An open geospatial database as a tool for geoheritage management at national scale: The case study of Greece

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ABSTRACT
Geological heritage or geoheritage is of at least equal significance to – and sometimes also interwoven with – cultural heritage. Hence, it holds the potential of scientific, educational, cultural, aesthetic, and touristic value. Nevertheless, geoheritage has not attracted the same level of attention as cultural heritage to date, especially regarding its sustainable management and suitable conservation strategies. Yet actions and measures are mandatory to preserve and highlight geological heritage and to reduce threats that may cause its deterioration or even extinction. To this end, geospatial science and technology provide the means for documenting and dealing with geological heritage throughout the individual steps of the geoheritage management process. In this study, we present a holistic approach to geoheritage management at the national level for Greece, based on the implementation of a Geographical Information Systems (GIS) database that also enables the coupling of geoheritage with a plethora of readily available geospatial information from remote sensing and other sources. The results demonstrate that an appropriate, geospatial record of geological heritage can have a crucial contribution to geoheritage management from its identification, to its monitoring, protection, and exploitation for educational, scientific, recreational, and other purposes.

KEYWORDS
geoheritage; geoheritage management; GIS; Remote Sensing; Greece

Received: 4 January 2024
Accepted: 28 February 2024
Published online: 14 March 2024

Pantazopoulou, Z., Mouratidis, A., Alexakis, D. D., Tsioukas, V., Perivolioti, T.-M., Terzopoulos, D., Kalaitzis, P. (2024): An open geospatial database as a tool for geoheritage management at national scale: The case study of Greece. AUC Geographica 59(1), 60–76
https://doi.org/10.14712/23361980.2024.4

1. Introduction

1.1 Definition of geoheritage

The term “geoheritage” has evolved from the notion of “geological heritage”. The first use of the term was at the First International Symposium on the Conservation of our Geological Heritage, which took place in France, in 1991 (Brilha 2015). Since then, many different interpretations have been proposed for the aforementioned term.

Geoheritage is defined as the group of geological elements (items) or geological sites (geosites or geotopes) with outstanding scientific, cultural, and educational value (Fassoulas et al. 2012; Herrera-Franco et al. 2022; Thomas 2016). The term geological site or geosite comes from the Greek root “geo” (= Earth) and the Latin word “situs’’ (= sites) and refers to locations of geological interest. However, the geological elements should be evaluated for their uniqueness to be characterized as geological heritage (Brilha, 2018). Additionally, geosites with high touristic value can also be known as “geomonuments”, a term already used to promote some items of geoheritage to the general public (Brilha 2016).

Some authors suggested that geoheritage refers to those aspects of the Earth, which are important to our understanding of Earth history. By their nature, the geoheritage sites, which are akin to cultural heritage sites or documents, are among non-renewable resources (Bradbury 1993). Others (Semeniuk 1997) referred to geoheritage as nationally significant features of geology, including igneous, metamorphic, sedimentary, structural, paleontological, geomorphic, pedologic or hydrologic attributes that offer important information or insight into the formation or development of a continent, or that can be used for research, teaching or as a reference site. However, it has also been argued that “geoheritage consists of all the significant Earth features and continuing processes that we wish to keep, sustain, conserve, manage and interpret for their natural heritage value” (Osborne 2000). According to several authors (Brilha 2002; Gonggrijp 1999; Zagorchev and Nakov 1998), geoheritage relates to the importance of the site (locally, regionally, nationally, and internationally), and its use (educational, scientific, and recreational), as well as the need to conserve it. Education is here perceived in its broader sense of education, training, capacity building and outreach, including all levels and types (formal, informal, non-formal) of education in a lifelong learning context.

For the present study, geoheritage is considered as the global, regional, and local geological elements, such as igneous, metamorphic or sedimentary rocks, minerals, fossils, stratigraphic, tectonic, pedologic, paleontological structures and other geosites (or geotopes). It also encompasses important sites and specimens, which offer information and insights into the formation and evolution of the Earth, the evolution of life, the climate and landscapes of the past and present, along with the geological history of the sites where they are found (Brocx and Semeniuk 2007; Carcavilla et al. 2009; Zafeiropoulos et al. 2021).

Geomonuments have equivalent significance as historical and archaeological monuments. Consequently, they have scientific, educational, cultural, aesthetic and touristic value. Thus, sustainable management and suitable conservation strategies are mandatory to preserve geoheritage and to reduce threats that may cause the deterioration of geological heritage and its surrounding environment. Moreover, the links and integration between geological and cultural heritage are recently being more and more discussed (Bollati et al. 2023; Pijet-Migoń and Migoń 2022).

1.2 Management of geoheritage

The management process of geological heritage includes a variety of steps or stages, which depend on the type of geoheritage as well as the cartographic scale used – the latter not being independent from the type/size/geographic scale of each geological heritage item (Burlando et al. 2011; Theodosiou 2010; Zouros 2004, 2005; Zouros and Valiakos 2010). Nevertheless, some of these stages are common and applicable to most geoheritage elements (Fig. 1). These span from the original investigation/identification, mapping and/or scanning, monitoring and protecting, to “higher-level” management activities related to its sustainable exploitation for various purposes (education, culture, tourism, promotion of local products etc.), as well as an overall assessment for the value of each geoheritage element.

For example, a petrified tree trunk is first found (Identification), spatially described (Delineation) and scanned with a terrestrial laser scanner (Mapping or

Fig. 1 Stages (steps) of geological heritage management process applicable to most types of geoheritage. The process starts at the bottom of the pyramid with the most fundamental (lower) stages (e.g. identifying, mapping) and follows through the final (higher) steps such as exploitation and promotion for various purposes (aesthetic, touristic, educational etc.).

Scanning). Subsequently, it is defined for its characteristics and determined for its origin (Interpretation), preserved locally with technical and/or chemical measures (Protection) and continually followed for its potential degradation and changes (Monitoring). In higher (later) stages of management, it may be highlighted e.g. by building roads for securing access to the specific geosite (Exhibition), evaluated for its scientific, educational or touristic importance (Assessment), used for different purposes such as research, education, tourism etc. (Exploitation) and finally, communicated and disseminated together with all the relevant activities, developed material and other outputs related to the specific geoheritage (Promotion).

1.3 The role of geospatial science and technology

Geospatial information has become the backbone of modern society and one of the main drivers of decision making. The traditional technologies of Remote Sensing (spaceborne, airborne, or ground-based), Global Navigation Satellite Systems (GNSS) and Geographical Information Systems (GIS) have been used for the collection and processing of large volumes of geospatial information since decades, at ever increasing resolution and accuracy. In today's era of Big Data, these fundamental elements of what is broadly defined as "Geospatial Science and Technology" are now coupled with web-mapping, Artificial Intelligence (AI), Internet of Things (IoT) and related capabilities. Together with smartphones, tablets, other internet and geolocation-enabled devices, equipment and related applications, they constitute a geospatially-enabled ecosystem that is continuously changing everyday life and opening new horizons in practically every sector of the economy worldwide (Goodchild 2022; Liu et al. 2022; Mouratidis and Koutsoukos 2016).

The increasing development of terrestrial/ground-based (e.g. 3D laser scanners) (Fassoulas et al. 2022; Marsico et al. 2015; Pasquaré Mariotto et al. 2023; Perotti et al. 2020; Ravanel et al. 2014), aerial (e.g. Unmanned Aerial Vehicles/UAVs) (Papadopoulou et al. 2022; Santos et al. 2018) and space-based (e.g. multispectral optical or Synthetic Aperture Radar/SAR) Remote Sensing techniques (AbdelMaksoud et al. 2019; Németh 2022; Singh et al. 2021), together with the tremendous advancement of GIS technologies (Bendaoud et al. 2015) have the potential to contribute significantly to the effective management of geoheritage. Remote Sensing technologies have thus great prospects as a low-cost, non-destructive tool for dealing with geoheritage. Nevertheless, to date, in the majority of scientific publications, the use of geospatial science and technology refers to applications for the management of cultural heritage (Agapiou et al. 2015; Elfadaly et al. 2020; Stewart 2017; Wilson 2021). Remote Sensing data of varied spectral and spatial resolutions have been interpreted to detect, identify, monitor, map and prospect cultural heritage (or the cultural aspects of heritage) sites or objects, but also their surrounding landscape. Remote Sensing has also been used for the investigation and prediction of environmental change and scenarios through the development of GIS-based models and decision-support instruments (Ayad 2005; Hadjimitsis et al. 2013).

