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Impact of Climate Change and Other Disasters on Coastal Cultural Heritage: An Example from Greece

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Abstract

Protection of coastal cultural heritage is among the most urgent global priorities, as these sites face increasing threats from climate change, sea level rise, and human activity. This study emphasises the value of innovative geospatial tools and data ecosystems for timely risk assessment. The role of land administration systems, geospatial documentation of coastal cultural heritage sites, and the adoption of innovative techniques that combine various methodologies is crucial for timely action. The coastal management infrastructure in Greece is presented, outlining the key public authorities and national legislation, as well as the land administration and geospatial ecosystems and the various available geospatial ecosystems. We profile the Hellenic Cadastre and the Hellenic Archaeological Cadastre along with open geospatial resources, and introduce TRIQUETRA Decision Support System (DSS), produced through the EU's Horizon project, and a Digital Twin methodology for hazard identification, quantification, and mitigation. Particular emphasis is given to the role of Digital Twin technology, which acts as a continuously updated virtual replica of coastal cultural heritage sites, integrating heterogeneous geospatial datasets such as cadastral information, photogrammetric 3D models, climate projections, and hazard simulations, allowing for stakeholders to test future scenarios of sea level rise, flooding, and erosion, offering an advanced tool for resilience planning. The approach is validated at the coastal archaeological site of Aegina Kolona, where a UAV-based SfM-MVS survey produced using high-resolution photogrammetric outputs, including a dense point cloud exceeding 60 million points, a 5 cm resolution Digital Surface Model, high-resolution orthomosaics with a ground sampling distance of 1 cm and 2.5 cm, and a textured 3D model using more than 6000 nadir and oblique images. These products provided a geospatial infrastructure for flood risk assessment under extreme rainfall events, following a multi-scale hydrologic–hydraulic modelling framework. Island-scale simulations using a 5 m Digital Elevation Model (DEM) were coupled with site-scale modelling based on the high-resolution UAV-derived DEM, allowing for the nested evaluation of water flow, inundation extents, and velocity patterns. This approach revealed spatially variable flood impacts on individual structures, highlighted the sensitivity of the results to watershed delineation and model resolution, and identified critical intervention windows for temporary protection measures. We conclude that integrating land administration systems, open geospatial data, and Digital Twin technology provides a practical pathway to proactive and efficient management, increasing resilience for coastal heritage against climate change threats.

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1. Introduction

Climate change significantly affects coastal zones, posing serious threats to vulnerable natural ecosystems and coastal cultural heritage sites [1]. Sea level rise, storms, and increased water temperatures are among the most prominent consequences of climate change in the Mediterranean basin [2]. Coastal management plays a pivotal role in mitigating these impacts through a range of public policies, including proactive measures and community engagement [3].

Various studies have been carried out investigating the spatial models used to tackle climate change in coastal areas [4,5]. This study investigates the land administration tools and geospatial ecosystems that are currently available in order to combine individual models and various techniques. It also examines how coastal management is implemented in Greece, presenting the key stakeholders and national legal framework. The land administration tools include the Hellenic Cadastre and the Hellenic Archaeological Cadastre geospatial ecosystems, as well as the TRIQUETRA knowledge database—compiled through a newly launched EU-funded initiative that serves as a decision support system (DSS) for effective risk mitigation and site remediation in response to climate change and other natural hazards. As part of the TRIQUETRA project, Aegina Kolona has been selected as a pilot coastal cultural heritage (CH) site to evaluate climate-related threats and natural hazards risk on coastal CH. Tools such as photogrammetry, geophysical surveys, slope stability and seismic analysis, floor risk assessment, and ship-induced waves assessment, along with climate analysis, are adopted into a multi-disciplinary methodology. A new era in spatial documentation has begun, and initiatives should take advantage of the new opportunities that have emerged.

The article is structured as follows: Section 2 focuses on the policies and actions adopted by international organisations to tackle climate change and protect coastal areas and coastal cultural heritage in particular. Section 3 analyses how coastal zone management and land administration is applied in Greece. The legal framework and the role of responsible authorities in spatial data collection and management are presented. The Section 4 emphasises the role of land administration ecosystems in coastal CH protection. Land administration geospatial ecosystems such as the Hellenic Cadastre, the Hellenic Archaeological Cadastre, Open Data, and other open data available for coastal CH management are presented. The section also highlights the role of Digital Twins and photogrammetric methods in coastal land administration and CH management that are incorporated in the TRIQUETRA tool. Finally, a flood risk assessment scenario under extreme events is applied on the coastal CH site of Kolona on the Aegina Island in Greece. The results are presented in the Section 5. The discussions of the current research are given in the conclusion to this article.

