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ORIGINAL ARTICLE

Classification and Quantification of Urban Geodiversity and Its Intersection with Cultural Heritage

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Abstract
Urban geodiversity is a complex entity that includes both natural and anthropogenic geological and geomorphological elements, thus requiring broad and interdisciplinary approach to its inventorying and assessment. To estimate and evaluate the widest possible range of urban geodiversity, and to explore the intersection between geo- and cultural heritage, an inventory of 615 natural and anthropogenic geological features of the city of Poznań, Poland, has been established. The preferences of the general public were studied to examine the possibilities of developing urban geotourism. Statistical analyses allowed the estimation of the reliability of the assessment method. The study shows that in the urban environment, anthropogenic geodiversity is rich, although in most cases it scores low in the evaluation. The results of the quantitative assessment reveal few significant correlations showing that the criteria used are not overlapping. However, the preferences of potential geotourists are not consistent with the outcome of the quantitative evaluation. Landforms significantly altered or completely destroyed by human geomorphosites, located in the city centre and close to tourist venues, were selected the most times by the users of the interactive map, but none of these geodiversity sites are included in existing geosite inventories, and most of them ranked low in the assessment process. Studies of potential geotourists' preferences are therefore required before any strategy for tourism development is adopted.

Keywords Qualitative assessment · Quantitative assessment · Evaluation methods · Urban geodiversity inventories

Introduction

Urban geodiversity encompasses the geological, geomorphological and hydrological features (Gray 2019) of urban territories. It constitutes a complex entity that embraces both natural and anthropogenically induced and in situ and ex situ geological elements. The part of geodiversity that is important for societies due to its scientific value (Brilha 2016) and/or some other kind of exceptional value (cultural, educational, touristic; Caetano and Ponciano 2021) is regarded as geoheritage. Although some earlier definitions of urban geoheritage (Habibi et al. 2018) refer to natural geological features and exposures, humans contribute to the overall geodiversity in urban areas. On the other hand, many geodiversity elements have been inevitably lost due to anthropogenic pressure (invisible landforms of Clivaz and Reynard 2018). The anthropogenic imprint on geodiversity in densely populated regions escalates due to the unprecedented rate of urbanisation. The percentage of terrestrial urbanised areas increased from 0.23% in 1992 to 0.53% in 2013 (Zhou et al. 2018), and the global urban extent expanded from 1985 to 2015 by nearly 10,000 km^2 per year (Liu et al. 2020). Detailed analyses of geodiversity in densely populated areas are therefore of the utmost importance.

Although there are many studies related to urban geodiversity, most of them are limited to selected elements of the overall geodiversity pool, for example, geomorphosites (Reynard et al. 2017), anthropogenic geosites (Kubalíková et al. 2017), building stones (De Wever et al. 2017), archaeogeosites (Bizzarri et al. 2018), geocultural sites (Kubalíková et al. 2020) and hypogean geosites (Melelli et al. 2021). A more complex study of urban geodiversity was attempted by Habibi et al. (2018), who tentatively divided the geological features that appear in an urban environment into forms (which denote the physical appearance of the geodiversity element) and types (which refer to the geological information that can be interpreted from the feature).

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Geodiversity forms were further divided by Habibi et al. (2018) into in situ and ex situ features, which is consistent with other classifications (Brilha 2016) that embrace both in situ occurrences of geodiversity features and displaced geodiversity elements that are, for instance, stored in museum collections or used as building/decorative stones. Another urban geodiversity classification was first conceptualised by Palacio-Prieto (2015) and formally introduced by Reynard et al. (2017), who divided geomorphosites into lato sensu geodiversity sites, which represent all geological features located in urbanised areas, and stricto sensu geodiversity sites, which reflect interactions between the natural environment and urban development. The second category includes both natural and anthropogenic geodiversity elements, which is consistent with the view of Kubalíková et al. (2017), who placed man-made features, referred to as secondary geodiversity, within an urban geodiversity framework. However, the position of anthropogenic landforms within heritage remains poorly explored, as they can be situated at the boundary between cultural and natural diversity (Kubalíková et al. 2021b). According to Palacio-Prieto (2015), buildings and other man-made elements of the city that were developed under particular geological conditions or have undergone certain geological processes through time can be placed within the range of urban geodiversity. Such anthropogenetic geodiversity elements can be of significant value for cultural development and the community's sense of place, which leads to the conclusion (drawn by Rodrigues et al. 2011) that the cultural heritage related to the abiotic, natural environment can be treated as a geocultural diversity element and included in urban geodiversity typology. The importance of interconnections between geological and cultural aspects of diversity has been stressed by Gordon (2018a) and Habibi et al. (2018). Recent studies of urban geodiversity (e.g. Kubalíková et al. 2020) explore the combination of abiotic components with the cultural and historical components of diversity.

The inclusion of geocultural and geohistorical elements of diversity in the description of urban geodiversity involves the recognition of the material (tangible) and immaterial (intangible) elements of heritage. The concept of intangible cultural diversity is well established (Vecco 2010), and within Earth sciences, it was explored in studies of geomythology (Vitaliano 2007; Goemaere et al. 2021), but its relation to the preselection and evaluation of geodiversity features is a relatively new field of study, recognised by Reynard (2009) and Rodrigues et al. (2011), among others, and developed further in more recent contributions, for instance, Gordon (2018b), Szepesi et al. (2020) and Caetano and Ponciano (2021). Frequent interconnections between cultural, historical and geological heritage within the urban environment demand the inclusion of intangible geocultural assets in studies of urban geodiversity.

Urban geodiversity can play an important role within modern societies and rapidly growing cities because of several reasons:

- It contributes to the landscape (cityscape) and is a powerful constraint on urban development (Vereb et al. 2020), conditioning the directions for city expansion (Pica et al. 2017).
- It provides resources but can also cause or be affected by natural hazards (Kubalíková et al. 2020).
- It interacts with culture, architecture and historical heritage, contributing to the socio-economic landscape and city streetscape (Habibi et al. 2018).
- It has an important potential to promote geotourism (Palacio-Prieto 2015) and supports the environmental education of the general public and students in schools located within urban areas (Kubalíková et al. 2020).
- It influences biotic components of the city and the landscape of parks and gardens (Portal and Kerguillec 2018).

Consequently, studies on the geodiversity of urban areas are significant for the future of societies for the following reasons:

- Unique geological elements located in highly urbanised areas are in danger (Chan and Godsey 2016).
- Geomorphological features disappear gradually from the landscapes of densely populated areas (Clivaz and Reynard 2018).
- The vulnerability of geodiversity sites in urban landscapes requires a different approach to geoconservation compared to rural areas (Vereb et al. 2020).
- The development of urban geotourism can raise awareness of the importance of geodiversity for the conservation and future of cities (Kubalíková et al. 2020).
- Urban geodiversity studies raise awareness of geological hazards (Kong et al. 2020) and contribute to knowledge on the use of geomaterials for building purposes (Del Lama et al. 2015).
- The fragmented understanding of urban geoheritage demands studies that capture a wider range of geodiversity elements (Habibi et al. 2018).
- Active city growth will reveal new geological features (Kubalíková et al. 2017).

Given that most of the earlier studies were fragmented and focused on selected aspects of urban geodiversity, which were restricted to the natural or anthropogenic diversity of geological features or encompassed a limited number of geodiversity sites and elements, the aim of the present study is to estimate and evaluate the widest possible range of urban geodiversity. This requires the inclusion of all geodiversity forms sensu Habibi et al. (2018), both natural and anthropogenic, stricto sensu and lato sensu, in situ and ex situ, the selection of explicit identification and assessment procedures, and the exploration of intersections between cultural and geological diversity. To examine the potential of geodiversity in developing urban geotourism, the preferences of the general public are also analysed. The city of Poznań in Poland is used as a study area. Within the administrative borders of this municipality, both outstanding geosites with great scientific potential and unsatisfactorily researched geodiversity elements are present. Poznań's geotourism is relatively poorly developed, although the city is located in the centre of the planned Morasko Geopark (Zwoliński et al. 2017). This confirms the suitability of Poznań as a case study area for the study of urban geodiversity and its geotouristic potential.

Study Area

The city of Poznań is located on the Polish Lowland within the Central European Plain in central-western Poland (Fig. 1). It covers an area of 262 km^2, and its population exceeds 500,000 inhabitants (Zaręba et al. 2021). The natural landscape of Poznań and the adjacent areas was shaped during the Late Weichselian glaciation, in between the two standstill positions of the Scandinavian Ice Sheet, the Leszno-Brandenburg Phase (25–21 ka) and Poznań-Frankfurt Phase (17 ka; Tylmann et al. 2019). Moraine plateaus and outwash plains constitute most of the city's area (73%). Northern suburban areas are occupied by terminal accumulative and push moraines of the Poznań Phase. Subglacial and erosional valleys that show NW–SE and NE-SW orientation are incised into flat moraine plateau (Zwoliński et al. 2017). Eskers, kames and kame terraces and dead-ice moraines constitute the less remarkable landforms of the city landscape. The glacial landforms of the city are composed of Pleistocene tills, gravels and sands, which are accompanied by Miocene-to-Pliocene clays exposed within the glaciotectonic structures of the Poznań Phase push moraines (Widera and Chomiak 2019).

During the latest Pleistocene and Holocene, the complex floodplain and terrace system of the Warta River, incised into the surrounding moraine plateaus, developed along the valley passing through the area of contemporary Poznań in

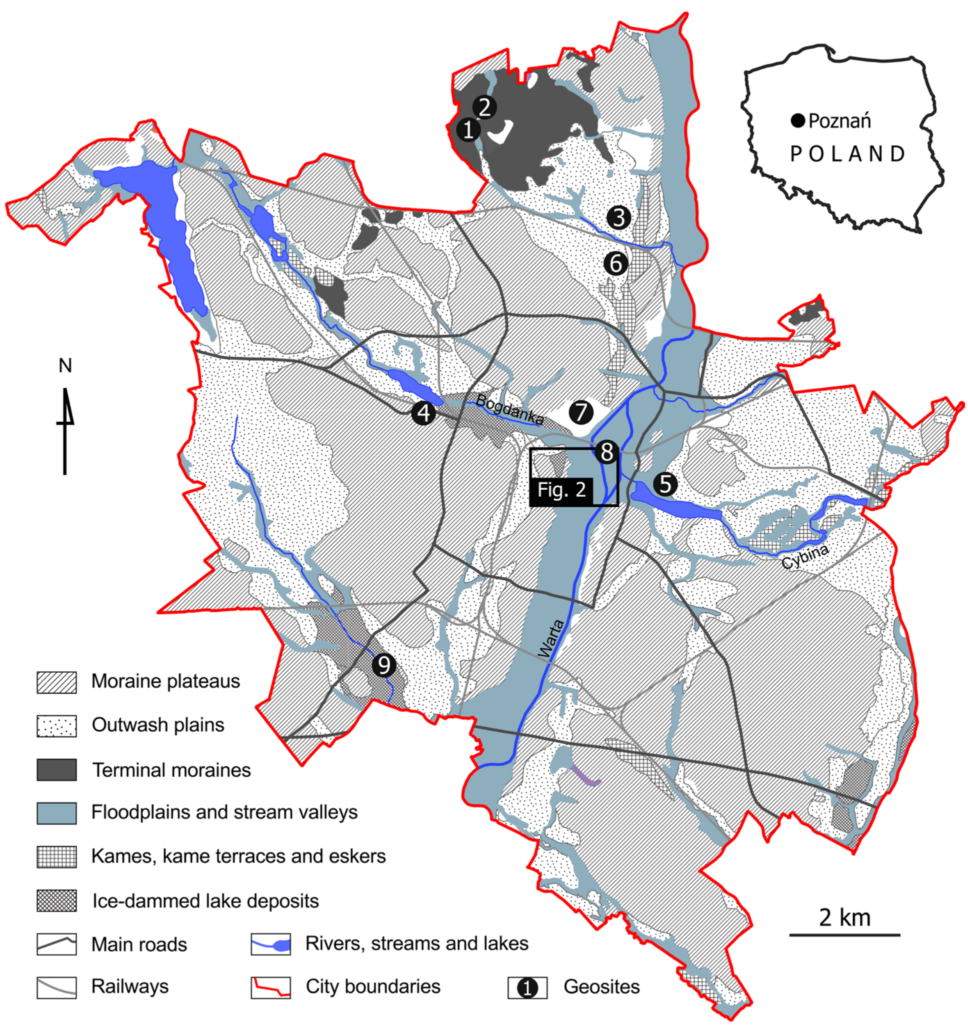


Fig. 1 Simplified geological map of Poznań, modified after Chmal (1996) and Cincio (1996). Geosites included in the Central Register of Polish Geosites: 1, Góra Moraska (terminal moraine); 2, Morasko Meteorite nature reserve; 3, rock garden at the Institute of Geology; 4, erratic boulders in the Botanical Garden; 5, erratic boulders in the Millenium Park. Geosites designated by Zwoliński et al. (2017, 2018): 6, Żurawiniec peat bog; 7, Prussian fortress; 8, Genius Loci Archaeological Reserve and Warta River valley; 9, Szachty (disused clay pits)

the S–N direction (Kaniecki 2013). The valley, deeply cut into the terminal morainic hills of the Poznań Phase and occupied by a multichannel, meandering or anastomosing river (Zwoliński et al. 2017), became a favourable area for medieval settlement. Other prominent geological features present within the city's administrative boundaries include endorheic basins of meteoritic origin and crater lakes that are unique in Poland and rare on a global scale (Choiński et al. 2019).