1.4 Geoheritage databases in the world

Some efforts for creating geoheritage databases have been implemented around the world (Ballesteros et al. 2022; Bendaoud et al. 2015; Martin et al. 2014; Suma and Cosmo 2011). These focused on different geographical scales, from national, to regional or local level and/or to specific or generic geoheritage types. They have also typically addressed just some of the aspects of geoheritage management (e.g. identification, interpretation, visualization, assessment, promotion or exploitation) and rarely the full spectrum of management stages. GIS has inherently received a prominent role in most of these cases and has been often combined with web mapping services. Thus, there is hardly any experience from studies that address a wide geographical area, all types of geoheritage and all stages of geoheritage management at the same time.

1.5 Study Area

As per the geographical area investigated, owing to its geotectonically privileged location at the convergence of two tectonic plates, Greece has a very complex geological history and geodiversity, which is complemented by an even richer historical and cultural background.

Located between the converging African and Eurasian plates, Greece is characterized by an abundance of geosites and is therefore considered a "natural geological laboratory" (Papanikolaou 2021; Spyrou et al. 2022) that is unveiling insights on geodynamics and related phenomena as well as geological processes. Rocks, fossils and other geological elements reveal the palaeogeography of the broader Greek territory, which is today reflected in a complex geomorphological environment shaped mainly by active tectonics, but also exogenous processes. Mountains, mountain ranges, island complexes, lakes, rivers, caves, beaches consist some of the rich geomorphological features extending up to almost 3,000 m of elevation and contributing to the geodiversity of the country (Drinia et al. 2022).

As a result, though occupying a relatively small area, the Greek territory is scattered with a variety of geological formations, landforms, fossils and other geoheritage elements. These are in many cases interwoven with elements of cultural heritage – with some of the latter being of global importance and recognition and thus also of high scientific, educational and touristic value. All this is reflected in the 19 UNESCO World Heritage Sites (Centre n.d.), as well as 8 geoparks with global recognition listed in the World Network of UNESCO Geoparks (UNESCO Global Geoparks | UNESCO n.d.), located in the country. For the ensemble of the aforementioned reasons, Greece provides an excellent test site the purposes of this study.

1.6 Objectives

In this context, the goal of this study is to use Greece as a paradigm of the contribution to a geospatially-enabled management of geoheritage over a large geographic area, with the specific objectives of:

a) Producing an open geoheritage GIS database at national level.
b) Highlighting the benefits of having such a database as a stand-alone infrastructure.
c) Demonstrating the added value and immense further potential of exploiting the database together with additional geospatial data (both remotely-sensed and other).

2. Methodology

2.1 Retrieval and verification of information regarding geoheritage in Greece

The original information for creating the database for geological heritage sites was drawn from a variety of sources, such as research articles, other publications, official websites of local management authorities (municipalities or other organizations), other internet sources, and in some cases from personal communication and testimonies from local communities.

The location of each geoheritage site was recognized and thoroughly verified with the maximum possible accuracy (in the order of a few meters), by exploiting national geospatial data as well as publicly available layers, such as Google Earth™, Google Maps™ and OpenStreetMap, in an open-source GIS software (QGIS) environment. Only these verified entries were considered for registration in the database. Nevertheless, the inherent geolocation uncertainty of some types of geoheritage (e.g. caves, quarries etc.), when represented by a point feature/geometry, was considered later and is discussed further within the geospatial analysis section. With these considerations, approximately 350 entries were qualified for this first version of the database.

2.2 Creation of the GIS Database

As a general methodological concept for the content and structure of a GIS geoheritage database, the following elements ought to be considered:

a) Availability of a GIS software (commercial or open source).
b) Choice of a Coordinate Reference System (national or international).
c) Storage of the database (locally or online).
d) Source(s) from which the infomation for geoheritage will be retrieved (may be official national records or not, in situ observations, publications etc.).
e) Attributes to be included for each geoheritage entry (can be relatively easily amended at a later stage).
f) Categorisation (possibly including sub-categories) of the geoheritage entries, which may be different

Tab. 1 Fields created in the attribute table of the geoheritage GIS database and their respective description.

No	Field Name	Type	Description
1	Id	Integer	A unique number given to each entry, in order to identify it in the database.
2	Name	Text	A name for each geoheritage location or element.
3	Details	Text	Some basic characteristics (e.g. properties, history, value etc.) of the geoheritage element are provided. Practically endless information can be added, if a geodatabase (*.gdd) format is being used for the database.
4	Link	Text	Link(s) to official website(s) in which reference is made to the specific geoheritage element either by local bodies or by the managing authority.
5	Ingest date	Date	The date of ingestion or last modification of the geoheritage element in the database.
6	Access	Text	If the location/element is freely accessible then it is designated as “Open”, while if there is an entrance fee or other restrictions it is designated as “Restricted”. In case it is not at all possible to visit the site, it is then classified as “Inaccessible”.
7	Price	Double	The general admission fee price information (in Euros) is given for sites with restricted access.
8	Museum	Text	Information is given on whether there is an associated exhibition or a museum (Yes/No).
9	Type	Text	General category of geological heritage to which the site belongs.
10	Code	Text	Short code corresponding to the aforementioned type/category of geoheritage.
11	Culture	Text	Reference to any connections with cultural heritage e.g. geomythological and/or archaeological sites (Yes/No).

Tab. 2 Snapshot of the attribute table containing the first 20 entries of the database.

Id	Name	Details	Link	Ingestdate	Access	Price	Museum	Type	Code	Geo-mythology
1	Nymfo-petres	A series of rocks, standing upright and creating the impression of a "stone forest".	–	23-12-20	Open	0	No	Geomorpho-logical	NG 06	Yes
2	The Petrified Forest of Lesvos	The Petrified Forest of Lesvos is a fossilized ecosystem that includes hundreds of standing and lying petrified tree trunks.	http://www.petrifiedforest.gr/	24-12-20	Restricted	5	Yes	Paleonto-logical	NG 03	No
3	Vatika Petrified Palm Forest Agios Nikolaos	Petrified palm forest of the coastal zone of Agios Nikolaos	https://www.visitvatika.gr/el/nature/petrified-forest.html	24-12-20	Open	0	Yes	Paleonto-logical	NG 03	No
4	Cave of Lakes-Kastria	Cave of Lakes consist of 13 in total small or large lakes succeed one another.The terrestrial areas alternate with lakes ones until the cave's end. The total lenh of cave is nearly 2Km.	https://www.kastriacave.gr/	28-12-20	Restricted	9	Yes	Cave	NG 05.1	No
5	Meteora	The gigantic rocks of Meteora resulted from the conglomerates erosion and the rapid uplift	https://whc.unesco.org/en/list/455/	04-01-21	Open	0	Yes	Geomorpho-logical	NG 06	No
8	Cave St. Georgiou Kilkis	St.Georgiou Kilikiw is one of the most important cave in Greece. THe cave has great paleontological value	–	04-01-21	Open	0	Yes	Cave	NG 05.1	No
6	Thracian Meteora	Thracian Meteora is located 15Km to the north Iasmos. The rocks of the Astrean rock formations are the same material with Meteora in Kalabaka.	–	04-01-21	Open	0	No	Geomorpho-logical	NG 06	No
7	Boucharia-Nohtaria	At the area of Mikrovalto and Livadero 40Km south of Kozani are the natural formations of rocks that lave been created dy the corrosion of the ground. Boucharia resemble chimneys,Nohtaria tall pyramid	–	04-01-21	Open	0	No	Geomorpho-logical	NG 06	No
9	Mirror rift Arkitsa	A rare geological phenomenon is a vertical rocky (limastone) surface over the highway. The surface is 300m length and 80m heigh.	–	04-01-21	Open	0	No	Structural	NG 01	No
10	Thermal Springs of Edipsos	The springs of Edipsos are more than 80. The temperature of the water ranges from 28oC-86oC and it is rich in magnesium,calcium and iron.	–	11-01-21	Open	0	No	Thermal Springs	NG 08	No

