

## Article

# Threats to Cultural Heritage Caused by the Global Sea Level Rise as a Result of the Global Warming

Mateusz Ciski \*  and Krzysztof Rzaśa 

Department of Land Management and Geographic Information Systems, Faculty of Geoengineering, Institute of Spatial Management and Geography, University of Warmia and Mazury in Olsztyn, 10-720 Olsztyn, Poland; krzysztof.rzasa@uwm.edu.pl

\* Correspondence: mateusz.ciski@uwm.edu.pl

**Abstract:** Climate change resulting from global warming has an increasing impact on Earth. The resulting sea level rise is starting to be noticed in some regions today, and based on projections, could have severe consequences in the future. These consequences would primarily be felt by residents of coastal areas, but through the potential for irreparable damage to cultural heritage sites, could be significant for the general public. The primary aim of the research undertaken in this article was to assess the threat to cultural heritage objects on the case study area of Tri-City, Poland. A review of available elevation data sources for their potential use in analyses of sea level changes was required. The selection of the optimal data source for the cultural heritage threat analysis of historic sites was carried out. The analyses were conducted for three scenarios, using ArcGIS Pro 2.7 software. A series of maps were thus prepared to show the threats to specific historic sites for various global sea level rise scenarios. Even with the slightest rise in sea level, monuments could be permanently lost. The authors point out that a lack of action to stop climate change could result not only in economic but also cultural losses.



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**Keywords:** global warming; climate change; global sea level rise; flood risk management; floodplains; cultural heritage; geodata; GIS

## 1. Introduction

### 1.1. Threats to Cultural Heritage

Climate change is a phenomenon that manifests itself, among other things, in an increase in the average temperature of our planet. Climate change has been singled out as a major challenge currently facing the world [1]. This has negative effects on the economy, health, and society, but above all on the environment at a global level (rising sea levels due to polar melting, changes in ecosystems, desertification of areas, ocean acidification, and so on) [2]. Sea level rise creates a particularly significant threat to populated coastal areas [3,4].

Issues related to the impacts of ongoing climate change form the basis of many scientific studies. Aspects range from the natural sciences to the social and political sciences [5]. However, there is less research on the effects of climate change on cultural heritage. More research is needed to identify and understand the risks of climate change in this area [2,6]. The impact of climate change on cultural heritage, both tangible and intangible, is a reality in many countries around the world [2,7]. From the effects of rising sea levels to the increasing incidence of various extreme events (e.g., extreme winds, storms, and tornados; extreme precipitations, flooding, and flash floods; heatwaves and drought; and pollution peaks), many cultural heritage sites are directly under threat [8]. Degradation of cultural objects may also be related to air pollution: either in strong correlation (e.g., recession of façades in limestone or marble soiling of stone surface, soiling of glass, chemical leaching of medieval stained glass, and metal corrosion) or in weak correlation (salt crystallization in porous walls, freeze-thaw damage in porous materials,

submersion of monuments due to sea level rise, swelling-shrinkage of expansive clay minerals in soils, and biomass accumulation on facades in urban areas) [9]. Climate change impacts are functioning as risk multipliers to problems that are already apparent and affect cultural heritage sites [10]. One can see a strict relationship between climate, cultural heritage, and the human factor [11].

Global warming is one of the major environmental problems facing the world today [12]. The increase in temperature caused by anthropogenic emissions from the pre-industrial period to the present will continue to cause further long-term changes in the climate system, such as sea level rise [13]. Understanding the effects that climate has on different types of cultural and natural heritage leads to a consensus in recognizing that rising sea level, caused by climate change, can lead to the destruction of certain elements of cultural and natural heritage if adaptation and mitigation measures are not implemented [14]. Studies carried out by various authors indicate that a large threat occurs for cultural heritage, for example in Mombasa, Kenya [1], Venice, Italy [15], Scotland [16], Corsica [17], Easter Island [18], and others [19–21].

### *1.2. Scenarios of Global Sea Level Rise*

Out of numerous studies, three sets of scenarios (or “projections”) were selected to analyze the cultural heritage threat assessment, conducted in the case study area. The term “scenario” is used to refer to the projections of the future—in this case, future global sea level rise. “Scenarios” do not forecast future events, but they do describe future potential events in a way that helps with decision-making under conditions of uncertainty [22]. All scenarios were made for the year 2100.

The first chosen scenario is the result of the Special Report of Intergovernmental Panel on Climate Change (IPCC), which is a body of the United Nations, dedicated to providing the world with objective information relevant to understanding the scientific basis of the risk of human-induced climate change [23]. The Special Report, entitled “Climate Change 2014. Synthesis Report” [24], defines the following scenarios (or Representative Concentration Pathways—RCPs): RCP2.6, RCP4.5, RCP6.0, and RCP8.5; every scenario differs in terms of probability and gravity. In 2019, IPCC published another Special Report, entitled “The Ocean and Cryosphere in a Changing Climate” [25], in which the RCP2.6, RCP4.5, and RCP8.5 scenarios were revised. Updated IPCC scenarios for the global sea level rise in the year 2100 are as follows: RCP2.6—mean: 0.435 m, likely range: 0.285 m–0.589 m; RCP4.5—mean: 0.549 m, likely range: 0.385 m–0.724 m; RCP8.5—mean: 0.842 m, likely range: 0.609 m–1.105 m.

In 2009, the National Oceanic and Atmospheric Administration from the United States Department of Commerce created a Technical Report entitled “Global Sea Level Rise Scenarios for the United States National Climate Assessment” [26], in which these three (of total six) global sea level rise scenarios were projected: B1—mean: 1.04 m, likely range: 0.81 m–1.31 m; A2—mean: 1.24 m, likely range: 0.98 m–1.55 m; and A1F1—mean: 1.43 m, likely range: 1.13 m–1.79 m. This study was selected for the second scenario.

The third chosen scenario is the result of the global sea level rise scenarios for the United States National Climate Assessment report, from 2012 [22]. The report was prepared by the National Oceanic and Atmospheric Administration (NOAA) of the United States Department of Commerce. NOAA projects four global sea level rise scenarios: “Highest”—mean: 2.0 m, “Intermediate-High”—mean: 1.2 m, “Intermediate-Low”—mean: 0.5 m, and “Lowest”—mean: 0.2 m.

The results of the above studies are collected and summarized in Table 1 below.

**Table 1.** Summary the results of the studies on global sea level rise. Source: own elaboration, on the basis of [22–26].

Study	Scenario	Mean Global Sea Level Rise Prediction	Likely Range:
IPCC [23–25]	RCP2.6	0.435 m	0.285 m–0.589 m
	RCP4.5	0.549 m	0.385 m–0.724 m
	RCP8.5	0.842 m	0.609 m–1.105 m
2009 NOAA [26]	B1	1.04 m	0.81 m–1.31 m
	A2	1.24 m	0.98 m–1.55 m
	A1F1	1.43 m	1.13 m–1.79 m
2012 NOAA [22]	“Lowest”	0.2 m	-
	“Intermediate-Low”	0.5 m	-
	“Intermediate-High”	1.2 m	-
	“Highest”	2.0 m	-

Scientists from all over the world agree on the threat arising from climate change. The selected scenarios vary in value but always assume rising sea levels. The level of threat to coastal areas is not only derived from Mean global sea level rise, but also from local conditions [22].