The anthropogenic transformation of the natural landscape had commenced by the end of the early Middle Ages, during the tenth century, when the settlement located at the island of Ostrów Tumski became a major military and political centre of the Piast Dynasty (Kóčka-Krenz 2015). The independent city, contemporary Old Town, was founded by Duke Przemysł I in 1253, on the left bank of the Warta River near the mouth of Bogdanka Stream, one of its tributaries (Fig. 2; Zaręba et al. 2021). Until the end of eighteenth century, the city belonged to Poland and continued its demographic development, although on the spatial scale, the evolving urbanised area was still enclosed within the ring of medieval town walls (Kóčka-Krenz 2015) in an area of 0.8 km^2. Under Prussian and, subsequently, German rule (from 1793 to 1918), the spatial expansion of the city commenced with the dismantling of the medieval defensive walls, and it continued in the beginning of the twentieth century with the abolition of the inner ring of the Prussian fortifications (Zaręba et al. 2021). During this period, extensive anthropogenic (communication, military and mining) landforms dramatically changed the topography of the city and its surroundings. From 1919, when Poznań returned to Poland, its area increased more than six-fold (Zwoliński et al. 2018), fostering rapid urbanisation and further extensive transformation of the natural landscape; communication incisions, vast planated surfaces and artificial water reservoirs are the most spectacular evidence of this. However, the most important human imprint on the geomorphological features of the city is the reduction and constriction of the Warta River channels and the sharp diminishing of the network of its tributaries.

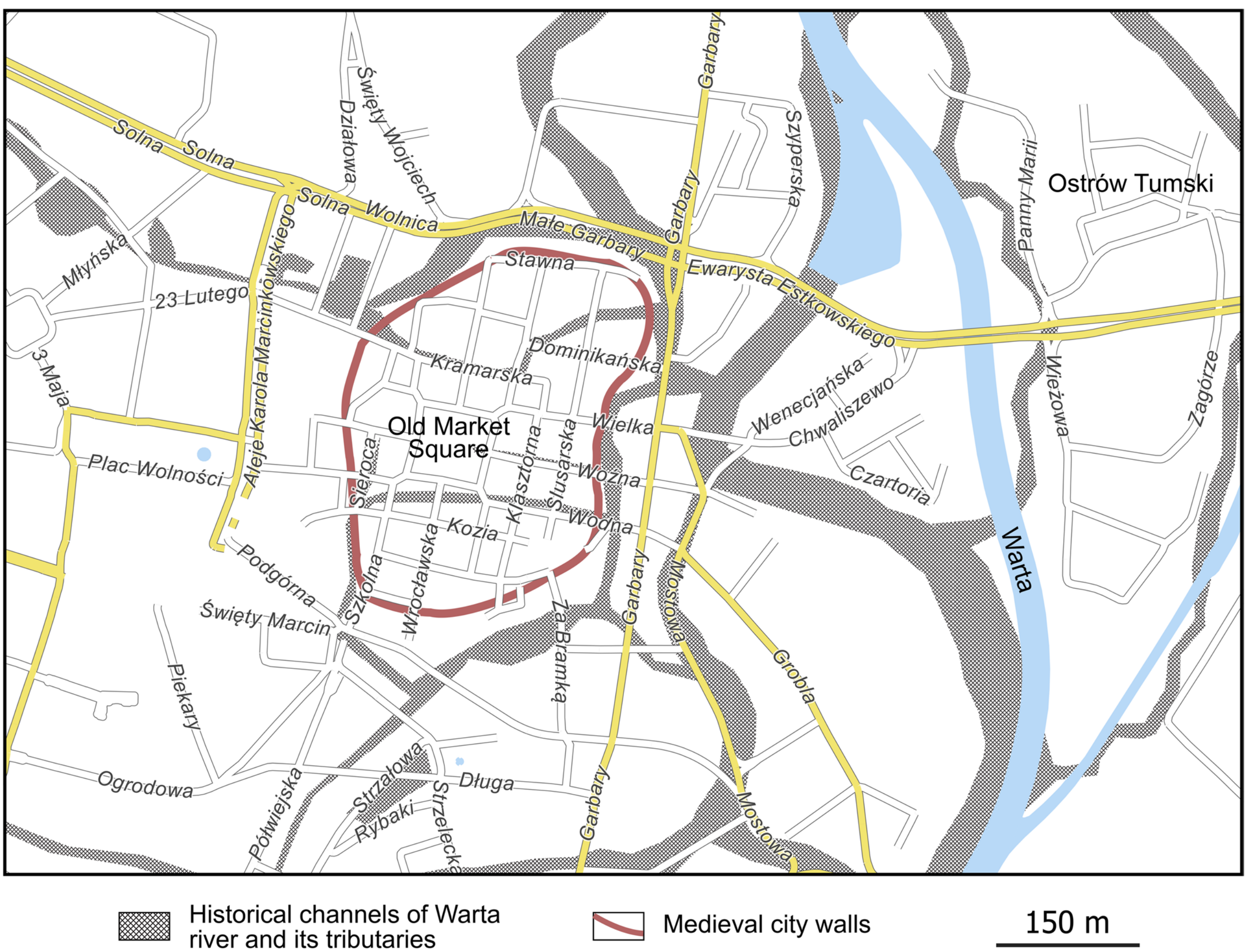


Fig. 2 Map of the centre of Poznań, showing the extent of the medieval town (location of the city walls after Kóčka-Krenz 2015) and historical river channels

Over the last thousand years, this multichannel, meandering-to-anastomosing river evolved into a single-channel, artificially straightened waterway (Zwoliński et al. 2017), and most of its tributaries, which drained the slopes of adjacent moraine plateaus and outwash plains, disappeared. As a result, many fluvial landforms were significantly altered or completely erased, persisting in the landscape as palimpsests in the network of streets, squares and parks and representing true invisible landforms sensu Clivaz and Reynard (2018).

The city of Poznań is listed among the most popular urban tourism destinations in Poland, with the number of overnight stays per 1,000 permanent residents placing it in the fifth position (Zaręba et al. 2021). Business tourism related to international fairs also plays an important role. However, the number of foreign tourists is relatively low compared to other Polish cities (Zaręba et al. 2021). Higher education institutions are well developed, with the number of students per 1000 inhabitants among the highest in the country (Stryjakiewicz et al. 2010), contributing to the expansion of knowledge and creative industries (Chapain et al. 2010).

The Central Register of Polish Geosites (https://cbdgportal.pgi.gov.pl/geostanowiska/; Warowna et al. 2013) includes six geosites located within the administrative borders of the city of Poznań (four rock gardens and/or erratic boulders, the Morasko Meteorite natural reserve and morainic hills of Góra Moraska; Fig. 1). Zwoliński et al. (2017, 2018) described in detail five other geodiversity features that should be considered as geosites (one natural and four man-made or bearing a significant human imprint; Fig. 1). However, the complex interplay between natural and anthropogenic factors that shaped the landscape of Poznań requires a more detailed study utilising a wider set of geodiversity forms and elements, in order to fully assess the geological diversity of the city and its relationship to the city's cultural and historical heritage.

Methods

This study includes the following steps:

- The identification and description of urban geodiversity elements (qualitative evaluation).
- The quantitative assessment of geodiversity elements.
- The estimation of the general public's preferences.

Qualitative Evaluation of the Urban Geodiversity

For the purpose of the present study, the classification of urban geoheritage developed by Habibi et al. (2018) is used as a framework for the description of the urban geodiversity, and it is supplemented by the inventories of the urban geodiversity forms from other scientific papers, which are summarised in Table 1. These lists were subsequently used to establish a clear and complete classification of urban geodiversity elements, for the purpose of selecting the widest possible range of geodiversity types present in the urban environment of Poznań (Table 2). This step was necessary to ensure that the criteria for the selection of geodiversity elements are clear and replicable; the lack of detailed information regarding the preselection procedure in many earlier papers was pointed out by Mucivuna et al. (2019). On the other hand, the use of this list enables one to include the aspects of diversity related to interactions between abiotic, biotic and cultural environments, which, according to Kubalíková et al. (2020), is important for recording the full range of the urban geodiversity. Due to the prevalence of anthropogenetic sediments and landforms in urbanised areas, the list of geodiversity forms is supplemented with a classification of the geomorphic impacts of human societies (Szabó 2010).

The information on geodiversity sites and elements within the city boundaries of Poznań was obtained from the following sources (for a complete list of references, see Online Resource 1):

- Scientific papers and monographs on the geological environment of the city, published in both English and Polish.
- The Central Register of Polish Geosites (https://cbdgportal.pgi.gov.pl/geostanowiska/; Warowna et al. 2013).
- The 1:50,000 scale geological (Marks et al. 2006), lithogenetic and geoenvironmental (Sikorska-Maykowska et al. 2005) maps of Poland, published by the Polish Geological Institute and available at https://geolog.pgi.gov.pl/; the use of geological and morphometric relief maps allowed the recognition of the main geomorphological features of the area, similarly to the study of Tičar et al. (2017).
- Archival topographic maps.
- Archaeological and historical scientific papers.
- Articles and short notes regarding the usage of building and decorative stones, published in non-academic journals.
- Documents and photographs digitised and included in the Cyryl database (https://cyryl.poznan.pl/), which stores information related to the history of Poznań.
- Publications related to the cultural heritage of the city.
- Fieldwork (aimed at the verification of written sources and the identification of additional geodiversity features in areas where their density was low).

The sources used in this study allow a full range of geodiversity elements, listed in Table 2, to be recorded. A complete list of preselected geodiversity sites and elements is

Table 1 Classifications of urban geodiversity used in earlier studies, supplemented with types of geomorphic impacts of human societies on natural geomorphological processes (Szabó 2010)

	Szabó (2010)	Pelfini and Bollati (2014)	Kerguillec and Portal (2015)[1)]	Kubalíková et al. (2017)	Pica et al. (2017)	Habibi et al. (2018)	Kubalíková and Bajer (2018)	Pica et al. (2018)	Kubalíková et al. (2020)	Bornyak et al. (2020)	Melelli et al. (2021)
Natural features											
Constraints of the physical environment on the urban development							+	+			
Ecological aspects related to geodiversity									+		
Geoparks						+					
Natural exposures						+	+			+	
Natural landforms		+			+	+	+	+			
Soils							+				
Springs										+	+
Stratotypes										+	
Viewpoint geosites						+	+				
Anthropogenic (man-made) features											
In situ											
Anthropogenic landforms and grounds undivided; modified natural landforms					+	+	+		+		
Land form type	+										
Accumulation landforms	+										
Excavation landforms	+										
Planated landforms	+										
Land form origin											
Agricultural landforms (agricultural terraces, piles, ramparts)				+							
Celebration landforms (menhirs, dolmens, cromlechs)				+							
Communication landforms (road and railway cuttings, tunnels)			+	+		+					
Funeral landforms (funeral hills, burial mounds, crypts, tombs, ossuaries)				+							
Industrial landforms (industrial fields, underground factories)			+	+							
Military landforms (craters, ramparts, fortification systems)			+	+							
Mining landforms (quarries, pits, collapse sinks, dumps, heaps)			+	+		+				+	+
Recreational landforms				+							
Research landforms				+							

Table 1 (continued)