Id	Name	Details	Link	Ingestdate	Access	Price	Museum	Type	Code	Geo-mythology
11	Gorge Samaria	The Gorge of Samaria and a large area has been characterized as National Park. Along the gorge you will find 22 sources of drinking water.	https://www.samaria.gr/en/tips-crossing-samaria/	11-01-21	Restricted	5	No	Gorge	NG 09.5	No
12	Gorge Ha	The Gorge of Ha is a beautiful technical gorge in Crete. The gorge is about 1.5 Km long, very narrow and the walls rise up hundreds of meters.	https://petraoncrete.com/ha-gorge/	11-01-21	Open	0	No	Gorge	NG 09.5	No
13	Gorge Nekroi	The gorge of Nekroi in Zakros is an important archaeological gorge due to the large number of the graves found in the caves allong the gorge.	–	11-01-21	Open	0	No	Gorge	NG 09.5	No
14	Gorge Kotsyfos	The gorge starts at Kannevos village and ends at Plakias. The total length is 1800 m	–	11-01-21	Open	0	No	Gorge	NG 09.5	No

in each country, depending on the special geoenvironmental context, number of geoheritage sites, significance of the geoheritage items, purpose of the databse etc.

In this study, QGIS version 3.16 (Hannover) and Google Earth™ were used to implement the database and register all entries, with the initial coordinate reference system being Geographic WGS 1984 (EPSG 4326). During this first implementation, the database has been stored and processed locally. The coupling with external information such as national databases and Copernicus data (e.g. topography, land cover etc.) was carried out through Web Map Services (WMS) or direct downloading and importing in a GIS.

The table of elements (or attribute table) included eleven fields (Tab. 1) with the respective type (number, text, date etc.) and related information (Tab. 2).

2.3 Categorization of geoheritage in the database

The strategy for dividing geoheritage into broad categories (types) was to cover the variety of geological heritage elements in Greece, in a relatively simple, but comprehensive approach. To this end, 14 distinct categories were identified, covering both natural and anthropogenic geosites (Tab. 3 and Fig. 2).

More specifically, the type NG01 of natural geosites includes places of tectonic interest, such as seismic faults, folds, or tectonic windows. Category NG02 is related to outcrops of formations with specific interest/meaning for the prevailing processes in the area's geological history. NG03 is intended to cover locations of invertebrate or vertebrate fossils and/or excavation sites. Places of (visible to the naked eye) special or rare mineralogical and petrological composition are categorized in geoheritage type NG04. Type NG05 is associated with surficial or underground karstic features like sinkholes, poljes and caves. Other features formed by geomorphological processes like weathering, erosion and deposition are categorized under NG06. Places of (active or historical) volcanic activity (craters, phreatic explosions,

Tab. 3 Basic categorization of geoheritage sites of Greece for the GIS database, under the two broad categories of natural and anthropogenic geosites.

Natural Geosites (NG)	
1	Structural sites (NG01)
2	Stratigraphic sites (NG02)
3	Paleontological sites (NG03)
4	Mineralogical-Petrographical sites (NG04)
5	Karstic features (NG05)
6	Geomorphological features (NG06)
7	Volcanic sites (NG07)
8	Thermal Springs (NG08)
9	Other Environments (NG09)
10	Glacial and Periglacial features and processes (NG10)
11	Landscapes (NG11)
Anthropogenic Geosites (AnG)	
12	Mines (AnG01)
13	Quarries (AnG02)
14	Development projects sites (AnG03)

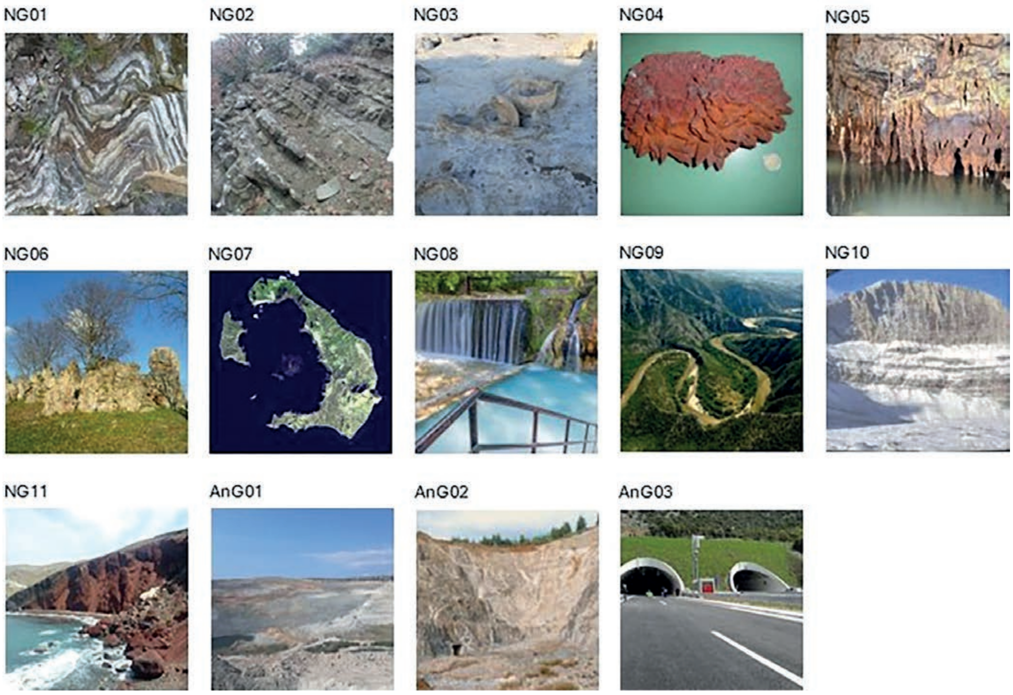

Fig. 2 Indicative examples of geological heritage sites, belonging to each of the 14 distinct categories identified in Tab. 3.

volcanic gas releases) fall under geoheritage category NG07. Thermal springs are considered as a special category under NG08. Special, extensive, and dynamic environments with their associated structures and processes, which unveil essential geological elements of the area where they are encountered and are not very commonly regarded as geoheritage (e.g. rivers, lakes, coastal areas, deserts, gorges, waterfalls etc.), form a separate category (NG09). Glacial and periglacial formations and processes (for Greece, it essentially concerns remnants of glacial activity from the last ice age – 100,000–10,000 years ago) are included in within type NG10. The last natural geoheritage category (NG11) is related to large geographic scale landscapes (e.g. mountains or mountain ranges, plains, basins, trenches, islands) that provide some vital information or constitute a unique and special geological appearance that reveals an important element of the geological history of the Earth.

Regarding anthropogenic geosites, they include active or inactive mines (AnG01) and quarries (AnG02), which, apart from the given geological interest, may also have considerable touristic, educational and historical value. The last category (AnG03) includes sites of other ancient and modern development projects and artificial structures, which constitute tangible proof of power of humans to shape the geo-environment. This category may e.g. encompass tunnels, canals, drainage works, road constructions etc. Quarries and mines could also have been included in this category; however, the separation is considered useful because of Greece's historically intense mining activity.

2.4 Geospatial analysis

Geospatial analysis was performed, in order to demonstrate the significance and prospective uses of the database at national level. To this end the Administrative Regions of Greece were taken into consideration (Fig. 3), along with some other basic, meaningful parameters (elevation, land cover, climate change) from EU's Copernicus Programme that could indicatively be of value to potential users. Additionally, as an indicative demonstration of local (site-level) usage of the database, a case study from the Island of Milos was implemented. Both open-source GIS (QGIS) and commercial GIS (ArcGIS™) software were used for the analyses.

