magenta); direction sign (orange). (Right): Basic characteristics of the trail M1.



Figure 7. Vertical profile of the selected part of a trail.



Figure 8. Presentation of multimedia material based on the individual sections of the route.

First, the side information panel provides the geometric characteristics of the route, i.e., total length, level of difficulty and the maximum and average gradient. Emphasis is given to the charts, with the total estimated walking time and the distinction of the route in proposed sections. Each section follows the horizontal plan, depicted in a high-resolution orthophoto, with the starting and ending points marked. These points define the proposed direction of the route. The text documents provide information about changes in direction and elevation, intersections with other trails, the steepness of inclines and declines, land cover, watershed boundaries and terrain ruggedness in order to help pedestrians and hikers to understand the difficulty of the trail, plan their route accordingly and recognize the types of ecosystems they may encounter. Images of signs along the trail, natural features such as rock formations, streams and forests, as well as cultural, religious and historic monuments and points of interest, enrich the text documents and enhance perception of the

trail. Moreover, trail markers, directional signs, safety information and indications, as well as interpretive signs that enable easy and safe navigation, have been spatially recorded, captured and presented in the form of text and images (Figure 9 top).



Figure 9. Proposed structural and safety interventions and video file thumbnail, uploaded to YouTube.

Finally, for the video files, the title, the cover image (thumbnail) and their description are displayed in corresponding boxes (Figure 9 bottom). By selecting the thumbnail, the video is played in a relatively small pop-up window. The integrated viewing system is supported by YouTube and makes it possible to redirect to the official address where it has been posted.

5. Discussion

The developed geospatial tool provides valid knowledge for sustainable mobility and alternative touristic activities. The proposed integrated network introduces sustainable means of transportation throughout the broader region. It enhances awareness raising, promotion of lesser-known areas and points of interest of the region, and redistribution of visitor flows. The decision making process can be achieved through the proposed GIS-based analysis method and the Master Plan for walking routes can be used as guidance for trail management and operational planning. The proposed tool links geopolitical, economic and social operations with their spatial reference on a cartographic basis. Thus, it makes the strategy for sustainable development more precise and forward-looking, allowing for planning, maintenance and promotion. The easy-to-use and interactive services make the online GIS-based application a means of understanding basic knowledge and providing meaningful contact with the space and its historical and cultural context. It can also depict sets of measures and addresses the following actions:

- awareness raising and promotion of lesser-known monuments along the network;
- redistribution of visitor flows and transport accessibility;

- introduction of sustainable means of transportation;
- active collaboration between policy-makers.

Unlike the Nakahechi Heritage Route analysis [17] and Georoutes in Santa Elena province [21], the presented work integrates various types of data source (topographic surveying, photographic documentation, walking tour video recording, and archival research) to create a more comprehensive and heterogeneous dataset. It covers multiple factors and incorporates both on-foot and bicycle metrics, making it more versatile for tourist-centric historic sites with different transportation modes. Similar to the GIS-based Atlas of Roman Routes in the Danube Region [26], the geospatial tool provides an online solution for dissemination, remote access, and collaboration purposes, making it accessible to a wider audience. By providing valid knowledge for sustainable mobility and alternative touristic activities, the tool helps promote sustainable tourism practices and alleviate the burden on fragile ecosystems or culturally significant sites. It enables the identification and mapping of damaged sections of trails, overgrown vegetation, and other issues, which allows for specific interventions to improve the trail's condition and minimize environmental impacts.

The feedback obtained through crowdsourcing plays a vital role in improving the geospatial tool, refining the data integration process, enhancing trail planning and management, and addressing any concerns or issues identified by the users. It helps create a continuous feedback loop where the tool managers assess the input data, make necessary updates or improvements, and then provide feedback to the groups involved in the crowdsourcing process. The managers play a crucial role in maintaining the integrity of the tool and making informed decisions regarding data selection and utilization. Each of the following target audience could benefit from utilizing this tool:

