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The Combined Use of GIS and Generative Artificial Intelligence in Detecting Potential Geodiversity Sites and Promoting Geoheritage

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Abstract: The concept of geosites and geodiversity sites that document selected elements of geodiversity has proved to be extremely useful in the preservation and communication of the abiotic diversity of the Earth. However, the process of the designation, description, evaluation and, finally, promotion of geosites requires a fair amount of effort. This hinders the recognition of geosites and the development of geoparks in many areas that would otherwise benefit from their rich but undervalued abiotic environment. To rectify this, the present study introduces the use of automated geographic information system (GIS) mapping and generative artificial intelligence (GAI) for the designation and promotion of points of geological interest and potential geodiversity sites. When used effectively, these techniques permit the rapid development of geodiversity site inventories and, eventually, their dissemination to the general public and decision-makers. In this study, GAI is employed to produce diverse promotional content, both textual and visual, that facilitates geoscientific communication. A case study of an aspiring geopark located in Poland (Central Europe) is discussed, showing that GAI has the potential to enable the rapid development of easy-to-understand and diverse educational materials, limiting the amount of resources and labour required for the effective promotion of geodiversity.

Keywords: large language models; geoeducation; geoscientific communication; Glacial Greater Poland geopark

Citation: Wolniewicz, P. The Combined Use of GIS and Generative Artificial Intelligence in Detecting Potential Geodiversity Sites and Promoting Geoheritage. *Resources* **2024**, *13*, 119. https://doi.org/10.3390/resources13090119

Academic Editor: Federico Pasquaré Mariotto

Received: 22 July 2024
Revised: 16 August 2024
Accepted: 23 August 2024
Published: 27 August 2024

1. Introduction

The description of geological heritage is essential for the development of geotourism [1,2], facilitates the effective management and conservation of geological heritage [3,4], fosters geoscientific communication [5] and stimulates the promotion of geoheritage [6]. The dissemination of geoscientific knowledge usually involves the use of geosite and geodiversity site inventories that allow for the appreciation of abiotic nature in its natural environment. In most sources, geosites are defined as in situ occurrences of elements of geodiversity that exhibit high scientific value [7,8] or, in broader terms, as components of geodiversity with significant scientific, aesthetic, cultural or educational value [9]. The latter concept is equivalent to the geodiversity sites of Brilha [7]. Under the term "geodiversity", the natural range of geological, geomorphological, hydrographical and soil features is considered in most studies [10–12]. In situ and ex situ elements of geodiversity with exceptional scientific values, such as landforms, minerals, rocks, geological structures and sedimentary sequences, among others, are also referred to by using a more general term—geoheritage [7].

Although recent years have witnessed emerging examples of the integration of geodiversity into biodiversity research and conservation efforts [13–15], which is exemplified by the rise of the Conserving Nature's Stage framework that focuses on abiotic features of the environment, such as geodiversity, in order to ensure the protection of contemporary biodiversity [16–18], the concepts of geodiversity, geoheritage and geosites were initially developed by a relatively narrow group of specialists and remain disconnected from the related disciplines, namely biodiversity conservation [19], heritage studies [20] and ecology [21]. This suggests that significant promotional efforts are required to raise awareness of geoheritage in society and among researchers.

Numerous educational techniques were employed to improve the dissemination of geoscientific knowledge. Online access to repositories of geosites [22], geological itineraries [23,24], virtual tours [25,26], augmented reality [27], digital maps [28,29], virtual geosites [24,30], 3D models [31,32] and mobile applications [33–35] are among the most representative examples of such methods. It is generally accepted that the use of novel digital technologies is required to ensure the effective communication of scientific knowledge related to geosites [4,29,35,36].

The rapidly evolving generative artificial intelligence (GAI) is among the novel tools that have had a growing and transformative impact in educational settings [37–40] and proved to be useful in the creation of teaching materials [41], the development of personalised study plans and content [39], language translation [42] and interactive learning [43]. GAI is defined as an artificial intelligence system capable of generating new and realistic content [44], such as text, images, videos, maps and graphs. Although this term encompasses a broad subcategory of machine learning and artificial intelligence [45], the focus here is on techniques of natural language processing [46], namely on large language models (LLMs) that generate output strongly resembling responses given by humans [47]. LLMs constitute an important element of GAI and contribute to its rapid development [44]. Coupled with GAI solutions that support the generation of images, LLMs have become part of multimodal systems that have the ability to process both textual and visual information [48]. General-purpose LLMs can be further fine-tuned, that is, trained to improve their performance on selected tasks [49] or, alternatively, provided by theme-specific knowledge database to enable the generation of more informative and diverse texts; the latter technique is known as retrieval-augmented generation [50]. Selected LLMs are available under non-commercial licences and can be run and fine-tuned on local machines [51], which renders them particularly useful for specialised tasks that require expertise in highly specialised domains of knowledge. These features of GAI open up the possibility of its application in the promotion of geoheritage and geosites, which will be explored here in more detail.

Examples of early attempts at the implementation of GAI in geological and geospatial sciences include seismic data analysis [52], remote sensing [53] and time series forecasting [54]; for a complete list and systematic review, see Wang et al. [44] and Hadid et al. [55]. Educational examples in the realm of geosciences are, however, scarce, although the use of LLMs trained on geoscientific literature, such as K2 [56] has the potential to stimulate individual learning due to their knowledge reasoning ability. GAI has also been applied in the promotion of tourism [57].

Possible applications of GAI in the dissemination of knowledge related to geosites and geodiversity sites include the generation of summaries of geoscientific information (such as scientific descriptions of geosites) that can be easily understood by non-geologists, the preparation of geosite descriptions addressing different target groups, the automated generation of comprehensive promotional content from a list of keywords, the production of personalised explanations of geoscientific terms used in standard descriptions of geosites and the creation of visual reconstructions of past environments, landforms and geological settings. The availability of high-quality educational materials is of paramount importance for the promotion of geoheritage [58] and geoparks [59,60] and the development of educational tourism [61] and geotourism [62,63]. The same applies to cross-language tourism promotional materials [64]. GAI can also serve as an assistant in the process of geosite and geodiversity site identification and assessment, using the input from the geographic information system (GIS) to generate informative descriptions of potential geodiversity sites. The automated approach to geosite detection by employing GIS has been extensively studied in earlier contributions [65–67]. GAI has also the potential to facilitate the increasingly popular information filtering process that is frequently used in developing systematic literature reviews and knowledge mapping in the domain of geoheritage and geotourism studies [20,36,68–72].

The present contribution explores the potential of GAI in providing educational content for potential geodiversity sites located within an aspiring geopark located in a post-glacial setting in Poland in Central Europe to outline the possible future uses of artificial intelligence for the communication of geodiversity and geosites. Although the geological, landscape and cultural values of the study area are recognised and appreciated among researchers, the dissemination of this knowledge remains in its infancy, which renders the aspiring geopark of Glacial Greater Poland particularly appropriate as the case study.