More specifically, the Copernicus Land Monitoring Services were used to retrieve elevation data from the European Union Digital Elevation Model (EU-DEM) (Copernicus Land Monitoring Service – Reference Data: EU-DEM 2017), whereas the most recent Land Cover Change data between 2012–2018 were retrieved from Corine Land Cover (CORINE Land Cover n.d.).

Regarding climate change/sea level rise information, it was accessed via the Copernicus Climate Change Service. In particular, it was taken into account that for the next 100 years the average sea level rise for Europe will be between 20 cm and 40 cm (Copernicus Climate Change Service n.d.).

The land use change data underwent geospatial analysis in conjunction with the geoheritage database, to identify land use changes affecting or likely to disrupt sites of geological heritage. In this process, a buffer zone of 1 km was used to account for the inherent geolocation uncertainty of certain types of geoheritage (caves, quarries etc.).

Each geoheritage element was assigned the corresponding orthometric elevation using the available DEM. Subsequently, the geological heritage sites potentially at risk from sea level rise in the next 100 years were identified, by adopting the extreme 40 cm sea level rise scenario.

In total, the ensemble geospatial analyses of all the aforementioned parameters with the geoheritage database yielded indicative new insights, such as:

a) Number of geoheritage items per administrative district.
b) Geoheritage density.
c) Density of geoheritage sites, normalized per area of Administrative Region.
d) Distribution of geoheritage, in terms of type and elevation (surface relief).
e) Correlation of geoheritage sites with land cover change.
f) Impact of projected sea level rise on geoheritage sites in the next 100 years.

For the site-specific (local level) example, the famous cove of Kleftiko (meaning "Bandit's Lair" in Greek) was selected from the geoheritage database (Fig. 4). In particular, the focus was on an impressive limestone formation of about 65 m × 20 m × 10 m (length × width × height), just a few meters off the coast, which is one of the most popular tourist attractions on the island. The purpose was to demonstrate the monitoring potentialities with geospatial technologies (Remote Sensing and GIS). For this reason, three very high resolution (0.5–0.6 m) optical satellite data were used from the Worldview-2™ and Pleiades satellites™ for the years 2010, 2014 and 2023. These images were processed with the Sentinel Application Platform (SNAP) to retrieve the Natural Difference Water Index (NDWI) (McFeeters 1996), classify the result with K-Means unsupervised classification and calculate the area and perimeter of the rock formation for each image in a GIS.

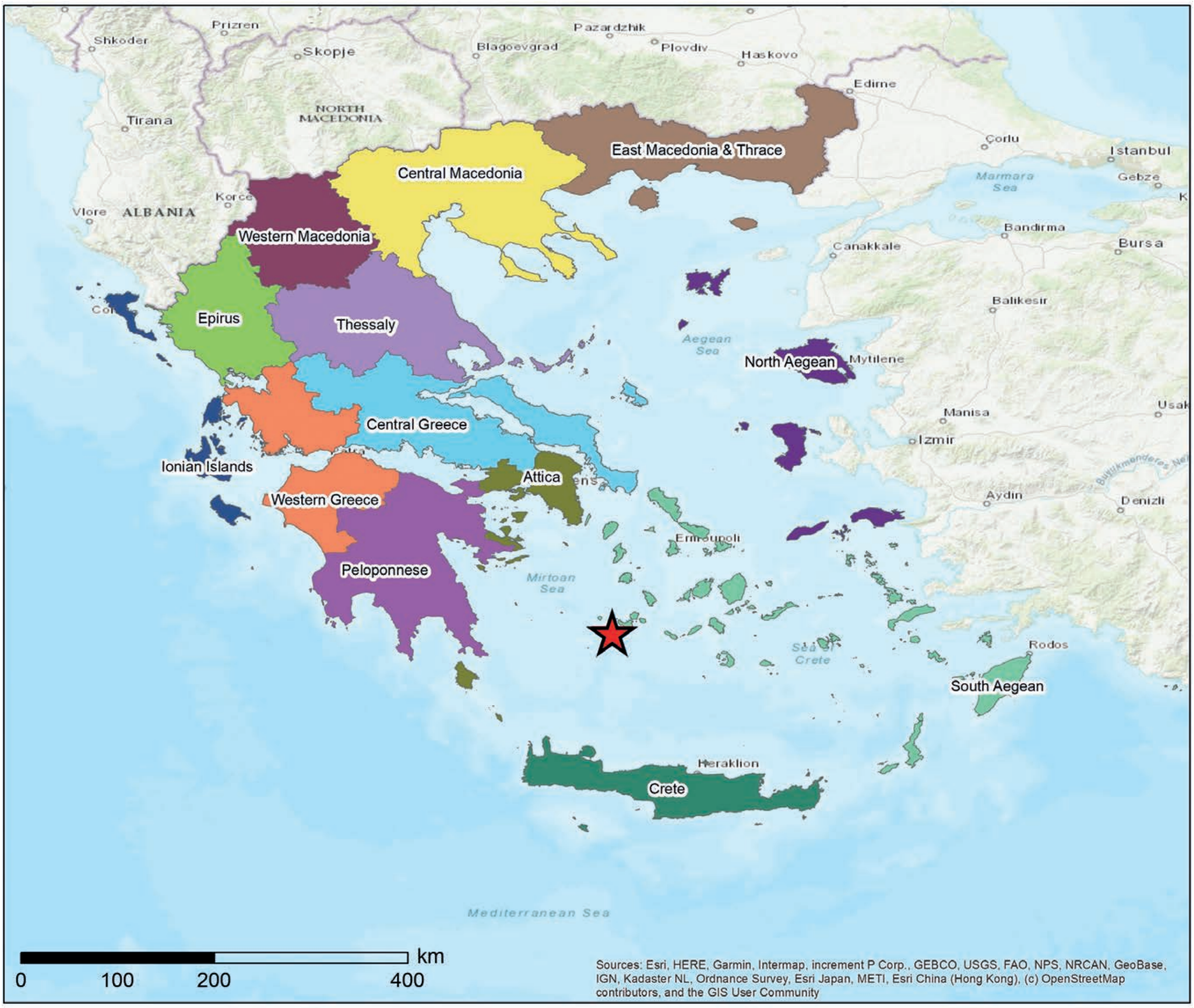

Fig. 3 The 13 Administrative Regions of Greece, which were considered as a basis for an initial geospatial analysis of geoheritage information. The red star indicates the location of "Kleftiko" on Milos Island, which was chosen to demonstrate a site-level usage of the database.

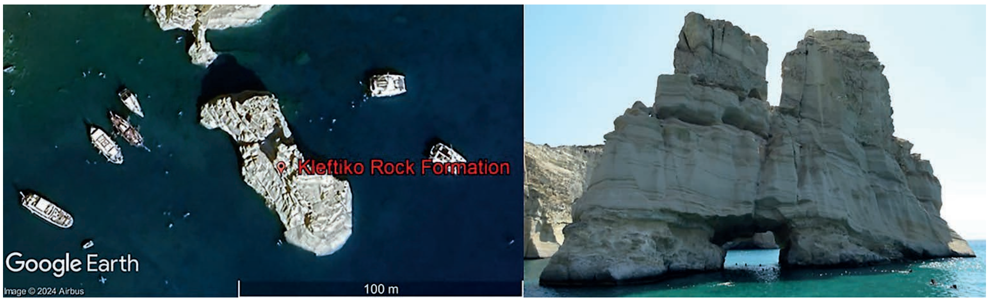

Fig. 4 Left: Google Earth image of the limestone formation in the area of Kleftiko on Milos Island, which falls under the NG06 (Geomorphological features) type of geoheritage. Right: Photo (view from the South) of the same rock mass from in situ observations (Source: A. Mouratidis).

3. Results

The open GIS database already includes a few hundreds of geological heritage elements all over Greece and is continually expanding. The database itself (or information regarding its migration) will be permanently available at the "Open Geospatial Database" of the Aristotle University of Thessaloniki (https://gis.web.auth.gr/), freely accessible for all purposes. A demo of the relevant web map is already available at the aforementioned website under https://gis.web.auth.gr/Webmaps/Geoheritage_171023_v3/index.html.