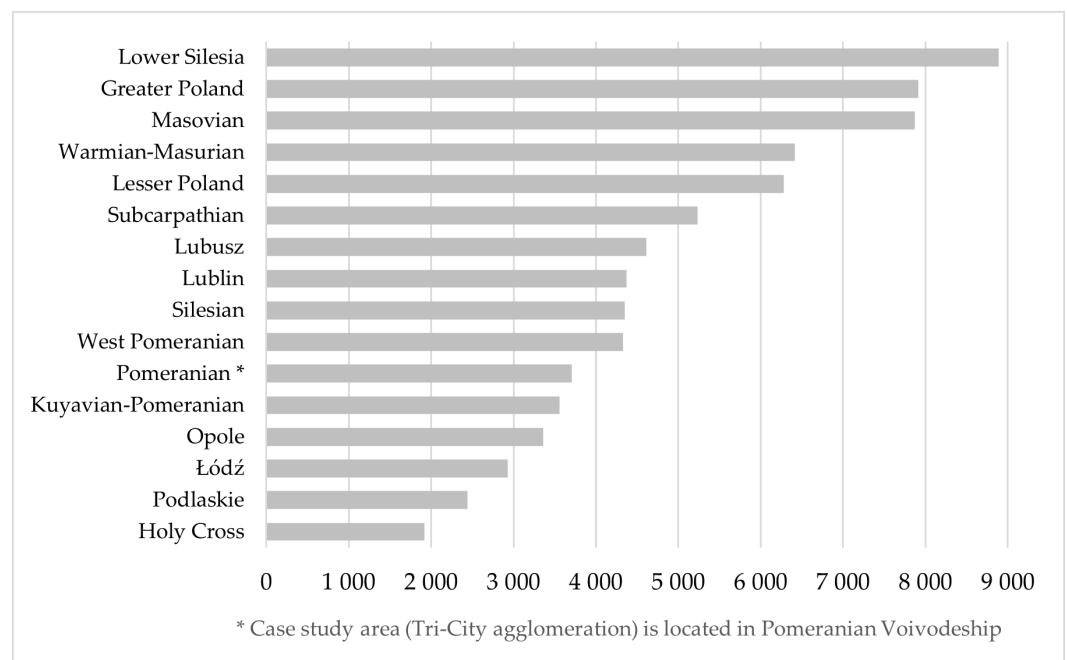
### 1.3. System of Monument Protection in Poland

The legal basis for the protection of monuments in Poland is the Act of 23 July 2003 on the protection of monuments and the care of monuments [27]. According to Article 3 of the above-mentioned Act, a non-movable monument is a real estate, its part or a complex of real estate, which is the work of humankind or is related to its activity and is a testimony to a past era or event; whose protection is in the public interest because of its historical, artistic, or scientific value. Art. 6 of the Act indicates that non-movable monuments may include: cultural landscapes, urban and rural systems, building units, works of architecture and construction, works of defense construction, technical objects, cemeteries, parks, gardens, and other forms of designed greenery, as well as places commemorating historical events or the activities of remarkable personalities or institutions. Non-movable monuments are registered by an entry in the register of objects of cultural heritage (*pol. Rejestr zabytków*), kept by the Voivodeship Conservators of Monuments [28]. The generic division of non-movable monuments was designed by The National Heritage Board of Poland (NHBP). NHBP is a state agency that gathers and disseminates information on heritage, sets standards for its protection and conservation, and aims to raise social awareness on the cultural heritage of Poland. In accordance with the rules developed by NHBP, non-movable monuments are included in Poland:

- Urban (urban and rural systems, districts, squares, and streets as urban interiors, protection zones, canals, railways, and others);
- Sacral (churches of different religions, monasteries, belfries, chapels, morgues, road-side shrines, sacral statues, and others);
- Defensive (castles, residential towers, defensive buildings, city walls and gates, fortresses and their elements, forts, and others);
- Public (public buildings, seats of government, schools, banks, postal offices, hotels, theatres and cinemas, barracks and prisons, train stations, hospitals, administrative buildings, and others);
- Mansions (village and city palaces, residential units, and others);
- Greenery (palace and mansion parks, gardens, city parks, avenues, villas and home gardens, elements of natural landscapes, and others);
- Farm (farm buildings, all individual farm buildings in rural homesteads, granaries, barns, warehouses, and others);

- Residential (residential buildings, houses, tenements, rural huts, vicarages and presbyteries, and others);
- Industrial (industrial buildings, production halls in factory units, engine houses, boiler rooms, shaft towers in mines, single-production buildings, forges, mills, windmills, water towers, bridges and viaducts, power plants, gas and water supply plants, and others);
- Cemeteries (cemeteries, single graves, church areas, and others);
- Miscellaneous (fences, gates and guardhouses, statues, fountains and wells, small park architecture, and others).

Residential, sacral, and greenery monuments are the most frequent types of non-moveable monuments in Poland. The number of non-movable monuments in voivodeships in Poland is presented in Figure 1.



**Figure 1.** The number of non-moveable monuments in voivodeships of Poland. Source: own elaboration on the basis of the data from The National Heritage Board of Poland.

Another form of historic site protection in the Polish legal system is culture parks. A cultural park can be created in order to protect the cultural landscape and to preserve landscape-distinctive areas with immovable monuments characteristic for the local building and settlement tradition. The cultural landscape is the result of transforming the natural landscape by a group or several cultural groups and the imposition of cultural elements from different eras. It is a natural space that was in the sphere of human interactions and, as a consequence of these influences, it took a cultural form. It arises as a result of the combination of natural and cultural influences, creating a specific, regionally separate structure [29]. Currently, there are 40 such facilities in Poland.

Historic Monument, in accordance with Art. 7 of the Act of 23 July 2003 on the protection and care of monuments, is the next legal form of protection of monuments in Poland. Recognition of the monument as a Historic Monument is a special form of ennoblement of a historic object. According to the criteria set by the National Centre for Research and Documentation of Monuments (currently, The National Heritage Board of Poland), a non-movable monument of trans-regional importance, of high historical, scientific, and artistic values relevant to the Polish cultural heritage, consolidated in the social consciousness by being a source of inspiration for future generations, may be covered by this form of additional protection [30]. Currently, there are 114 such facilities in Poland.

In Poland, there are also 16 objects included on the UNESCO World Heritage List. These are Historic Centre of Kraków, Wieliczka and Bochnia Royal Salt Mines, Auschwitz Birkenau German Nazi Concentration and Extermination Camp (1940–1945), Białowieża Forest, Historic Centre of Warsaw, Old City of Zamość, Castle of the Teutonic Order in Malbork, Medieval Town of Toruń, Kalwaria Zebrzydowska: the Mannerist Architectural and Park Landscape Complex and Pilgrimage Park, Churches of Peace in Jawor and Świdnica, Wooden Churches of Southern Małopolska, Park Mużakowski, Centennial Hall in Wrocław, Wooden Tserkvas of the Carpathian Region in Poland and Ukraine, Tarnowskie Góry Lead-Silver-Zinc Mine and its Underground Water Management System, and Krzemionki Prehistoric Striped Flint Mining Region.

In addition to the UNESCO World Heritage List, there are UNESCO Tentative Lists—lists of historical objects and places that each State Party intends to consider for nomination for the World Heritage List. In Poland, there are currently six objects on the Tentative List: Ancient and Primeval Beech Forests of the Carpathians and Other Regions of Europe—extension, Gdańsk—Town of Memory and Freedom, Modernist Centre of Gdynia—the example of building an integrated community, Paper Mill in Duszniki-Zdrój, The Augustów Canal, and The Dunajec River Gorge in the Pieniny Mountains.