2. Study Area

The study area is located in Central-Western Poland on the Polish Lowland, which belongs to the North European Plain. It encompasses an area of approximately 1900 km^2 and is enclosed within the borders of a single second-order administrative unit (powiat) that surrounds the city of Poznań (Figure 1a). The population of the area exceeds 400,000 inhabitants and shows a steady growth that results from migration from the central town of Poznań to its suburbs [73]. The landscape of the studied territory was shaped in the Pleistocene epoch, during the main still-standing phases of the Late Weichselian glaciation [74,75]. Most of the area is covered by sands, gravels and tills of glacial and fluvioglacial origin. Undulated moraine plateaus and flat outwash plains are dissected by deep subglacial and erosional valleys, some of which are filled by lakes (Figure 1b). The area is crossed from south to north by a deep valley of the Warta River that forms a water gap [76] and divides the region into two distinct sections that belong to separate natural geographical units: Poznań and Gniezno Lakelands. Among other prominent landforms that shape the landscape of the study area, terminal moraines, eskers, kames and kame terraces predominate (Figure 2). The absolute heights range between 45 and 155 m above sea level; slope angles do not exceed 10 degrees. The structure of land use is dominated by agricultural and forested areas, although the rapid development of suburban residential districts starting at the beginning of the twenty-first century is swiftly changing the traditional landscape [77,78]. Urban sprawl exerts strong pressure on the forested land surrounding the city of Poznań [76] and on protected areas located within the boundaries of the study area: Wielkopolski National Park and four landscape parks (Lednicki, Promno, Puszcza Zielonka, and Rogaliński; Figure 1a). National and landscape parks are also among the most important tourist destinations located in the study area [79].

The national database of geosites (Polish Central Register of Geosites) includes 13 geosites located within the study area (Figure 1a), which is far too low a number for effective geoeducational initiatives given that some of the sites are poorly accessible or located away from popular tourist destinations. More geosites and geodiversity sites have been proposed [80,81] but, unfortunately, they are not located in the area considered in the present contribution, but within the administrative boundaries of the city of Poznań. Several other scientific papers have also been published, but these related to the conservation and communication of the geodiversity of the area under study are rare [82–84]. However, the rapidly growing number of inhabitants in the study area and the increasing anthropogenic pressure on the natural environment [85] encourage the use of educational efforts to demonstrate and explain the diversity of the abiotic environment. Earlier attempts include the geopark initiative [86,87]. The aspiring geopark (introduced in different papers as Morasko Geopark, Poznań Water Gap Geopark and Glacial Greater Poland Geopark), which is planned to include our study area, would benefit from a set of potential geosites and geodiversity sites, and the possibility of the rapid generation of promotional material by utilising GAI tools reduces the amount of time required to provide the public with engaging resources.

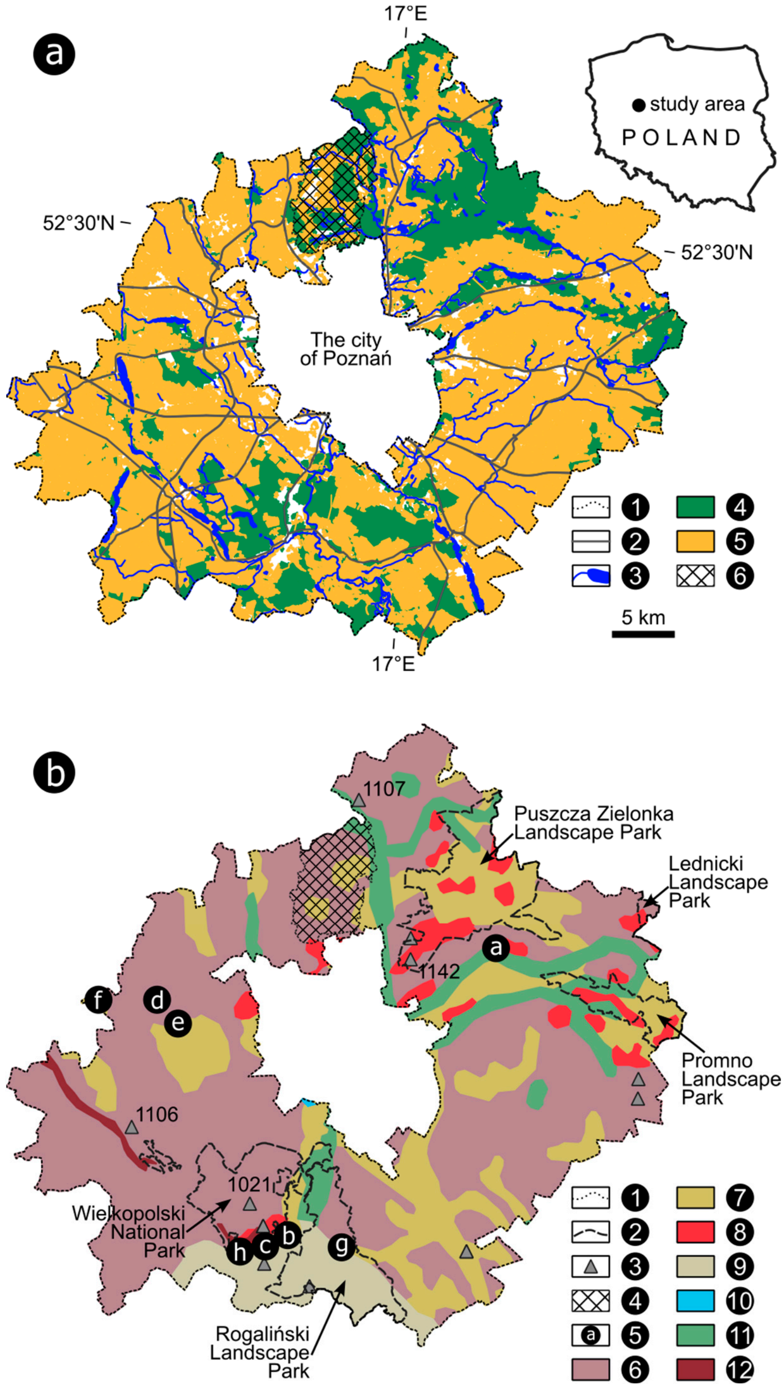

Figure 1. Maps of the study area: (**a**) Land use patterns; 1—administrative borders of the study area; 2—main roads; 3—hydrographic network; 4—forests; 5—agricultural areas; 6—Biedrusko military area; (**b**) Geological map (elaborated from the 1:50,000 scale Detailed Geological Map of Poland published by the Polish Geological Institute): 1—administrative borders of the study area; 2—national and landscape parks; 3—geosites from the Polish Central Register of Geosites (numbers refer to sites in the Supplementary Materials, Table S1; note that not all geosites are included in Table S1 due to their limited accessibility); 4—Biedrusko military area; 5—locations of landforms shown in Figure 2; 6—tills, gravels and sands of moraine plateaux; 7—sand and gravels of outwash plains; 8—terminal moraines; 9—sands of ice-marginal valleys; 10—clays of ice-dammed lakes; 11—alluvial silts/sands and peat; 12—eskers.

Figure 2. Examples of the most prominent landforms and other geodiversity elements that shape the landscape of the study area. For location of photographs, see Figure 1b. (**a**) Moraine plateau; (**b**) Human-transformed terminal moraines in the former clay pit; (**c**) Esker; (**d**) Tunnel-valley lake; (**e**) Small endorheic depression; (**f**) Kame; (**g**) Oxbow lake; (**h**) Erratic boulder.