	Szabó (2010)	Pelfini and Bollati (2014)	Kerguillec and Portal (2015)[1)]	Kubalíková et al. (2017)	Pica et al. (2017)	Habibi et al. (2018)	Kubalíková and Bajer (2018)	Pica et al. (2018)	Kubalíková et al. (2020)	Bornyak et al. (2020)	Melelli et al. (2021)
Urban landforms (terraces, ramparts, waste dumps, urban underground)				+							
Water system landforms and littoral landforms (water reservoirs, dams, polders, water canals, wells)				+		+	+				+
Geocultural features											
Buildings associated with well-known geologists or geological events										+	
Geodiversity features reflected in the arts (literature, music, myths)							+		+		
Geoeducational facilities in situ							+		+		
Links between geoheritage and archaeological heritage			+	+		+	+	+			
Local products linked to or inspired by geodiversity									+		
Toponyms that reflect geodiversity aspects							+		+		
Industry						+					
Geo-engineering solutions						+					
Mines						+					+
Sites of environmental pollutions and other disturbances						+					
Destroyed or covered (invisible) landforms					+						
Urban features related to the early landscape of the city								+			
Urban geohazards								+			
Viewpoints							+		+		
Ex situ											
Churches, cemeteries, historical monuments, statues						+			+		
Pavements and building stone; decorative and ornamental stones						+	+	+	+	+	
Natural history museums, collections of geological objects						+	+	+		+	
Rock gardens							+				
Archaeological and historical museums						+					
Plants, factories and other enterprises utilising geological resources						+					

Table 1 (continued)

	Szabó (2010)	Pelfini and Bollati (2014)	Kerguillec and Portal (2015)[1)]	Kubalíková et al. (2017)	Pica et al. (2017)	Habibi et al. (2018)	Kubalíková and Bajer (2018)	Pica et al. (2018)	Kubalíková et al. (2020)	Bornyak et al. (2020)	Melelli et al. (2021)
Geoparks						+					
Traditional constructions						+					

[1]Modified in Portal and Kerguillec (2018)

included in Online Resource 1, with references to the sources from which they were obtained. No preselection filters and criteria were used; all geodiversity elements received from all sources are featured in the database. Descriptions of each element were prepared to ensure the replicability of the study, following the methodology described by Reynard et al. (2016). To enable better comprehension, an Excel spreadsheet, rather than descriptive cards, was used to store information about the geodiversity elements (Online Resource 1). For features that are points, their corresponding geographic coordinates are provided, whereas polygonal geodiversity features are stored in the Shapefile format (Online Resource 2).

Quantitative Assessment of Urban Geodiversity

Although there are many methods for the quantitative evaluation of geodiversity sites and elements, relatively few of them were designed for urban areas (Kubalíková et al. 2020), and urban geodiversity inventories are still rare (Vereb et al. 2020). According to Mucivuna et al. (2019), many earlier studies lack a clear explanation of the choice of a specific method. To identify the best procedure for quantitative evaluation, a detailed list of assessment criteria used in earlier studies of urban geodiversity was compiled (Table 3). For the purpose of the present contribution, a method of Kubalíková et al. (2019) was utilised. The rationale for the decision is as follows:

- Methods that do not provide an explicit explanation regarding numerical assessment, i.e. the meaning of the values attributed to each criterion (as in Pica et al. 2016), are excluded.
- Subsequent steps of this contribution include the study of the general public's preferences, which are related to the educational and geotouristic potential of geodiversity elements and sites; thus, the methods that do not measure additional values, or do not detach them from pure scientific importance in a separate group (as in Vereb et al. 2020), are also excluded.
- Methods that assign values not applicable in urban areas are omitted; for instance, Brilha (2016) employs indicators of the density of the population, logistics and proximity of recreational areas, which would return the same (and highest) values for most geodiversity sites included in this study.
- Most geodiversity sites located in urban areas are under strong anthropogenic pressure (Kong et al. 2020) or are formed by a complex interplay between natural and human factors, so the methods that do not explore the

Table 2 Classification of urban geodiversity used in the present study, derived from the earlier works summarised in Table 1

Urban geodiversity form			Number of geodiversity elements	Percentage of geodiversity elements
Natural features				
In situ	Lato sensu	Biotic-abiotic interconnections	3	0.5%
		Natural exposures	–	–
		Natural landforms	222	36.3%
		Soils, rocks, minerals, fossils and mineral resources	153	25.0%
		Springs	–	–
		Viewpoints	6	1.0%
	Stricto sensu	Constraints of the physical environment on the urban development	5	0.8%
		Geoparks	–	–
		Stratotypes	–	–
Anthropogenic (man-made) features				
In situ	Lato sensu	Artificial landforms		
		Land form type		
		Accumulation landforms	51	8.3%
		Excavation landforms	15	2.5%
		Planated landforms	5	0.8%
		Land form origin		
		Agrogenic landforms	–	–
		Communication landforms	18	3.0%
		Industrogenic landforms	–	–
		Military landforms	19	3.1%
		Mining landforms	18	2.9%
		Recreational landforms	3	0.5%
		Research landforms	–	–
		Sacral and funeral landforms	–	–
		Urbanogenic landforms	1	0.2%
		Water management landforms	43	7.0%
		Viewpoints (artificial)	3	0.5%
	Stricto sensu	Destroyed or covered (invisible) landforms	35	5.7%
		Urban features related to the early landscape of the city	–	–
		Urban geohazards	15	2.5%
		Geocultural features		
		Archaeological monuments	2	0.3%
		Buildings associated with well-known geologists or geological events	–	–
		Geodiversity features reflected in the arts (literature, music, myths)	4	0.7%
		Geoeducational facilities in situ	–	–
		Local products linked to or inspired by geodiversity	–	–
		Toponyms that reflect geodiversity aspects	2	0.3%
		Industry		
		Geo-engineering solutions	2	0.3%
		Mines and plants utilising geological resources	23	3.8%
		Sites of environmental pollutions and other disturbances	5	0.8%
Ex situ	Lato sensu	Archaeological and historical museums (with references to geodiversity)	–	–
		Building, decorative and ornamental stones	70	11.4%
		Natural history museums and exhibits, geological collections	1	0.2%
		Places of worship, cemeteries, historical monuments and statues	26	4.2%
		Rock gardens	4	0.7%
		Traditional constructions	–	–

Table 3 Assessment criteria employed in earlier studies of urban geodiversity. Weights and coefficients used in these evaluation methods are not included. Groups of criteria (after Kubalíková et al. 2021a) are used for the clarity of the table, but note that different authors place the same attributes in different categories. NA, not specified

Groups of criteria[1)]	Criterion	Pica et al. (2016)[2)]	Petrović et al. (2017)	Pica et al. (2017)	Kubalíková et al. (2019)	Kubalíková et al. (2020)[3)]	Moradipour et al. (2020)[4) 5)]	Moradipour et al. (2020)[4) 6)]	Moradipour et al. (2020)[4) 7)]	Vereb et al. (2020)[8)]	Kubalíková and Zapletalová (2021)	Kubalíková et al. (2021a)	Martín-Martín et al. (2021)[4) 5)]	Martín-Martín et al. (2021)[4) 6)]	Martín-Martín et al. (2021)[4) 7)]	Vegas and Díez-Herrero (2021)[9)]
Scientific value	**Rarity (uniqueness) and importance**	0–5	0–1	NA	0–1	0–1	1–4	1–4		0–3	0–1	0–1	1–4	1–4		1–4
	Palaeogeographical significance					0–1					0–1	0–1				
	Geological diversity; diversity of the Earth science features (phenomena); number of geodiversity features				0–1	0–1	1–4					0–1	1–4	1–4		
	Key locality												1–4			
	Primary geological interest									0–3						
	Secondary geological interest									0–3						
	Scientific knowledge		0–1		0–1		1–4					0–1	1–4			
Educational value	**Interpretative potential; educational research and interest**		0–1				1–4	1–4		0–3	0–1	0–1		1–4		
	Representativeness	0–5	0–1		0–1	0–1	1–4				0–1	0–1	1–4			1–4
	Understanding of geological history															1–4
	Flexibility for educational use															1–4
	Existing interpretative materials and facilities; promotion		0–1		0–1						0–1	0–1				1–4
	Geosite information in printed and online media															1–4
	International information (number of languages)															1–4

Table 3 (continued)

Groups of criteria[1)]	Criterion	Pica et al. (2016)[2)]	Petrović et al. (2017)	Pica et al. (2017)	Kubalíková et al. (2019)	Kubalíková et al. (2020)[3)]	Moradipour et al. (2020)[4) 5)]	Moradi-pour et al. (2020)[4) 6)]	Moradipour et al. (2020)[4) 7)]	Vereb et al. (2020)[8)]	Kubalíková and Zapletalová (2021)	Kubalíková et al. (2021a)	Martín-Martín et al. (2021)[4) 5)]	Martín-Martín et al. (2021)[4) 6)]	Martín-Martín et al. (2021)[4) 7)]	Vegas and Díez-Herrero (2021)[9)]
Tourist value	**Visibility of geodiversity features**			NA	0–1	0–1		1–4			0–1	0–1		1–4		
	Accessibility; distance and walking time to interpretation centers and/or public transport	0–5	0–1		0–1	0–1		1–4	1–4		0–1	0–1		1–4	1–4	1–4
	Accessibility for people with disabilities															1–4
	Logistics; tourist infrastructure and facilities (accomodation, restaurant, shops, information centres)		0–1		0–1	0–1					0–1	0–1		1–4		1–4
	Vicinity of road network		0–1													
	Vicinity of urban centers		0–1													
	Proximity of recreational areas or other tourist attractions; surrounding landscape and nature		0–1					1–4						1–4		1–4
	Viewpoints		0–1					1–4								
	Density of population							1–4	1–4					1–4	1–4	
	Number of visitors		0–1													
	Surface area		0–1													
	Safety				0–1	0–1		1–4			0–1	0–1		1–4		1–4
	Touristic attractiveness			NA												
	Tour guide service		0–1													
	Economic level							1–4						1–4		

Table 3 (continued)

Groups of criteria[1)]	Criterion	Pica et al. (2016)[2)]	Petrović et al. (2017)	Pica et al. (2017)	Kubalíková et al. (2019)	Kubalíková et al. (2020)[3)]	Moradipour et al. (2020)[4) 5)]	Moradipour et al. (2020)[4) 6)]	Moradipour et al. (2020)[4) 7)]	Vereb et al. (2020)[8)]	Kubalíková and Zapletalová (2021)	Kubalíková et al. (2021a)	Martín-Martín et al. (2021)[4) 5)]	Martín-Martín et al. (2021)[4) 6)]	Martín-Martín et al. (2021)[4) 7)]	Vegas and Díez-Herrero (2021)[9)]
Conservation value	**Integrity and current status of the geodiversity site (degree of damage)**		0–1		0–1	0–1	1–4			0–3	0–1	0–1	1–4			1–4
	Vulnerability (current threats); possible deterioration of geological elements; natural sustainability		0–1			0–1		1–4	1–4	0–3	0–1	0–1		1–4	1–4	1–4
	Proximity to areas/activities with potential to cause degradation								1–4						1–4	
	Suitable number of visitors		0–1													
	Anthopogenic impacts and threats; urban development								1–4	0–3						1–4
	Legislative protection	0–5	0–1			0–1			1–4	0–3	0–1	0–1			1–4	1–4
	Use limitations						1–4	1–4					1–4	1–4		1–4
Additional value	**Cultural (historical, archeological, artistic, architectonic) value; historical urban geomorphology**		0–1	NA		0–1	1–4	1–4		0–3	0–1	0–1		1–4		1–4
	Importance for the history of geology									0–3						
	Ecological value (relation to biotic nature); additional natural values		0–1			0–1					0–1	0–1				
	Scenery; aesthetic, landscape, scenic value	0–5		NA		0–1		1–4			0–1	0–1		1–4		1–4

[1]After Kubalíková (2013) and Kubalíková et al. (2021a), modified

[2]Elaborated after Pica et al. (2014)

[3]Elaborated after Kubalíková (2013); Kubalíková and Kirchner (2016)

[4]Elaborated after Brilha (2016)

[5]Scientific value

[6]Educational and touristic use

[7]Degradation risk

[8]Elaborated after De Wever et al. (2015)

[9]Elaborated after Suzuki and Takagi (2018)

interconnections between natural and anthropogenically induced geodiversity (Petrović et al. 2017) are excluded.
- The modifications of methods introduced by separate research teams, other than the author of the original procedure (Moradipour et al. 2020; Martín-Martín et al. 2021), are not used to avoid the ambiguous choice between competing approaches to quantitative evaluation.

Among the remaining evaluation procedures, the method employed by Kubalíková et al. (2019), based on a preliminary approach of Kubalíková (2013), was selected. The procedure is relatively stable (albeit modified), used in several subsequent papers written by the same research team and oriented on anthropogenic geodiversity sites, which dominate the urban area of the present study. The methods based on Kubalíková (2013) take into account the cultural, historical and ecological importance, although they are included only in the added value group of criteria. However, the underestimation of cultural assets in the quantitative evaluation of geodiversity sites is an important drawback of most procedures developed so far (Pica and Del Monte 2021).