The geospatial analysis of geoheritage sites in conjunction with the Administrative Regions provides an overview of the number of geoheritage items per Administrative Region (Fig. 5), which can be also normalized by the area of each Region (Fig. 6), in order to yield more comparative results thereto. Disregarding the boundaries of Administrative Regions, an overall density of geoheritage sites at National level can be extracted (Fig. 7), which shows the concentration of geological heritage in specific areas. Another basic output is the distribution of geoheritage per type, which can be easily visualized through the database (Fig. 8).

By using a DEM, the geoheritage sites can also be classified based on the surface relief where they occur and thus categorized from lowland to mountainous geosites, which adds another layer of useful information for various purposes (Fig. 9).

With respect to the land cover change data, it can be observed (and quantified) that several geoheritage sites are in the vicinity of land cover changes between 2012 and 2018 (Fig. 10), which may indicate a potential threat for the geoheritage.

Regarding the climate change impact assessment, the endangered geoheritage sites can be identified for

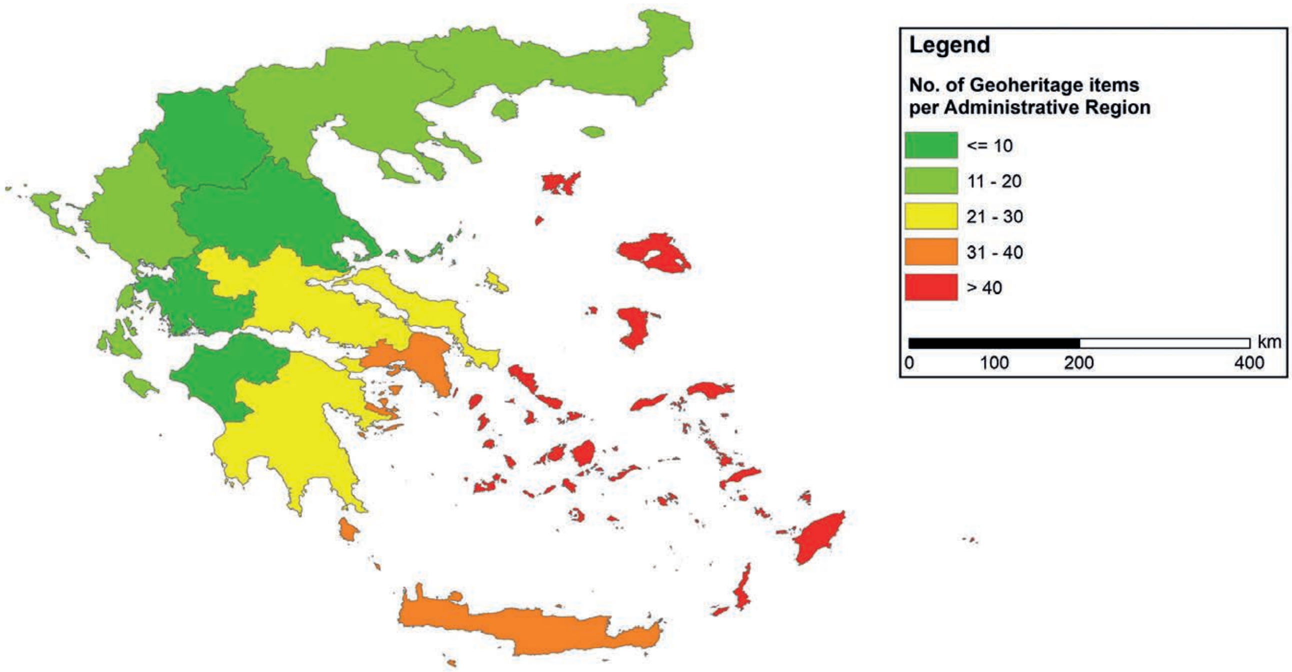

Fig. 5 Number of geoheritage items per Administrative Region.

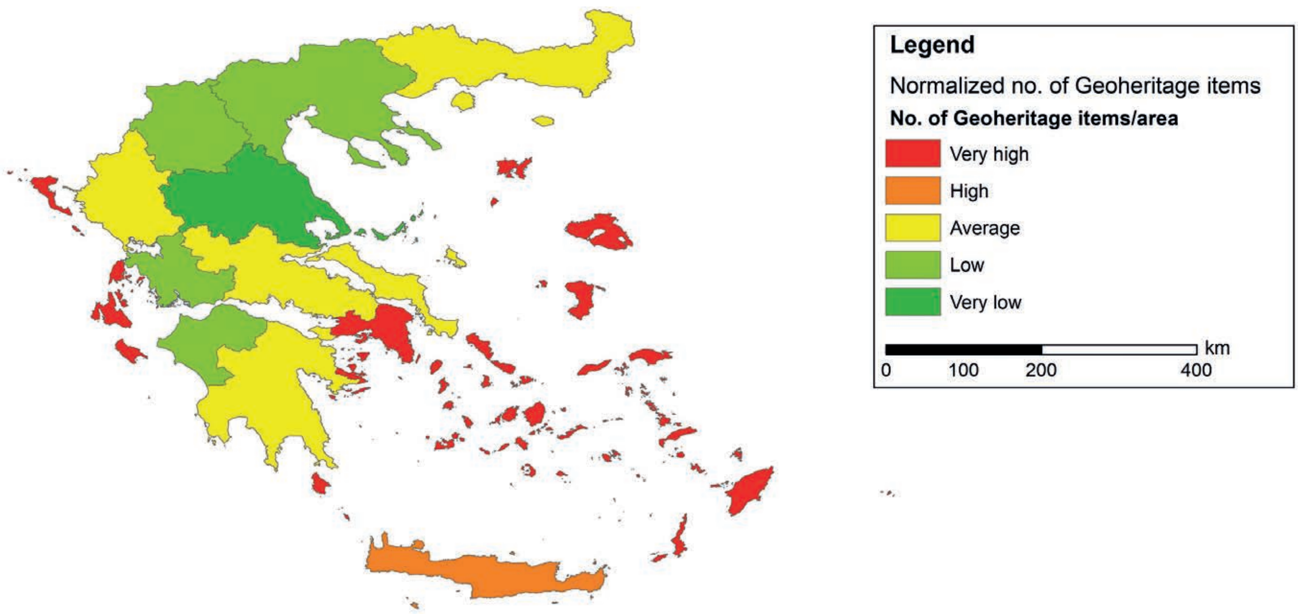

Fig. 6 Number of geoheritage sites normalized per Administrative Region area.

