Heritage Science

REVIEW

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Bibliometric analysis of GIS applications in heritage studies based on Web of Science from 1994 to 2023

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Abstract

Heritage holds significant historical, cultural, or natural value. GIS technology integrates spatial and attribute data of heritage sites, providing a powerful modern tool for better understanding, preservation, and management of heritage resources. To reveal the progress and trends in GIS applications in heritage studies (GIS-Heritage), this study collected and analyzed 1026 relevant research articles published between 1994 and 2023 from the Web of Science database. The analysis was conducted using the VOSviewer software for bibliometric and visualization analysis. The results demonstrated that Italy has made the largest contributions in the field of GIS-Heritage. There exists a close collaboration among research institutions. Journals like the *Journal of Cultural Heritage* played crucial roles. The most influential authors include Brown, Agapiou, and Nicu. The key research themes identified encompass cultural heritage, GIS, sustainable development, spatial analysis, archaeology, conservation, and photogrammetry. Based on the findings of the bibliometric analysis, this paper puts forward future research recommendations in the field of GIS-Heritage, focusing on data integration, technological innovation, as well as interdisciplinary and international collaboration.

Keywords GIS, Cultural heritage, Remote sensing, Photogrammetry, Spatial analysis, Sustainable development, Geodiversity, Biodiversity

Introduction

The term "heritage" refers to the cultural and natural legacies passed down by a nation, region, or cultural group [1]. Cultural heritage encompasses the tangible and intangible manifestations of human history and culture, including historic buildings, archaeological sites, traditional crafts, and cultural traditions [2, 3], while natural heritage covers natural landscapes, biodiversity and geodiversity, involving ecosystems, plant, animal and fungi species, as well as the geological features [4–6]. These heritages hold significant historical, cultural, or natural value, representing the uniqueness and legacy of a society or culture. Conducting heritage studies contributes to the understanding, preservation, and transmission of cultural and natural patrimony [7], facilitating a better comprehension of the evolution and development of history, culture, and civilization [8], promoting the protection of cultural diversity and cultural identity [9], and fostering tourism and economic development [4]. Heritage studies have undergone a long history of development, gradually expanding to cover a wide range of research areas, including archaeology, history, anthropology, ecology, geography, paleontology, and geology, among others. Particularly, the establishment of UNESCO and the formulation of the World Heritage List have significantly propelled the rapid development of heritage studies [10]. To date, heritage studies not only focus on traditional cultural heritage but also extensively address the research of natural and modern cultural heritage, thereby adapting to the ever-changing social demands.

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GIS (Geographic Information System) is a technology used for capturing, storing, managing, analyzing, and visualizing geographic data [11]. GIS integrates geographical spatial data, such as maps, satellite images, and terrain data, and attributes, such as demographic statistics and land use, to create visual maps and conduct spatial analysis, facilitating a better understanding of spatial relationships and decision-making [12]. Due to its technical features, GIS holds significant potential applications in heritage studies. Firstly, GIS provides precise geographical positioning of heritage sites, aiding stewards in the better management and protection of heritage resources [1, 11]. Secondly, GIS can be used to analyze and assess the impacts of natural and anthropogenic threats on heritage, such as geological disasters, Global Change, and urban expansion, to implement appropriate conservation measures [1, 2, 13]. Furthermore, GIS can be employed for the digital recording and document management of heritage, as well as for interpreting historical geographical information, thereby enhancing the understanding of the history and cultural background of heritage [1]. With the emergence of historical urban landscape methodologies, the application of GIS in heritage studies has gradually evolved, encompassing a wide range from heritage preservation to risk assessment, integrating modern technologies such as Historic Building Information Modelling (HBIM) with heritage information modeling, digital preservation techniques, and others, providing a powerful modern tool for better understanding, protection, and management of heritage resources [8, 14–16].

GIS technology plays a crucial role in heritage studies, effectively promoting the sustainable conservation and transmission of heritage resources. In GIS applications in heritage studies (GIS-Heritage), given the current era of rapid digital technological changes and innovations, the academic and industrial sectors need to identify the specific research directions and future development trends worth focusing on. While some review studies on GIS-Heritage have already been conducted [3, 4, 17], it is noteworthy that scholars are more concerned with discussing technical solutions and future visions rather than conducting empirical analysis based on large-scale statistical data. In specific scientific fields, bibliometric methods have been widely used in review studies to help researchers objectively and comprehensively understand research trends and future development directions in specific fields [18, 19]. In the field of GIS-Heritage, although some scholars have conducted bibliometric analyses on specific topics, such as the integration of GIS and BIM and cultural heritage BIM [12], there has been no dedicated bibliometric analysis discussing the overall status and development directions of GIS-Heritage to date.

Therefore, to provide a comprehensive overview of the research achievements in GIS-Heritage, this paper, through bibliometric analysis, summarizes the latest progress, research directions, and future development trends in GIS-Heritage research, providing valuable references for scholars and practitioners in the GIS-Heritage field.

Methodology

The research framework is illustrated in Fig. 1. The Web of Science database was chosen as the data source for bibliometric analysis of GIS-Heritage publications and the co-occurrence network of keywords using VOSviewer software. The selection of the Web of Science database is justified by its broad academic coverage, high-quality literature, comprehensive citation data, and global reach, making it an ideal data source for bibliometric analysis [18, 20]. VOSviewer software was chosen for its specialized application in handling and analyzing scientific literature data, enabling researchers to visualize and comprehend relationships, collaboration networks, citation patterns, and co-occurrence networks among documents [20, 21], establishing VOSviewer as a widely applied tool in bibliometric analysis.

Bibliographic data retrieval

For database selection, three major databases within the Web of Science were chosen: the Science Citation Index Expanded (SCIE) from 1975 to the present, the Social Sciences Citation Index (SSCI) from 1975 to the present, and the Arts & Humanities Citation Index (AHCI) from 1975 to present, to cover journal literature in the fields of natural sciences, social sciences, and humanities.

Regarding the retrieval strategy, the search expression used in the Web of Science was: TS = ("geograph* inform* system*" OR GIS) AND TS = (*heritage*). Firstly, the TS search approach guaranteed that information relevant to GIS-Heritage could be retrieved in the title, abstract, and keywords. Secondly, the selected terms guarantee relevance to GIS-Heritage, considering characteristics of keywords such as "heritage," "geoheritage," "geology heritage," "geomorphology heritage," and "biological heritage." The use of TS = (*heritage*) ensures coverage of heritage-related literature while excluding "biodiversity" and "geodiversity" as direct search terms to maintain relevance to heritage studies.

Regarding document types, the selection was limited to Article, Review Article, and Early Access. This choice is justified as SCIE, SSCI, and AHCI databases primarily contain journal literature, and while most papers are original research articles, they may also include proceeding papers, meeting abstracts, and editorial materials. Excluding document types other than Article, Review

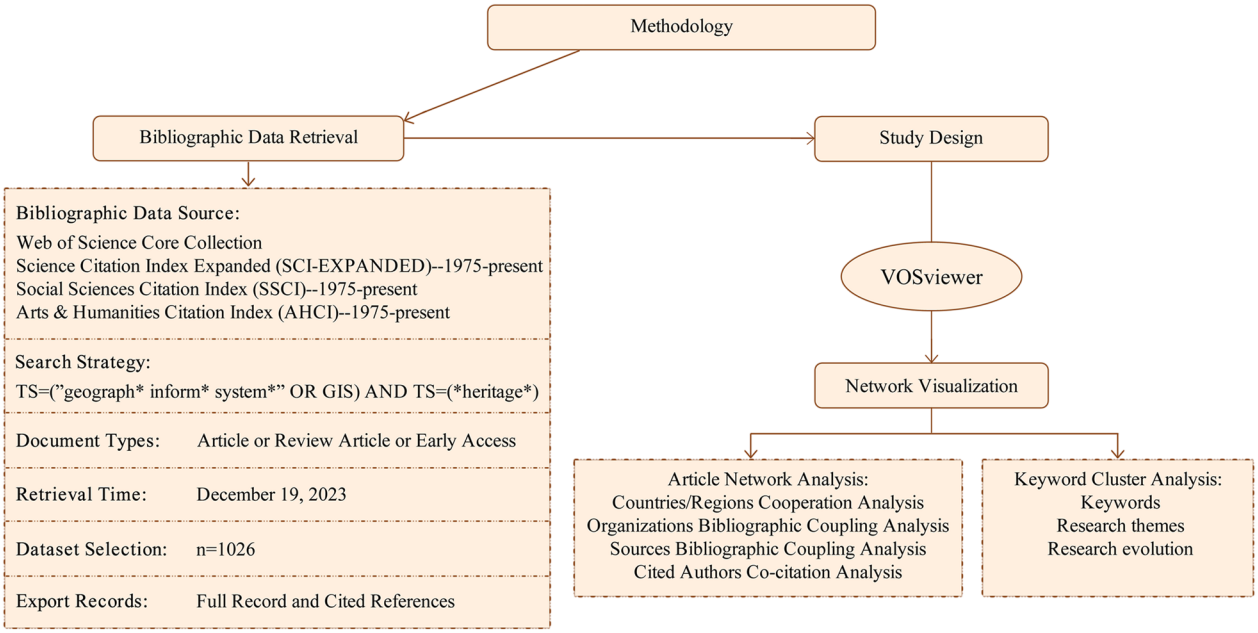

Fig. 1 Bibliometric Analysis Framework for GIS-Heritage (1994–2023)