After values are attributed to each criterion for all geodiversity elements selected during the qualitative evaluation, sums were calculated for all values and for each of the five groups of metrics included in the assessment method of Kubalíková et al. (2019). The strength of possible associations between the criteria was measured using a non-parametric Spearman correlation coefficient (Borradaile 2003), which is appropriate for ordinal and interval variables. To adjust for possible intercorrelations and overlapping criteria (an issue noted by Mucivuna et al. 2019), principal component analysis (PCA; Everitt 2006) was performed using R statistical software. The results of PCA allowed the estimation of the criterion's independence.

General Public Preferences

Additional information on the scientific value of a geodiversity site or element can be retrieved from scientific publications (references for the corresponding geodiversity elements are given in Online Resource 1), whereas the geotouristic preferences of the general public can be further studied using questionnaires, interviews and data retrieved from the Internet. Due to the high number of geodiversity elements obtained from the qualitative evaluation, the last method was chosen.

To estimate the level of interest among potential geotourists, an interactive map of Poznań, based on the JavaScript library Leaflet.js and OpenStreetMap.org data, was designed. The map includes additional layers with points and polygons that represent geodiversity elements (Fig. 3). Clicking on these opens a new window with details on the selected element (in Polish). This restricts the potential user community to only those who speak Polish, but this limitation is of minor importance given that only a relatively small proportion of trips to Poznań originate from abroad (Zaręba et al. 2021). The coordinates of the clicked polygons/points are anonymously recorded in the database. The map is available at https://zywaplaneta.pl/po-poznaniu/ on the geoeducational website maintained by the author, which is viewed by readers that describe themselves in the communications with the author as teachers, parents of children interested in Earth science, amateur collectors, sport tourists and students. Given that many geotourists come from these groups (Drápela et al. 2021), the website can be used to measure the geotouristic potential of geodiversity sites. Counts were recorded from March 2021 to August 2021, starting during the COVID-19 lockdown. The numbers of clicks on features added during this period was not used in subsequent analyses. In March and April 2021, the link to the interactive map was published in several local online and printed media and pointed out as a feasible touristic alternative during social distancing, which helped to increase the number of visitors to the website. The data obtained from the interactive map were used to identify the most intensively selected geodiversity elements and places that are the most interesting for potential geotourists.

Results

Urban Geodiversity Forms

The list of urban geodiversity sites and elements of the city of Poznań includes 615 items (Online Resource 1). Among these items, polygonal features that represent landforms and outcrops of sediments dominate (497 items). The inventory of building and decorative stones, and geocultural and industrial geodiversity elements, which are saved as points with geographic coordinates, includes 118 items. Natural landforms related to glacial landscape features and the fluvial environment of the Warta River valley dominate (222 geodiversity elements, 36.3% of the total number of features; Table 2 and Fig. 4). Soils, rocks, minerals, fossils and mineral resources are next (153 items, 25.0%). This geodiversity form includes natural occurrences of such geodiversity elements (mostly tills, fluvioglacial gravels and sands and peat); rocks and fossils in building stones are not included here. Building, decorative and ornamental stones are third (70 geodiversity elements, 11.4%). Although the natural features are most common (389), artificial accumulation (51) and water management (43) landforms are numerous, which underlines the importance of anthropogenic changes within the urban environment. Although the city of Poznań is not

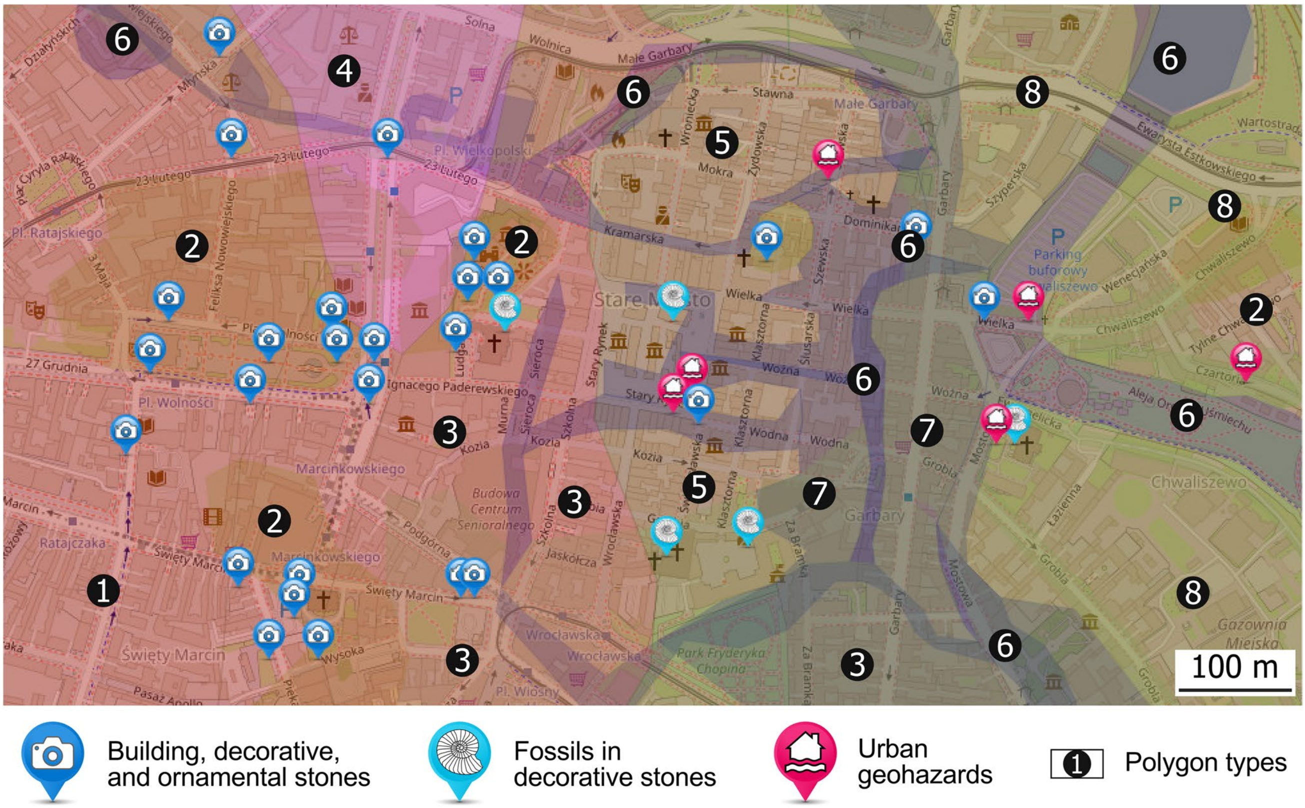


Fig. 3 Part of the interactive geodiversity map of Poznań used for the estimation of the general public's preferences. Coloured map overlays represent types of polygons: 1, moraine plateau; 2, planated landforms; 3, slope of the moraine plateau; 4, clays of ice-dammed lakes; 5, floodplain; 6, invisible landforms (former river and stream channels); 7, urban hazards (flood risk); 8, accumulation landforms on floodplain. Numbers of polygons are not shown on the interactive version of the map

perceived as exhibiting a significant variety of geological features, the geodiversity elements identified in this study span most of the geodiversity forms (Fig. 5).

Most geodiversity elements (323) were retrieved from geological maps. Published works focused on the anthropogenically induced changes of the river network (e.g. Kaniecki 2013; for a complete list of source publications, see Online Resource 1) contain references to 90 features, which is consistent with the abundance of fluvial deposits within the city administrative boundaries. Historical maps (76 geodiversity elements) and fieldwork (31) were other important sources of data. Natural landforms and sediments, retrieved from the 1:50,000-scale geological map of Poland, cover 99.64% of the total city area. Anthropogenic features are concentrated within the medieval urban centre and along the valleys of the Warta River and its tributaries (Fig. 6).

Evaluation of Urban Geodiversity

Among the geodiversity elements that scored highest during the evaluation (Figs. 7–8), anthropogenic features located in the city centre predominate (8 of the 10 items that received the highest scores). The geosite included in the Polish Register of Geosites that ranked highest (Morasko Meteorite nature reserve) occupies the fifth place. One of the potential urban geosites proposed by Zwoliński et al. (2017) scored better (the Genius Loci Archaeological Reserve, third place). Geodiversity elements that encompass many aspects of cultural and historical heritage, show multiple geological features (building stones that include fossils, erratic boulders in the crypts of the cathedral that refer the visitor to both Pleistocene glacial processes and basic rock types), and are located close to the tourist venues received high scores. Mean total values are higher for the anthropogenic features (other than landforms) than in case of the natural geodiversity elements (Fig. 9). Places of worship, historical public buildings with natural ornamental stones, museums, rock gardens and intangible forms of geodiversity (myths, toponyms) received the highest scores.

Although the natural geological features have relatively low mean scientific value (Fig. 9), five of them appear among the top 10 items that exhibit the greatest scientific value and scored highest. They are accompanied by anthropogenic geodiversity elements that include many diversified geological features (a rock garden, a museum

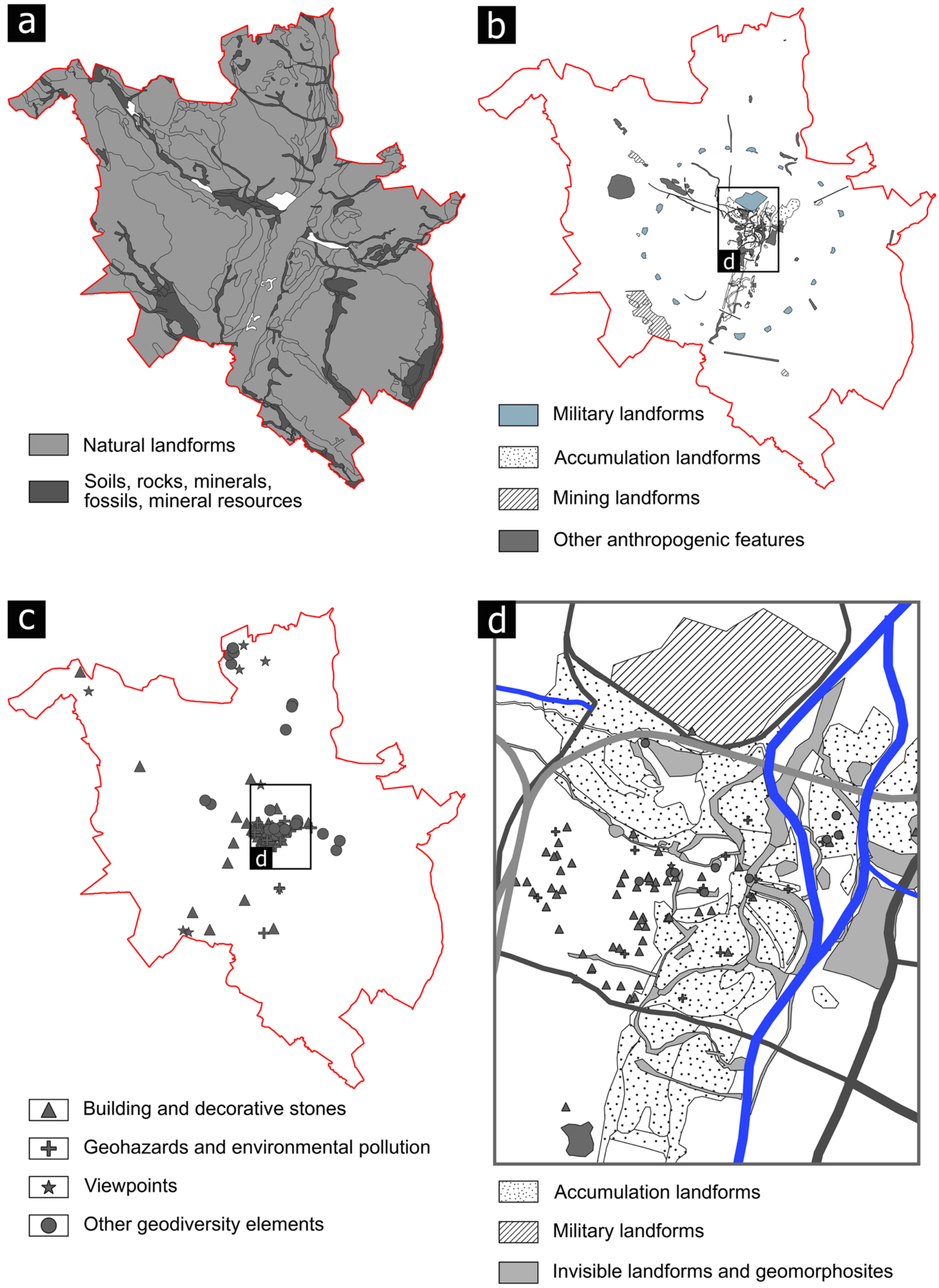


Fig. 4 Distribution of natural and anthropogenic geodiversity elements on the map of Poznań. **a** Extent of natural landforms and sediments represented by polygons. **b** Distribution of anthropogenic (secondary) geodiversity elements defined by polygons. **c** Geodiversity sites and elements represented by points. **d** Extent of selected polygonal anthropogenic geodiversity elements in the city centre, accompanied by locations of geodiversity sites defined as points. For explanation of symbols, see legend of Fig. 4c

of geological sciences) and by historical monuments abundant in building and decorative stones, many of which are from locations that are not quarried today. Three of the 10 items that scored highest in the scientific value group of criteria are located within the city centre and represent anthropogenic geodiversity. Natural features, accompanied by the rock garden and the Earth Museum, predominate among geodiversity elements that show the greatest educational value. The method used for the quantitative assessment of tourist value returns equivocal results: 158 objects obtained the same highest-possible score of 4 points, which results from the same scores obtained by elements that are located in the city centre and offer easy access to tourist facilities. Destroyed, military and mining landforms exhibit the lowest tourist value (Fig. 9). Among the features with the highest added (historical, cultural, ecological) value, the best results were obtained by anthropogenic objects that show a significant diversity of building and decorative stones (Fig. 9); all of these monuments are located in the city centre. Similar results were obtained for the measurement of the conservation value.