5. **Tourists and Visitors:** Tourists and visitors interested in exploring and experiencing historic trails can utilize the web-based platform of the tool to plan their itineraries, learn about points of interest, view multimedia content, and gain insights into the historical and cultural significance of the trail network. The interactive maps and 3D visualizations enhance the visitor experience and enable them to make informed decisions about their trail exploration.
6. **Local Communities:** The tool can be valuable for local communities residing near the historic trails. It can engage local community members by involving them in data collection, contributing to the geodatabase, and providing input on the maintenance and development of the trails. It also facilitates sustainable community-based tourism initiatives, leading to economic benefits for the local population.
7. **Heritage Organizations:** Organizations dedicated to the preservation and promotion of cultural heritage can exploit the tool to manage and safeguard historic trails effectively. It assists in identifying conservation needs, prioritizing maintenance activities, ensuring the preservation of heritage assets and supporting educational initiatives.
8. **Environmental and Conservation Agencies:** Environmental and conservation agencies can benefit from the tool's capabilities in identifying issues along the trails, such as damaged sections or ecological threats. They can use the geospatial information to assess the impact of trail usage on the environment, monitor biodiversity, and plan conservation measures and sustainable management practices, ensuring the balance between heritage preservation and ecological conservation.
9. **Urban and Regional Planners:** Urban and regional planners involved in the development and management of sustainable cities and communities can utilize the tool to incorporate historic trails into their planning processes and embrace cultural heritage as a vital component. The geospatial tool provides valuable information for decision-making regarding the integration of trails with urban infrastructure, land-use planning, and tourism development.
10. **Government Authorities and Policy Makers:** Government authorities responsible for heritage preservation, tourism development, and regional planning can make informed policy decisions and attain sustainable development goals, such as those outlined in the UN Sustainable Development Agenda 2030. The comprehensive data

and analysis offered by the tool facilitate evidence-based planning, identification of priorities, and allocation of resources.

6. Conclusions

The paper provides necessary technical, legal, historic and administrative information related to the developed tool and its use. The heterogeneous dataset derives from topographic surveying, photographic documentation, walking tour video recording and extensive archival research. The GIS reference points trace the historic routes. A unique geodatabase, which is based on relational model technology and includes vector spatial entities, mosaics and tabulated data, is developed within the ArcGIS Pro environment. The connection between spatial and descriptive information is achieved through an object-oriented data model, according to which descriptive information is integrated into the corresponding spatial entities in the form of attribute fields. The calculation of the necessary geometric information (e.g., length of paths, distances of points of interest) is conducted by performing map algebra operations, alongside the visualization of specialized information by spatial, descriptive queries or correlations between attribute fields of spatial entities. Damaged sections of trails, overgrown vegetation, signage and wayfinding markers, as well as lack of handrails, seating or rest areas along the trail, have been also, detected, spatially identified, analyzed and mapped in order to form specific interventions. Finally, the developed geodatabase, enriched with multimedia information relevant to landmarks, natural features, scenic viewpoints or other points of interest, is disseminated in the context of ArcGIS online. The web application embeds 2D maps with built-in features, such as bookmarks, measurement tools and search bars. Interactive elements include (i) pop-ups that display short information and images about specific points or features along the trail and (ii) dynamic visualization of the vertical profile of each trail, namely the 3D representation of its elevation, including the high points, low points, and changes in slope.

Author Contributions: Conceptualization, C.P., C.I. and S.S.; methodology, C.P., A.-M.B., K.A. and M.G.; software, A.-M.B., K.A. and M.G.; validation, C.P., C.I. and S.S.; formal analysis, S.S.; investigation, R.C. and F.B.; resources, A.-M.B., K.A., R.C. and F.B.; data curation, R.C.; writing—original draft preparation, A.-M.B., K.A. and M.G.; writing—review and editing, C.P., C.I. and A.-M.B.; visualization, S.S., A.-M.B. and M.G.; supervision, C.P. and C.I.; project administration, C.P. and C.I.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received funding from the Hellenic Ministry of Environment and Energy, project “Guidelines for planning and strategy for the development of hiking and cycling trails in Thessaly region” (project code: 91008800 and ADA: Ψ7PB46ΨΖΣ4-ΔΧ0).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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