Article, and Early Access ensures the research nature of the retrieved literature.

No starting date was specified regarding the date range, and the last search was conducted on December 19, 2023.

Following this retrieval process, a total of 1026 relevant documents from the years 1994 to 2023 were obtained.

Lastly, to ensure the replicability of the method, no manual screening of the retrieved data was conducted. Instead, the 1026 relevant documents were directly selected from the Web of Science and exported as full records and cited references for use as the bibliographic data in this study.

Study design

Bibliometric analysis is a method used to study and evaluate scientific literature. Common subjects of bibliometric analysis include the most productive countries/regions, institutions, journals, and authors in the research field, as well as the quantity, quality, collaborative relationships, citation relationships, co-occurrence relationships, and more of scientific literature. This analysis can be used to analyze the overview and development trends of a scientific field [22, 23].

In this study, VOSviewer software (version 1.6.19) was utilized for bibliometric analysis. This software is used to create various analysis graphs to illustrate the relationships between documents. In the bibliometric analysis graphs based on VOSviewer, circles, and labels represent a node, where a larger circle indicates greater importance of the node. Lines represent relationships or connections between nodes, with thicker lines indicating stronger relationships. Nodes or lines of the same color represent the same cluster.

The dataset of 1026 GIS-Heritage-related documents was imported into VOSviewer, generating bibliometric analysis graphs, including cooperation analysis, bibliographic coupling analysis, co-citation analysis, and co-occurrence analysis for keywords. Before conducting co-occurrence analysis on author keywords, synonymous terms with similar meanings, such as various singular and plural forms of "geographic information system," were merged into "GIS." Ultimately, these bibliometric analysis graphs revealed the relationships and co-occurrences among nodes representing countries/regions, research institutions, literature sources, cited authors, keywords, and more.

Study limitations

While providing a valuable perspective on the GIS-Heritage field, it is essential to acknowledge the following limitations of this study. First, the choice of SCIE, SSCI, and AHCI within the Web of Science database and the restriction to the article, review article, and early access types may overlook GIS-Heritage literature in other disciplinary areas, such as engineering or non-English literature. Second, as the Web of Science is an abstract database without direct provision of full-text data, the complexity of GIS technology and the diversity of GIS integration with other modern technologies necessitate in-depth interpretation of document content through

abstracts and full-text readings when analyzing cross-relationships between different clusters, potentially introducing subjectivity into content analysis and literature citation.

Article network analysis

Publication trend analysis

Analyzing the publication trends by year can assess the activity within the research field. Figure 2 presents the distribution of publication years for 1026 relevant GIS-Heritage documents. The data cutoff date for 2023 is December 19th. GIS-Heritage research literature was first indexed in Web of Science in 1994 [24] and then in 1996 [25]. Subsequently, from 1999 to 2023, research articles in the GIS-Heritage field have been published annually, showing a noticeable growth trend. Particularly, from 2016 to the present, there has been a significant increase in the number of publications, indicating a sustained and relatively high level of research activity within this field.

The sustained high level of activity in the GIS-Heritage field from 2016 to the present may be attributed to the continued advancement of GIS technology and its widespread application in heritage research. Currently, there is a global surge in heritage research [20, 22, 26], suggesting that this level of activity within the GIS-Heritage field is expected to persist.

Countries/regions cooperation analysis

Figure 3 presents the co-authorship network of countries/regions in the GIS-Heritage field identified by VOSviewer, displaying 21 countries/regions (with at least 15 publications and no fewer than 15 citations) out of 93 countries/regions in the dataset.

Table 1 lists the top 10 countries/regions contributing to GIS-Heritage, ranked by the number of documents.

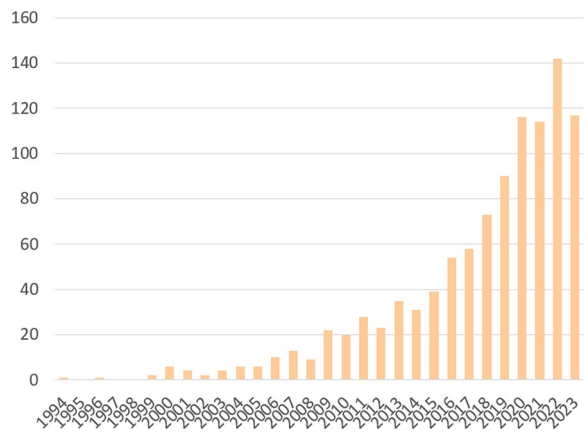

Fig. 2 Publication trend analysis of GIS-Heritage (1994–2023)

Figure 3 and Table 1 indicate that from 1994 to 2023, Italy has been the most prolific and highly cited country in the GIS-Heritage field among 93 nations or regions worldwide. Italy, China, Spain, the USA, and England are significant collaborators, showing strong cooperation and high citation numbers.

It is noteworthy that, in terms of publication quantity, European countries occupy seven out of the top 10 positions. Europe's leading position in GIS-Heritage research is a result of a combination of cultural, environmental, and socio-economic factors. These factors include abundant heritage resources, substantial investments, economic prosperity, basic needs fulfillment, and high-quality education, collectively fostering a profound understanding and appreciation of heritage resources. This places Europe at the forefront of GIS-Heritage research, making significant contributions to the field's development [27–30].

Organizations bibliographic coupling analysis

Organizations bibliographic coupling analysis can reveal the academic collaboration network among different research institutions. Figure 4 presents the bibliographic coupling analysis of organizations in the GIS-Heritage field identified by VOSviewer, displaying 13 organizations (with at least 10 publications and no fewer than 10 citations) out of 1432 organizations in the dataset.

Table 2 lists the Top 10 organizations contributing to GIS-Heritage, along with their countries, ranked by the number of documents.

Figure 4 and Table 2 indicate that, in terms of publication quantity, the Chinese Academy of Sciences exhibits high activity in GIS-Heritage research. Regarding collaboration, European universities show close cooperation, with Consiglio Nazionale delle Ricerche (CNR) collaborating with the Chinese Academy of Sciences. In terms of citations, both the Chinese Academy of Sciences and CNR have received significant attention, while Cyprus University of Technology and Universidade do Minho have high average citation numbers, indicating extensive attention and citations for the research conducted by these organizations.

Sources bibliographic coupling analysis

Sources bibliographic coupling analysis can identify the important journals in a specific research field and their interdisciplinary research characteristics. Figure 5 presents the bibliographic coupling analysis of sources in the GIS-Heritage field identified by VOSviewer, displaying 10 sources (with at least 15 publications and no fewer than 15 citations) out of 351 sources in the dataset.

Table 3 lists the Top 10 sources contributing to GIS-Heritage, ranked by the number of documents.