2. Literature Review—International Trends

Climate change constitutes the greatest threat to coastal areas and coastal CH worldwide. As a result, many governmental and non-governmental organisations, the European Union, and independent relevant authorities are taking action, introducing land policies and measures to tackle this challenge. Climate change has significant implications for the various coastal ecosystems that are highly vulnerable to environmental fluctuations [6], such as sea level rise, storms, and storm surges, as well as saltwater intrusion, increasing water temperatures, broader alterations in the hydrological cycle, and ocean acidification [7]. It is estimated that, by 2100, coastal flooding will affect 360 million people worldwide, while sea level rise remains one of the most significant consequences for low-lying coastal zones. Storm surges already affect millions of people every year [8].

The EU policy framework, aimed at addressing the impacts of climate change on coastal areas, includes specific directives such as the Floods Directive and the Marine Strategy Framework Directive. It also encompasses instruments relevant to enhancing the climate resilience of coastal areas, such as Integrated Coastal Zone Management (ICZM) and Maritime Spatial Planning (MSP). The 2021 EU Strategy for Adaptation to Climate Change also places a strong focus on coastal zones [9]. Furthermore, the Union for the Mediterranean (UfM) and the European Centre for Medium-Range Weather Forecasts (ECMWF) have joined forces to support Mediterranean countries and regional partners in addressing the challenges posed by climate change [10].

From this perspective, the protection of coastal CH is of critical importance. UNESCO, the specialised agency of the United Nations responsible for promoting collaboration in education, science, and culture, has adopted specific instruments for CH safeguarding. The gap left by the 1972 Convention concerning the Protection of the World Cultural and Natural Heritage was eventually addressed by the 2003 Convention for the Safeguarding of the intangible CH [11], which introduced an integrated approach to environmental preservation and sustainable development. At its 29th session in 2005, the World Heritage Committee recognised that climate change impacts are already affecting many natural and cultural world heritage properties and are likely to impact many more in the future. Consequently, in 2006, UNESCO in collaboration with nearly 50 experts on climate change and world heritage, published the report 'Predicting and Managing the Effects of Climate Change on World Heritage' along with a 'Strategy to Assist States Parties to Implement Appropriate Management Responses'. This publication [12], which included various case studies on climate change and world heritage, contains a dedicated section focused on marine biodiversity. Venice and its lagoon were given as a unique example at risk due to sea level rise in the Mediterranean Basin. However, Venice is not the only case. Mourtzas and Kolaiti [13] have explored the emerging threat posed by sea level rise to the iconic UNESCO archaeological site of Delos in the Cyclades, Greece. Their research presents projected flooding scenarios that may affect the island as early as 2150.

Research on the preservation of coastal CH is structured around three pillars. The first pillar focuses on the phenomenon of climate change—its origins [14], impacts [15], and the policies adopted by countries to mitigate it and sustain coastal ecosystems [6]. The second pillar investigates the conceptual framework of coastal management, as derived from the background guidelines of Agenda 21 (United Nations Conference on Environment and Development, UNCED). The third pillar examines the national legal frameworks governing coastal areas [16]. Having examined the first pillar, the following section explores the remaining two pillars to present a holistic approach to coastal management in relation to coastal CH in Greece.

The three-year TRIQUETRA Horizon Europe project (2023–2025) developed a technical toolbox and a methodological framework for assessing and mitigating climate change risks and natural hazards threatening CH in the most efficient way possible [17,18]. This is actually a decision support system for risk identification, quantification, and mitigation concerning endangered CH sites across Europe. It takes its name from the concept of a "trifecta" approach to cultural heritage risk management, reflecting its focus on three interconnected steps: risk identification, risk quantification, and risk mitigation.

3. Coastal Zone Management and Administration in Greece

3.1. General Overview

Integrated coastal zone management (ICZM) was first established in the United States during the 1970s through the enactment of the Coastal Zone Management Act by Congress in 1972 [19]. The core principles of this legislation were later incorporated into Agenda 21, the global action plan for sustainable development adopted in June 1992 at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro. Agenda 21 emphasises the conservation, sustainable development, and rational use of marine and coastal resources. In particular, Chapter 17 of this document—entitled 'Protection of the oceans, all kinds of seas, including enclosed and semi-enclosed seas, and coastal areas and the protection, rational use and development of their living resources'—explicitly calls upon coastal states to adopt appropriate national measures and mechanisms to ensure the effective implementation of these objectives [20].