3. Materials and Methods

In the present study, we utilise a case study approach [88]. It is known to be appropriate in the preliminary stages of research on a given topic and when the development of more structured tools is in its infancy [89]. Although GAI has a much longer history than recent LLMs such as ChatGPT, its applications in geoeducation and geoheritage promotion are scarce; the use of the case study approach is therefore adequate at this stage of research. Moreover, multiple data sources, such as vector and raster layers, supplemented by unstructured text input, are integrated into the present contribution, which also favours the utilisation of a case study as a research strategy [90].

The study is designed to include the following steps:

1. The identification of points of interest (potential geodiversity sites) by employing an automated method that involves the use of GIS;
2. The generation of informative and promotional materials for stakeholders, local communities and potential geotourists using GAI;
3. The manual verification of results by using data layers in GIS, photographs available publicly on the Internet and field work.

3.1. Identification of Points of Interest

Although the identification of geosites and most geodiversity sites requires careful field work, the initial list of points of interest is obtained by using GIS in the present contribution. The inaccessible Biedrusko military area located in the northern part of the planned geopark (Figure 1a) and covering 64 km^2 is excluded from the study. Simple map algebra and vector operations within the Qgis environment are employed, but future attempts may also involve machine learning techniques such as artificial neural networks [91]. The input data include four layers representing (1) the topography of the studied area, (2) land use patterns, (3) the transport network and (4) lithological diversity; for detailed list of the data sources, see Table 1.

Table 1. Input data used to generate lists of potential geodiversity sites. All datasets are available under the CC-BY 4.0 licence.

Data Set	Layer	Resolution/Scale	Publisher
Digital Terrain Model (DTM) [1]	Topography	Ground resolution of 100 m	Head Office of Geodesy and Cartography of Poland
Topographic Objects Database (BDOT10k) [2]	Land use patterns; transport network	1:10,000	Head Office of Geodesy and Cartography of Poland
Detailed Geological Map of Poland [3]	Lithological diversity	1:50,000	Polish Geological Institute

[1] The dataset is available at https://dane.gov.pl/en/dataset/792,numeryczny-model-terenu-o-interwale-siatki-co-najmniej-100-m (accessed on 26 August 2023). [2] The dataset is available at https://dane.gov.pl/en/dataset/2030,dane-obiektow-topograficznych-o-szczegolowosci-zap (accessed on 26 August 2023). [3] The dataset is available at https://dane.gov.pl/en/dataset/1574,szczegoowa-mapa-geologiczna-polski-w-skali-150-000-smgp (accessed on 26 August 2023).

Most of the study area is covered by monotonous moraine plateaus and outwash plains. Thus, we decided to use a very low threshold value for the slope angle (2 degrees). The geological map that represents the diversity of rock types has been significantly simplified to reduce the number of detailed lithological units by merging them into a lower number of 23 general classes, representing the most common landforms and sediment types, making the map easier to comprehend for a reader without a geoscientific background. The list of lithological and geomorphological units used in the study is included in the Supplementary Materials, Table S2.

Earlier studies [81] showed that the geodiversity sites that gain the most attention from the general public are located in accessible areas that show high general tourism potential. To adjust for this, points of interest located in areas with elevated topographical diversity (slope angles greater than 2 degrees), within forests or arable land, close to the transportation network and at lithological boundaries were selected (Figure 3). In addition, a simple algorithm is used to identify local topographic peaks located outside of the built-up areas. This permits the recognition of points located on hilltops that could provide a broad view of the landscape. Such sites, included in the classification of viewpoint sites of Migoń and Pijet-Migoń under the category of natural points on hilltops [92], are recognised as valuable geosites with high educational potential [92–94]. To locate culminations within the study area, the concept of geomorphons, that is, elementary units of terrain [95], is employed for extraction of peak morphologies from raster layer representing the topography of the area [96]. However, more advanced methods that permit the selection of viewpoints, such as viewshed analysis, are also available [97]. Local topographic culminations are identified here by detecting geomorphons that represent peak morphologies (parameter DN = 2 in the r.geomorphon extension for GRASS GIS 7.8.7 software [96]). To reduce repeatability of the locations, the points located on the same lithological boundaries or at distances less than 400 m were removed (Figure 3). The same was applied to topographical heights lower than 85 m a.s.l. The complete framework used for selection of points of interest, implemented in Qgis 3.22.11, is outlined in Figure 3.

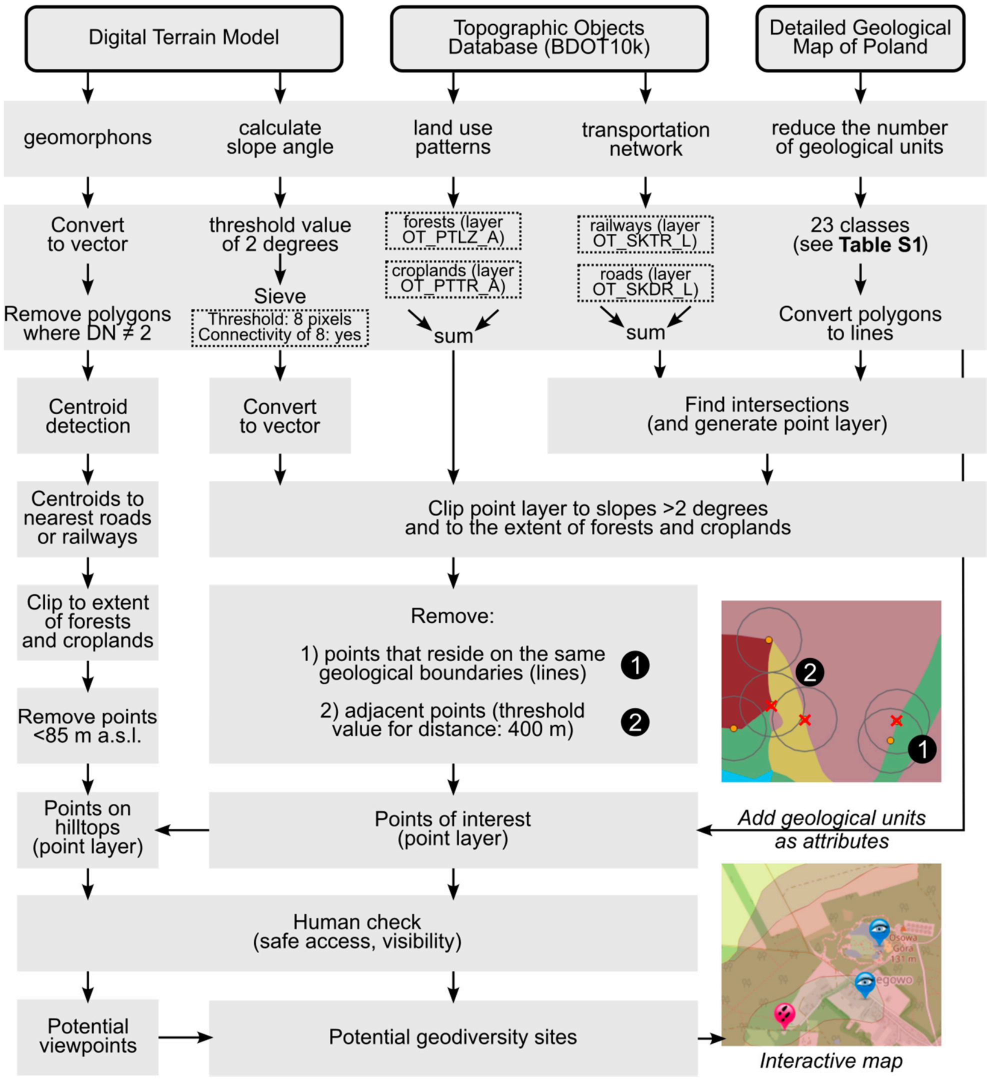

Figure 3. Framework used for the selection of points of interest (potential geodiversity sites), implemented in Qgis.