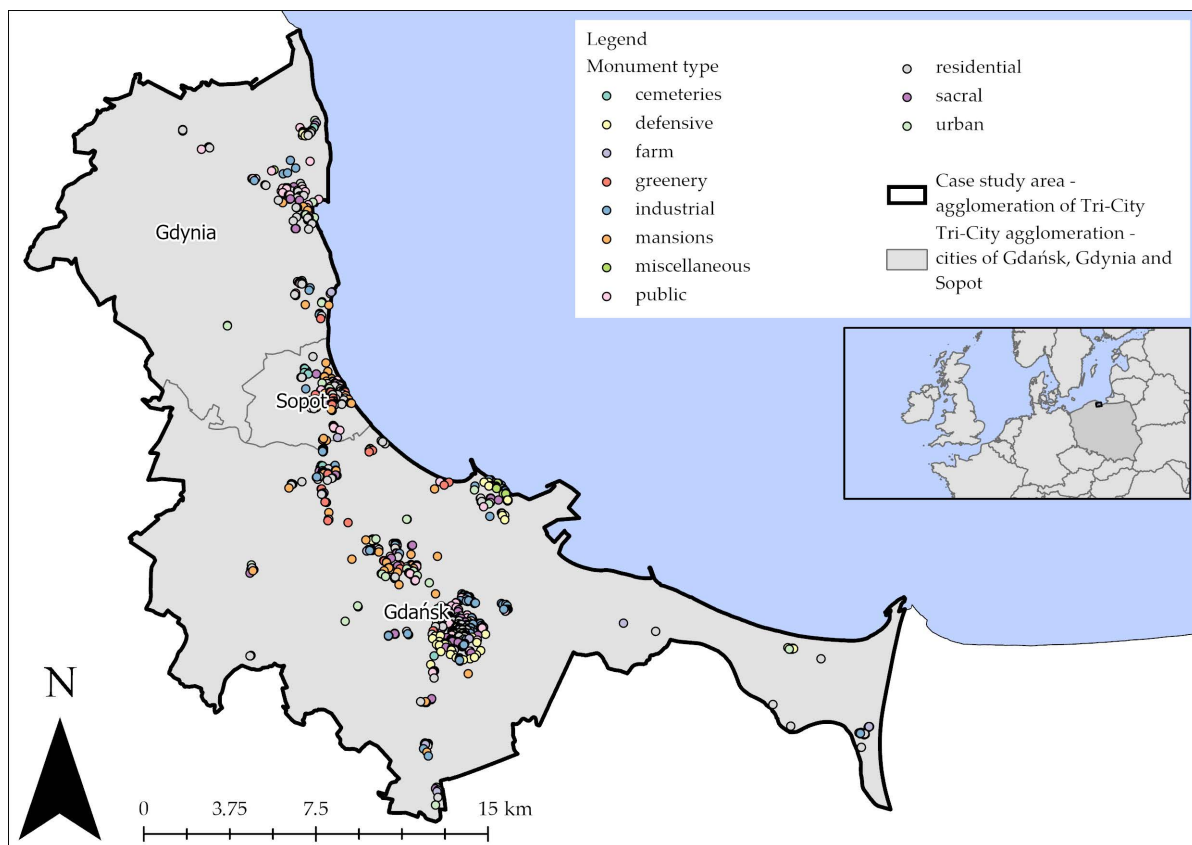
Cultural heritage threats caused by global warming apply to historical sites located on the Baltic Sea coast in Poland. For the purposes of this article, the research covered monuments located in the Tri-City, which is an urban agglomeration consisting of three cities: Gdańsk, Gdynia, and Sopot. Gdańsk is the capital of the Pomerania Voivodeship, located in northern Poland, on the coast of the Baltic Sea. Gdańsk is one of Poland's oldest cities with a history going back a thousand years. In the area of the Tri-City, one can find a large number of different historic objects, which are protected according to the rules of the system of monuments protection in Poland.

In total, there are 1139 non-movable monuments in the Tri-City (which is about 30% of all non-movable monuments in the Pomeranian Voivodeship), including 860 in Gdańsk, 144 in Gdynia, and 135 in Sopot. In addition, in Tri-City, there are also monuments protected as Historic Monuments—5 in Gdańsk and 1 in Gdynia. It should also be noted that, in Tri-City, there are two objects on the Tentative List of the UNESCO World Heritage List (list of the objects that each State Party intends to consider for nomination for the UNESCO World Heritage List [31])—Gdańsk: Town of Memory and Freedom (4 November 2005) and Modernist Centre of Gdynia: the example of building an integrated community (26 September 2019).

At the time of writing this article, sessions of the Extended 44th session of the World Heritage Committee, in Fuzhou (China), 16–31 July 2021 were in progress. One of the issues discussed during the session is the List of World Heritage Nominations. One of the historical objects located in Gdańsk is on the nomination list: Gdańsk Shipyard—the birthplace of “Solidarity” and the symbol of the Fall of the Iron Curtain in Europe.

The study area covers an area of ca. 418 sqkm within the administrative borders of the Tri-City. Figure 2 presents the case study area together with the locations of the non-movable monuments.

According to NHBP division, there are 11 types of monuments. In the Tri-City agglomeration, of the total 1139 monuments, residential monuments constitute the largest number—373 sites, or nearly 33%. Defense-related monuments constitute 165 in total (or approximately 14.5%), and industrial monuments (which include monuments related to the coastal character of the city)—140, or approximately 12.3%. The least number of monuments is in the type of cemeteries (9 objects, which is less than 1% of monuments). Detailed data including the type of monuments, the number of monuments, and its share in the total number, are presented in Table 2.



**Figure 2.** The study area of Tri-City. Source: own elaboration using ArcGIS Pro 2.7, on the basis of the data from The National Heritage Board of Poland and Polish National Register of Borders [31].

**Table 2.** Summary of monument types by NHBP division, within the Tri-City agglomeration. Source: own elaboration.

Monument Type	Number of Monuments	Share of Monuments
Residential	373	32.7%
Defensive	165	14.5%
Industrial	140	12.3%
Public	113	9.9%
Mansions	101	8.9%
Sacral	70	6.1%
Miscellaneous	53	4.7%
Greenery	51	4.5%
Urban	33	2.9%
Farm	31	2.7%
Cemeteries	9	0.8%

#### 1.4. Aim and Motivation for Undertaking the Study

Research on climate change and its threats is in its early stages, and relational measures of citations of articles on this topic are very low, confirming that the thematic approach is new [2,5]. The research conducted by the authors fills the gap in this area and expands the knowledge in the topic of the vulnerability of effects of global warming. Global sea level rise threats affect various spatial aspects, primarily related to developed land. In this study,

the authors focused on the threat to cultural heritage sites; the study covered the Tri-City agglomeration area in northern Poland.

The main aim of this study was to conduct a threat assessment of cultural heritage sites conducted on a case study area. The implementation of this goal required a review of available elevation data sources for its potential use in the analysis of sea level changes caused by global warming, which resulted in the need for a selection of the optimal data source for cultural heritage site threat assessment of monuments located in Tri-City, Poland.

## 2. Materials and Methods

The implementation of the research objective, as a first step, required the selection of global sea level rise scenarios. In this study, the authors focused on analyzing the impact of global sea level rise on cultural heritage as a result of global warming; a thorough literature review was conducted [3–5,12–26]. As a result of this analysis, it was decided to select three scenarios with three different global sea level rise scenarios (0.842 m, 1.04 m, and 2.0 m), as described in detail in the previous section.

Due to the fact that sea level change along the coast is the sum of eustatic, glacial isostatic adjustment (GIA), and tectonic factors, the authors decided to examine whether local GIA and tectonic factors could additionally influence sea level rise scenarios. GIA describes the adjustment process of the earth to an equilibrium state when loaded by ice sheets, whereas tectonic factors are the changes in the shape of the sea basins caused by plate tectonic processes. According to studies conducted by many authors, including [32–35], in some parts of the world, the influence of glacial isostatic adjustment and tectonic factors is very evident, such as on the Mediterranean coast [36].

By contrast, studies performed on the case study of the Baltic Sea [37–41] indicate a marginal effect of these factors on sea level rise, estimated at about  $0.33 \text{ cm yr}^{-1}$  in sea level [37], resulting in an additional rise of Baltic Sea level of approx. 2.42 cm in a projection for the year 2100. This value was added to the global sea level rise scenarios presented earlier. The final values for the projected rise in sea levels of the Baltic Sea are as follows: Scenario 1—0.866 m, Scenario 2—1.064 m, and Scenario 3—2.024 m.

With the three global sea level rise scenarios defined, the next research steps involved analysis using GIS tools.

The established research was accomplished in the following steps:

1. Gathering the necessary spatial data for the case-study area. Acquisition of polygon data representing the boundaries of the study area (data from the Polish National Register of Borders [42]) and point data representing the location of cultural heritage sites (data from The National Heritage Board of Poland).
2. Determining the parameters of the optimal elevation data source to perform the assumed analyses.
3. Assessing available elevation data sources.
4. Selecting the optimal source to perform the assumed analyses.
5. Performing threat assessments of cultural heritage sites in the chosen case study area, under selected global sea level rise scenarios.

The selection of threatened monuments is accomplished with the “Extract Values to Points” tool from “Spatial Analyst” toolbox in ArcGIS Pro 2.7. This tool extracts raster cell values on the basis of a set of point features and stores these values in the attribute table of the output feature class. In this study, this generates the monuments (set of point features) located in the threatened areas; these points are then placed on a separate layer. Due to the size of the case study area and the large number of points, for readability, the points should be visualized with large symbols—in some cases (when the threatened area is smaller), the points can obscure the threatened area. Nevertheless, by using this tool, the user is ensured that all points on the map are located in the threatened areas (and that the selected point has a specific raster cell value assigned to it).

In order to perform accurate hydrographic analyses of various types, an accurate Digital Elevation Model (DEM) is required. A DEM is a representation of the Earth's

topographic surface excluding trees, buildings, and other surface objects. The accuracy of the prediction of hydrographic analysis is related to the accuracy and spatial resolution of the DEM [43], and the quality of DEM used in raster analyses can significantly affect the detection of topographic features [44].