During the same period, the coastal states of the Mediterranean region initiated cooperative efforts aimed at protecting this semi-enclosed sea. In 1975, the Mediterranean Action Plan (MAP) was adopted as a multilateral environmental agreement in the context of the Regional Seas Programme of the United Nations Environment Programme (UNEP) [21]. In 1976, the Convention for the Protection of the Mediterranean Sea Against Pollution was adopted. This Convention was signed by 21 Mediterranean countries, including Greece, as well as the then European Economic Community (EEC), and was entered into force in 1978.

In 1995, the contracting parties amended the Barcelona Convention, renaming it the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean [22]. The revised convention, accompanied by seven protocols that have been adopted and annexed to it, constitutes the primary regional legally binding Multilateral Environmental Agreement (MEA) in the Mediterranean region.

One of these protocols is the Protocol on Integrated Coastal Zone Management in the Mediterranean (ICZM Protocol), which provides a common legal framework for the promotion and implementation of ICZM across the region [23]. It was signed in Madrid in 2008 and entered into force in March 2011. Among its key obligations, Article 8 of the ICZM Protocol highlights the need for delineation of the coastal zone as a fundamental responsibility of the states that are party to the protocol.

3.2. State Agencies Involved in Coastal Zone Management and Available Geospatial Data in Greece

Greece's shoreline is 13,676 km long—the longest in the Mediterranean basin and one of the longest in the world [24]—and its management relies on the availability and effective use of geospatial data, which is collected, maintained, and distributed by a wide range of state authorities, agencies, and research institutions. This data includes critical information such as the high sea level line, land use classification polygons, protected land polygons, infrastructure, population statistics, socio-economic parameters, and environmental indicators related to climate change and natural processes.

Law 5092/2024 aims to modernise the management of the country's legal coastal zones, with a focus on ownership status, environmental protection, and the sustainable development of such areas. The law retains the legal definitions of the seashore area, defined as the area between the shoreline and the high sea level line, while introducing a transparent digital procedure for the concession or transfer of simple land use rights over the seashore areas [25]. It also establishes clear regulations, obligations or responsibilities, and restrictions for the land use right holders, particularly regarding ensuring unhindered public access, environmental safeguards, and the safety of bathers. Furthermore, the legislation provides for citizen oversight and complaint mechanisms through the use of platforms and digital technology, alongside inspections carried out by state and municipal authorities. It also introduces strict fines and criminal sanctions for violations [26].

In the domain of natural environmental protection, the current legal framework identifies parts of the seashore that are classified as "areas of high-protection where no interventions are allowed", known as "untouched beaches". These are parts of the seashore of exceptional natural beauty, ecological, or geomorphological value, identified with the contribution of the Natural Environment and Climate Change Agency. A total number of 238 of these highly protected areas have been included in the Natura 2000 network [26].

The Hellenic Cadastre geospatial ecosystem provides data related to the shoreline, the high sea level line, and the coastal buffer, which is a legal boundary line parallel to the high sea level line, usually of 10 m width, as well as cadastral maps, property boundaries, and land use classifications, through its WebGIS platform [27].

The Ministry of Environment and Energy is responsible for spatial and urban planning, offering data on Urban Control Zones, General Urban Plans, and Local Spatial Plans [28]. On geodata.gov.gr, open access is provided to Natura 2000 maps, in collaboration with the Natural Environment and Climate Change Agency, which manages additional datasets concerning protected areas, biodiversity, and zoning within Natura sites [29].

The Hellenic Ministry of Culture provides spatial and attribute data on archaeological sites, the CH protected zones, and their buffer zones, the immovable individual monuments, the underwater CH sites, and the state land that was acquired by the Greek state for archaeological purposes [30].

The Hellenic Statistical Authority offers spatial data on population distribution and economic activities in coastal areas, which are essential for planning sustainable development strategies [31]. The Hellenic Navy Hydrographic Service maintains nautical charts, bathymetric data, and coastal mapping, which are vital for port infrastructure and coastal morphology studies [32].

The National Observatory of Athens, through its Geodynamic Institute, provides datasets on shoreline changes, coastal erosion, and dynamic climate change models [33]. Similarly, the Hellenic National Meteorological Service supplies climatological and meteorological data for the coastal zone, including wind patterns, wave activity, and sea level monitoring [34].

Institutes of the Hellenic Centre for Marine Research contribute valuable oceanographic data, including water quality, pollution levels, and marine biodiversity, through advanced platforms such as the POSEIDON system [35].

The National Geospatial Data Infrastructure Portal (geodata.gov.gr) serves as the central platform for geospatial data distribution in Greece, in line with the EU INSPIRE directive. It aggregates datasets from dozens of public bodies and supports open access to spatial information [36].

In addition, universities and research centres generate thematic geospatial data within the framework of various research projects, which are often available through institutional repositories or specialised geoportals.

Finally, municipalities and regional authorities produce and manage geospatial data related to land use, local infrastructure, and more. They also operate their own geoportals to support planning and decision-making at the local level.