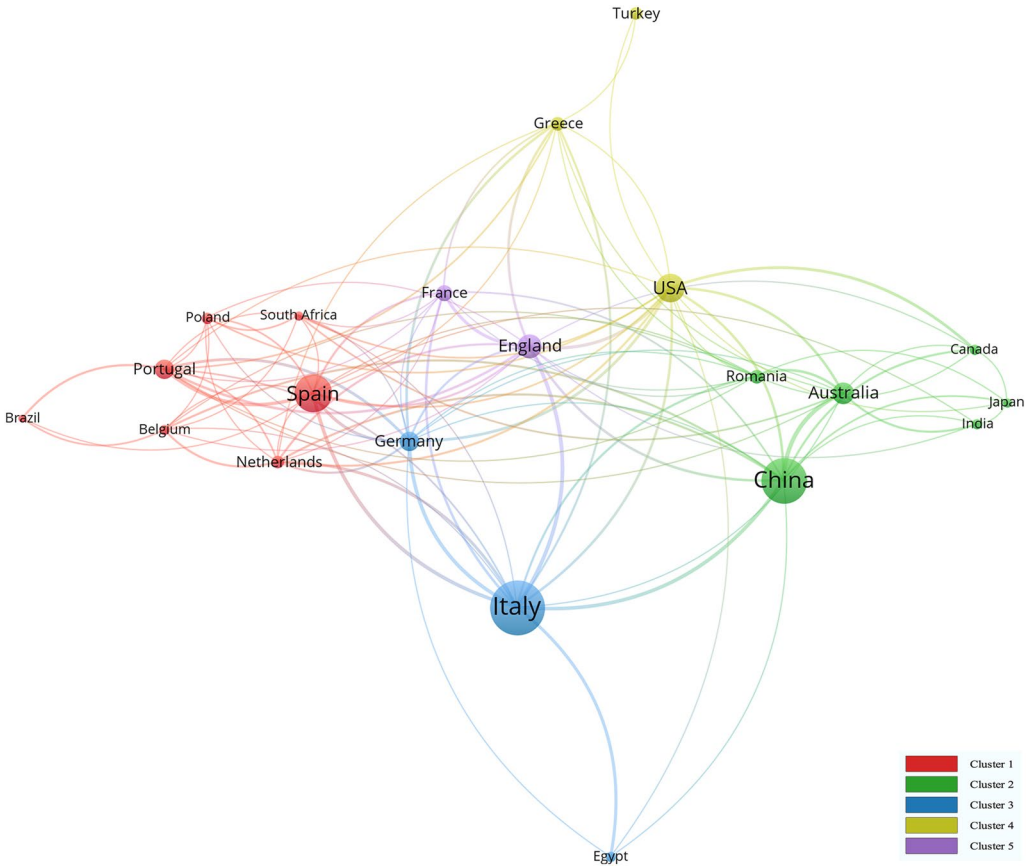

Fig. 3 Mapping of countries/regions co-authorship analysis

Table 1 Top 10 countries/regions contributed to the GIS-Heritage

No	Country/region	Cluster	Continent	Documents	Citations	Links	Avg. pub. year
1	Italy	3	Europe	193	3187	14	2018
2	China	2	Asia	150	1152	12	2020
3	Spain	1	Europe	115	1969	14	2018
4	USA	4	America	79	1590	16	2015
5	England	5	Europe	63	1160	14	2016
6	Australia	2	Oceania	57	1563	10	2015
7	Germany	3	Europe	49	2332	14	2016
8	Portugal	1	Europe	47	946	13	2018
9	France	5	Europe	37	639	10	2018
10	Romania	2	Europe	31	499	12	2018

Figure 5 and Table 3 demonstrate that, in terms of publication quantity, *Sustainability* and *Journal of Cultural Heritage* are the major sources in the GIS-Heritage field. In terms of citation impact, *Journal of Cultural Heritage* and *International Journal of Architectural Heritage* stand out with high citation counts and average citations, indicating their significant role in GIS-Heritage research. By examining the JCR subject categories of the Top 10 sources, it becomes evident that these journals span various disciplines, including environmental science, chemistry, earth science, geographic information, remote sensing, and architecture. This highlights the interdisciplinary nature of GIS-Heritage research.

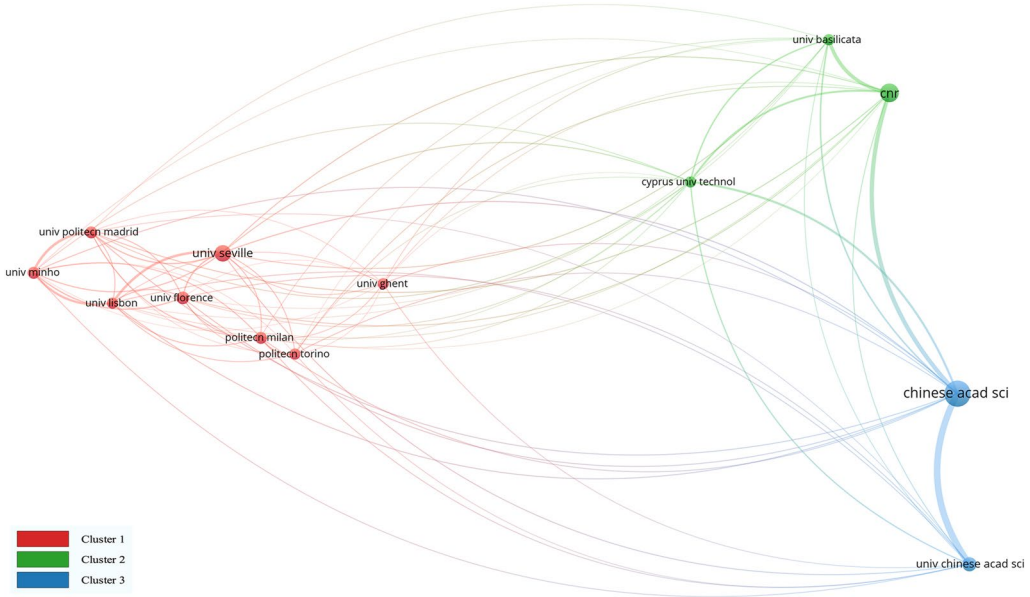

Fig. 4 Mapping of organizations bibliographic coupling analysis

Table 2 Top 10 organizations and their Countries contributed to GIS-Heritage

No	Organization	Country	Cluster	Documents	Citations	Avg. citations
1	Chinese Academy of Sciences	China	3	33	485	14.6
2	Consiglio Nazionale delle Ricerche	Italy	2	21	337	16.0
3	University of Seville	Spain	1	18	187	10.3
4	University of Chinese Academy of Sciences	China	3	14	213	15.2
5	University of Florence	Italy	1	12	163	13.5
6	Polytechnic University of Milan	Italy	1	11	204	18.5
7	Universidade do Minho	Portugal	1	11	210	19.0
8	Universidad Politécnica de Madrid	Spain	1	11	93	8.4
9	Cyprus University of Technology	Cyprus	2	10	299	29.9
10	Politecnico di Torino	Italy	1	10	152	15.2

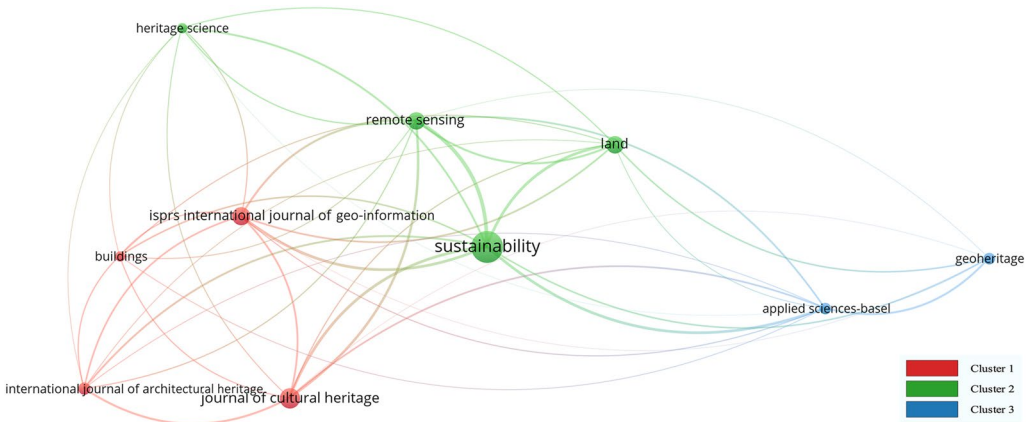

Fig. 5 Mapping of sources bibliographic coupling analysis

Table 3 Top 10 journals contributed to the GIS-Heritage

No	Journal	Cluster	Documents	Citations	Avg. citations	Journal Impact Factor	Category Quartile
1	Sustainability	2	93	557	5.9	3.9	Q2
2	Journal of Cultural Heritage	1	46	1041	22.6	3.1	Q2
3	ISPRS International Journal of Geo-Information	1	38	292	7.6	3.4	Q2
4	Remote Sensing	2	36	434	12.0	5.0	Q1
5	Land	2	35	139	3.9	3.9	Q2
6	International Journal of Architectural Heritage	1	20	277	13.8	2.4	Q3
7	Applied Sciences-Basel	3	19	156	8.2	2.7	Q2
8	Geoheritage	3	19	184	9.6	2.9	Q2
9	Buildings	1	15	58	3.8	3.8	Q2
10	Heritage Science	2	15	62	4.1	2.5	Q2