The author has manually and tentatively scanned the list of points of interest to exclude sites located near industrial facilities, in densely built-up areas, near extensive agricultural facilities and in other locations that are not particularly interesting to potential geotourists. No field work has been carried out at this stage of research due to the high number of sites detected using GIS.

The list of points of interest has been exported from Qgis in CSV format, to enable data transfer to GAI models. For each site, the lithology of neighbouring geological units has been recorded; the lithology at each topographic culmination has also been saved in a CSV file. The contents of the files are included in the Supplementary Materials, Tables S3 and S4. The sites removed during the manual check performed by the author are not included in the tables.

To allow the comparison of the list of points of interest obtained from the GIS environment with the outcome of traditional assessment procedures relying on field work, the author has compiled an additional catalogue of potential geosites using the results of his own field studies during the years 2018–2023. The purpose of this strategy is to evaluate the applicability of GIS-based techniques for the identification of potential geodiversity sites in areas for which either no significant field work has been completed or published sources related to geosites and geoheritage are available. In Qgis, buffer zones with a radius of 500 m are introduced around each geodiversity site included in the database compiled by the author, and a test for the presence of automatically generated points of interest within the buffer is carried out to determine whether the algorithm employed in the present study is capable of detecting the same geodiversity sites that were mapped manually during field studies.

3.2. Generation of Content

A self-hosted LLM, Llama 3 (https://llama.meta.com/; accessed on 22 August 2024), available under a non-commercial licence [98] and downloaded and deployed on a local machine, is used for the generation of descriptions of potential geodiversity sites. Although commercial solutions, hosted on the provider's servers, offer improved efficiency due to the utilisation of dedicated high-performance processing units [51], the application of local LLM installations provides the user with superior control over the training process and improved data privacy. Similarly to the frequently used LLM ChatGPT, whose code is not available to the public, Llama utilises transformer-based neural networks to enable natural language generation [98], although its earlier versions showed slightly inferior [99] or similar [100] performances compared to the commercial ChatGPT-3 model. However, the diverse text corpora used to train Llama facilitate the application of this model in a variety of languages and domains [98].

To enable the generation of geosite descriptions, the in-context technique known also as few-shot learning [101] is employed. The method uses a few examples provided to the model to guide its subsequent responses. Although few-shot learning underperforms compared to the full training of the LLM [102] and struggles to generate content using domain-specific terminology [103], it does not require the time-expensive training of general-purpose models. In contrast, the fine-tuning approach involves additional training, which is a more time-consuming procedure, but allows the customisation of the LLM to perform more efficiently in task-specific contexts that are not supported by the original model [101].

In the present study, few-shot learning is the appropriate choice, because the model is used exclusively to generate standard summaries and descriptions based on the data provided by the author and keywords obtained from the GIS environment, to facilitate scientific communication, and such applications are fully supported by existing LLMs. First, the model is provided with a few pairs consisting of a predefined input and an example output (Figure 4), both in English and in Polish. Subsequently, the model is fed the contents exported from Qgis 3.22.11 software, for which it independently generates short (1–2 sentences long) introductions to individual geodiversity sites (in English and Polish), including information on lithology and landforms, following the examples provided in the earlier stage.

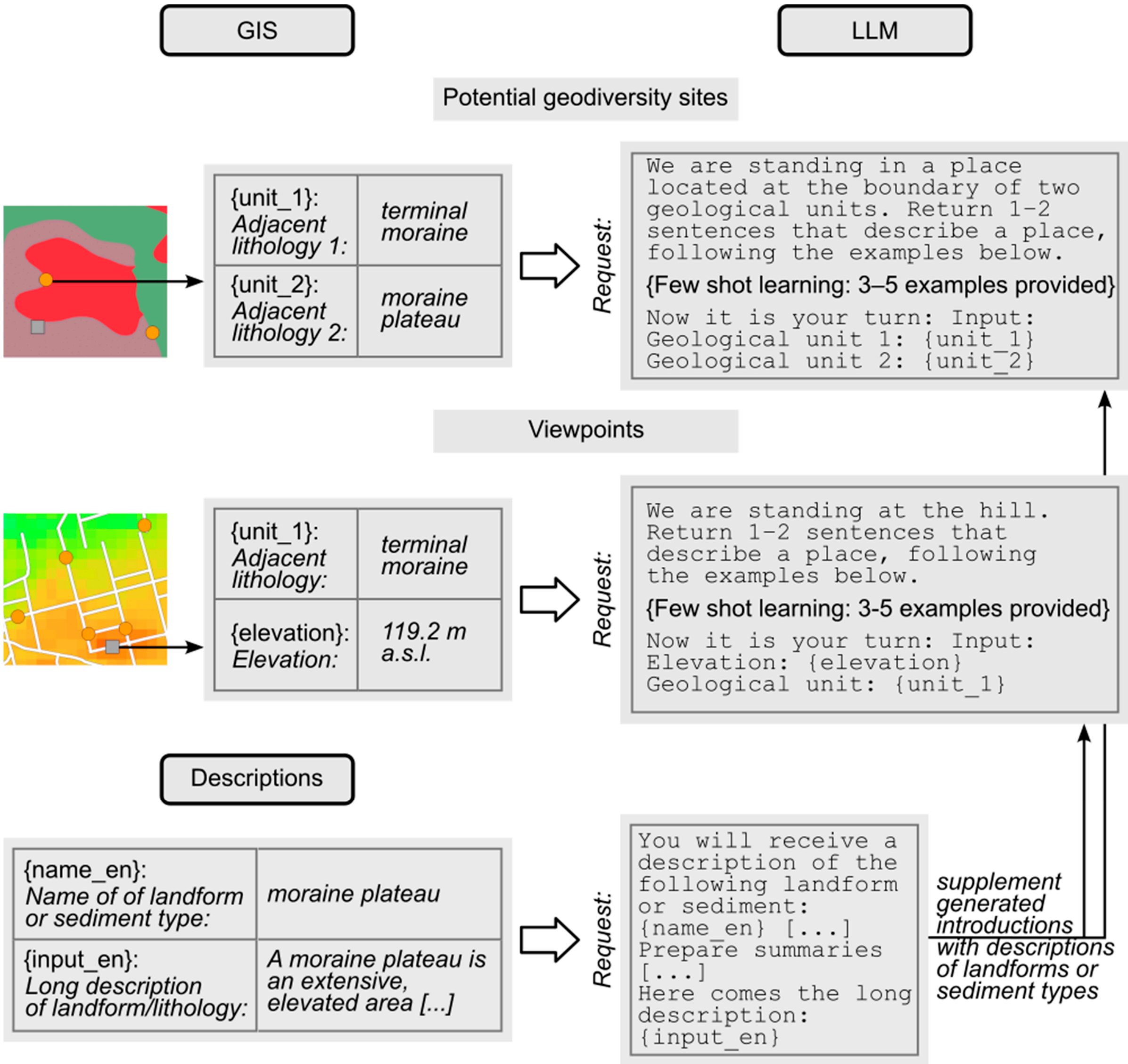

Figure 4. Framework for content generation that uses GAI.