The complexity and diversity of all stakeholders that are active in the coastal land management and their produced geospatial data underscore the importance of interoperability, coordination, and data integration to ensure efficient and sustainable coastal zone management in the context of climate change adaptation, as well as a timely and effective response to natural disasters.

As the phenomenon is extended, many other countries that face similar challenges due to climate change in the Mediterranean basin fund and cooperate with various institutions on a national, regional, or local scale. For example, in Italy, several official institutions are actively involved in the collection, processing, and dissemination of geospatial data related to climate change. The Italian Institute for Environmental Protection and Research (ISPRA) operates a national geoportal offering spatial datasets on temperature anomalies, precipitation trends, hydrological balance, and drought indices [37]. The Euro-Mediterranean Center on Climate Change (CMCC) consists of the Institute for the Earth System Predictions, the Institute for Climate Resilience, and the European Institute on Economics, maintains climate data, and has developed forecasting and data visualisation systems [38]. ENEA, the national agency for energy and sustainable economic development [39], takes initiatives particularly through the CoCliCo coastal climate services [40]. The ARPA agency (Agenzie Regionali per la Protezione Ambientale) is also involved on a regional scale [41]. Collectively, these entities provide a robust framework for spatial monitoring climate dynamics across diverse Italian ecosystems and administrative levels. Respectively, in France and Spain, several national research and governmental agencies are actively involved in collecting, analysing, and publishing geospatial data for monitoring, understanding, and mitigating the impacts of climate change, specifically in coastal zones.

4. Land Administration Tools and Geospatial Ecosystems

Land administration refers to the process of documenting and storing information about land ownership, value, and use [42], while systems refer to the technical framework that supports these functions. In other words, land administration is defined as the process of determining, recording, and disseminating information about the tenure, value, and use of land when implementing land management policies, while LAS are the basis for conceptualising rights, restrictions, and responsibilities related to people, policies, and places [43].

Geospatial Ecosystems—a relatively new term in this context—emphasise the interaction among various geospatial systems [44]. These geospatial ecosystems play a critical role in securing land tenure, which can be dramatically affected by climate change and natural disasters. In addition, available information about the ownership and responsibility status of each land parcel may easily support the compilation of a disaster risk reduction plan, e.g., for the planning of concrete actions, streamlining budgets, and enacting available personnel and equipment. This section presents in detail the LA geospatial ecosystems that have been implemented in Greece, outlining their potential role in the protection of coastal CH.

4.1. Land Administration and Geospatial Ecosystems

4.1.1. The Hellenic Cadastre

The Hellenic Cadastre was instituted in 1995 and plays a pivotal role in land management, providing accurate information on legal, technical, and other regulatory aspects on real estate under the responsibility and guarantee of the state [45]. The implementation of the Hellenic Cadastre is a long-term project of significant importance for the sustainable development of the country, and, despite significant delays [46], the project has reached its final stage of completion. The new land administration system is a systematic and on-going title registration information system in fully digital form under the responsibility of the Hellenic Ministry of Digital Governance, responsible for both the collection of all necessary geospatial information concerning land parcels and the registration of all legal rights on them as attribute documentation. More specifically, the Hellenic Cadastre records the land parcels (geolocation, addresses, shape, boundary nodes, and size) and attribute information about each real property (rights, restrictions, right holder's data, etc.) and registers all transactions that create or modify rights, restrictions, and responsibilities on them [47]. It covers the whole jurisdiction of Greece, guarantees land tenure, and provides all necessary geospatial information openly. As a consequence, it may effectively protect the coastal zones and coastal CH by providing exact geolocation information, as well as information about who has the ownership, the responsibility, or any other rights on each CH land parcel (Figure 1).

Figure 1. Registration of the Shoreline is presented in blue, seashore is shaded in red, high sea level line is presented in red, and the coastal buffer line is presented in yellow. Source: Hellenic Cadastre [48].

By law, the seashore area from the shoreline up to the high sea level line in Greece is state-owned land, meaning that its ownership cannot be transferred. It can be accessed and used freely by the public, unless rights to use (for regulated specific uses) are commissioned by the state to the private sector or municipalities. Such rights include rental rights to use the land and the sea for the creation of private beaches, fisheries, shipyards, etc. The delineation of the high sea level line is a mandatory process during cadastral surveying, as it constitutes an administrative act aimed at defining the boundary line between the state land and the private land parcels that may exist in the coastal zone. This process facilitates the formal legal documentation of state-owned assets while ensuring the effective management of the coastal zone and the protection of its vulnerable seashore ecosystems. The procedure for high sea level line delineation is governed by Law 5092/2024, which is currently in force.