Upon observation, it is noted that for journals with a large number of publications in the GIS-Heritage field, the relationship between their journal impact factor, category quartile, and the quantity, citation impact, and average citation count in GIS-Heritage is not readily apparent. For instance, journals like *Sustainability* and *Applied Sciences-Basel* have substantial annual publication volumes, possibly explaining their prolific output in GIS-Heritage research. In contrast, journals with smaller annual publication volumes such as *Journal of Cultural Heritage*, *ISPRS International Journal of Geo-Information*, *International Journal of Architectural Heritage*, *Geoheritage*, and *Heritage Science* specialized in GIS-Heritage, making unique contributions to the field.

Cited author's co-citation analysis

The cited author's co-citation analysis can identify the most influential groups of authors within a specific research field and their academic connections. Before utilizing VOSviewer for analysis, it is essential to note that, due to the data exported from Web of Science only including the first author of cited references, the co-citation analysis considers only the first authors and excludes other contributors. Figure 6 presents the co-citation network of cited authors in the GIS-Heritage field identified by VOSviewer, displaying 12 authors (with at least 44 citations) out of 32,445 cited authors in the dataset.

To elucidate the information about the 12 authors and their cited references in the GIS-Heritage dataset, a further step involves co-citation analysis of cited references using VOSviewer. From a dataset of 47,012 cited references, 110 references with a citation frequency exceeding 8 were selected. These were matched manually with the 12 authors identified in Fig. 6. After this matching process, it was found that "UNESCO," "European Commission," "Cetin," and "Reynard" lacked highly cited references, while the other eight authors had one or more related highly cited references.

Subsequently, the details of these cited references were retrieved from databases like Web of Science and Google Scholar, and a more detailed analysis of the authors' research interests and themes was conducted

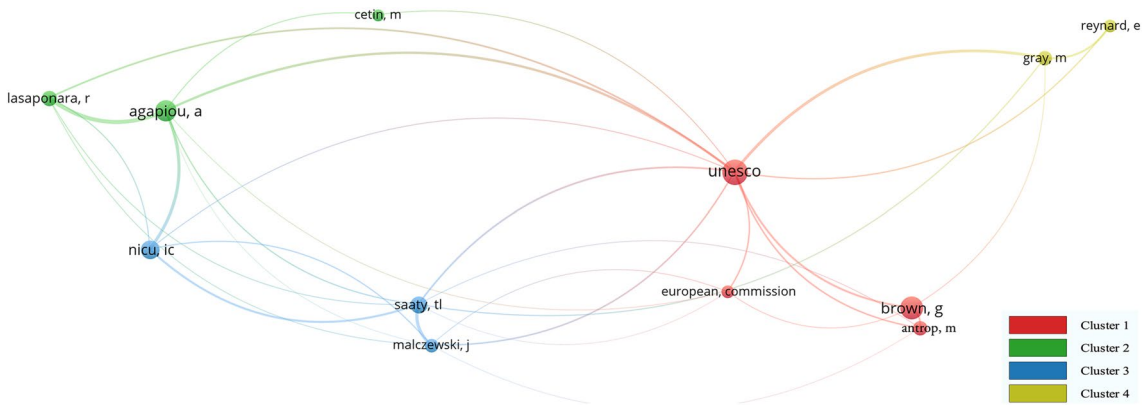

Fig. 6 Mapping of cited authors' co-citation analysis

to ensure an accurate understanding of their work, as shown in Table 4.

Figure 6 shows that, according to VOSviewer data, the institutions with the highest co-citation frequencies are UNESCO and the European Commission, while the authors with the highest co-citation frequencies include Brown, Agapiou, Nicu, and others. As indicated in Table 4, the eight authors hail from diverse countries/regions such as Australia, Belgium, Cyprus, Italy, Romania, USA, Canada, and England. They are affiliated with renowned national research institutions like CNR and prestigious universities such as the University of London, spanning the fields of geography, geomatics, and environmental analysis in GIS-Heritage research.

Notably, China ranks as the second-highest contributor in terms of publication volume in the GIS-Heritage field (as shown in Table 1), with the Chinese Academy of Sciences leading in publication output (as depicted in

Table 4 Cited authors and their highly cited references in the GIS-Heritage field

Cited Author	Cluster	Cited Reference	Year
Brown, G (University of South Australia, School of Natural and Built Environments, Australia)	1	Mapping spatial attributes in survey research for natural resource management: Methods and applications [31]	2005
		The relationship between place attachment and landscape values: Toward mapping place attachment [32]	2007
		Measuring change in place values using public participation GIS (PPGIS) [33]	2012
		Public Participation GIS: A Method for Identifying Ecosystem Services [34]	2012
		Key issues and research priorities for public participation GIS (PPGIS): A synthesis based on empirical research [35]	2014
		Empirical PPGIS/PGIS mapping of ecosystem services: A review and evaluation [36]	2015
Antrop, M (Ghent University, Geography Department, Belgium)	1	Why landscapes of the past are important for the future [37]	2005
Agapiou, A (Cyprus University of Technology, Department of Civil Engineering and Geomatics, Cyprus)	2	Cultural heritage management and monitoring using remote sensing data and GIS: The case study of Paphos area, Cyprus [38]	2015
		Impact of urban sprawl to cultural heritage monuments: The case study of Paphos area in Cyprus [39]	2015
		Risk assessment of cultural heritage sites clusters using satellite imagery and GIS: the case study of Paphos District, Cyprus [40]	2016
Lasaponara, R (CNR, Istituto di Metodologie per l'Analisi Ambientale, Italy)	2	Detection of archaeological crop marks by using satellite QuickBird multispectral imagery [41]	2007
Nicu, IC (Alexandru Ioan Cuza University, Interdisciplinary Research Department—Field Science, Arheoinvest Platform, Romania)	3	Cultural heritage assessment and vulnerability using Analytic Hierarchy Process and Geographic Information Systems (Valea Oii catchment, North-eastern Romania). An approach to historical maps [42]	2016
		Effect of natural risk factors upon the evolution of Chalcolithic human settlements in Northeastern Romania (Valea Oii watershed). From ancient times dynamics to present days degradation [43]	2016
		Tracking natural and anthropic risks from historical maps as a tool for cultural heritage assessment: a case study [44]	2017
		Frequency ratio and GIS-based evaluation of landslide susceptibility applied to cultural heritage assessment [45]	2017
		GIS-based evaluation of diagnostic areas in landslide susceptibility analysis of Bahluiet River Basin (Moldavian Plateau, NE Romania). Are Neolithic sites in danger? [46]	2018
		Natural risk assessment and mitigation of cultural heritage sites in North-eastern Romania (Valea Oii river basin) [47]	2019
Saaty, TL (University of Pennsylvania, Wharton School, USA)	3	A scaling method for priorities in hierarchical structures [48]	1977
Malczewski, J (University of Western Ontario, Department of Geography, Canada)	3	GIS-based land-use suitability analysis: a critical overview [49]	2004
		GIS-based multicriteria decision analysis: a survey of the literature [50]	2006
Gray, M (University of London, Department of Geography, England)	4	Geodiversity: developing the paradigm [51]	2008
		Geodiversity: Valuing and Conserving Abiotic Nature [52]	2004

Table 2). However, among the institutions with the highest co-citation frequencies in the GIS-Heritage dataset, neither the Chinese Academy of Sciences nor Chinese authors with the highest co-citation frequencies are identified (as shown in Table 4). This observation may be attributed to China being the most recent contributor to the GIS-Heritage field in terms of the average publication year (as shown in Table 1). It implies that the substantial and recent research from China requires time to accumulate broader academic influence in the GIS-Heritage domain, suggesting the potential for emerging countries outside Europe and the USA to make significant contributions in the future.