The complete requests sent to the Llama LLM are shown in the Supplementary Materials, Table S5. The code in Python that permitted the automated generation of descriptions for all points of interest is included in Supplementary Materials, Table S6. Similar requests can be sent to the OpenAI API to interact with the ChatGPT LLM. The same result can be obtained without the use of Python scripts, but this involves the manual preparation of requests separately for each site, which is not a feasible solution.

To further introduce the reader of the generated content to the geology of the study area, the LLM is provided with long (from less than 60 to more than 450 words) and detailed scientific definitions of landforms and lithologies, written in both English and Polish, accompanied by explanations of the processes that led to the formation of these geodiversity elements. The content given to the LLM is written manually by the author in Polish to avoid copyright infringements and translated into English using the commercial ChatGPT-4 model (Supplementary Materials, Table S7). Using these descriptions, short (1–3 sentences long) texts aimed at the general public are generated separately for each lithological type and/or landform. Eventually, the explanations produced for an individual site consist of (1) a short introduction to the geological and geomorphological features; and (2) more comprehensive but easy-to-understand descriptions of these features and their origin. The complete framework used for interaction with LLM is shown in Figure 4 and the Python code is included in the Supplementary Materials, Table S6. Note that descriptions were not generated for three of the landforms and/or sediment types that are not represented in the database of potential geodiversity sites.

The texts generated for sites that reveal the same geological features differ from one another because the LLM produces them independently for each point of interest. Thus, the user rarely encounters repeated content, and each explanation draws the user's attention to other aspects of the selected landform or lithology. Such diverse descriptions demand a significant amount of labour when descriptions are written manually.

Geoscientific interpretation benefits from visuals, such as images, reconstructions and 3D models [32,35]. The use of paintings and dioramas has a long tradition in geoconservation and geotourism [104]. The production of such media requires substantial resources, which are usually not available at the early stages of the initiatives aimed at the promotion of a local geosite or the development of a geopark. Thus, in the present contribution the automated generation of visuals is used to illustrate the most common glacial landforms that shape the landscape of the study area. A multimodal LLM Stable Diffusion [105], released by Stability AI, is employed to generate novel images from textual requests sent to the model [48,106]. The commercial interface of the model (available at https://dreamstudio.ai/generate; accessed on 26 August 2023) has been prioritised over the manual installation of the LLM due to its significant system requirements. Contrary to the text generation process, many experiments were required; they were aimed at designing the appropriate text queries that allow the production of scientifically correct images. This would demand a significant amount of time in the case of a multimodal LLM installed on a local machine. The model has been employed to generate reconstructions of landforms such as terminal moraines, moraine plateaux, outwash plains and endorheic depressions, visualising their appearance at the end of the Pleistocene, shortly after the retreat of the Pleistocene continental glacier, and in the Holocene, before significant human intervention occurred.

3.3. Validation of Generated Data

The content obtained from the LLM is manually scanned to ensure its accuracy. The parts of the sentences that include incorrect geoscientific information or, in the opinion of the present author, obscure the understanding of the character, origin or structure of geological features are marked in red in the Supplementary Materials, Tables S3 and S4. The quality of the language is also evaluated. The parts of descriptions that require further manual editing are highlighted in yellow.

The further validation of potential geodiversity sites for which descriptions have been generated using the LLM includes the inspection of images available on the Internet and the field study. Points of interest that, according to the prior experience of the author, appeared to be not particularly appealing to general tourists were removed from the final inventory. In case of doubts, the potential geodiversity site has been kept in the database, because further evaluation involving the use of numerical ratings obtained from potential geotourists is planned.

The content that has been edited, verified during the field study and accepted after manual review is used to generate the interactive map of the study area and the planned geopark, which are freely available on the Internet, on the geopark website (https://www.wielkopolskaglacjalna.pl/?page_id=985; accessed on 22 August 2024) and on the author's geoscientific website (https://zywaplaneta.pl/powiat-poznanski/; accessed on 26 August 2023). Both maps are in Polish and feature geodiversity sites from the database assembled by the author, geosites from the national inventory and points of interest selected from Qgis, with descriptions and graphical reconstructions obtained from the LLM. Geodiversity sites are represented as markers that can be clicked by the visitor for more information. The content generated by the LLM is loaded and shown on the map in a separate panel that appears after the user selects the chosen point of interest (Figure 5).

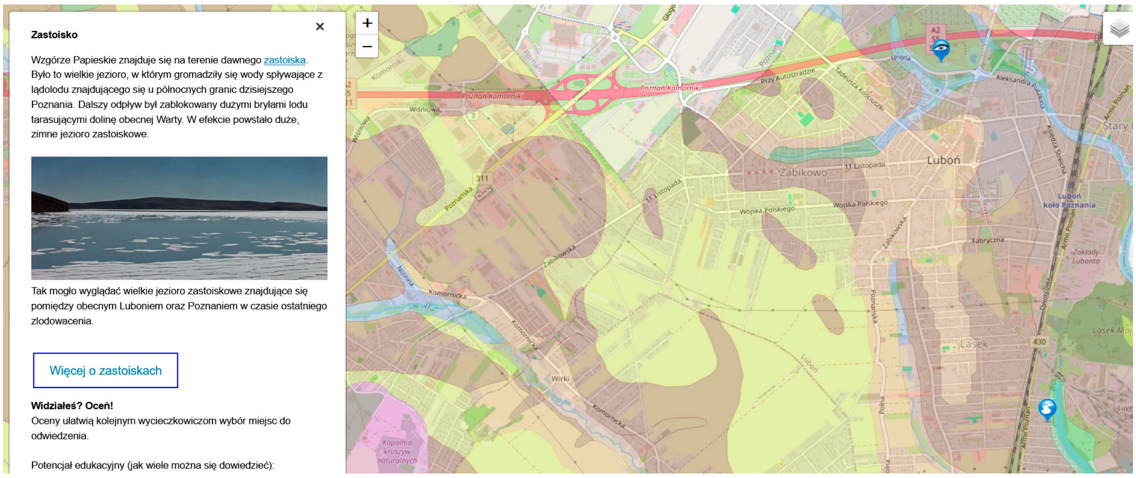

Figure 5. Interactive map of the study area; the content generated by the LLM is shown in the panel after the user selects a point of interest. The map colours represent individual lithological units from the geological map. The meaning of the Polish text, shown in the left panel, is as follows: "It was a large lake where the waters accumulated, flowing from the ice sheet located at the northern borders of today's Poznań. Further outflow was prevented by large ice blocks obstructing the valley of the present-day Warta River. As a result, a large, cold proglacial lake was formed. This is how the proglacial lake, located between present-day Luboń and Poznań during the last glaciation, might have looked". The first two sentences are only partially visible in the figure. Note the presence of links that redirect the user to other web pages where detailed explanations regarding landforms and geological features are provided.