The definition and registration of the high sea level line and its delineation in the cadastral records and diagrams follow a clearly regulated procedure. The seashore parcels are registered as state-owned property and are marked by polygonal features in the cadastral system, organised across separate, thematically structured layers. Figure 1 shows the seashore area shaded in red and the high sea level line polygon marked in red, based on the ratified diagram. A "coastal buffer" of 10 m width, parallel to the high sea level line towards inland, marked in yellow, is also shown. This coastal buffer may be private land, unless part of it is expropriated by the state for the construction of public works, such as roads, etc. The width of this buffer may vary according to the needs of each region.

The cadastral office is responsible for issuing updated cadastral documents, reflecting any adjacent properties that are affected by the delineation. The archaeological sites located within the seashore zone are displayed in the Hellenic Cadastre as state assets belonging to the Hellenic Ministry of Finance.

4.1.2. The Hellenic Archaeological Cadastre

The Hellenic Archaeological Cadastre (HAC) is a relatively new land administration system in service of CH protection and preservation. The project was launched in 2011 by the Hellenic Ministry of Culture, and it is in full operation currently by the responsible Directorates and Ephorates of Antiquities as well as the citizens. The project builds upon previous initiatives, such as the "Polemon" a registry system of the 1990s and the "Permanent list of Monuments". The HAC is based on the systematic collection, coding, and recording of data and metadata, spatial localization and visualisation, storage, and management in a database management system of archaeological sites and historic sites, including their buffer zones and sites of natural beauty, as well as underwater archaeological sites, immovable monuments from prehistoric to modern times, and state-owned land, such as private parcels and buildings, which are expropriated, purchased, or donated for archaeological reasons [49].

The HAC is constituted of an integrated information system accessible to the civil servants who collect, update, and store the relevant data and a Web Portal where data is displayed on a map, and it is open to everyone. In order to work properly, the HAC used the orthophotos provided by the Hellenic Cadastre as basemaps, and it is under discussion so that the two different systems can interoperate. Also, the data centre will be transferred to G-Cloud provided by the Ministry of Digital Governance, ensuring that its security is guaranteed.

The HAC represents a critical digital tool that supports the rational management and protection of coastal cultural heritage, underwater archaeological sites, and shipwrecks, while simultaneously contributing to effective spatial planning, infrastructure development, and investment decision-making. The new LAS filled the existing gap of missing information, fragmentation of data, and outdated surveys that no longer meet the standards for spatial documentation. It may also support various scenarios for anticipated catastrophic hazards due to climate change by providing accurate, georeferenced data on coastal and off-shore archaeological sites.

The first example (Figure 2) shows the map of Greece with all registered CH parcels in the HAC; it is clear that a great number of those are located within the coastal areas, with some of them in areas characterised as vulnerable to climate change events and hazards. The second example shows the region of South Attica (Figure 3), indicating the island of Delos, a UNESCO-nominated coastal archaeological site which will face significant challenges by 2050 due to sea level rise in the Mediterranean basin (Figure 4). The extract provided by the Web Portal contains valuable information about the boundaries of the archaeological site and the relevant acts. The authorities may act proactively by applying models in order to face the challenges that will occur in a few years. The boundaries of the sites are given in great accuracy, so amendments due to sea level rise may be monitored in detail, and technical works may be applied in order to protect the specific areas.