Fig. 5 Examples of features that represent different categories of urban geodiversity, following the classification from Table 2. **a** Natural landforms and viewpoint: a view towards terminal moraines of the Poznań Phase (no. 587). **b** Constraints of the environment on the urban development: remains of moraine plateau and higher fluvial terraces used as a fortified settlement (no. 43). **c** Accumulation landforms: former river channel (no. 5). **d** Planated landforms: Freedom Square located on the place of historical Musza Góra hill (no. 605). **e** Mining landforms: former clay pits at the Szachty (no. 118). **f** Artificial viewpoints: tower at the Szachty (no. 583). **g** Destroyed landforms: meandering course of Mostowa St. located at the historical river channel (no. 3). **h** Urban geohazards: historical flood mark at the Old Market Square (no. 531). **i** Building and decorative stones: Ordovician limestone from Öland (Sweden) with nautiloid shell, sample from the Earth Museum (no. 580), used as decorative stone in 503, 506, 507 and 537; scale bar equals 4 cm. **j** Places of worship, cemeteries, statues: Hygieia statue at the Freedom Square (no. 543). **k** Rock gardens: the largest erratic boulder in Poznań (no. 602). **l** Military landforms: Prussian fortifications of the former Posen (fort VII, no. 137). Numbers of sites refer to the identification codes in Online Resource 1

The matrix of correlation coefficients shows relatively low values (Table 4), with the strongest positive intercorrelations between the following criteria: (1) integrity and vulnerability and (2) vulnerability and tourist facilities. A significant negative correlation is recorded between the (1) ecological significance and tourist facilities and (2) ecological significance and integrity. The principal component analysis (Table 5) indicates that the first three components account for 56% of the total variance, confirming that the explanatory variables are poorly correlated and that it is not possible to use these components to summarise the data in subsequent analyses without a significant loss of information. The first principal component has high coefficients for (1) tourist facilities, (2) integrity or current status, and (3) vulnerability. The second component show high values for (1) existing interpretative materials and facilities, (2) rarity, and (3) scientific knowledge. Third principal component shows a contrast between (1) number of the Earth

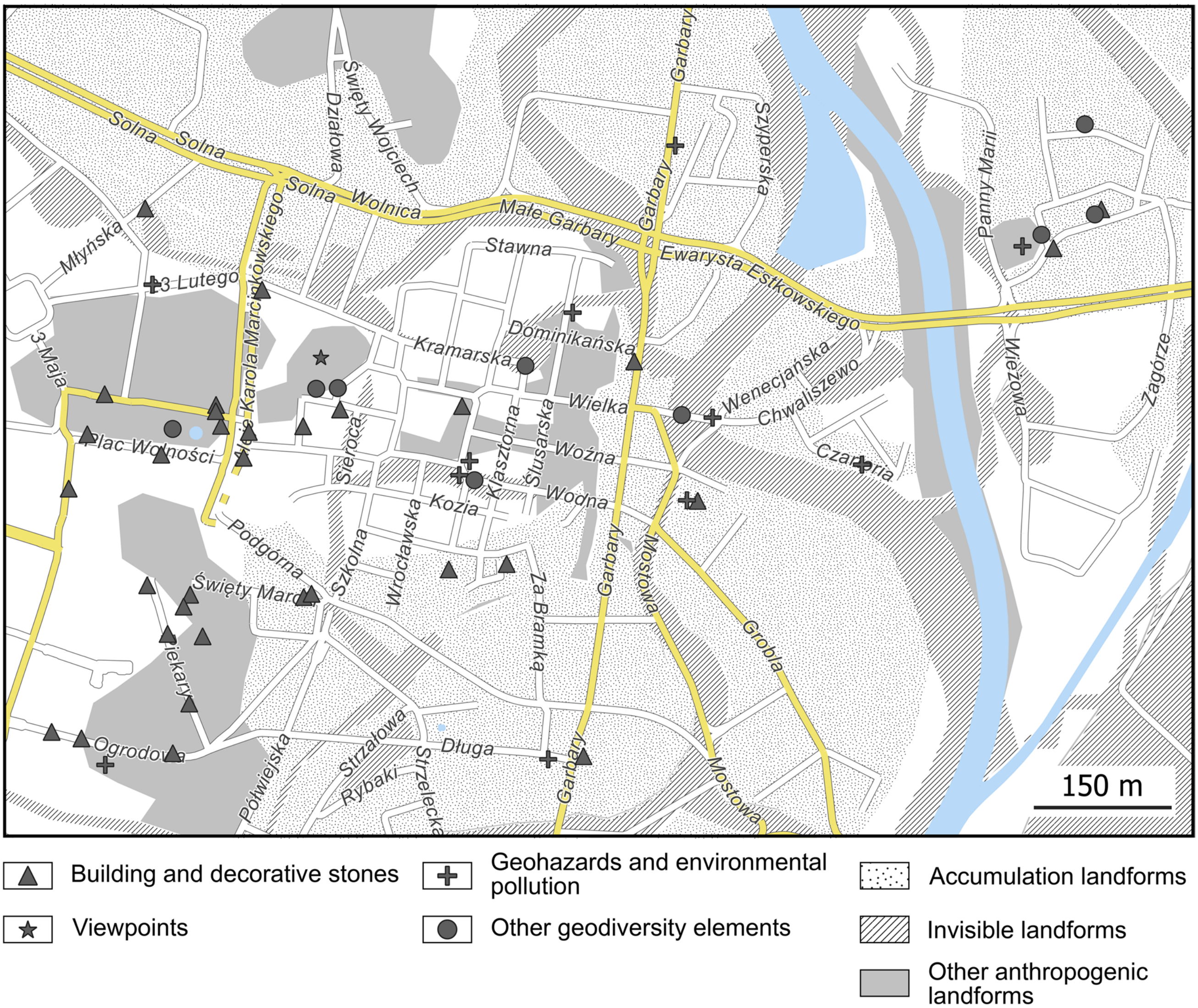


Fig. 6 Geodiversity features of the city centre

science geodiversity features and (2) cultural and historical significance.

Preferences of Interactive Map Users

The digital interactive map of Poznań has been used by 3,129 unique visitors. A total of 48,491 clicks on 565 geodiversity elements were recorded. Among the features represented by points, places of worship, cemeteries and historical public buildings that feature natural building and where ornamental stones occur were clicked on most (13 of such geodiversity elements are among the top 20 most commonly selected items; Fig. 10 and Online Resource 1). Historical flood marks are next (6 places on the list of the 20 most clicked features). Only one natural (primary) geodiversity element ranked within the top 20 (place 15 on the list; the point located within the Morasko Meteorite reserve); this is also the only geosite included in the Polish Registry of Geosites that appears among the most popular items. Nine of the 20 most clicked features (mostly historical flood marks) are located within the medieval city centre (Fig. 11). Other intensively selected geodiversity elements occupy the southern part of the city, west of the Warta River (Fig. 10a). The southeastern peripheries of the city received the lowest numbers of selections by the users of the interactive map (Fig. 10b). The density of clicks is significantly higher on the western bank of the Warta River and decreases sharply with the straight-line distance from the city centre (Fig. 12).

Within the geodiversity elements represented by polygons on the interactive map, all 20 features that obtained the most clicks per 1000 m^2 are of anthropogenic origin (Fig. 9). The

Fig. 7 Locations of geodiversity sites and elements that ranked highest (obtaining 9.0 or more points) during the quantitative evaluation. Scores for groups of criteria are visualised on radar charts. Examples of geodiversity sites with highest total score: 1, Morasko Meteorite nature reserve (no. 581); 2, Kaiser's Castle (no. 577); 3, Antoniego Padewskiego Church (no. 513); 4, Devil's Stone (no. 616); 5, the Cathedral (no. 508); 6, historical pavement of Wysoka St. For precise locations of 3–6, see Fig. 8. Numbers of sites refer to the identification codes in Online Resource 1

first natural geodiversity element retrieved from the geological map was ranked 29 (clays of ice-dammed lakes). None of the geosites included in the Polish Registry of Geosites ranked within the 50 most clicked polygons. Thirteen of the 20 most frequently selected features are located within the medieval city centre (Fig. 11). Among the 20 most popular polygons, destroyed (invisible) landforms are the most common (16), 14 polygons belong to the water management landforms, and accumulation landforms are next (12; each polygon can be ascribed to more than one geodiversity form). The highest density of clicks within polygons was obtained for the medieval centre of Poznań (Fig. 13), in the immediate vicinity of the Old Market Square and within the medieval gord of Ostrów Tumski; minor hotspots are recorded near Bernardyński Square, where many destroyed landforms that represent the past course of the Warta River are mapped, and along the former course of Bogdanka Stream.

The points and polygons that received the highest number of clicks on the interactive map received relatively low total scores in the quantitative assessment (Fig. 11). Most of them rank high in the tourist value group of criteria, but their scientific and educational value is limited. Notable exceptions include the cathedral and the geodiversity sites located in the northern part of the city (Morasko Meteorite nature reserve and the Earth Sciences Museum), which are significantly important for both scientific and educational purposes.

Discussion

Qualitative Evaluation

A precise and thoroughly described selection procedure for potential geodiversity elements, which according to Mucivuna et al. (2019) is a mandatory step in geodiversity assessment, permitted the identification of 615 natural and anthropogenic geological features, far more than in most previous studies of urban geodiversity. This shows the importance of explicit procedures at the preselection stage of research and underlines the broad range of geodiversity in densely populated areas. Although most geodiversity elements were