4. Results

Using the automated approach to the geodiversity site selection process, implemented in Qgis, a total of 658 points of interest have been found. After manual screening and the removal of the points located in places that are subjectively recognised as not appropriate for the development of geotourism (e.g., located near active industrial facilities), the number of potential geodiversity sites was reduced to 268 (Figure 6 and Supplementary Materials, Table S3). The automated detection of topographic culminations returned 76 points of interest, from which 31 were manually selected for the subsequent stages of the study, by excluding the points located in the vicinity of built-up and industrial areas (Figure 6 and Supplementary Materials, Table S4).

The list of potential geosites and/or geodiversity sites compiled by the author during the field work is shown in Figure 6 and in Supplementary Materials, Table S1. Out of 143 sites, 59 (41.3%) have their counterparts in the database of points of interest generated in Qgis, located within a distance of 500 m. Five out of 13 geosites listed in the Polish Central Register of Geosites (38.5%) have also been identified by the automated detection method implemented in Qgis. Other geodiversity sites mapped by the author and geosites listed in the national inventory are located in areas where the algorithm used in Qgis did not find any points of interest.

Short introductions to descriptions of 268 potential geodiversity sites and 31 points located at hilltops generated by the Llama LLM reveal that the language model performs much worse in Polish than in English, although this may partly result from a lower number of examples in Polish provided at the few-shot learning stage. 134 introductions in Polish were marked as requiring additional editing effort (44.8%), and 10 include either incorrect geoscientific information or can be easily misinterpreted by the reader (3.3%), while in one case, the LLM failed to generate output in Polish, using English instead. However, the overall performance of the model is much better in English. Although nine of the introductions are either not accurate or contain information that can be misunderstood (3.0%), the quality of the language is also much better when considering output generated in English rather than in Polish, with only four texts marked as demanding a significant improvement (1.3%). The issues detected in the text received from LLM are marked in the Supplementary Materials, Tables S3 and S4.

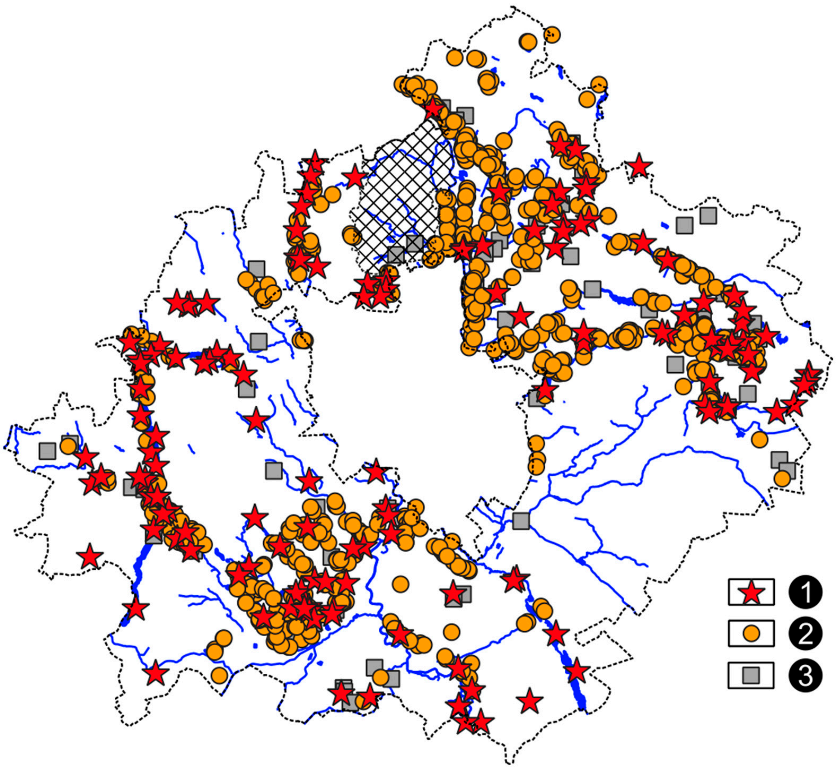

Figure 6. Map of points of interest detected in Qgis, with potential geosites and/or geodiversity sites identified by the author during the field work. 1—Geodiversity sites mapped during field work; 2—Points of interest detected in Qgis; 3—Positive topographic features detected in Qgis. For other explanations, see Figure 1a.

Summaries that introduce the reader to landforms, geological units and/or sediments that are outcropping at the given point of interest, obtained from the LLM by using the longer scientific texts prepared by the author, show similar patterns (Supplementary Materials, Table S8). Most descriptions (114; 91.2%) generated in English are accurate and do not need any additional editing effort, although some shorter, sentence-long summaries have been merged into longer descriptions. In contrast, the LLM failed to generate text in Polish in the case of more sophisticated landforms and geological and geomorphological units (three out of 20 geological units; 15%), such as the Pliocene clays and alluvian fans, providing the summaries in English. Moreover, 22 summaries (20%) that were generated in Polish included significant inaccuracies in the scientific content, while 53 (48.1%) required additional proofreading.

The generation of graphical reconstructions is a more labour-intensive process, requiring the preparation of unique requests sent to the multimodal LLM for each generated image. Six digital images showing the most prominent landforms of the study area were produced (Figure 7) using a diverse set of requests included in the Supplementary Materials, Table S9.

Further field studies aimed at the evaluation of the geotouristic and educational potential of points of interest identified in the GIS environment led to the removal of 123 (41.1%) out of 299 sites that were used at the stage of automated content generation, due to their similarity to other sites in their vicinity or their proximity to industrial facilities. The remaining 176 sites are considered viable candidates for geodiversity sites or geosites and were featured in the interactive map, which is available online at the website of the aspiring geopark, together with the database of geodiversity sites assembled by the author (Figure 8).

The auto-generated sites and their descriptions raised the number of geodiversity sites to 266 (an increase of 123%). The final list of geodiversity sites from the national inventory, the author's list, and generated by using GIS and LLMs, as shown on the online map on the website of the aspiring geopark, is included in the Supplementary Materials, Table S10 and shown in Figure 8.

Figure 7. Reconstructions of past environments generated in Stable Diffusion. Requests (prompts) sent to the multimodal LLM are given in the Supplementary Materials, Table S9: (**a**) endorheic depression; (**b**) forefield of an ice sheet; (**c**) ice-dammed lake; (**d**) hummocky moraine plateau with small depressions and hills; (**e**) distal outwash plain near the ice-marginal valley, with windblown aeolian sand sheets; (**f**) terminal moraine.