Issues related to the technical requirements and challenges of using raster data in spatial analysis are widely studied [43,45–48]. Based on the literature analysis, a number of DEM source parameters with which to describe the raster data were determined for global sea level rise analyses. The parameters were divided into three groups: data availability, data download, and data specifications. A key element of spatial analysis using GIS tools is the availability of spatial data, and difficulties arise at the very acquisition of data: spatial data services may require a fee to download data or require registration. Downloading data involves several important aspects: the size of the files being downloaded is important, as well as the format of the data. Raster data feature a set of attributes, among which the most important for spatial analysis are the level of the Earth’s surface coverage, as well as horizontal and vertical resolution.

The description of the parameters divided into groups is shown in Table 3.

**Table 3.** DEM sources parameters. Source: own elaboration, on the basis of [43–46,49,50].

<b>Data Availability</b>			
Download charge	The user costs to download the data. Increasing global digitization means that a lot of spatial data are available free of charge (often due to legal arrangements, e.g., the European INSPIRE initiative). If access to spatial data is hindered by fees, some services allow free data samples to be downloaded. In this case, the user can test the data before purchase.		
	None	Fee	Fee with a free data sample
Registration	The requirement to register for the service. The best variant of this parameter for the user is that no registration is required.		
	None	Free registration	Paid registration/ subscription
<b>Data download</b>			
File size	The size of the DEM file downloaded by the user. One file usually means one raster tile. Processing larger files can be problematic for older machines with less computing power.		
	Small	Medium	Large
Format	The data format should be user-friendly, meaning a commonly used format, and compatible with many GIS programs.		
	Yes		No
<b>Data specifications</b>			
Earth coverage	Level of DEM coverage of the Earth’s surface. The limitation in coverage of certain types of DEMs may be a problem for a user with a particular case study area.		
	Complete	Incomplete	Partial
Horizontal resolution	Horizontal resolution determines how much area is covered by one raster cell. A lower value of this parameter means higher spatial accuracy, but also a larger file size and longer processing time.		
	Approx. <1 m	Approx. 1–5 m	Approx. 6–24 m
Vertical resolution	Vertical resolution means elevation value—information on how frequently the DEM records a difference in elevation. A lower value of this parameter is particularly important for detailed analyses.		
	Approx. <1 m	Approx. 1–5 m	Approx. 6–24 m

For the purposes of the carried out research, the authors defined a set of optimal parameters, which should characterize the DEM data source, used for the assessment of the global sea level rise threats related to cultural heritage objects. It was decided that:



- Data should be free of charge—charging for access to spatial data can be a serious barrier for a large share of users, especially those without outside funding. Therefore, the optimal situation is no data fee.
- Registration to a hosting service does not have to be required—this parameter is a nuisance to working with data and does not affect the research process too much; nevertheless, the optimal situation is that there is no need for registration.
- File size should be as low as possible—downloading multi-gigabyte data may be a problem for some users without a fast Internet connection; additionally, processing large files may require hardware with high computing power. Therefore, the optimal value of the parameter is a small download size (less than 1 GB).
- The data format should be user-friendly—depending on the user’s level of experience with GIS software, handling less popular, less frequently used, and less compatible formats with different GIS software may be a problem. Some of the most user-friendly formats include GeoTIFF and JPEG2000.
- Earth coverage should be as complete as possible—due to the selected case study area, DEMs covering different parts of the world may be needed by the user. Therefore, the most optimal option is to provide as much coverage of the Earth’s surface as possible.
- Horizontal resolution should allow locating the given object—this parameter is closely related to the nature of the research carried out by the user; therefore, the optimum solution is the highest possible resolution (i.e., such that it allows localizing the analyzed phenomenon and object).
- Vertical resolution should not exceed 1 m—similarly to horizontal resolution, the highest possible resolution (about 1 m) is optimal. In the case of studies of areas prone to flooding, this accuracy is particularly important, as the studies are based on very precise values (as indicated in the global sea level rise scenarios).

A source that meets the above requirements to the greatest extent possible can be used for the analyses indicated above. The literature analysis identified potential global sea level rise scenarios that have a viable scientific basis. It was decided to carry out research for three scenarios: global sea level rise of 0.866 m, 1.064 m, and 2.024 m.

### 3. Results

#### 3.1. Chosen Available Data Sources

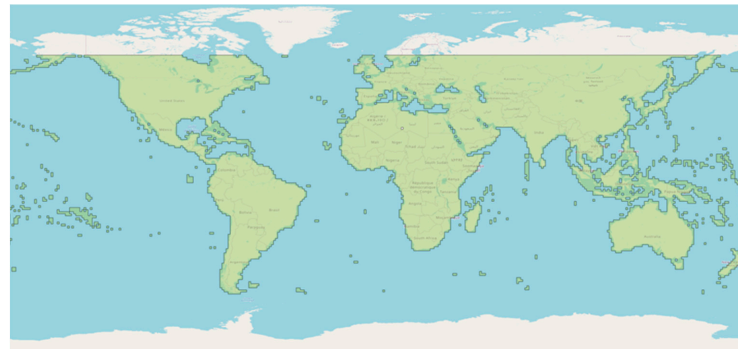
The following analysis allowed for the selection of three DEM data sources: SRTM 1 Arc-Second Global, EU-DEM v1.1, and Polish DEM.

The Shuttle Radar Topography Mission (SRTM) was an international mission conducted by the space agencies of the United States (NASA), Germany (DLR), and Italy (ASI) to collect data from the Endeavour space shuttle to develop a Digital Elevation Model of land located from 56° S to 60° N. The result of this mission is the successively published DEM, from 2001 to 2004, commonly known as SRTM. This was the first mission of its kind to provide such a DEM with this level of detail and uniform in accuracy for nearly 80% of Earth. The SRTM mission was the first time a single-pass radar interferometry method was used to acquire DEM from the Earth’s orbit [51,52]; it was a milestone in the field of remote sensing and was described as the most dramatic advance in cartography since Mercator [53]. The SRTM featured two synthetic aperture radars, C radar (C band system, from NASA’s Jet Propulsion Laboratory) and X radar (X band system, DLR’s Astrium). The goal of C radar was to generate contiguous mapping coverage, and X radar generated data along discrete swaths 50 km wide [51].

The spatial resolution for basic SRTM DEM is, depending on latitude, from 1 arc-second (30 m at the equator) to 3 arc-seconds (90 m at the equator).

Digital elevation models are arranged into tiles, each covering one degree of latitude and one degree of longitude, named according to their southwestern corners. “SRTM 1 Arc-Second Global” dataset provides elevation data with worldwide coverage of data at a resolution of 1 arc-second (30 m) and open distribution of this high-resolution global dataset (some tiles above 50° north and below 50° south latitude are sampled at a resolution

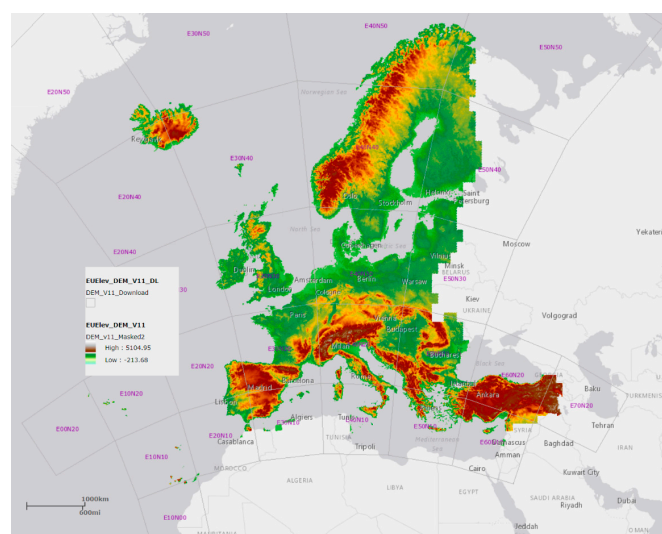
of 2 arc-second by 1 arc-second). Data were obtained from the “Earth Explorer” service of the United States Geological Survey (USGS) website [54]. Access to the data is free, and only a free registration on the site is required. The spatial coverage of tiles available for download is shown in Figure 3.