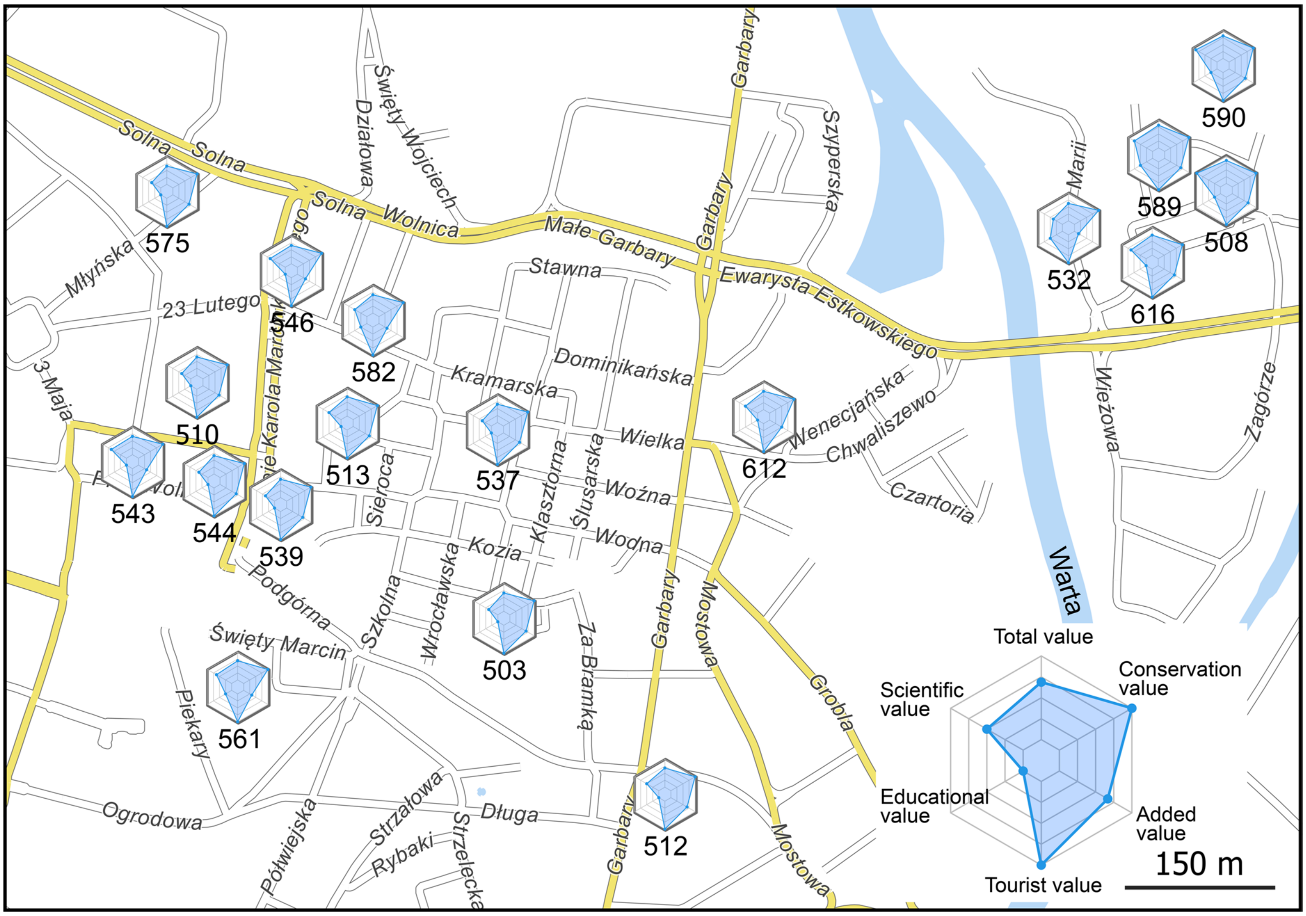


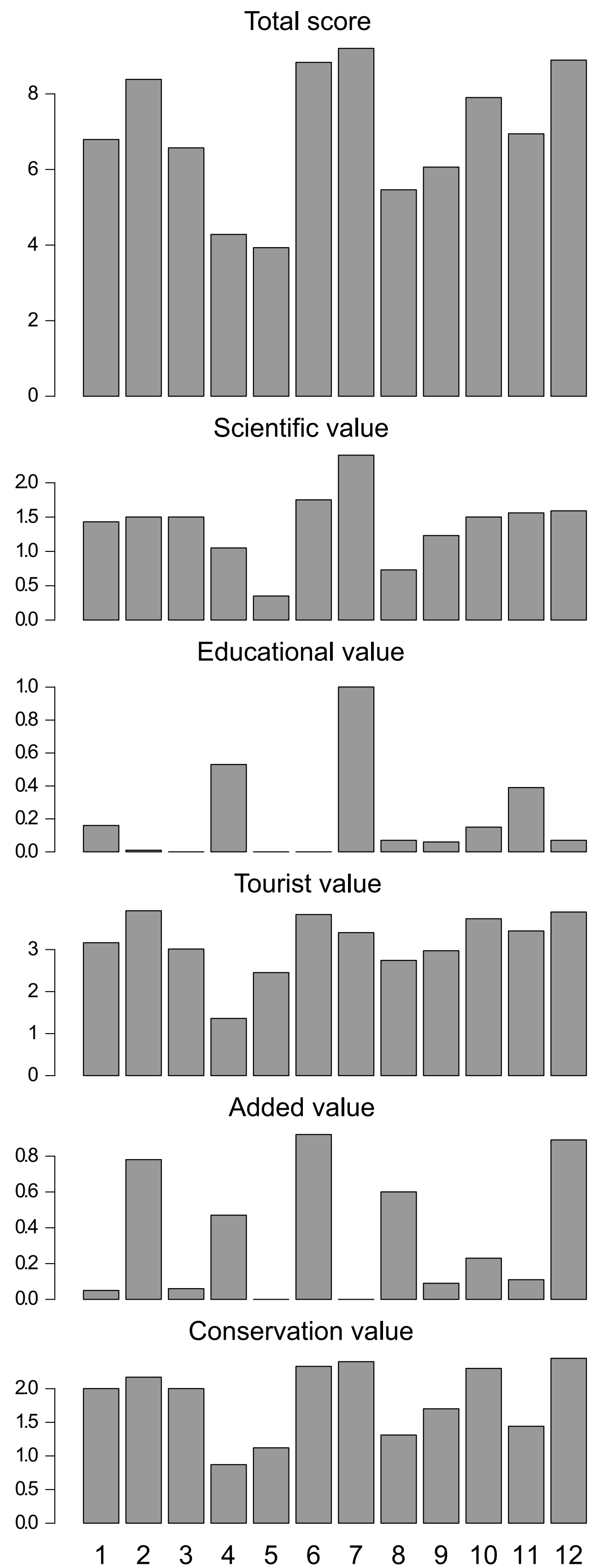
Fig. 8 Geodiversity sites and elements that scored highest (obtaining 10.0 or more points) during the evaluation and are located in the city centre. Scores for groups of criteria are shown on radar charts. Numbers of sites refer to the identification codes in Online Resource 1

retrieved from geological maps and constitute a natural element of the landscape, the abundance and diversity of anthropogenic features is striking (Fig. 4b–d). This, along with the presence of intangible geocultural heritage in the inventory, proves the importance of including secondary geodiversity features in studies of geoheritage (Kubalíková et al. 2017).

Although the inventory contains more geodiversity elements than described in earlier papers (Zwoliński et al. 2017, 2018), it is still far from being complete. First, the information regarding anthropogenic transformations of the landscape, gathered from historical maps and earlier contributions, is in most cases limited to the city centre. Thus, the qualitative evaluation of the geodiversity of the outskirts of the city is based mostly on fieldwork and the contents of geological, lithogenetic and geoenvironmental maps. Due to the scarcity of data sources, the density of geodiversity elements diminishes with the distance from the city centre (Fig. 4b–c). The inclusion of subsurface data obtained from drill cores would allow a more precise estimation of the anthropogenic movement of the sediment. Most of the city's territory can presumably be described in terms of planated or accumulation landforms, and the total extent of the man-made elements of the landscape should be mapped and included in the database.

The contents of the inventory show that the geodiversity features transformed significantly through time over the last thousand years and that the human factor contributed the most to these alterations. As a result, anthropogenic landforms overlap natural landscape features that were subjected to human intervention (Figs. 2 and 4, Online Resource 2). An individual geodiversity element can therefore demonstrate sediments or landforms developed in past climatic or tectonic natural conditions that have undergone contemporary, anthropogenically induced changes. This phenomenon can be called the imbrication of temporal scales (Santos et al. 2019), and geodiversity sites that are now changing under dynamic conditions are called evolving passive geomorphosites (Pelfini and Bollati 2014). Such landforms and sediments in many cases do not possess intrinsic scientific value, but they can have an important impact on the research on the anthropogenic changes of landscape and potential for

Fig. 9 Distribution of scores obtained from the quantitative evaluation among geodiversity forms. Bar plots show the arithmetic mean of evaluation results for different forms of urban geodiversity. Geodiversity forms: 1, accumulation, communication and planated landforms; 2, building, decorative and ornamental stones; 3, invisible landforms; 4, military landforms; 5, mines and mining landforms; 6, myths and toponyms; 7, natural history museums and exhibits, geological collections and rock gardens; 8, natural landforms, soils, rocks, minerals, fossils and mineral resources; 9, other anthropogenic features and landforms; 10, urban geohazards; 11, viewpoints and viewpoint geosites; 12, places of worship, cemeteries, historical monuments and statues ▶



developing scientific communication strategies. Future contributions should consider such landforms and sediments in a more coherent way, for example, by establishing compound (Pescatore et al. 2019) or composite (Coratza and Hobléa 2018) geomorphosites and by using such associations of landforms and/or sediments to designate new geosites and to plan effective geotouristic and educational facilities.

The geodiversity inventory of Poznań includes geological features of different scales, from major landforms of glacial origin to a single boulder with great historical and geo-mythological significance (Devil's Stone). Efficient geoconservation strategies should operate on all scales, from regional down to the individual rock sample (Brocx and Semeniuk 2007). The presence of small-scale geological or geomorphological features embedded within larger structures and linked to them by genetic relationships is known as the imbrication of spatial scales (Santos et al. 2019). According to Mucivuna et al. (2019), most contributions to the geodiversity assessment fail to embrace this phenomenon. In the present study, the presence of smaller-scale features within a broader context is demonstrated by using GIS-based mapping, with points that represent small structures (an individual meteorite crater, for instance) located within polygons that refer to more extensive geodiversity elements (the natural reserve for the protection of impact structures). Future urban geoheritage studies could also integrate a more detailed investigation of the relationships between the natural landscape, the urban fabric and the streetscape (Portal and Kerguillec 2018).

Quantitative Assessment

Kubalíková et al. (2020) noted that the verification of the suitability of the criteria used for the assessment of geodiversity within urban areas requires their application for the evaluation of many sites and features of both natural and cultural contexts. Such an attempt is made in the present study. The evaluation method of Kubalíková et al. (2019) is employed in this contribution, following the suggestions of earlier researchers who recommended the application of

Table 4 Matrix of correlation coefficients between all criteria employed in the quantitative assessment of urban geodiversity (after Kubalíková et al. 2019). The most significant correlations are marked in bold

	Integrity or current status	Number of geodiversity features	Rarity	Scientific knowledge	Representativeness	Existing interpretative materials and facilities	Accessibility	Safety	Tourist facilities	Visibility of geodiversity features	Ecological significance	Cultural and historical significance	Legislative protection	Vulnerability
Integrity or current status	1	-0.11	0.12	0.43	0.1	0.14	0.47	0.59	0.58	0.3	**-0.68**	0.14	-0.25	**0.7**
Number of geodiversity features	-0.11	1	0.23	0.06	0.21	0.26	0.11	-0.2	-0.18	-0.11	0.17	-0.04	0.02	-0.27
Rarity	0.12	0.23	1	0.13	0.12	0.31	0.02	0.03	0.01	0.05	-0.02	0.11	0.14	0.09
Scientific knowledge	0.43	0.06	0.13	1	0.15	0.25	0.19	0.2	0.53	-0.16	-0.34	0.13	0.05	0.44
Representativeness	0.1	0.21	0.12	0.15	1	0.26	-0.18	-0.41	-0.15	0.11	0.13	0.06	-0.04	-0.08
Existing interpretative materials and facilities	0.14	0.26	0.31	0.25	0.26	1	0.04	0.08	0.06	0.1	-0.06	0.05	0.19	0.09
Accessibility	0.47	0.11	0.02	0.19	-0.18	0.04	1	0.4	0.55	0.25	-0.52	0.27	-0.18	0.37
Safety	0.59	-0.2	0.03	0.2	-0.41	0.08	0.4	1	**0.61**	0.28	**-0.66**	-0.06	-0.32	0.54
Tourist facilities	0.58	-0.18	0.01	0.53	-0.15	0.06	0.55	**0.61**	1	0.07	**-0.79**	0.2	-0.15	**0.68**
Visibility of geodiversity features	0.3	-0.11	0.05	-0.16	0.11	0.1	0.25	0.28	0.07	1	-0.07	0.29	-0.06	0.09
Ecological significance	**-0.68**	0.17	-0.02	-0.34	0.13	-0.06	-0.52	**-0.66**	**-0.79**	-0.07	1	-0.01	0.26	**-0.66**
Cultural and historical significance	0.14	-0.04	0.11	0.13	0.06	0.05	0.27	-0.06	0.2	0.29	-0.01	1	0.47	0.16
Legislative protection	-0.25	0.02	0.14	0.05	-0.04	0.19	-0.18	-0.32	-0.15	-0.06	0.26	0.47	1	-0.06
Vulnerability	**0.7**	-0.27	0.09	0.44	-0.08	0.09	0.37	0.54	**0.68**	0.09	**-0.66**	0.16	-0.06	1

Table 5 Results of principal component analysis for evaluation criteria. The most significant loadings (< − 0.35 and > 0.35) are marked in bold. PC, principal component

	PC 1	PC 2	PC 3
Importance of components			
Standard deviation	2.08	1.43	1.19
Proportion of variance	0.31	0.15	0.1
Cumulative proportion	0.31	0.46	0.56
Loadings			
Integrity or current status	**0.4**	0.04	0.14
Number of geodiversity features	− 0.1	0.31	**0.45**
Rarity	0.04	**0.39**	0.1
Scientific knowledge	0.24	0.35	0.02
Representativeness	− 0.06	0.28	0.32
Existing interpretative materials and facilities	0.05	**0.46**	0.27
Accessibility	0.33	− 0.07	0.23
Safety	0.36	− 0.19	− 0.02
Tourist facilities	**0.42**	0	− 0.09
Visibility of geodiversity features	0.06	0.06	0.01
Ecological significance	**− 0.41**	0.07	− 0.05
Cultural and historical significance	0.14	**0.36**	**− 0.44**
Legislative protection	− 0.1	**0.4**	**− 0.57**
Vulnerability	**0.39**	0.03	− 0.15

existing techniques rather than the introduction of new ones (Mucivuna et al. 2019). For the same reason, no modifications in the framework described by Kubalíková et al. (2019) were proposed.