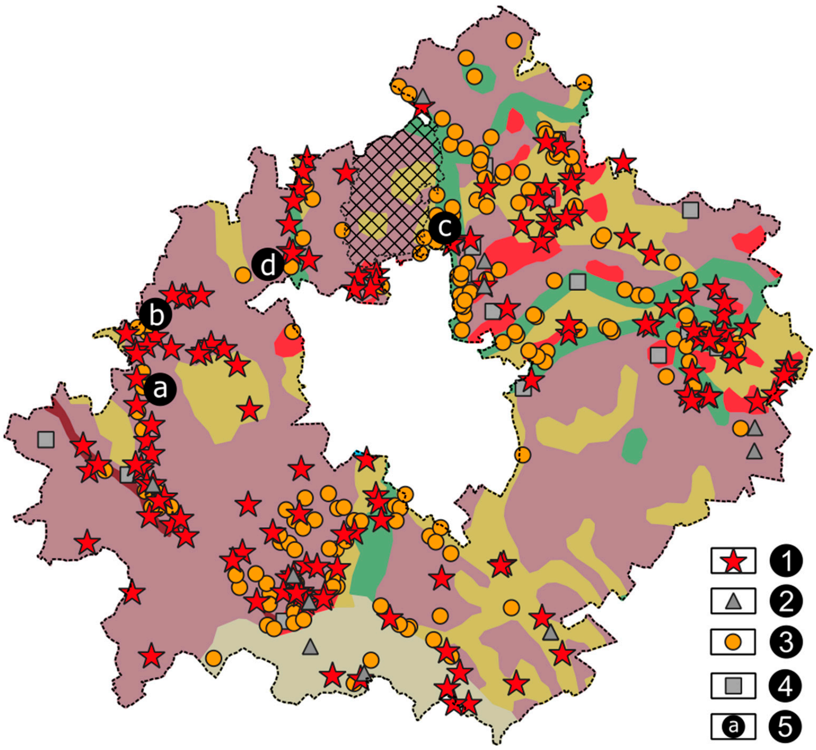

Figure 8. Final database of potential geodiversity sites published in interactive maps of the study area. The list of individual sites is provided in Supplementary Materials, Table S10. 1—Geodiversity

sites mapped during field work; 2—geosites from the Polish Central Register of Geosites; 3—Points of interest detected in Qgis; 4—Positive topographic features detected in Qgis; 5—Potential geo-cultural sites shown in Figure 9. For other explanations, see Figure 1b.

Figure 9. Examples of points of interest generated from GIS that show strong cultural dimension and can be used in the future as potential geo-cultural sites. For locations of sites, see Figure 8: (**a**) The cross in Więckowice, located on the steep slope of the kame terrace. (**b**) The Jankowice Palace on the moraine plateau, facing the kame terrace. (**c**) Forest Education Centre "Łysy Młyn" in an old watermill, located in the deep valley near the terminal moraine. (**d**) Saint Faustine footpath on the slope of the moraine plateau.

5. Discussion

The study shows that although existing geosite databases are of great importance in the promotion of geodiversity, it is possible to start the development of a geodiversity site inventory based exclusively on GIS selection and LLM content generation, with the verification process in the field involved in the last stage of research. This permits the rapid development of potential geodiversity site inventories in areas where geoheritage has not yet been extensively studied, in remote regions and in places that exhibit a great diversity of geological features. However, the framework applied in the present study, aimed at the identification of potential geodiversity sites, performs poorly in predicting the locations of geosites from the national inventory, which is consistent with earlier statements that geoheritage does not necessarily correlates with geodiversity [107], and areas with low geodiversity metrics can be rich in geoheritage. Moreover, certain geosites can be included in inventories because of their high cultural values that are not considered in the present methodology. On the other hand, the framework produces a long list of points of interest that display geodiversity elements that are common within the study area but can be easily overlooked. Earlier studies showed that such features are attracting the attention of potential geotourists [81].

In the present study, GAI is employed to generate descriptions of potential geodiversity sites that are diverse and easy to understand. The production of customised learning materials is among the most important applications of GAI in educational settings [108]. Other potential uses of LLMs in geosite promotion include the generation of content tailored to the needs of specific target groups, such as general and pure geotourists sensu Božić and Tomić [109], families with children and students in geosciences. LLMs are also capable of translating scientific and educational content across many languages [103], which makes the communication of geoheritage more productive. The development of such diverse sets of educational materials is in many cases hampered by the lack of funds and educational experience of scientific staff, and GAI has the potential to fill this gap.

The LLM used in the present study shows an inferior efficiency in the production of content in Polish compared to the quality of the output produced in English. The issue can be mediated by the use of other, commercial models such as ChatGPT-4, which in the present contribution has been employed solely as a translation tool. However, the poorer performance of LLMs in local languages is generally known [110] and the risk of limited accessibility of the GAI for selected regions and languages is recognised in previous studies [103].

5.1. Challenges of the Use of GAI

The use of GAI raises challenging ethical concerns [110–113]. LLMs are trained on vast corpora of text that may include proprietary sources. Their use in the generation process could result in copyright infringements and plagiarism [114–116]. In the present contribution, these legal issues are mediated through the use of descriptions written by the author, and the system is urged to use solely the input provided during the generation process. However, this does not solve the problem of the extensive LLM training that was required to gain the basic abilities to use natural language, which demanded in turn a separate corpus [117,118]. Although some of the LLMs are provided along with the corpora used during the training process, most of the providers do not maintain transparency about the data sets that are employed.

The present study does not compensate for copyright issues related to artwork generation [119], which in the future may severely affect the use of multimodal LLMs for geosite promotion and for the production of visual reconstructions of past environments. Training data sets include images released under differing licence agreements, with a significant share of copyrighted works [120] that pose a risk of copyright infringement when such graphical material is reused for the generation of novel images. This is particularly challenging when considering the reconstruction of ecosystems from a very distant past, for which training data sets would include a limited number of images published in journals and curated by museums, elevating the possibility of the illegal reuse of copyrighted visuals. In the present study, more generic images that show glacial landforms modelled in the periglacial climate are generated, which limits the risk of the reproduction of unique copyrighted reconstructions, but this issue would severely affect the use of GAI in the promotion of palaeontological geosites.

Other issues related to the use of artificial intelligence include the lack of transparency and explainability [121]. Similar to other machine learning methods that involve the use of neural networks, GAI acts as a "black box" [55,122,123] that offers limited explanations of its decisions [123]. This severely affects the interpretability of the model, making it difficult to comprehend the justification for specific predictions and opinions. In the present study, GAI is used exclusively to generate natural language texts from data and write summaries, and the model is not making significant decisions. This reduces the negative influence of limited explainability, but this could change with the application of machine learning at other stages of the selection of potential geodiversity sites.

The use of GAI in scientific communication is significantly hampered by its inclination to generate false facts called hallucinations [124,125]. In the present study, the ability of the model to produce fictional content is limited by the use of predefined source texts. The LLM was asked to summarise the content provided in the request, without using any other sources of knowledge. The geoscientific output was in most cases correct, although the poorer performance in Polish results in the production of descriptions that at least in some cases are difficult to understand and prone to misunderstanding.

Among other drawbacks of contemporary LLMs, high computational power, and related environmental costs [117], the lack of scientific accuracy of the data used for training [103] and the scarcity of training data sets in specific domains such as the geosciences [55] are frequently pointed out.

5.2. Limitations of the Study

The present contribution has some obvious limitations. The study would benefit from a better understanding of the perception of geodiversity sites among local communities and potential geotourists. The digital map of the study area, available on the Internet, offers a rating system that allows users to provide feedback on individual geodiversity sites, but more time is required to obtain a substantial number of votes. The comments and opinions of geotourists proved to be valuable in assessing the criteria that affect geosite visits [126]. Moreover, effective geoheritage interpretation in geoparks is not possible without paying closer attention to the values and activities of local communities [20]. This shows that the effective promotion of geosites cannot be decoupled from efforts aimed at better understanding the demands and expectations of local stakeholders and geotourists.