From Fig. 6 and Table 4, it is evident that four influential author clusters exist in GIS-Heritage research, corresponding to four color-coded clusters (red, green, blue, and yellow).

The red cluster primarily includes UNESCO, the European Commission, and scholars in related fields, such as Brown and Antrop. The central theme of the red cluster revolves around public participatory GIS (PPGIS), with Brown as a representative author. Brown and his collaborators focus on spatial mapping of ecosystem services, local values, and public participation, providing in-depth and comprehensive perspectives on public involvement in natural resource management and local community decision-making [31, 34–36].

The green cluster authors include Agapiou, Lasaponara, and Cetin, with Agapiou as the focal point. The green cluster concentrates on cultural heritage monitoring and remote sensing. Agapiou and collaborators explore the impact of urban sprawl on cultural heritage and the use of satellite data and GIS for cultural heritage risk assessment, emphasizing the role of remote sensing technology and GIS analysis in effectively managing and safeguarding cultural heritage [38–40].

The blue cluster authors include Nicu, Saaty, and Malczewski, with Malczewski and Nicu as representatives. The blue cluster focuses on the application of GIS in natural disasters and land-use research. Nicu addresses the assessment of cultural heritage vulnerability to natural disasters, frequency ratio, and the application of GIS in landslide susceptibility assessment [42, 44, 45, 47]. Malczewski's research centers on methods for land-use suitability analysis [49, 50], providing decision support tools for protecting and managing cultural heritage and mitigating the impact of natural disasters.

The yellow cluster authors include Gray and Reynard, with Gray as the central figure. The yellow cluster centers on the study of geological diversity. Gray's work spans the value, conservation, and development paradigms of geological diversity, examining the evolution and application of geological diversity as a concept. This includes the selection and assessment of geological World Heritage sites and applications in geological conservation, tourism, and parks [51, 52].

Through an analysis of the research directions and notable works of these highly influential groups of authors in GIS-Heritage, it is evident that they bring diverse research interests and methodologies to the field. Their contributions cover a range of disciplines, including social sciences, cultural heritage management, geographic information science, land-use planning, and geology. The variety of research methods and technological tools, such as PPGIS, remote sensing, and multicriteria decision analysis, reflects the interdisciplinary nature of this field. The differences among author clusters enrich the dimensions of GIS-Heritage research, providing diverse perspectives for the development of this field.

Keyword cluster analysis

Keywords

Keywords are the core terminology representing the main content of a literature piece, and a group of high-frequency keywords within a specific field of literature can reflect the research hotspots of that field. In bibliometrics, high-frequency keywords and their clusters can be identified through keyword co-occurrence network analysis using software such as VOSviewer [53, 54]. From a total of 3413 author keywords in the dataset, 42 high-frequency keywords were identified based on a co-occurrence frequency greater than 10, and the co-occurrence network analysis is depicted in Fig. 7.

According to the colors of the keyword nodes in Fig. 7, the keywords can be categorized into seven clusters. Table 5 presents the top 42 keywords in Fig. 7, along with the cluster, occurrences, links, Total Link Strength (TLS), and average publication year (Avg. pub. Year) metrics. The keywords are first sorted in ascending order by cluster and then in descending order by TLS.

Total Link Strength (TLS) serves as an indicator measuring the overall strength of connections between keywords in the co-occurrence network. Keywords with higher TLS values indicate stronger connections with other keywords in the network. In this study, the keyword with the highest TLS is GIS, followed by cultural heritage and remote sensing. Additionally, sustainability, spatial analysis, archaeology, conservation, and photogrammetry, among other keywords, exhibit prominent centrality within their respective clusters, providing clues for tracking research focal points and frontiers of GIS-Heritage.

Research themes

Based on the keyword cluster analysis results from Fig. 7 and Table 5, key research themes in GIS-Heritage can be categorized into seven main topics. To elucidate the

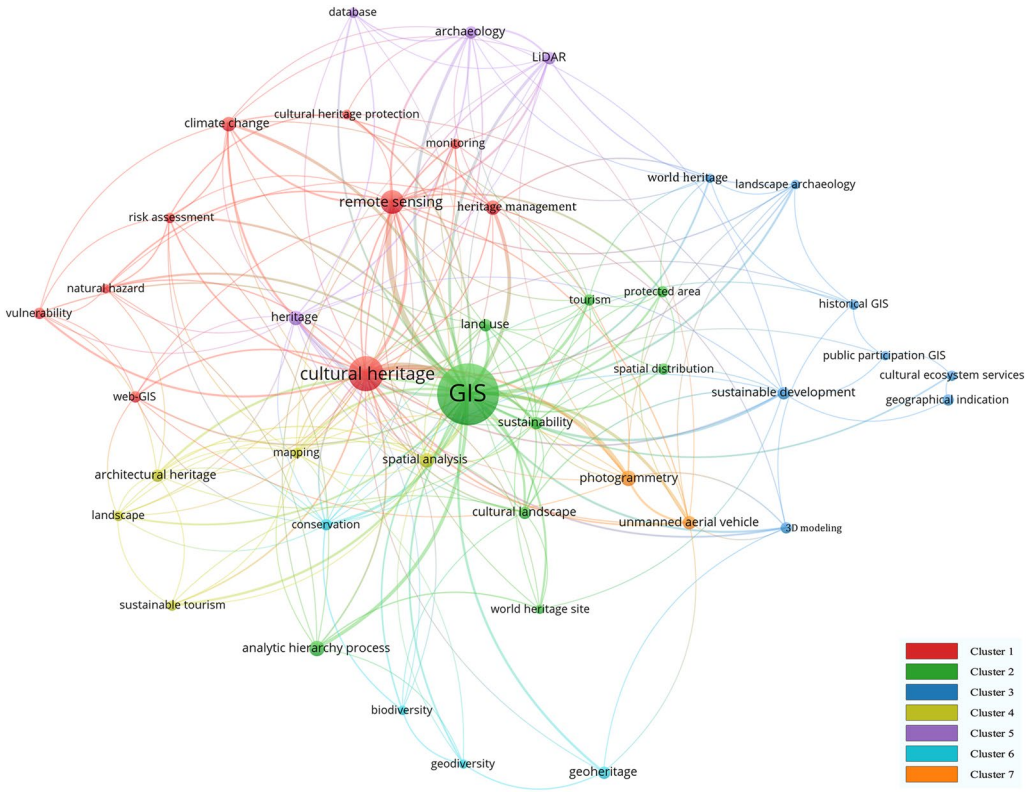

Fig. 7 Mapping of keywords co-occurrence analysis

content characteristics of the 42 author keywords identified in Fig. 7, along with the relationships and associations among keywords within each cluster, a systematic literature review was conducted. This involved retrieving 1026 GIS-Heritage-related documents through the Web of Science using the Author Keywords (AK) field and reviewing abstracts. Relevant literature focusing on the effective use of GIS technology in heritage studies was selected for in-depth reading to support the analysis of GIS-Heritage research themes and specific research directions.

Cluster 1 (Red): cultural heritage

Cluster 1 (Red): This cluster comprises 10 items, with "Cultural heritage" being the central keyword. Specifically, Cluster 1 mainly addresses the following four aspects:

Firstly, Cultural Heritage Protection and Management: Some literature explores the pivotal role of GIS technology in the protection and management of cultural heritage, covering tangible cultural assets, archaeological sites, architectural heritage, and landscape heritage. GIS is used to assess factors such as vulnerability, environmental risks, and visual integrity, aiding in the formulation of strategies for protecting and sustainably managing cultural heritage. For instance, Abdrabo et al. applied GIS technology to Egypt's rich tangible cultural heritage, defining a hazard identification framework and establishing a geographical database to identify multiple hazards and threats to the country's cultural heritage protection strategy, such as high temperatures, humidity, and climate change [55].