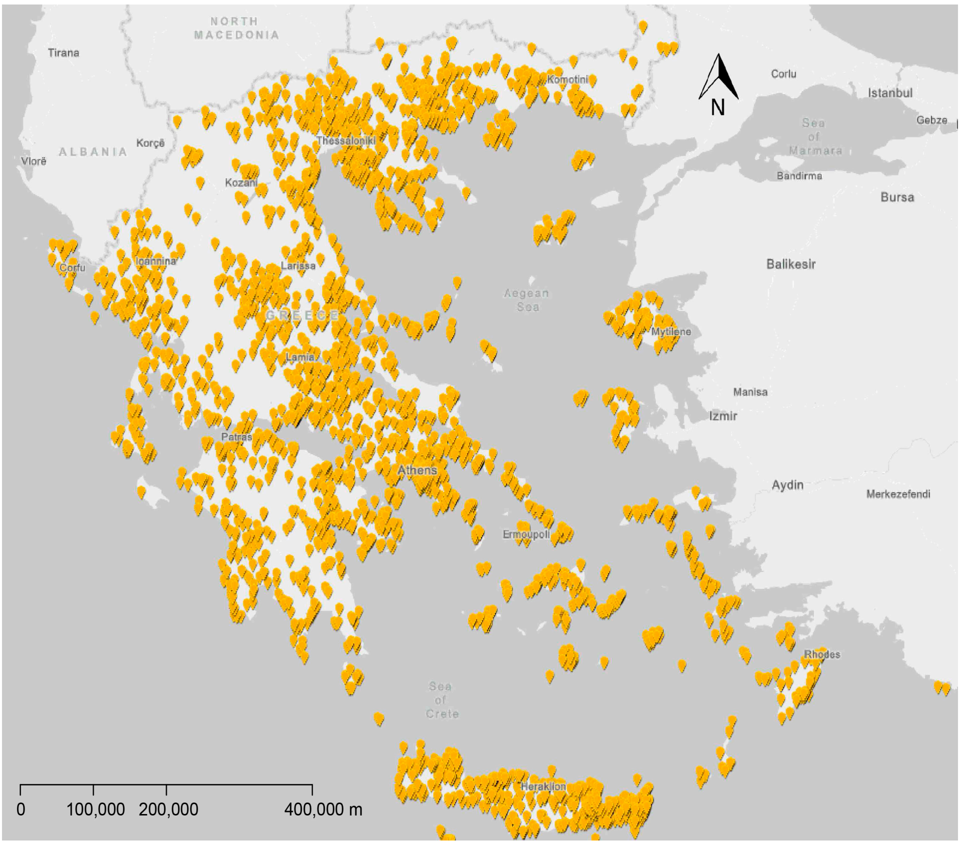

Figure 2. The map of Greece with all registered CH parcels in the HAC [50].

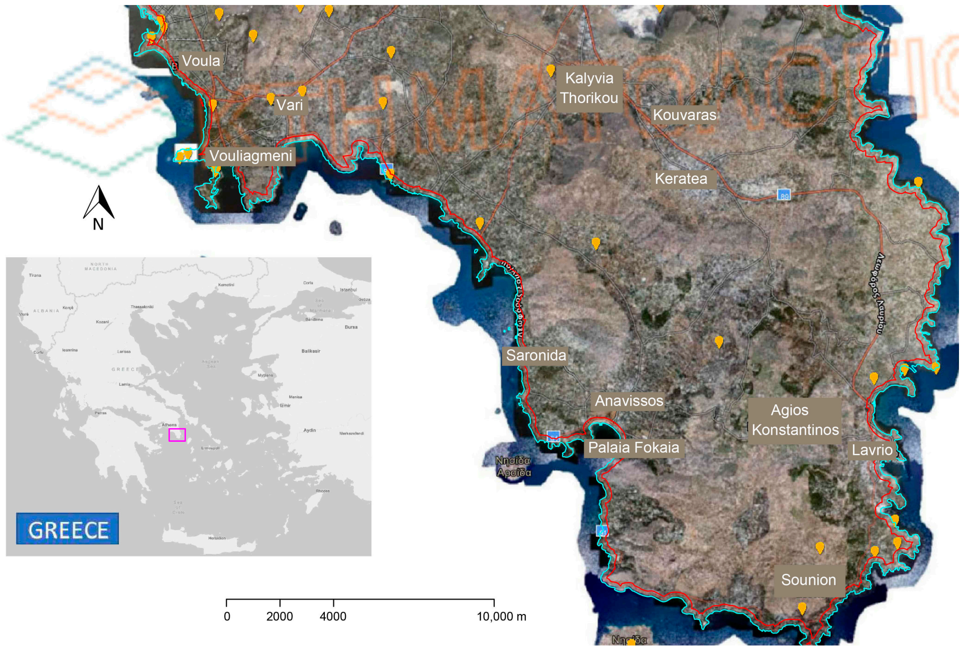

Figure 3. The registered CH parcels in the South Attica region, close to Athens [50]; shoreline in blue, 200 m buffer in red. The map was created using the orthophoto of the official mapping agency "Ktimatologio S.A".