**Figure 3.** The spatial coverage of tiles available for download in SRTM. Source: USGS—EarthExplorer [54].

European Digital Elevation Model EU-DEM v1.0 is a digital elevation model of European Environmental Agency (EEA) countries (EEA member countries—Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, and United Kingdom; cooperating countries—Albania, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia, and Serbia). The EU-DEM is a hybrid product based on Shuttle Radar Topography Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM); data were fused by a weighted averaging approach. The EU-DEM v1.1 is a resulting dataset of the EU-DEM v1.0 upgrade. A number of properties were upgraded, for example, geo-positioning and vertical accuracy. EU-DEM v1.1 upgrade was coordinated through the Copernicus program [48].

EU-DEM v1.1 is available in GeoTIFF format; the dataset is divided into  $1000 \times 1000$  km tiles, at 25 m resolution with vertical accuracy:  $\pm 7$  m. The spatial coverage of tiles available for download is shown in Figure 4.



**Figure 4.** The spatial coverage of the tiles available in EU-DEM v1.1, along with a preview of the data. Source: EU-DEM v1.1—Copernicus Land Monitoring Service [55].

DEM data download service is available through the Polish Geoportal service; it enables the download of DEM data available in the Polish Central Geodetic and Cartographic Resource (*pol. Centralny Zasób Geodezyjny i Kartograficzny*) [56]. The data are provided in the form of tiles that correspond to the extent to the PUWG 1992 coordinate system at a scale of 1:5000. Text files containing the elevation value of points in a regular grid with a mesh of 1 m were interpolated from the point cloud from laser aerial scanning (LIDAR). The resolution (horizontal accuracy) is approximately 1 m, while the average height error (vertical accuracy) is approximately 0.1 m.

Data are available for free through the Polish Geoportal and are only available for the territory of Poland. The spatial coverage of tiles available for download is shown in Figure 5.



**Figure 5.** The spatial coverage of tiles available for download in Polish DEM. Source: Polish DEM—Geoportal [57].

Analysis of raster data hosting services and accurate data specifications allow for comparison of DEM source parameters for global sea level rise analyses. See Table 4 below for the full technical specifications of the selected DEMs.

**Table 4.** Full technical specifications of the selected DEMs. Source: own elaboration, on the basis of USGS [54], Copernicus Land Monitoring Service [55], and Polish DEM—Geoportal [57].

DEM	SRTM 1 Arc-Second Global	EU-DEM v1.1	Polish DEM
Available data formats	BIL, DTED, GeoTIFF	GeoTIFF	ARC/INFO ASCII GRID
Tile extent—N	~55 decimal degrees	4,000,000 m	718,832 m
Tile extent—S	~54 decimal degrees	3,000,000 m	716,507 m
Tile extent—W	~18 decimal degrees	4,000,000 m	483,740 m
Tile extent—E	~19 decimal degrees	5,000,000 m	485,781 m
Tile size	~1 dd × ~1 dd (approx. 111,700 m × 65,600 m)	1,000,000 m × 1,000,000 m	~2325 m × ~2041 m

Table 4. Cont.

DEM	SRTM 1 Arc-Second Global	EU-DEM v1.1	Polish DEM
Tile area	~7,000,000,000 sqm	1,000,000,000,000 sqm	~4,750,000 sqm
Geographic Coordinate System	WGS 1984	GCS ETRS 1989	ETRS 1989
Pixel type	Short integer	Floating point	Floating point
Pixel depth	16 bit	32 bit	32 bit
Unit	Decimal degrees	Meters	Meters
Horizontal accuracy	~30 m	25 m	~1 m
Vertical accuracy	9–16 m	+/- 7 m	+/-0,1 m
Geodesic cell size	~30.9 m × 35.7 m	25 m × 25 m	~1 × ~1 m

The following raster tiles, covering the case study area, were downloaded from the respective raster data hosting services: SRTM—n54\_e018, EU-DEM—E40N30M, and Polish DEM—a mosaic of 136 rasters, N 54° from 36'15" to 16'15", and E 18° from 58'7" to 20'36". The downloaded raster tiles are presented in Figures 6–8.

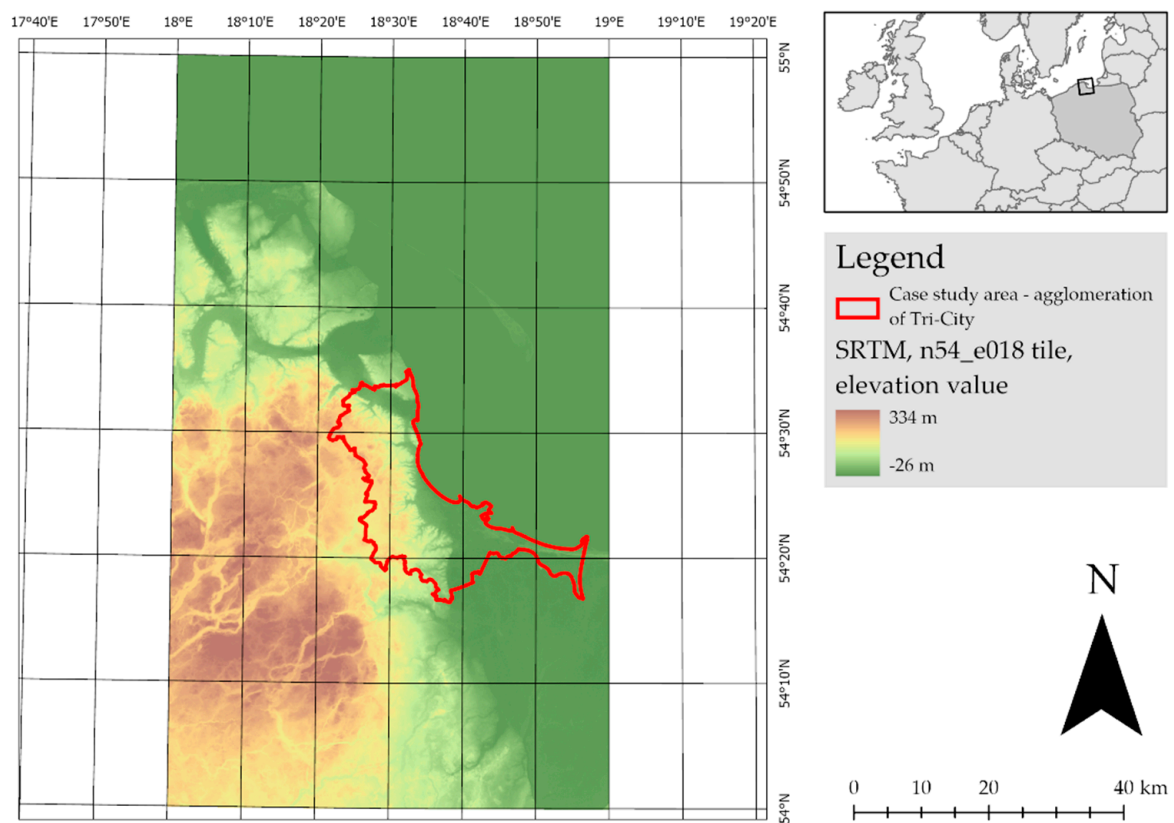


Figure 6. SRTM, n54\_e018 tile. Source: own elaboration, on the basis of USGS [54].