Principal component analysis proves that the method used in this study after Kubalíková et al. (2019) performs well when numerous geodiversity elements are assessed. The relatively low values of the correlation coefficients (close to zero) and the limited amount of the total variance explained by the first three components show that the criteria do not overlap. The first component is largely concerned with the current status of a geodiversity site and its touristic exploitation. The second component might be regarded as the index of its uniqueness and educational use, while the third separates geodiversity elements that are of great importance for Earth science from those that stand near the border with cultural heritage. However, the low amount of variance explained by these components limits their suitability for providing a lower-dimensional summary of the assessment criteria. The original variables are therefore used in the figures and tables that show the results of the quantitative evaluation.

Many geodiversity elements that are widely recognised as powerful educational resources ranked low in the educational value group of criteria. In most cases, this is caused by the scarcity of existing interpretative materials that refer to the geological or geomorphological characteristics of the feature.

Future additions to the study design might include the usage of statistical analyses in (1) a comparison of the performance of many assessment methods and (2) for mapping the differences between the geodiversity inventories of several cities located in different geomorphological and geological contexts. A more detailed investigation of urban geoheritage types sensu Habibi et al. (2018) is another possible direction of research; a preliminary version of such a study can be found in Kong et al. (2020).

General Public Preferences

Geodiversity sites represented by points are less densely spaced outside the city centre (Fig. 4). This means that on the city peripheries they are rendered as markers that are available for instant selection, whereas in the inner city, markers are grouped in clusters and are accessible for clicking when the map is enlarged. Consequently, the markers located at the city outskirts are selected more often than those within the medieval urban centre. Among the latter, geodiversity features labelled as related to geological hazards (marked on the map by an icon that depicts a flood; Fig. 3) are preferred by visitors. However, no geosites associated with geohazards are included in the Polish Registry of Geosites nor are they proposed by Zwoliński et al. (2017, 2018), which shows that the preferences of the general public were not considered in the process of the designation of potential geodiversity sites. Among the geodiversity features located on the city peripheries, those related to palaeontology and marked with an icon of an ammonite shell are among the most frequently selected. This reveals the potential of fossil-bearing decorative stones for educational purposes. The locations of such rock types inside and on the facades of buildings should therefore be included in urban geodiversity inventories.

In general, the points and polygons that were selected most on the interactive map (Figs. 10–11) are different from those that received the highest scores during the quantitative evaluation (Figs. 7–8). The investigation of the preferences of the public is therefore an essential component of effective geosite and geodiversity site assessment in an urban environment, allowing the identification of themes that stimulate potential geotourists or participants in geoeducational activities and leading to the inclusion of corresponding features in geodiversity inventories. In the present study, the historical channels of the Warta River and its tributaries, infilled or modified due to anthropogenic influences, were identified as an important topic that gained the attention of map users and has significant educational potential.

Invisible landforms sensu Clivaz and Reynard (2018) scored low or moderate during the quantitative assessment

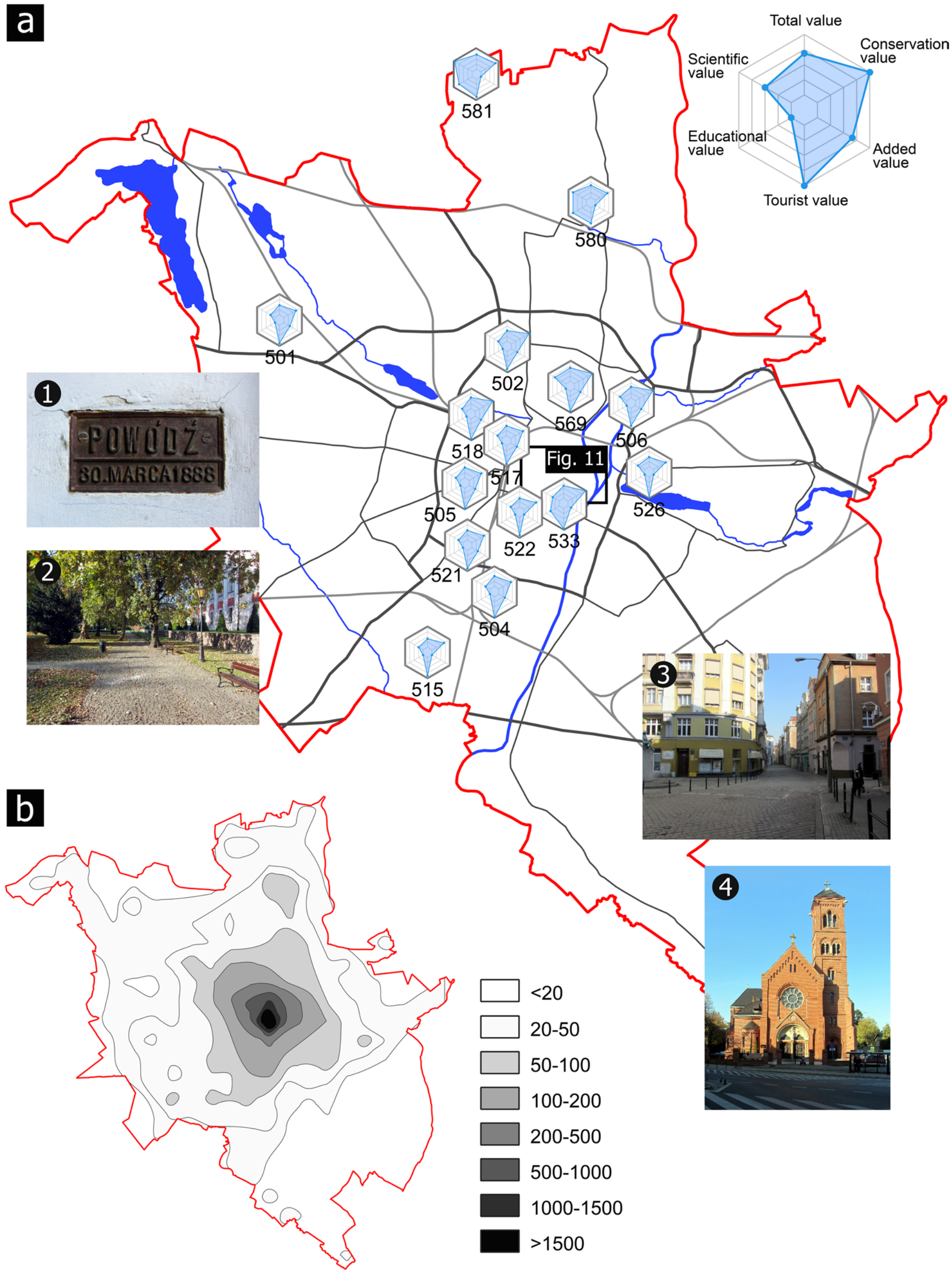


Fig. 10 Features most frequently selected by users of the interactive map. **a** Polygons that obtained most clicks and are located outside the city centre. Examples of geodiversity features that were selected most intensively on the interactive map: 1, historical flood mark at the Bożego Ciała Church (no. 533); 2, city park located in the historical moat (no. 29); 3, presumable historical channel of Bogdanka stream (no. 7); 4, St. Florian's Church (no. 518). For precise locations of 2–3, see Fig. 11. Numbers of sites refer to codes in Online Resource 1. **b** Number of clicks per unit area (1 km^2) counted from the interactive map of Poznań

in all groups of criteria. However, geodiversity elements included in this group are among those most often clicked by the website visitors. Given that several of them were added during the study and are not included in usage statistics, the results of the quantitative evaluation differ significantly from the preferences and interest of the general public. This finding is also supported by a conclusion drawn by Pica and Del Monte (2021), who stressed that geocultural diversity is depreciated in most evaluation methods designed for urban and anthropogenic environments. Future improvements of existing assessment procedures should allow a more balanced evaluation of the landforms that disappeared from the landscape due to the human intervention, at least when geoeducational and cultural potential is taken into consideration. Moreover, although the artificially planated landforms are not available for scientific study, their sediment in many cases remains preserved in the subsurface, can be reached in boreholes or wells and may exhibit scientific value. However, these landforms were given low total scores during the evaluation because their accessibility and visibility is set equal to zero.

Studying visitors' perception of geological features in urban settings is an important task (Petrović et al. 2017), but better comprehension requires that cities be viewed as

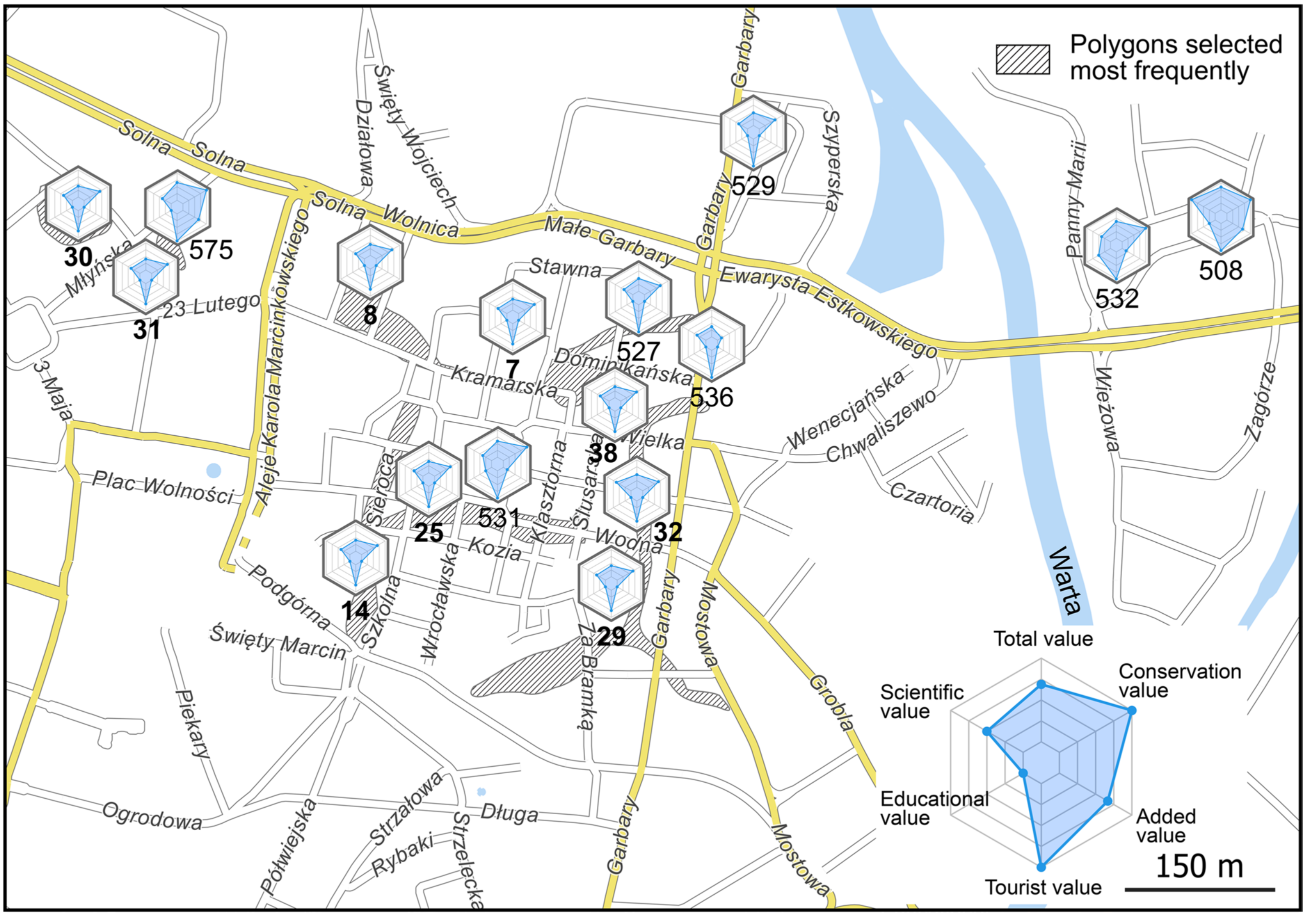
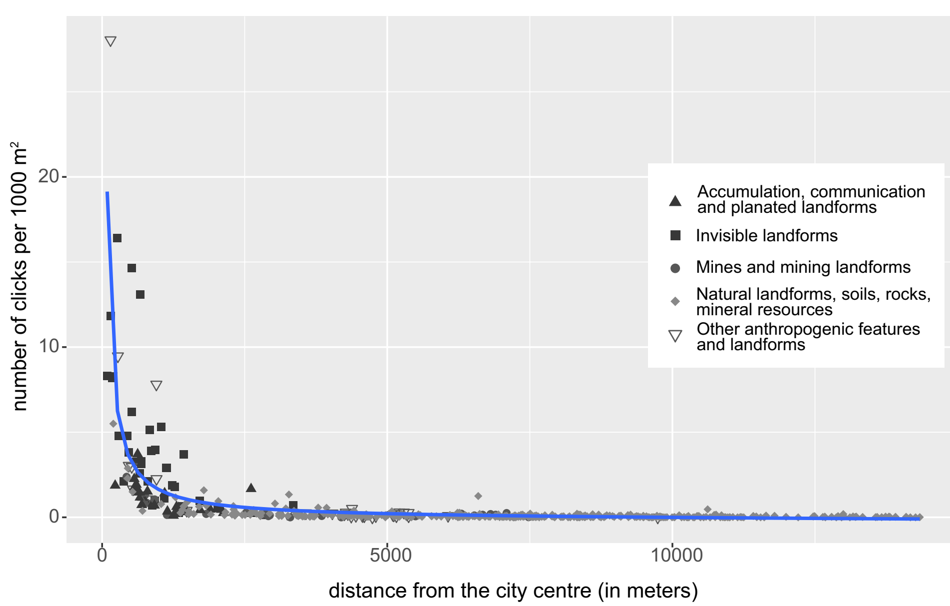