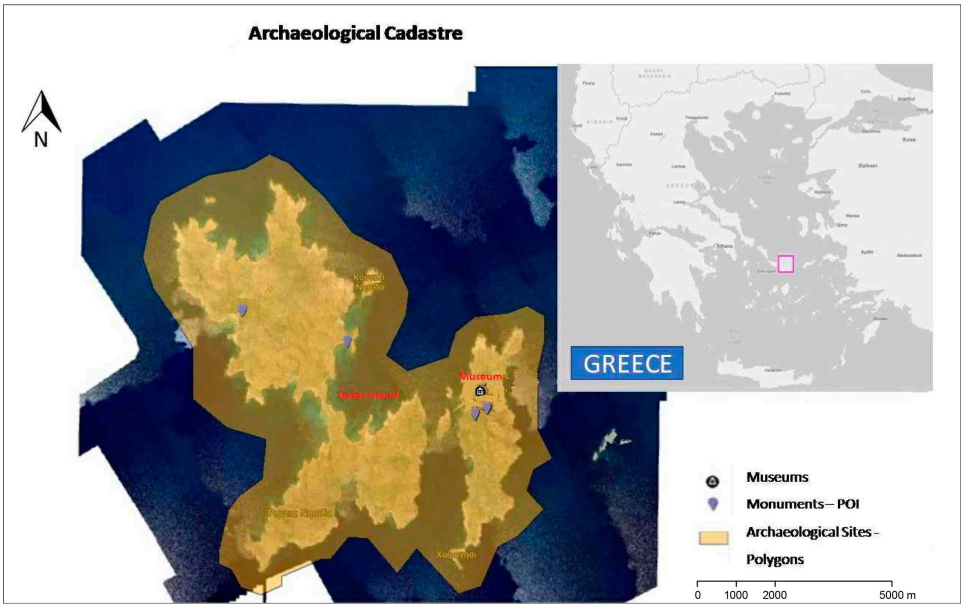

Figure 4. The archaeological site of Delos, nominated as a UNESCO World Heritage Site [50]. The boundaries of the archaeological site are given in yellow. The extract of the Hellenic archaeological Cadastre was created using the orthophoto of the official mapping agency "Ktimatologio S.A" and was modified by the authors.

The fourth example indicates Santorini Island and its cultural resources (Figure 5). The various stakeholders may be easily informed about the archaeological sites located in the area of interest, the zones of protection, and their buffer zones. They may be informed where construction is permitted or where the responsible Ephorate of Antiquities should take action before any excavations.

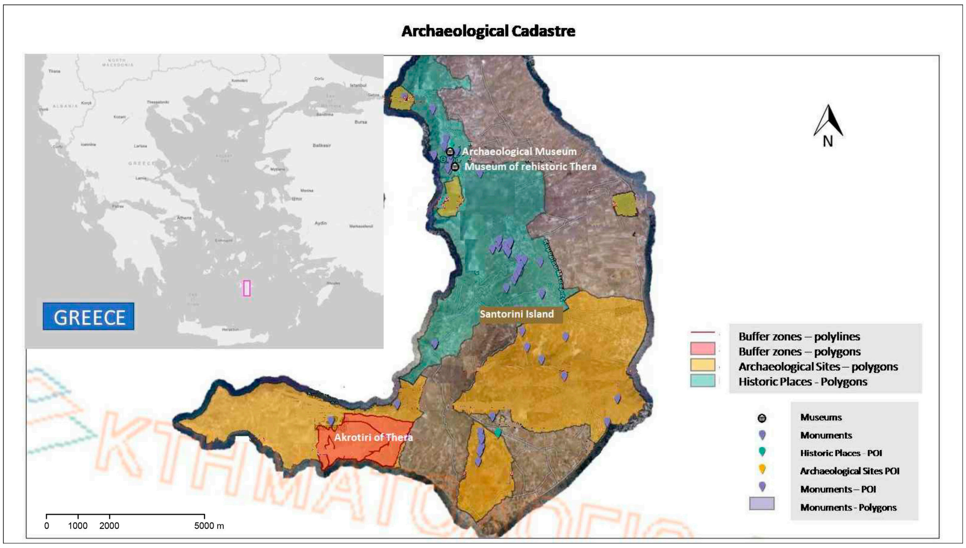

Figure 5. Santorini Island as it is depicted in HAC [50]. Yellow: Archaeological sites; Red: Buffer zones; Blue: Historic places; Purple: Immovable monuments. The extract of the Hellenic archaeological Cadastre was created using the orthophoto of the official mapping agency "Ktimatologio S.A" and was modified by the authors.

To summarise, the LAS establishes a unified, interoperable, and technologically advanced platform that ensures accuracy in the spatial identification and supports coherent and efficient policy implementation.

4.1.3. Open Data and Other Geospatial Ecosystems Available for Coastal Cultural Heritage Management

Beyond the foundational geospatial frameworks provided by the National Cadastre and the Archaeological Cadastre, a broader set of open-access geospatial data sources also plays an important role in supporting coastal cultural heritage documentation and risk management efforts. In recent years, a wide range of open access data sources and geospatial ecosystems has become available through both national and international portals, enabling the application of interdisciplinary approaches in cultural heritage research, risk identification and quantification, climate impact modelling and preservation planning, and, hence, decision support.