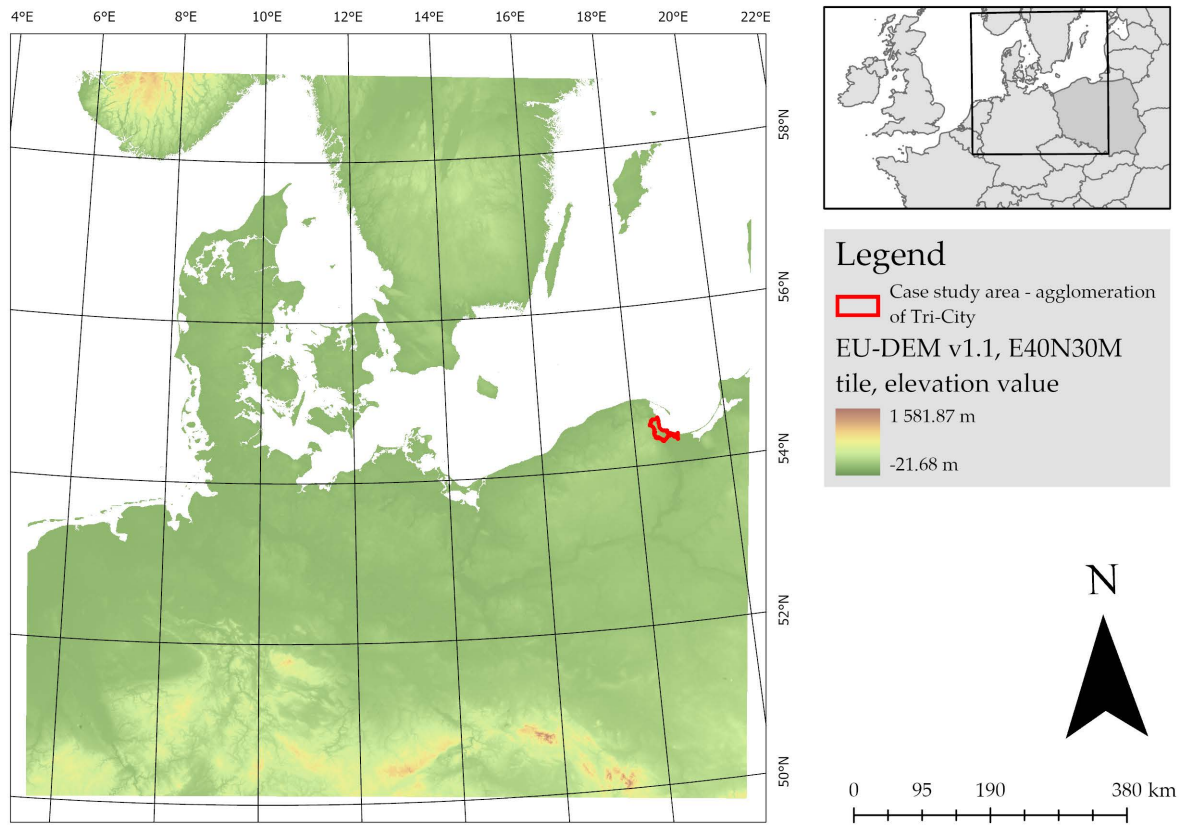


Figure 7. EU-DEM v1.1, E40N30M tile. Source: own elaboration, on the basis of Copernicus Land Monitoring Service [55].

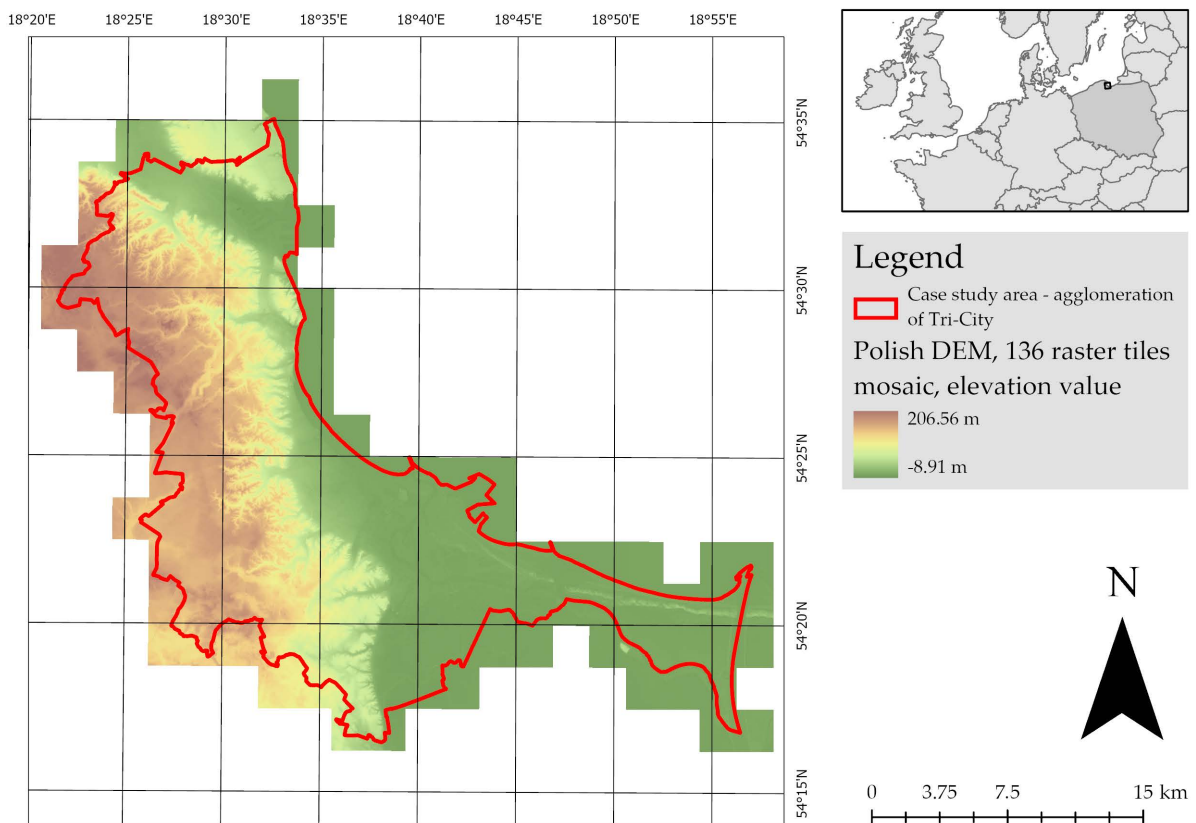


Figure 8. Polish DEM, 136 raster tiles mosaic. Source: own elaboration, on the basis of Polish DEM—Geoportal [57].

The analysis allowed for the comparison of DEM source parameters in terms of global sea level rise analyses, which are presented in Table 5.

**Table 5.** DEM source parameters for global sea level rise analyses, for selected DEMs. Source: own elaboration.

Parameter Group	Data Availability		Data Download		Data Specifications		
	Download charge	Registration	File size	Format	Earth coverage	Horizontal resolution	Vertical resolution
SRTM 1 Arc-Second Global	None	Free registration	Small (~13 MB)	Yes	Incomplete	Above 25 m	Approx. 6–24 m
EU-DEM v1.1	None	Free registration	Large (~6 GB)	Yes	Partial	Above 25 m	Approx. 6–24 m
Polish DEM	None	None	Small (~18 MB)	Yes	Partial	Approx. <1 m	Approx. <1 m

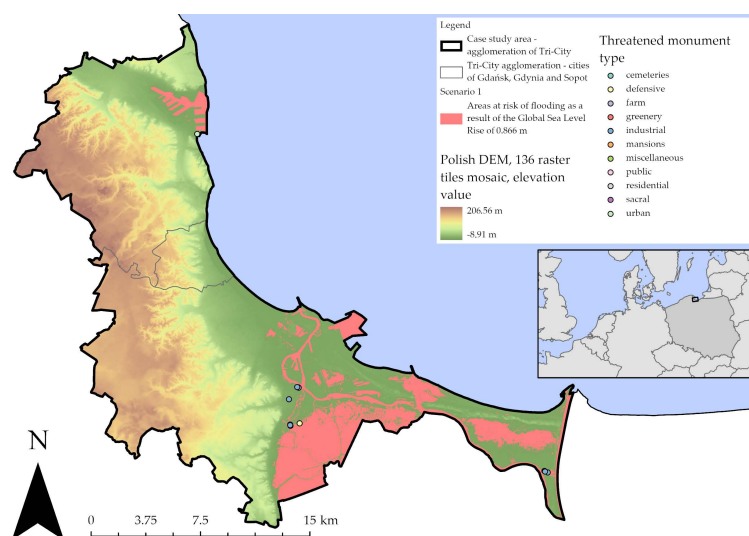
Gray cells indicate best parameter option.

Based on the defined set of parameters that should characterize the DEM data source used for the global sea level rise threat assessment of cultural heritage sites, it was decided that the Polish DEM meets the objectives to the greatest extent. Polish DEM obtained the best score in the Data availability parameter group. The horizontal and vertical resolution of Polish DEM is clearly superior to the other sources, overshadowing the inferior result for Earth coverage. Polish DEM was therefore used in the next stage for spatial analysis using GIS software for the case study area.

### 3.2. Case Study

Out of the analyzed global sea level rise scenarios, three were selected as the basis for the analysis of cultural heritage threats caused by global sea level rise as a result of global warming.