Fig. 11 Most frequently selected points (more than 260 clicks) and polygons (more than 8 times per unit area of 1000 m2) located within the city centre. Numbers refer to the identification codes of geodiversity features listed in Online Resource 1. Numbers of polygons are marked in bold

Fig. 12 Scatterplot illustrating the relation between number of selections on the interactive map and the distance from the medieval city centre (Old Market Square). Geodiversity sites and elements visualised near the right border of the chart are located in suburbia



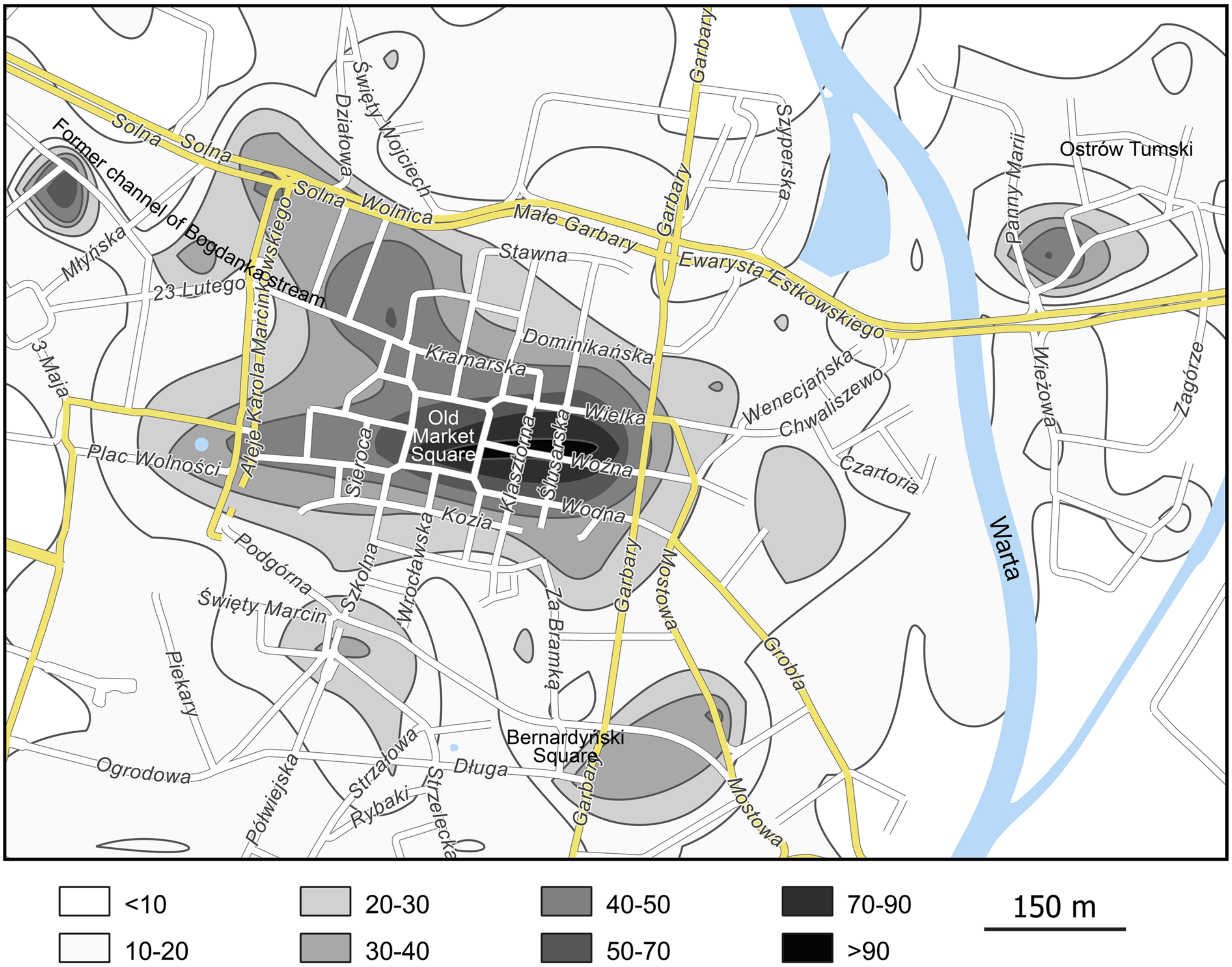


Fig. 13 Density of clicks within the city centre (per unit area of 10,000m^2), counted from the interactive map of Poznań

socioecological systems (Habibi et al. 2018). The present study of the preferences of the public is basic and limited to the Internet. Future attempts should include the investigation of the behaviour of geotourists at geodiversity sites and touristic attractions. Such analyses were not possible in a pandemic situation and during a time of social distancing.

The current study confirms that a change of conservation strategies from a geosite-based to a landscape-based approach (Lugeri et al. 2021) significantly improves the management of geodiversity. An individual geological feature (for instance, a historical river channel) is usually embedded inside a wider context (e.g. floodplain of a past anastomosing river). Educational and conservation strategies should embrace a complex set of geodiversity elements that are linked by genetic relationships; the imbrication of spatial/temporal scales (Santos et al. 2019) and compound geomorphosites (Pescatore et al. 2019) thus forms an important part of the urban geodiversity.

Urban Geotourism

The geodiversity of urban areas is traditionally perceived as a good starting point for the development of urban geotourism. Petrović et al. (2017) state that geological features and geosites are an alternative to traditional heavily visited destinations. Habibi et al. (2018) point out to the diversification of tourist programmes and development of innovative forms of tourism, whereas Kubalíková et al. (2020) argue that urban geotourism can contribute to better comprehension of the geodiversity imprint on the city landscape. The identification and evaluation of urban geodiversity elements is perceived as an introductory step to developing urban geotourism, and such studies represents an emerging field in geoheritage research (Vereb et al. 2020).

Many authors claim that geotourism should not be focused solely on natural geodiversity; they argue that it should also include elements of cultural heritage (Rodrigues et al. 2011) and that secondary (anthropogenic) geodiversity represents a valuable resource for geotouristic activities (Kubalíková et al. 2017). However, as noted in previous studies, stimulating a city's inhabitants so that they appreciate the geodiversity of their surroundings is not straightforward (Rodrigues et al. 2011), and the touristic potential of geosites in an urban environment is not sufficiently recognised by the public (Kubalíková et al. 2020). Moreover, this study shows that the results of expert evaluations do not overlap with the decisions of potential geotourists and geosites that have significant scientific importance can play a subordinate role for the general public when compared to less meaningful geodiversity sites located near popular tourist destinations or in the historical city centre. The results also highlight the potential of invisible landforms for raising awareness in potential geotourists about changes in the urban landscape, geological hazards and nature conservation.

Earlier studies suggested that urban geotourism offers an alternative to traditional touristic activities and destinations (Kubalíková et al. 2020). However, the present contribution shows that broadening the list of touristic attractions is not an easy task. Geodiversity elements that received the highest number of clicks on the interactive map are also traditional touristic destinations or are located near the popular tourist venues, but they were not included in standard geodiversity inventories such as the Central Register of Polish Geosites. These sites should be identified before any strategy for tourism development is adopted.

Urban geotourism is prone to shifts in fashion (Ashworth and Page 2011); thus, the usage of geodiversity elements that possess significant educational and/or geotouristic potential can have an impact on urban geotourism's diversification. On the other hand, the extension of the touristic product line is not straightforward, and the cities that build up their image based on their ambiance or way of life generally have more potential to diffuse the range of touristic products, increasing the possibility of generating repeated visits (Ashworth and Page 2011). This suggests that the promotion of new touristic attractions can be ineffective in many cities, whereas uncovering the geological context of existing tourist attractions can enhance visitors' experiences and contribute to the overall image of the city. In any situation, further analyses of the tourists' interest profiles are essential for the identification of potential geotouristic products, bearing in mind that it is not an easy task to delineate the difference between the touristic and other motivations behind activities undertaken in an urban environment (Edwards et al. 2008).

The results of the present study have implications for local authorities and policy-makers, encouraging them to investigate the preferences of potential tourists before any geotourism development strategies are adopted. Geoscientists should contribute to the process by performing a comprehensive and holistic geodiversity assessment to broaden the range of geodiversity assets that can be used for geotourism purposes and to implement a successful conservation plan. Comprehensive studies of urban geodiversity could also contribute to its better recognition as part of natural capital and incorporation into ecosystem assessments, leading to its full integration into local and national development policies and spatial planning (Gray et al. 2013). Therefore, cooperation between government agencies and academics is required to ensure proper management and protection of geodiversity and to provide resources for educational activities and geotourism.

Conclusions

The application of a coherent and explicit framework for the identification of geodiversity sites and elements permits one to record a rich collection of natural and anthropogenic features that is more diversified than those in studies constrained to selected forms of urban geodiversity. Human-induced transformations of the landscape are responsible for the following peculiarities of the urban environment: (1) complex geological structures and landforms overlapping on both spatial and temporal scales and (2) the presence of invisible geomorphosites.

Statistical analyses show that the criteria used in the quantitative assessment do not overlap and are not significantly correlated with one another. The most significant drawback of the method is related to the low scores obtained by invisible landforms, regardless of their genuine value and potential for research and education. Future studies should include a comparative analysis of many evaluation procedures to confirm their relevance and employ the geodiversity inventories of several cities located in different geological contexts.

The investigation of the preferences of the general public reveals that the geodiversity sites that are most interesting for potential geotourists differ from those that ranked highest in the quantitative evaluation. Anthropogenic and invisible landforms located in the city centre and close to traditional tourist destinations were among the sites most frequently selected by the users of the interactive map. However, most of these geodiversity sites and elements are not included in geoheritage inventories nor were they proposed for consideration as possible future geosites.

Analyses of the preferences of the public also revealed that potential geotourists are more interested in the geological peculiarities of existing tourist attractions than in geosites. This stresses the importance of performing widespread studies of potential geotourists' preferences before any strategy for tourism development is adopted. The incorporation of existing tourist attractions for geotouristic purposes (by providing new educational facilities, for instance) and a shift towards a landscape-based approach in geodiversity conservation are other important directions of future research on urban geoheritage.

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Data Availability Submitted as Online Resource 1–2.

Declarations

Competing Interests The author declares no competing interests.

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