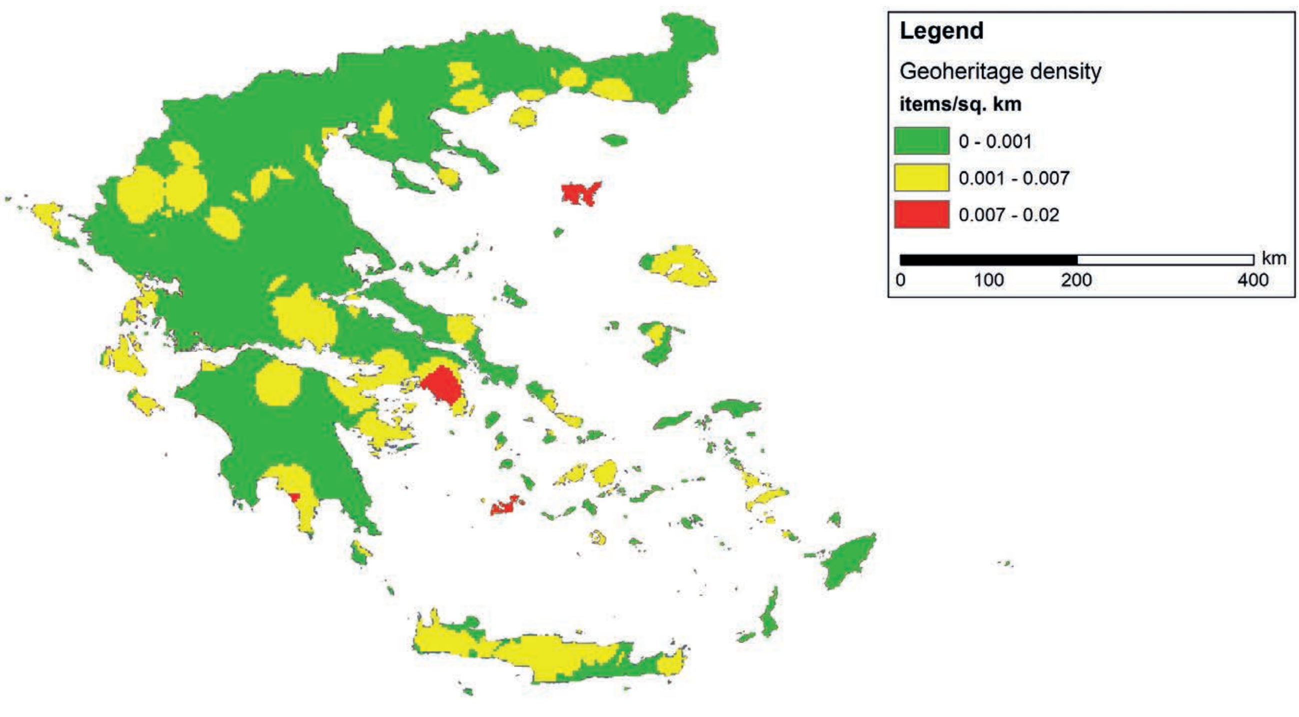

Fig. 7 Geoheritage density throughout the country.

different climatic projections and sea level rise scenarios (e.g. Fig. 11).

Finally, for the site-specific application demonstration on Milos Island, the Kleftiko rock mass was delineated from the satellite imagery in three processing steps (Fig. 12). This allowed the monitoring of this major rock formation, providing evidence for assessing the progress of erosional processes (and thus the degradation of the geoheritage site), by measuring the changes in its area and perimeter (Tab. 4).

4. Discussion

The geological heritage database developed in this study is a dynamic tool aimed at highlighting all kinds of geoheritage from local to global impact. It is a rare example of addressing the topic in such a holistic approach, by covering a relatively large geographical scale, while including all types of geoheritage and all stages of geoheritage management. The database was developed within the framework of a PhD research,

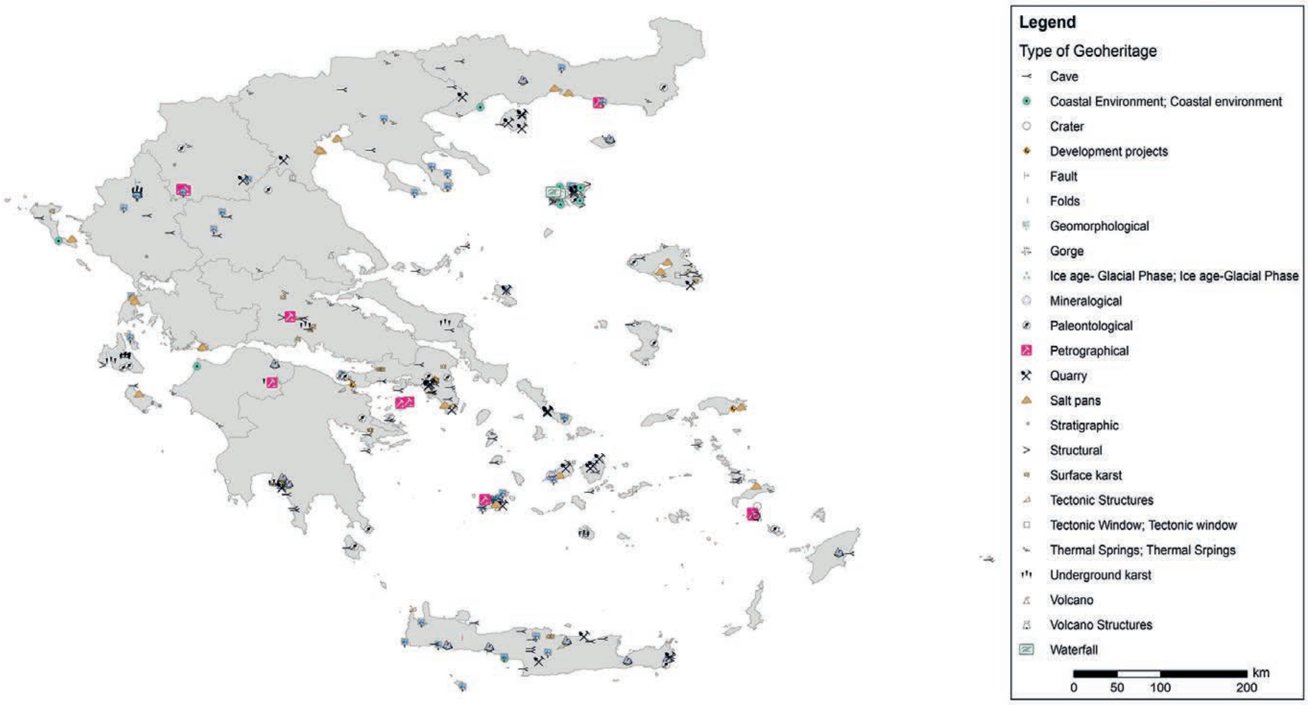

Fig. 8 Distribution of geoheritage sites per type.

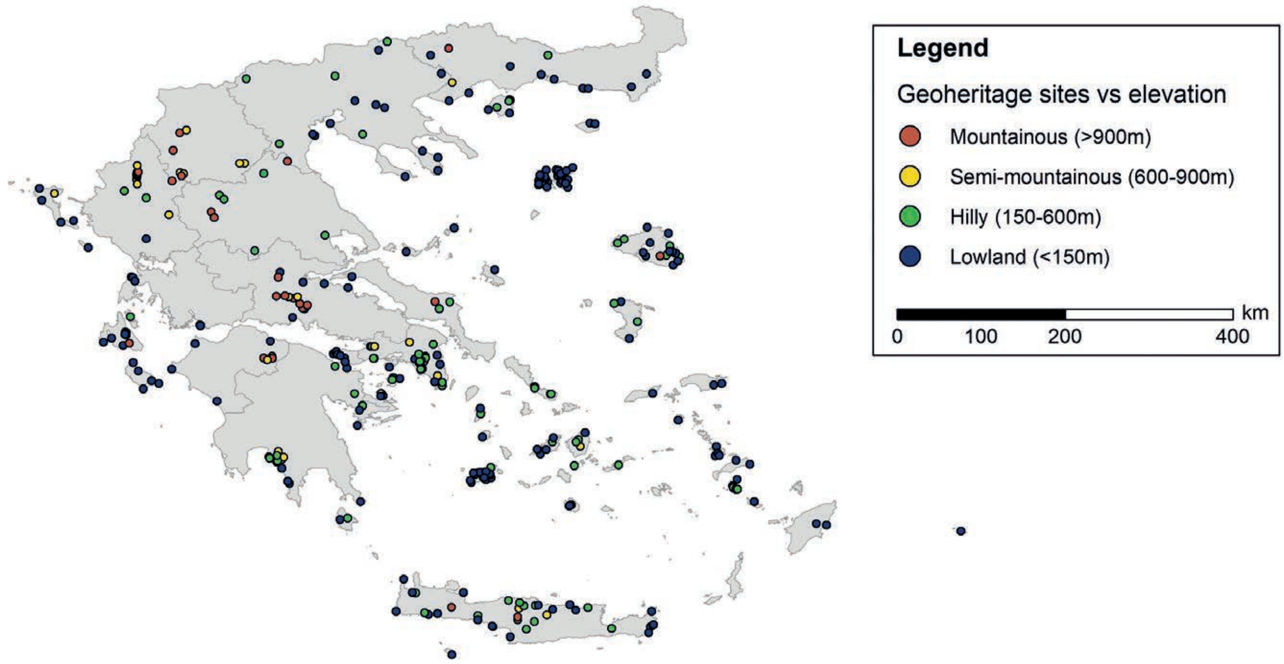

Fig. 9 Classification of geoheritage sites per surface relief according to Dikau's classification (Dikau 1989).

but aims at continuous enrichment, development, correction when deemed necessary and foremost at its exploitation by national or local authorities as well as the general public. This will not only contribute to the optimization of the overall geoheritage management but will also render the registered geosites more widely known and further develop the citizens' sense of responsibility in maintaining geological heritage elements for future generations. In this context, education in its very broad sense is of paramount importance and can maximize its potential through the use of open data (Coughlan 2020) – which is the case for the geoheritage database.