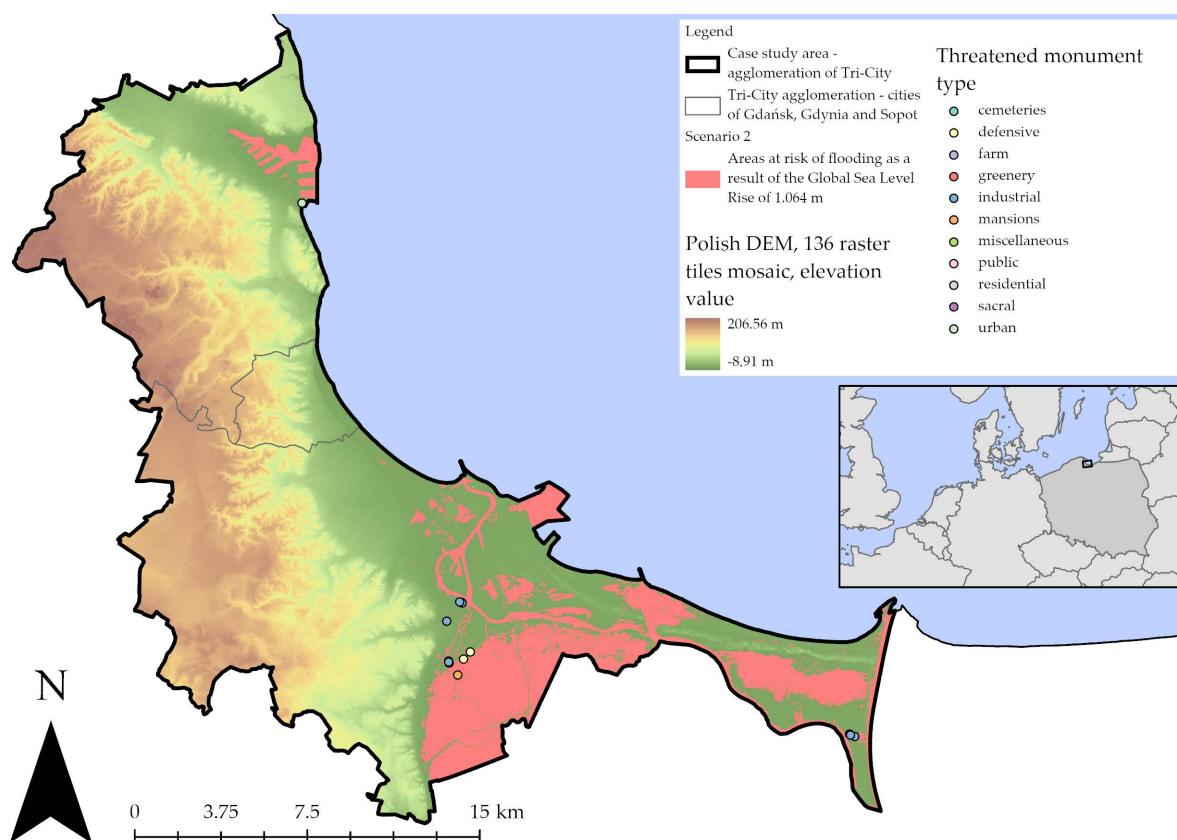
The lowest global sea level rise scenario is the result of the IPCC report marked RCP8.5, and its mean value is 0.842 m. The next one is the result of the NOAA report from 2009, marked B1, and its mean value is 1.04 m. The highest scenario is the result of the 2012 NOAA report and equals 2.0 m. These values, increased by an additional 0.024 m resulting from local GIA and tectonic factors, became the basis for analysis using GIS tools. Figure 9 shows scenario 1 for the year 2100, along with the location of monuments threatened by flooding in this scenario.



**Figure 9.** Global sea level rise scenario 1 for the case study area (the year 2100). Source: own elaboration using ArcGIS Pro 2.7, on the basis of the data from Polish DEM.

The first scenario would not pose a major threat to heritage sites in Tri-City, although even such a small change would carry significant implications. Of Tri-City's total area (approximately 418 sqkm), an estimated 51 sqkm could be at risk of flooding, which is roughly 12% of the agglomeration area; there are 12 cultural heritage sites in the affected area. These are mainly objects derived from the coastal character of historic industrial structures—inclined planes, locks, or canals. Among the threatened monuments is also the Great Mill (pol. Wielki Młyn)—a medieval historic watermill in the Old Town of Gdańsk, built by the Teutonic Order in 1350.

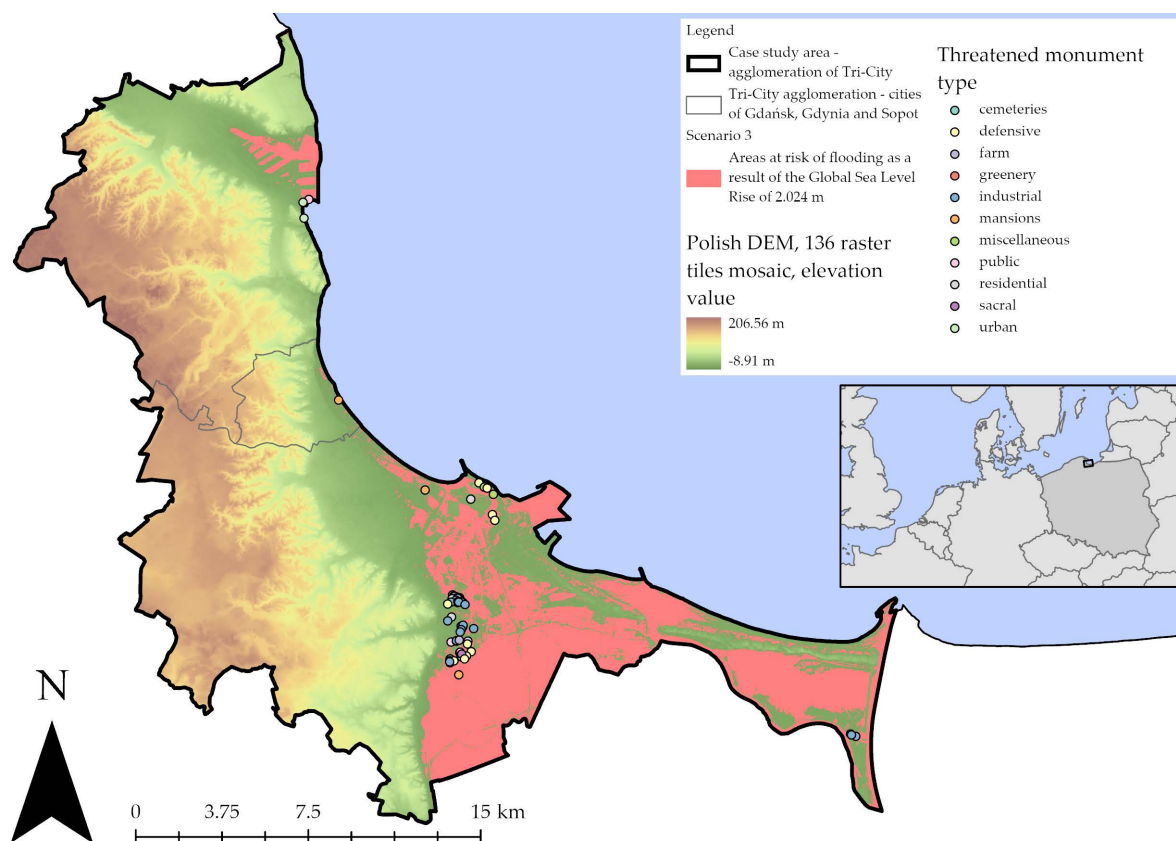
Figure 10 shows scenario 2 for the year 2100, along with the location of monuments threatened by flooding in this scenario.



**Figure 10.** Global sea level rise scenario 2 for the case study area (the year 2100). Source: own elaboration using ArcGIS Pro 2.7, on the basis of the data from Polish DEM.

The second scenario, due to the slight differences in values, resulted in a similar outcome as the first scenario. An estimated 54 sqkm could be at risk of flooding, which is roughly 13% of the agglomeration area. There are 15 cultural heritage sites in the affected area. Three additional objects (from 12 affected by the first scenario) are also objects derived from the coastal character of Tri-City.

Figure 11 shows scenario 3 for the year 2100, along with the location of monuments threatened by flooding in this scenario.