In the present study, the content generation depends on the manual preparation of detailed explanations of geological features, from which the LLM produces diverse, short and user-friendly descriptions of individual landforms and sediment types. In the case of vast databases of geosites, including varied geodiversity elements, landforms, and lithological types, the use of geoscientific language models, trained on a diverse corpus of geological sources, would be beneficial. LLMs for Earth Sciences are already available [56], although their use at local scales and in languages other than English requires further training.

The present study design does not account for hydrographical and soil components of geodiversity, although many points of interest recognised in Qgis are located in the proximity of rivers, streams and lakes, due to the significant geomorphic variation in their vicinity. Future research efforts would benefit from the use of soil maps and layers that represent the hydrographic network. Another potential improvement can be obtained by the application of LLMs for the identification of geosites within unstructured texts such as earlier geoscientific papers in which the sites located within the present study area are discussed. In the present contribution, the scientific value of the localities is not evaluated. Thus, the sites detected by the algorithm can be designated as points of geological interest or potential geodiversity sites, not geosites.

The framework employed in the present study does not account for geo-cultural sites, that is, geodiversity sites that bridge the natural and cultural heritage of the area of interest [127]. Earlier studies have shown that they have gained significant interest among potential geotourists [81] and the importance of geosites that exhibit significant cultural values is widely accepted [128–130]. Educational strategies involving geosites would, therefore, benefit from the inclusion of geo-cultural sites, which are well-known from the post-glacial setting of Western Poland [131]. This requires significant changes in the stage of the identification of points of interest in the GIS environment, although some geodiversity sites that show strong cultural components are present within the locations selected by the present algorithm (Figure 9). Moreover, a more intensive use of GAI is necessary to prepare valuable descriptions of geo-cultural sites. However, this would also make copyright issues more likely, since the explanations regarding the sites would encompass not only geological and geomorphological features but also their historical use and comments on the cultural importance of selected sites. This involves more intensive use of the LLM, which could potentially mimic the copyrighted material from its training data sets.

5.3. Future Directions

Future improvements in the study design could include the use of machine learning and artificial intelligence in the selection of potential geosites and geodiversity sites. There are published attempts of the utilisation of such methods in the estimation of geodiversity features [91,132,133]. The replacement of simple vector operations and map algebra with machine learning would improve the efficacy of automated geodiversity site designation.

The present study also uses a very limited range of possibilities offered by GAI, which is expected to transform the educational process from a teacher-centred model to a learner-oriented model [134], by enabling the easy generation of learning material for recipient groups differing in age and in expertise in geosciences [135]. In the future, the availability of video content creation tools can also further contribute to the use of GAI in geoeducation, because animations and virtual models have already proven useful in the promotion of geoheritage [31].

In the present study, the use of LLM was restricted to the Llama model. However, a detailed comparison of the generative capabilities of available models in the geoscientific domain would enable the selection of the LLM that is most appropriate for use in geoheritage communication.

The framework employed in the present study can potentially stimulate the use of crowdsourcing [136], facilitating the delivery and inclusion of the data provided by online communities. The locations and descriptions of the potential geodiversity sites have been made available on the Internet for comments, and in the future, the modules that enable the contribution of new content by visitors are planned to be integrated into the online map. Moreover, the existing system that enables the user to rate the educational, aesthetic and tourist potential permits future adaptations of the list of geodiversity sites to the needs of geotourists.

6. Conclusions

The case study shows that GAI can be effectively used to generate diverse descriptive and visual content aimed at the promotion of geosites. Coupled with an automated system for the identification of potential geodiversity sites implemented in the GIS environment, the procedure employed in the present contribution allows the rapid creation of an inventory of geodiversity sites with digital assets for effective geoscientific communication. The framework involved here performs well when geosite promotion efforts are in their infancy and educational materials are scarce, as shown in the case of an aspiring geopark located in Central Poland.

A low-resource few-shot learning technique has proven sufficient in the present study to obtain geosite descriptions from a general-purpose LLM; time-consuming fine-tuning has not been necessary. On the other hand, the present contribution shows that despite the fast growth of GAI, the support for languages is very uneven, and the presence of geoscientific terms renders the text difficult to process by the LLM in languages other than English. The full adoption of GAI within the realm of geoscientific education thus requires further efforts aimed at the fine-tuning of existing, general-purpose models and the development of expert, geoscience-oriented LLMs, fully supporting multiple languages.

In the case study, GAI has been used to generate descriptions of geosites intended for the general public and graphical reconstructions of glacial landforms. However, the rapid development of multimodal LLMs raises the possibility of the production in the near future of fully featured animations and videos explaining geological phenomena that culminate in the formation of geosites.

Although GAI can significantly facilitate content generation for the communication of geosites, it becomes more powerful when coupled with the detection and designation of potential geodiversity sites performed in GIS, and when geo-cultural sites are considered. Future research directions should therefore explore the use of machine learning methods in geodiversity site mapping and the utilisation of GAI in the promotion of sites that occupy the intersection of cultural and natural heritage. However, significant challenges such as copyright issues, support for local languages and the scarcity of LLMs tailored to geoscientific applications should be resolved.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources13090119/s1, Table S1: The list of potential geosites and/or geodiversity sites compiled by the author during the field work, including selected geosites from the Polish Central Register of Geosites; Table S2: The list of lithological and geomorphological units used in the study; Table S3: Points of interest saved from Qgis. The author removed sites located near industrial facilities, in densely populated areas, or near extensive agricultural facilities. Introductions to descriptions of potential geodiversity sites produced by Llama LLM are also provided. Parts of sentences that include incorrect geoscientific information that obscures the understanding of the character of geological features are marked in red. Parts of descriptions that require further manual editing are highlighted in yellow; Table S4: Topographic culminations saved from Qgis. The author removed sites located near industrial facilities, in densely populated areas, or near extensive agricultural facilities. Introductions to descriptions of potential geodiversity sites produced by Llama LLM are also provided. Parts of sentences that include incorrect geoscientific information that obscures the understanding of the character of geological features are marked in red. Parts of descriptions that require further manual editing are highlighted in yellow; Table S5: Complete requests (prompts) sent to Llama LLM to generate descriptions of geodiversity sites; Table S6: The Python code used to generate descriptions of potential geodiversity sites mapped in Qgis; Table S7: Content provided to Llama LLM to generate descriptions of landforms and sediment types in Polish, and their translations to English provided by ChatGPT-4 LLM; Table S8: Summaries that introduce the reader to landforms, geological units, and/or sediments that are outcropping at the given point of interest, obtained from LLM by using the longer scientific texts prepared by the author. Parts of sentences that include incorrect geoscientific information that obscures the understanding of the character of geological features are marked in red. Parts of descriptions that require further manual editing are highlighted in yellow. Note that the English and Polish summaries may differ significantly since they are generated independently by LLM.; Table S9: Requests (prompts) used to generate graphical reconstructions of landforms in the Stable Diffusion multimodal LLM; Table S10: Final list of potential geodiversity sites generated using GIS, with descriptions produced by Llama LLM and corrected by the author. Selected summaries generated by LLM were rewritten to comply with specific sites, while others were merged to form more coherent paragraphs. The descriptions of the landforms and sediment types are concise because they are linked in the interactive map to additional web pages that offer more detailed explanations, along with photographs (Figure 5).

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in Supplementary Materials, Tables S1–S10.

Conflicts of Interest: The author declares no conflict of interest.

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