The number of entries (about 350 to date) in the database has been sufficient to demonstrate the value and potential uses of a geospatially-enabled database, but it is envisaged that it will increase to higher numbers in the near future. In any case, what is more

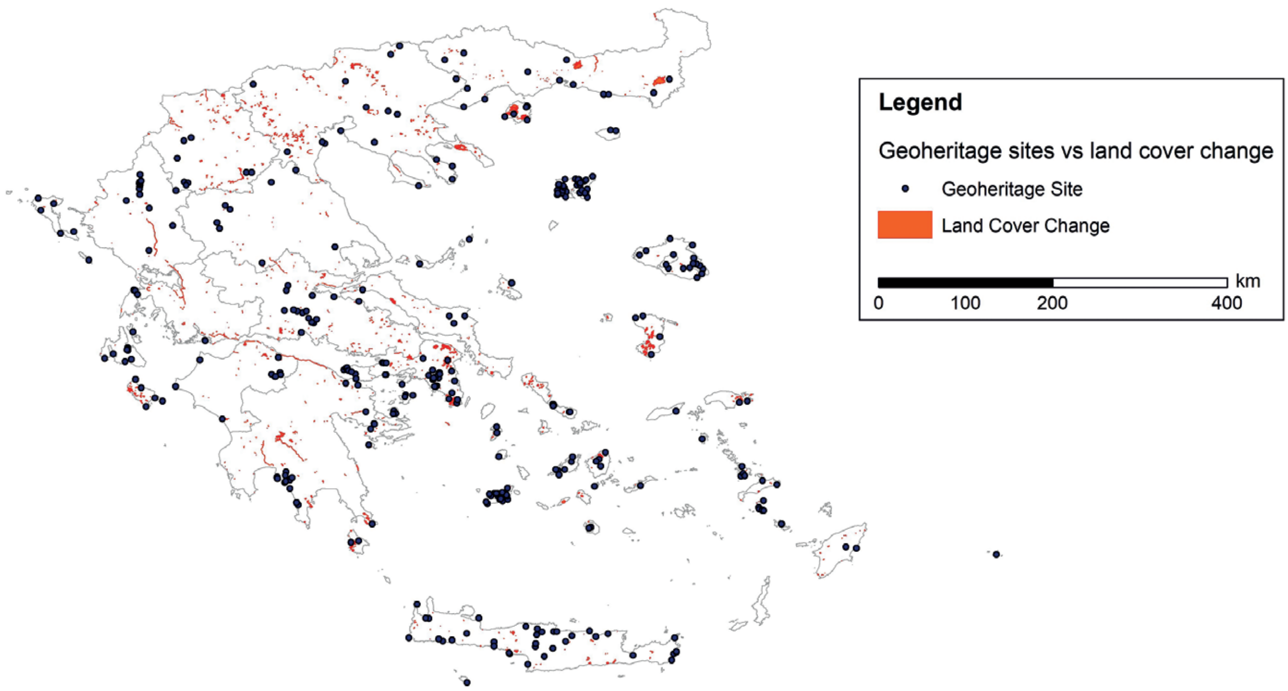

Fig. 10 Geoheritage sites vs Corine Land Cover Chance between 2012 and 2018.

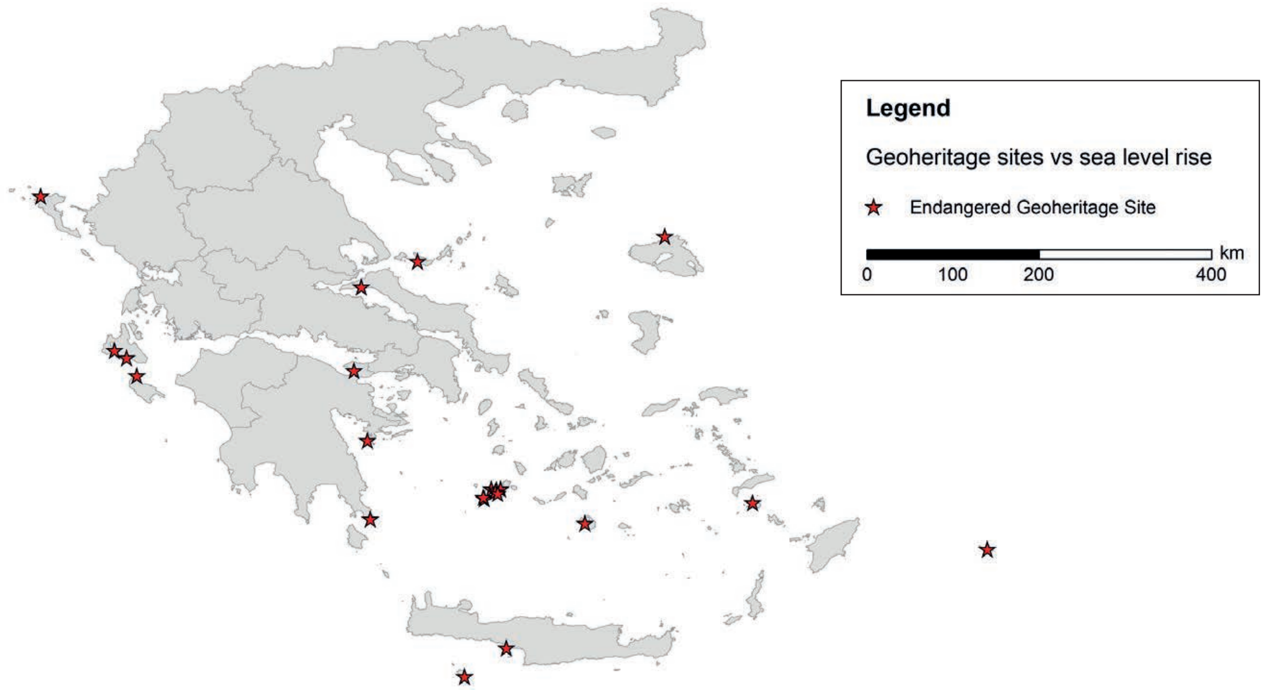

Fig. 11 Impact of 40 cm sea level rise on geoheritage sites in the next 100 years.

important is to maintain or even raise the quality standards set from the beginning (especially regarding verification and geolocation) rather than focusing on quantitative aspects.

GIS is the sine qua non for all the analyses and the fundamental connecting resource of all geospatial technologies and information for the purposes of this study. Due to the availability of all options, but also for reasons of convenience, both open source and commercial GIS were used. Nevertheless, it ought to be clarified that all the procedures presented herein, and many more, are feasible to be performed with freely available GIS software and related tools. This is considered particularly important, as it consolidates that the database if fully "open" at all stages, from its original assemblage to its operational use.