**Figure 11.** Global sea level rise scenario 3 for the case study area (the year 2100). Source: own elaboration using ArcGIS Pro 2.7, on the basis of the data from Polish DEM.

The third scenario (2.0 m sea level rise) could pose a serious threat to the city. Under this scenario, over 75 sqkm of the agglomeration is at threat of flooding, which is almost 18% of the total area. The southern part of the Old Town in Gdańsk (included in the UNESCO Tentative Lists), and thus a total of 79 cultural heritage sites, could be under serious threat. In addition to the sites described for scenarios 1 and 2, many historic buildings may be at risk: Polish Sailor's House (built in 1937), Villa Claaszen in Sopot (1903, one of the most characteristic residences located in Sopot), Historical Monument "Battlefield at Westerplatte" (commemorates the heroic defense of the Polish Military Transit Depot in the Free City of Gdańsk, September 1–7, 1939; the battle is considered a symbolic beginning of World War II), a villa on Sternicza Street 4, tenement on Rybołowców Street 9, Kaiser Shipyard in Gdańsk (ca. 1844, *ger: Kaiserliche Werft Danzig*; one of the first modern shipyards in Germany producing warships); and many other unique cultural heritage sites.

Analysis of threat to cultural heritage sites performed on the case study area of agglomeration of Tri-City was conducted for three scenarios (sea level rise by 0.866 m, by 1.064 m, and by 2.024 m), using ArcGIS Pro 2.7 software. In this way, a series of maps were prepared to show the threats to specific historic sites for various global sea level rise scenarios. The quantitative results of the analysis are presented in Table 6.



**Table 6.** Cultural heritage threats in Tri-City in Poland caused by Global Mean Sea Level Rise as a result of global warming. Source: own elaboration.

Scenario	Global Sea Level Rise	Number of Threatened Non-Movable Monuments	Area Threatened by Flooding	Share of Area Threatened by Flooding in Total Area of Case Study Area
Scenario 1	0.866 m	12	~51 sqkm	~12%
Scenario 2	1.064 m	15	~54 sqkm	~13%
Scenario 3	2.024 m	79	~75 sqkm	~18%

#### 4. Discussion and Conclusions

The research carried out in this article, regarding the potential threats to coastal areas caused by rising sea levels, aligns well with similar analyses conducted around the world [58–60]. Part of these studies focus generally on human-inhabited coastal areas and threats to developed areas, e.g., studies conducted for Mediterranean countries [17,36]; Mombasa, Kenya [1]; and Durban, southern Africa [61]. Among these studies, one can also find studies indicating threats to cultural heritage in, e.g., Venice [15], Scotland [16], Corsica [17], United States [19], France [19], and UK [19,20]. Rising sea levels are a threat to cultural heritage virtually around the world. The research conducted in this article confirms this threat also for the Tri-City in Poland and the cultural heritage objects located there.

GIS application has become an important tool in supporting individuals, businesses, and public authorities in decision-making. The studies also showed the effectiveness of GIS tools in flood risk assessment. GIS analysis allows local authorities to more effectively implement flood risk management by having access to research results showing areas particularly vulnerable to flooding; this allows the authorities to focus their activities on specific areas and sites, which can significantly reduce costs and increase the efficiency of flood risk management activities.

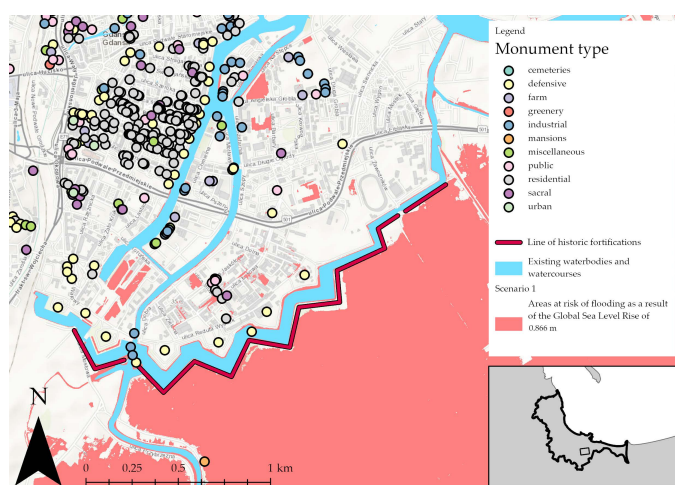
GIS software is a powerful tool that supports the research process in a wide variety of scientific fields [49,62–66], and GIS modeling allows to evaluate changes to the land due to sea-level rise [50]. Access to the relevant spatial data is an extremely important part of many spatial analyses performed in a GIS environment. The multitude of spatial data sources improves the research process, and the quality of geographic data to support flood threat assessment remains a challenge. Some DEM source parameters are more or less universal; however, the relevance of many parameters is directly related to the nature of the study and the needs of the researcher. The increasing digitization of the modern world is systematically increasing the availability of data that can be used for various spatial analyses. Nevertheless, the quality of these data varies. In each case, an important step is to specify the aim of the research. This aim ought to determine the creation of a data framework to match the optimal data source to a given analysis.

The performed analyses allowed to formulate the following conclusions:

- Studies carried out for Tri-City showed that even scenario 1 (sea level rise of 0.866 m) would entail irreversible damage to cultural heritage sites; even such a small change would carry significant implications. An estimated 51 sqkm (of Tri-City's total area of approximately 418 sqkm) could be at risk of flooding, which is roughly 12% of the agglomeration area; there are 12 cultural heritage sites in the affected area. The second scenario, due to the slight differences in values (sea level rise of 1.064 m), resulted in a similar outcome as the first scenario—an estimated 54 sqkm could be at risk of flooding (roughly 13% of the agglomeration area), with 15 cultural heritage sites in the affected area. Objects at risk for the first two scenarios are generally historic industrial structures. The worst-case scenario 3 (sea level rise of 2.024 m) poses a serious threat to the city; under this scenario, over 75 sqkm of the agglomeration is at threat of flooding, which is almost 18% of the total area. Accordingly, 79 cultural heritage sites could be under a serious threat; in addition to the industrial sites for scenarios 1 and 2, many

historic residential buildings may be at risk, as well as the southern part of the Old Town in Gdańsk, included in the UNESCO Tentative Lists. Many other studies show that densely populated areas are particularly threatened by rising sea levels. This study indicates that such threats could also affect cultural heritage sites, which are inextricably linked to the areas where people functioned and lived.

- In this study, the authors focused on analyzing the impact of global sea level rise on cultural heritage as a result of global warming; sea level change along the coast is the sum of eustatic, glacial isostatic adjustment, and tectonic factors. The authors decided to examine whether local GIA and tectonic factors could additionally influence sea level rise scenarios. The studies performed on the case study of the Baltic Sea [37–41] indicate a marginal effect of these factors on sea level rise, resulting in an additional rise of Baltic Sea level of approx. 2.42 cm in a projection for the year 2100. This value was added to the global sea level rise scenarios; however, it represented a very small percentage of the projected sea level: scenario 1—2.8%, scenario 2—2.3%, and scenario 3—1.2%. Studies performed in other parts of the world could show a significantly higher impact of GIA and tectonic factors, as shown by studies such as on the Mediterranean coast [36].
- Spatial analyses performed at the local scale typically rely on local data sources. This is confirmed by the case study carried out in the article. For global-scale analyses, where the level of detail is usually not as high, sources with a larger or even global scope may be more useful.
- Over the course of the research, the authors noticed an interesting phenomenon. Historic fortifications that originally served primarily as defenses against invaders today can provide an important line of defense against rising sea levels. Such is the case in Gdańsk, where the historic defensive walls of the Old Town can, in scenarios 1 and 2, protect the area from flooding. The specificity of defensive structures is the fact that they were raised on embankments or hills (often artificially elevated), additionally accompanied by moats. The authors noted that such topography may be an additional protective element for areas threatened by flooding as a result of the global sea level rise. This is shown in more detail in the following Figure 12.
- In the past, communities have coped with climate changes often by migrating [34]. However, while rebuilding a residential home in another location is an acceptable solution, it is impossible to restore a historic monument on a new site. Thus, more attention should be drawn to the threats posed by the global sea level rise to areas with cultural heritage sites.



**Figure 12.** Close-up on Old Town in Gdańsk, scenario 1—global sea level rise of 0.866 m. Source: own elaboration using ArcGIS Pro 2.7, on the basis of the data from Polish DEM.

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