Secondly, Application of Remote Sensing in Heritage Protection and Management: Some literature provides various methods and case studies on how GIS and remote sensing technologies are employed to monitor, protect, and study heritage resources. These studies span changes in land cover from lost medieval settlements to cave art and natural reserve areas, as well as the management of craft centers. The results of these methods and case studies contribute to advancing the protection and sustainable management of heritage resources [56–59].

Thirdly, the Impact of Global Change on Cultural Heritage: Some literature presents various case studies and methods on how current climate change threatens cultural heritage and how GIS and remote sensing technologies are used to assess and address these threats. The studies cover a variety of monuments, archaeological sites, historical buildings, and cultural landscapes facing threats related to climate change, such as

Table 5 Top 42 keywords of co-occurrence analysis

No	Keyword	Cluster	Occurrences	Links	TLS	Avg. pub. year
1	cultural heritage	1	128	31	134	2018
2	remote sensing	1	59	21	83	2018
3	heritage management	1	21	13	30	2017
4	climate change	1	22	12	29	2019
5	risk assessment	1	12	10	19	2015
6	natural hazard	1	10	9	17	2018
7	monitoring	1	11	9	14	2013
8	vulnerability	1	13	8	13	2019
9	web-GIS	1	13	8	12	2019
10	cultural heritage protection	1	10	6	10	2018
11	GIS	2	387	39	327	2017
12	land use	2	16	12	24	2018
13	analytic hierarchy process	2	26	8	23	2019
14	sustainability	2	16	11	22	2018
15	cultural landscape	2	18	12	20	2017
16	tourism	2	13	12	19	2018
17	protected area	2	14	8	15	2018
18	world heritage site	2	10	7	12	2018
19	spatial distribution	2	13	4	6	2020
20	sustainable development	3	17	11	20	2020
21	3D modeling	3	14	7	15	2018
22	landscape archaeology	3	10	8	15	2019
23	world heritage	3	10	8	12	2016
24	historical GIS	3	12	6	6	2017
25	cultural ecosystem services	3	11	3	5	2019
26	public participation GIS	3	10	4	4	2019
27	geographical indication	3	13	2	2	2019
28	spatial analysis	4	23	15	31	2017
29	mapping	4	11	16	23	2016
30	architectural heritage	4	16	10	16	2019
31	landscape	4	12	10	14	2017
32	sustainable tourism	4	11	7	14	2018
33	archaeology	5	17	13	33	2018
34	heritage	5	24	17	33	2019
35	LiDAR	5	18	12	29	2018
36	database	5	12	6	11	2016
37	conservation	6	15	15	25	2017
38	geodiversity	6	10	6	11	2019
39	geoheritage	6	16	5	11	2020
40	biodiversity	6	10	6	10	2015
41	photogrammetry	7	26	12	35	2018
42	unmanned aerial vehicle	7	19	11	28	2020

sea-level rise, high temperatures, floods, heavy rainfall, and fires. These studies highlight the crucial role of GIS and remote sensing technologies in identifying and managing threats [60–62].

Fourthly, Risk Assessment and Monitoring of Natural Disasters: Some literature emphasizes the importance of using GIS and remote sensing technologies for risk assessment and monitoring of natural disasters affecting

cultural heritage. These studies provide baseline data and valuable information for protecting heritage at risk from natural disasters, offering scientific support for implementing risk mitigation measures [63–65].

In summary, "cultural heritage" serves as a key theme in the GIS-Heritage field, and relevant research delves deeply into multiple critical aspects of GIS technology application. These include the protection and management of cultural heritage, the application of remote sensing in heritage protection and management, the impact of climate change on cultural heritage, and the risk assessment of natural disasters. This not only underscores the versatility of GIS technology in the cultural heritage domain but also provides robust support for a more comprehensive understanding and protection of cultural heritage.

Cluster 2 (Green): GIS

Cluster 2 (Green): This cluster comprises 9 items, with "GIS" being the central keyword. Specifically, Cluster 2 addresses the following five aspects:

Firstly, Analysis and Planning of Land Use: Some literature investigates how GIS and related methods are used to analyze and plan land use in cultural heritage areas, and how these land-use patterns impact cultural landscapes, conservation areas, sustainability, and tourism. For instance, Guerriero et al. conducted a risk assessment of the UNESCO World Heritage site of Derwent Valley Mills in the UK's Derwent Valley through a multi-criteria decision-making process using an Analytic Hierarchy Process (AHP) in a GIS environment, providing crucial information for disaster management and land planning in the region [66].

Secondly, Application of Multi-Criteria Analysis Techniques: Some literature focuses on the application of the Analytic Hierarchy Process (AHP) method in considering multiple risks. For example, Guerriero et al. applied AHP multi-criteria decision-making processes in a GIS environment for a multi-hazard susceptibility assessment, studying the case of Derwent Valley Mills UNESCO World Heritage site [66]. However, it is worth noting that the field of multi-criteria analysis includes other methods, as seen in Nicu's research, which applied AHP, frequency ratio, and statistical index methods for landslide susceptibility assessment, providing an approach for the protection of cultural heritage [67]. This highlights the importance of using different methods in multi-criteria analysis, as each method has potential value when considering multiple risk factors.

Thirdly, Sustainable Tourism: Some literature explores the application of GIS technology in the planning and management of sustainable tourism. This includes assessing the impact of tourism, identifying potential tourism development sites, managing cultural and natural heritage, and considering the perceptions and needs of destination residents to ensure the sustainability of heritage and the environment. For example, Al Shawabkeh et al. studied the development of four cities in Jordan from 1996 to 2020, evaluating how cultural and natural heritage influences urban development and its relationship with the sustainable tourism industry using GIS and quantitative methods, combined with case studies [68].

Fourthly, Conservation of Cultural Landscapes: Some literature investigates how GIS and related technologies are used to analyze the value, vulnerability, and conservation needs of cultural landscapes. These studies provide essential methods and case studies for the conservation and sustainable development of cultural landscapes. For example, Oikonomopoulou et al. used GIS analysis, fieldwork, and literature research to propose a new cultural route for the protection and development of the cultural landscape in the Mani Peninsula, Greece. This route connects tangible and intangible content of cultural heritage in the region with its landscape features, providing spatial planning tools for sustainable development in the area [69].

Fifthly, Spatial Distribution Analysis: Some literature offers practical cases of using GIS for spatial distribution analysis, covering protected areas, traditional villages, and tourist destinations. These studies emphasize the importance of government support, socio-economic factors, cultural factors, and the natural environment in protecting and developing cultural heritage [70–72]. These studies provide useful insights for formulating sustainable development strategies and cultural heritage protection plans.

In summary, "GIS" serves as a key theme in the GIS-Heritage field, playing a crucial role in various critical aspects of heritage research. It provides robust tool support not only for land use analysis but also for cultural landscape conservation, sustainable tourism planning, and spatial distribution analysis. Additionally, it fosters interdisciplinary research, laying a solid foundation for a more comprehensive understanding and effective protection of cultural and natural heritage.

Cluster 3 (Blue): sustainable development

Cluster 3 (Blue): This cluster comprises 8 items, with "Sustainable development" being the central keyword. Specifically, Cluster 3 addresses the following three aspects:

Firstly, Landscape Archaeology: Some literature explores the application of GIS and other technologies in landscape archaeology, focusing on the evolution of historical landscapes, soil erosion, health management, remote sensing analysis, and the rediscovery of

archaeological sites [27, 73, 74]. These studies underscore the significant role of GIS in researching the geographical distribution and evolution of ancient cultural heritage, contributing to informed decision-making in sustainable development and cultural heritage preservation.

Secondly, World Heritage Management: Some literature investigates how GIS technology is employed for the management and protection of world heritage to meet sustainable development goals. For instance, Li et al. utilized public participation GIS to explore changes in local meanings among residents near the Wulingyuan World Heritage site in China. The study revealed the impact of residents' livelihoods, economic conditions, and tourism industry growth on local meanings and emotions, emphasizing the importance of balancing world heritage preservation and sustainable development objectives [75].

Thirdly, Cultural Ecosystem Services: Some literature delves into the analysis of cultural ecosystem services using GIS technology in conjunction with participatory mapping and social media data. This involves understanding the importance of cultural ecosystem services, such as aesthetic value, cultural heritage value, recreation, and social relationships, in different regions to support decision-making for sustainable development [76–78].