Apart from hosting the database at institutional level, it shall also be made available via National storage

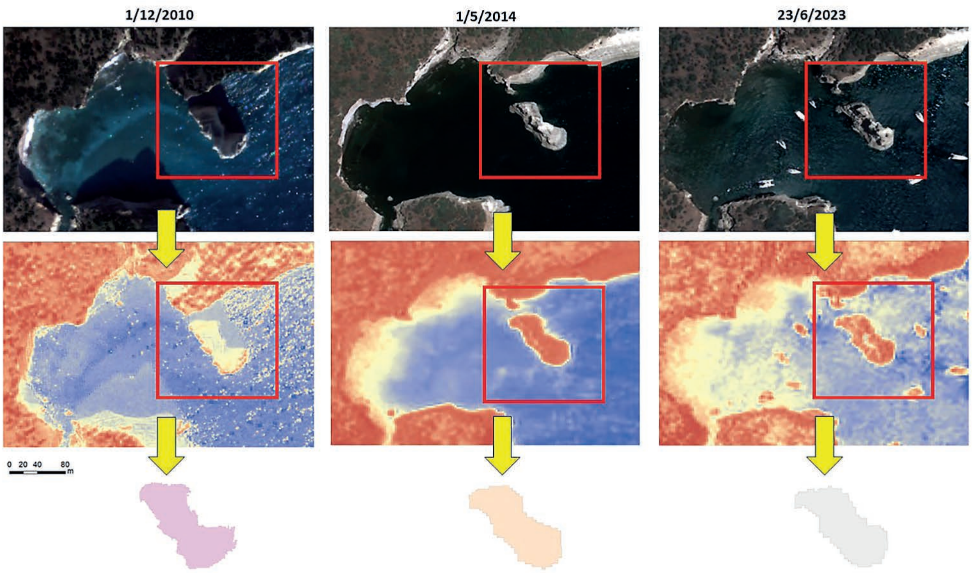

Fig. 12 Mapping and monitoring of the Kleftiko rock formation between 2010 and 2023. The set of three very high resolution images (first row) was used to extract NDWI (second row) and subsequently to isolate the relevant non-water area via K-Means supervised classification (third row).

Tab. 4 Monitoring changes of area and perimeter for the rock structure of Kleftiko on Milos Island during 2010–2023.

Date	Source	Area			Perimeter		
		Area (m^2)	Change (m^2)	Change (%)	Perimeter (m)	Change (m)	Change (%)
1 December 2010	Worldview-2	1747	–	–	341.65	–	–
1 May 2014	Pleiades	1692	−55	−3.1	237.35	−104.30	−30.5
23 June 2023	Pleiades	1643	−49	−2.9	242.00	4.65	2.0
		Total	−104	−6.0	Total	−99.70	−28.6

resources – such as the Hellenic Academic Research Data Management Initiative (HARDMIN) https://hardmin.heal-link.gr/en/about. This will ensure its viability as well as visibility at national level. The database will also be made available on ArcGIS online™, Environmental Systems Research Institute's (ESRI®) web-based mapping software for even higher visibility and possibility to combine it with a plethora of other readily available geospatial information online.

The results from the demo of geospatial analysis presented herein provide various insights into the geoheritage elements that would otherwise be very difficult or time consuming to retrieve. For example, if only absolute numbers of geological heritage sites are considered (Fig. 5), it can be deducted that there is a dividing line between a "rich" in geoheritage South and a relatively "poorer" North in the country. Conversely, the nomalization of geoheritage items by area (Fig. 6) reveals that almost all of the Greek islands and the Administrative Region of Attica have a proportionally higher number of geoheritage.

The main spatial reference unit used as a logical initial basis was that of the Administrative Regions, but more or less detailed spatial units can be used at will, like e.g. city boundaries, metropolitan areas, or any other meaningful spatial boundaries. This means that the operational scale of the database is very flexible and is only limited by the geolocation accuracy by which the geoheritage items were registered. As an indication, considering the few (3–5) meters of accuracy in this case, these correspond to a maximum cartographic scale of about 1 : 10,000 to 1 : 25,000. Regardless of spatial sub-units, when the ensemble of geoheritage entry locations is used, the density of geological heritage can be revealed in more specific areas, like particular islands or part of Attica in this case (Fig. 7).

The distribution of geoheritage by type (Fig. 8) and elevation (Fig. 9) throughout the country reveals spatial aspects of geological heritage which may be e.g. useful for touristic or educational purposes, but also of interest to the general public. For example, the concentration of specific types of mountainous geosites in Central Greece may indicate increased potential for revenues or educational field trips in the winter season, by exploiting the added value of geoheritage together with other cultural highlights in the area.

More advanced analyses incorporating external data like land cover or climate change information may produce higher level results, connecting geoheritage with a multitude of other parameters. For example, they reveal that geoheritage are indeed prone to land cover changes (Fig. 10), whereas more details on the nature of change can be easily retrieved from the attribute table of the Corine Land Cover dataset, which indicates the exact change in each case (from one land cover class to another), therefore being able to further assess the importance of each change concerning the nearby geoheritage site. In the case of sea level rise, 22 geoheritage sites are found to be endangered within the next decades (Fig. 11), an information that would prioritize interventions by the relevant protection authorities. Other risks, degradation and changes to geoheritage sites may also be assessed, with respect to their sensitivity, fragility, natural and anthropogenic vulnerability (García-Ortiz et al. 2014; Pelfini and Bollati 2014). Indicative additional options for exploiting the database in conjunction with other geospatial information and GIS capabilities include, but are not limited to:

– The detection of deformation over geoheritage sites with satellite-based Interferometric Synthetic Aperture Radar (InSAR) products from Copernicus (EGMS n.d.) or similar services (Foumelis et al. 2022).
– Implementation of vegetation, water, snow or other indices from satellite data, for accessing/monitoring the status of geoheritage sites.
– Combination with earthquake databases, to assess the seismic risk over geoheritage sites.
– Story telling (Antoniou et al. 2023) linked with georoute creation for enhancing public awareness of geoheritage in specific places (Georoutes of Nisyros n.d.).

The importance of the database is more evident when many (e.g. hundreds) of geoheritage sites are included in the analysis. Thus, its impact generally decreases with the decreasing geographical scale of reference, i.e. it is very high at national level, medium at regional level, and smaller at local level. Nevertheless, in case of existence of many geoheritage sites (high density) at regional or local level, the impact can also be equally high for relatively small geographical areas.

In site-level examples, such as that from Kleftiko on Milos Island, the contribution of the database itself is limited to the knowledge of geolocation for the (few or single) specific geoheritage item(s) that is (are) investigated. These examples are mainly highlighting the contribution of GIS analysis, not of the database, but mainly of the external geospatial data (remotely sensed or other) that are being used.

5. Conclusions

In terms of time and effort, the investment of constructing a thematically and geospatially accurate geoheritage database at National level is rather large. Nevertheless, once this complex and to a certain extend tedious task has been completed, having the GIS database available immediately provides practically infinite, relatively effortless, possibilities of extracting very useful information, depending on the user needs.

The GIS database offers practically endless possibilities for combining its data with remotely-sensed or other geospatial information, rendering it particularly useful in the overall management of geoheritage as well as in the decision-making process.

The geolocation accuracy of geoheritage sites in the database is of outmost importance, to fully harness its potential. Therefore the registration of entries in only meaningful when it adheres to the minimum accuracy standards set for the whole dataset, otherwise the functionality of the database as an ensemble is compromised.

The results of geospatial analysis presented herein indicate the potential uses of database and are subject to change, should more entries be registered and/or higher resolution information or accuracy is available (e.g. in terms of the land cover change or elevation of each geoheritage site).

Future work on the database itself, apart from increasing the number of records, may include the delineation of certain types of geoheritage in the form of polygon (e.g. caves, quarries), for increasing the accuracy of geospatial analysis, without the necessity of using buffer zones. Also, geolocating geoheritage sites with very precise (cm level) in situ Global Navigation Satellite System (GNSS) measurements, will also add value to the detailed analysis and combination with more refined geospatial information. Crowdsourcing and volunteering is another serious consideration for enlarging the database in terms of data volume and accuracy across the country, and, although it entails some higher risks of credibility, it will be explored in the near future.

The ultimate objective or vision behind and beyond the effective management of geoheritage with geospatially-enabled information is to raise public awareness on its value and at the same time contribute significantly to the development of local societies.

Acknowledgements

The study was supported by ESA Network of Resources (NoR) Initiative, in the context of a project on “Geospatial Data and Technology for Education (Geo-4Edu)” and in particular for accessing very high resolution satellite imagery.

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