In summary, "sustainable development" as a pivotal theme in the GIS-Heritage field emphasizes the crucial role of incorporating sustainable development principles into landscape archaeology, world heritage management, cultural ecosystem services analysis, and public participation GIS. These studies address the complex challenges of balancing heritage preservation, environmental conservation, and community well-being.

Cluster 4 (Yellow): spatial analysis

Cluster 4 (Yellow): This cluster comprises 5 items, with "Spatial analysis" being the central keyword. Specifically, Cluster 4 addresses the following two aspects:

Firstly, Spatial Analysis of Heritage Resources: Some literature discusses the spatial analysis of heritage resources using GIS to reveal their distribution and characteristics. For instance, Dong et al. conducted spatial analysis in Guizhou Province, China, using GIS tools to calculate the richness of intangible cultural heritage (ICH) and tourist resources. The study identified the spatial distribution of ICH and tourism competition, providing support for cities to formulate cultural and tourism development plans based on their resource advantages and disadvantages [72].

Secondly, Protection and Management of Architectural Heritage: Some literature explores the diverse methods and applications of GIS technology in the protection and management of architectural heritage, offering valuable information and methods for the conservation, management, and sustainable development of architectural heritage [79, 80]. The integration of various GIS & HBIM models provides comprehensive information for historical buildings, aiding in formulating more effective protection and management strategies. Specifically, Cardinali et al. highlighted the benefits of GIS & HBIM for vulnerability assessments and broader management of historical center heritage [81], while Li et al.'s research indicated potential applications, such as precise disaster prediction, automatic warning of structural damage, and intelligent monitoring through GIS & HBIM [82].

In summary, "Spatial analysis" as a key theme in the GIS-Heritage field encompasses the spatial analysis of heritage resources and the application of GIS technology to various aspects of architectural heritage. These studies emphasize the importance of GIS in heritage research, highlighting the critical role of spatial analysis in GIS applications.

Cluster 5 (Purple): archaeology

Cluster 5 (Purple): This cluster comprises 4 items, with "Archaeology" being the central keyword. Specifically, Cluster 5 addresses the following two aspects:

Firstly, Archaeology and LiDAR Technology: Some literature discusses the significant role of LiDAR technology in archaeological research, especially in revealing cultural heritage and archaeological sites in vegetated or coastal environments. These studies also emphasize the crucial role of GIS technology in integrating and analyzing multisource data to support cultural heritage management and protection [56, 83].

Secondly, Heritage Databases: Some literature utilizes GIS technology to establish and manage heritage databases, covering various types of heritage, including geological parks, language and ethnic maps, seismic damage, and archaeological sites. These databases record and study diverse heritage-related information, providing support for policy-making, scientific research, and public education [30, 84, 85].

In summary, "Archaeology" as a vital theme in the GIS-Heritage field not only highlights the importance of GIS in revealing cultural heritage and archaeological sites but also underscores the key role of GIS in integrating multisource data to support cultural heritage management and protection. These studies provide robust support for further deepening our understanding of the combination of archaeology and GIS.

Cluster 6 (Turquoise): conservation

Cluster 6 (Turquoise): This cluster comprises 4 items, with "Conservation" being the central keyword.

Specifically, Cluster 6 addresses the following three aspects:

Firstly, Geoheritage: Some literature discusses how GIS is used to analyze, showcase, protect, or manage geographic information data related to geological heritage. For example, Belay et al. focused on the Fentale-Metehara area, the largest and most spectacular bubble and bubble caves in the Ethiopian Main Rift Valley. They used GIS technology, based on frequency ratio models and non-hierarchical clustering analysis, to quantify and assess the susceptibility of bubbles and bubble caves. This provided support for formulating protection strategies [86].

Secondly, Geodiversity: Some literature explores how GIS is used to analyze, assess, and protect the richness and uniqueness of geological heritage resources. For instance, Abd El-Aal et al. conducted a comprehensive assessment of geological and archaeological heritage resources in the Najran Province of Saudi Arabia using GIS methods combined with field surveys. The study revealed the region's richness in geological diversity, especially in areas where archaeological sites and valuable geological features coexist [87].

Thirdly, Biodiversity: Some literature analyzes and addresses issues related to biodiversity conservation using GIS applications, providing valuable insights for better protection and enhancement of biodiversity. For example, Gatwaza and Wang analyzed population dynamics and their impact on land use/land cover changes around Akagera National Park (ANP) using GIS. The study emphasized the potential impact of human activities on wildlife habitat, subsequently affecting biodiversity negatively [88].

In summary, "Conservation" as a crucial theme in the GIS-Heritage field covers various aspects, from the protection of geological heritage resources (geoheritage) and the assessment of geological diversity (geodiversity) to the analysis of biodiversity. These studies demonstrate how effectively considering the interrelationships between Earth sciences, ecology, and cultural heritage can advance conservation efforts.

Cluster 7 (orange): photogrammetry

Cluster 7 (Turquoise): This cluster comprises 2 items, with "Photogrammetry" being the central keyword. Specifically, Cluster 7 addresses the following aspects:

Firstly, Photogrammetry: Some literature, combining GIS and photogrammetric techniques, digitizes, creates 3D models, and conducts spatial analysis of cultural heritage, providing new means for the research, preservation, and management of cultural heritage. For instance, Bayarri et al. utilized GIS and photogrammetry, along with ground-based laser scanning, drone flights, and ground-penetrating radar, to proactively protect the Paleolithic cave paintings in the Altamira Cave in the karst region. The study generated new cave maps, detailing the connections inside and outside the cave, offering valuable information for the research, management, protection, monitoring, and dissemination of cave art [57].

Secondly, Unmanned Aerial Vehicle (UAV): Some literature employs unmanned aerial vehicles (UAVs) to acquire high-quality aerial images, conduct 3D modeling, monitor the status of cultural heritage, and support archaeological and cultural heritage conservation efforts. For example, Guo et al. used UAVs and LiDAR scanners to capture external images and internal point clouds of a wooden tower, providing accurate data sources for modeling and supporting the digital preservation of architectural heritage and GIS data modeling [89].

In summary, "Photogrammetry" as an important theme in the GIS-Heritage field emphasizes the close association between photogrammetric techniques, UAV technology, and GIS technology. This underscores the critical role of these technologies in advancing research and protection efforts in the field of cultural heritage.

Research evolution

Given the continuous development and evolution in the GIS-Heritage domain, we generated a temporal evolution map of the 42 high-frequency author keywords in the GIS-Heritage field, based on the average publication year of each keyword in VOSviewer, as shown in Fig. 8.

Figure 8 demonstrates that, based on the average publication year of the keywords, research in the GIS-Heritage field has undergone stages of initial low attention, gradual increase in attention, and recent widespread attention. Specifically, it can be divided into four main periods: the early stage (before 2013), the middle stage (2014–2017), the mid-late stage (2018–2019), and the recent stage (after 2020).

Firstly, the early stage (before 2013) involved the keyword "monitoring." During this stage, the application of GIS in heritage research did not receive widespread attention.

Secondly, the middle stage (2014–2017) witnessed a gradual increase in the number of keywords, including "mapping," "land use," and "archaeology." Researchers began focusing on the potential applications of GIS in heritage research, particularly in map production, land use, and archaeology.

Thirdly, the mid-late stage (2018–2019) saw a sharp increase in the frequency of keywords such as "cultural heritage," "remote sensing," "heritage management," "climate change," and "risk assessment." During this stage, the application of GIS in heritage research received increasing attention, and the research focus shifted towards the protection and management of cultural

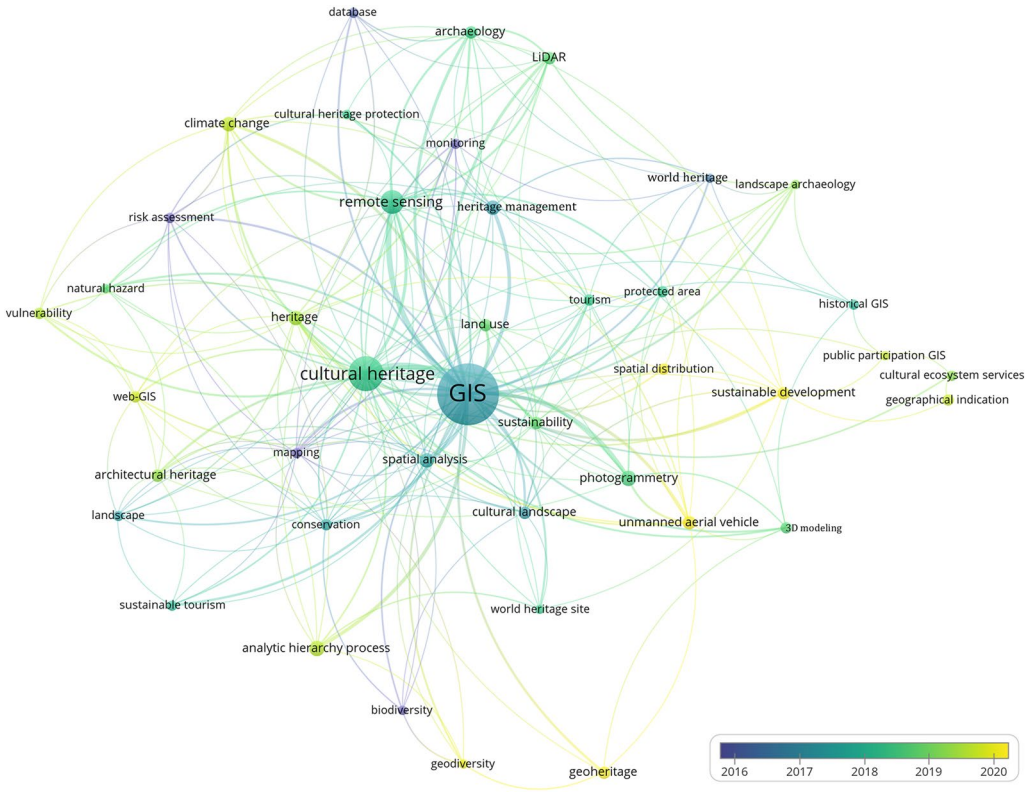

Fig. 8 Research evolution mapping based on keywords

heritage, as well as issues related to climate change and risk assessment.

Lastly, the recent stage (after 2020) witnessed a further increase in the frequency of keywords such as "unmanned aerial vehicle," "sustainable development," "geodiversity," and "geoheritage." This indicates that the application of GIS technology in heritage research has become increasingly diversified, including the use of unmanned aerial vehicles, sustainability studies, and analysis of geodiversity and geoheritage.

It should be noted that the delineation of these research stages is based solely on the average publication year data of the 42 high-frequency author keywords obtained from VOSviewer. Although it may not comprehensively reveal the research trends in the GIS-Heritage field, it still reflects the increasing importance and diversity of GIS technology in heritage research, spanning various domains such as cultural heritage management, climate change, and risk assessment.

Recommendations for future research

In general, the GIS-Heritage field has exhibited a trend towards diversified development but still faces some challenges, including data integration, technological innovation, and interdisciplinary, and international collaboration. This field continues to evolve and requires further research to address these challenges.

Data integration and interoperability

Firstly, the development of universal data standards and sharing platforms can be explored to facilitate data integration and interoperability among different types and geographical locations of heritage domains [38, 90]. This would enable different research teams to share and merge data, allowing heritage researchers and managers to better utilize geographic information for more comprehensive research and decision support.

Secondly, the development of comprehensive GIS tools can be explored to enable researchers and managers to access and analyze various cultural heritage data on a single platform. These tools can include system functionalities such as 3D modeling, risk assessment, and cultural heritage management, as well as geographical spatial data and attribute data such as meteorological data, sea-level rise models, and cultural heritage site information [55, 56, 91].

Technological innovation and the application of emerging technologies

Firstly, the integration of emerging technologies with GIS can be researched to enhance the visualization, interactivity, and protection of cultural heritage. This may involve the development of virtual reconstructions and interactive displays of cultural heritage based on virtual reality and augmented reality [57], as well as further research on the integration of GIS and BIM to promote the digital management and sustainable development of buildings and cultural heritage [12].

Secondly, the application of emerging methods in cultural heritage GIS databases and platforms can be explored to improve the efficiency of recording, protecting, and managing heritage resources. This can include the use of machine learning, deep learning, and other methods to automatically identify patterns of cultural heritage damage or potential threats and provide real-time monitoring and alerts [14], as well as the exploration of new remote sensing technologies, 3D scanning, and image processing methods to enhance the accuracy and efficiency of cultural heritage data [56, 57].

Interdisciplinary and international collaboration

Firstly, promoting interdisciplinary collaboration can encourage collaboration between GIS experts, archaeologists, historians, ecologists, meteorologists, geographers and geologists, and other related fields to conduct comprehensive heritage research. Interdisciplinary collaboration can facilitate the exchange of knowledge and resource sharing across different fields, leading to a more comprehensive understanding of the interrelationship between cultural heritage and the natural environment [2, 38].

Secondly, fostering international collaboration can focus on promoting international cooperation among international organizations, governments, and research institutions to establish international cultural heritage GIS databases and sharing platforms. This would involve sharing GIS data and technology, conducting cross-border heritage research, and jointly promoting global data sharing and research collaboration for the protection and inheritance of cultural heritage. This would better protect heritage resources and effectively address complex heritage challenges such as climate change and natural disasters [55, 68, 92].

Conclusion

Heritage, as a precious legacy of human cultural and natural history, plays a crucial role in sustainable development. The widespread application of GIS technology provides a powerful tool for a better understanding, preservation, and management of heritage resources, ensuring a rich cultural legacy for future generations. This study conducted a comprehensive bibliometric analysis of 1026 GIS-Heritage-related articles extracted from the Web of Science database, delving into the application of GIS technology in heritage research and revealing the development and trends in this field.

Firstly, this paper identifies the major trends in the GIS heritage field, focusing on the most influential countries, research institutions, and authors who have made significant contributions to the development of GIS-Heritage.

Secondly, the study delves into key research themes in the GIS-Heritage field, including cultural heritage, GIS, sustainable development, spatial analysis, archaeology, conservation, and photogrammetry. These diverse research themes reflect the multidimensionality of the field, providing crucial clues and directions for future research.

Finally, based on the research findings, the study proposed recommendations such as data integration, technological innovation, and interdisciplinary, and international collaboration. These recommendations aim to guide scholars and professionals to further expand research in the GIS-Heritage field and address the various challenges currently faced.

In comparison to prior research, particularly the comprehensive analysis of global heritage spatial technologies by Chen et al. [93], this study makes unique contributions and exhibits advantages in several aspects. Firstly, it focuses on the specific application of GIS technology in heritage research, providing a more detailed insight into this domain. Secondly, through the quantitative analysis of a substantial body of literature from 1994 to 2023, this study achieves a comprehensive understanding of the primary research themes and development trends in the GIS-Heritage field, offering valuable insights for future research.

While these review findings offer a deeper understanding of research and trends in the GIS-Heritage field, it is imperative to address certain limitations in future studies. For instance, on one hand, expanding the literature search scope, encompassing additional databases and non-English literature, is crucial for a more comprehensive grasp of the research dynamics within the GIS-Heritage domain. On the other hand, future research can employ diverse content analysis methods to reduce reliance on abstract data, delving into full-text data for a more comprehensive understanding of the practical applications and challenges of GIS technology in heritage research.

Abbreviations

GIS	Geographic information system
GIS-Heritage	GIS applications in heritage studies

BIM	Building information modeling
HBIM	Historic building information modelling
SCIE	Science citation index expanded
SSCI	Social sciences citation index
AHCI	Arts & humanities citation index
CNR	Consiglio Nazionale delle Ricerche
TLS	Total link strength
Avg. pub. Year	Average publication year
PPGIS	Public participation GIS
ICH	Intangible cultural heritage
AHP	Analytic hierarchy process

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-024-01163-y.

Additional file 1. Web_of_Science_Full_Record_and_Cited_References_1026. (This data file contains the full record and cited references of 1026 articles exported from Web of Science).

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Yong Huang completed entire paper independently including the collection and analysis of data, preparation of figures, writing and reviewing the manuscript.

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Availability of data and materials
As list of papers used in this research can be found in the Additional file 1.

Declarations

Competing interests
The author declares that he has no competing interests.

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