As mentioned in Section 3.2, one of the most important Greek open access sources is geodata.gov.gr, which provides open geospatial data and services for Greece, acting as the national open data catalogue, an INSPIRE-compliant Spatial Data Infrastructure (SDI), and a robust platform enabling the development of value-added services based on open data, such as vector and raster data on land use, archaeological zones, shoreline delineations, urban planning boundaries, and more. In addition, the Copernicus programme offers a wide range of thematic datasets through the Copernicus Land Monitoring Service (CLMS), the Copernicus Marine Service (CMEMS), and the Copernicus Emergency Management Service (EMS).

Furthermore, marine-oriented datasets, like those offered by the European Marine Observation and Data Network (EMODnet), the General Bathymetric Chart of the Oceans (GEBCO), and the Global Self-consistent Hierarchical High-resolution Geography Database (GSHHG), provide bathymetric and seabed information, which is useful for underwater and coastal CH documentation. Also, elevation and relief models, such as the Shuttle Radar Topography Mission (SRTM), the Earth Topography and Ocean Bathymetry Model (ETOPO1), and the Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG), offer representation of coastal topography and shoreline morphology. Moreover, climate datasets such as the Coordinated Regional Climate Downscaling Experiment for Europe (EURO-CORDEX), the ENSEMBLES Observation Dataset (E-OBS), and the NASA Sea Level Rise Projections support scenario-based impact modelling, especially when such datasets are integrated in Digital Twin environments.

Satellite imagery, e.g., from Sentinel-2 and Landsat-8, offer long-term Earth observation time series data, allowing for land cover analysis and change detection applications, vegetation monitoring, and more, while the European Ground Motion Service (EGMS) provides precise ground motion measurements from InSAR data, supporting land deformation monitoring near CH sites. Also, OpenStreetMap may offer spatial data of interest for cultural heritage sites, including infrastructure and land use. Additionally, the UNESCO World Heritage List (WHL) provides global references for CH site boundaries and locations.

It should be noted that while most of the above datasets are openly accessible, several other geospatial resources, particularly those maintained by national authorities, are subject to some access limitations. For example, the Hellenic Navy Hydrographic Service (HNHS), the Hellenic Centre for Marine Research (HCMR), the Greek Cadastre, and the Archaeological Cadastre provide valuable spatial data, but access is limited to viewing or requires formal request procedures, with restrictions on reuse and download.

This growing ecosystem of open and semi-open geospatial datasets is a valuable foundation for the development of data-driven workflows in coastal CH documentation and disaster risk management. In this context, disaster risk management refers to the systematic use of such data and digital tools to identify hazards, assess exposure and vulnerability, and support scenario-based analyses for cultural heritage sites. The focus lies on strengthening preparedness, assisting monitoring, and supporting decision-making, providing the necessary evidence base upon which effective adaptation and protection measures can be later designed. Table 1 provides an overview of open and public geospatial datasets relevant for coastal CH documentation and risk assessment, as described in the above paragraphs.

Table 1. Overview of open and public geospatial datasets relevant for coastal cultural heritage documentation and risk assessment.

Dataset Name	Type	Description	Access	Access Link
geodata.gov.gr	National administrative and planning datasets.	National open geospatial portal offering data from various public authorities including coastal boundaries, urban plans, archaeological zones and environmental restrictions.	Open access	http://geodata.gov.gr/ (accessed on 2 August 2025)
Copernicus CLMS	Land cover/use, bio-geophysical variables, ground motion, land satellite mosaics, reference and validation data.	Geographical information on land cover and its changes, land use, ground motion, vegetation state, water cycle and earth surface energy variables for Europe and the entire globe.	Open access	https://land.copernicus.eu/ (accessed on 2 August 2025)
Copernicus CMEMS	Sea level, currents, waves, salinity, temperature.	Marine data and services to enable marine policy implementation and support Blue growth and scientific innovation.	Open access	https://marine.copernicus.eu/ (accessed on 2 August 2025)
Copernicus EMS	Disaster response maps (floods, fires, etc.).	On-demand mapping, wildfires, floods, droughts, exposure mapping.	Open access	https://emergency.copernicus.eu/ (accessed on 2 August 2025)
EMODnet	Bathymetry, geology, seabed use, marine habitats.	EU marine data portal offering bathymetry, seabed, geology and usage datasets.	Open access	https://emodnet.ec.europa.eu/ (accessed on 2 August 2025)
HNHS	Nautical charts, bathymetric data, tide records.	Official nautical data provider in Greece.	Restricted access [1]	https://www.hnhs.gr/ (accessed on 2 August 2025)
HCMR	Marine and coastal research datasets.	Oceanographic data collected from Hellenic public and private organisations as well as data that are being exchanged within the International Network of Oceanographic Data Centres.	Restricted access [2]	https://www.hcmr.gr/en/ (accessed on 2 August 2025)
Sentinel-2	Multispectral satellite imagery.	High-resolution EO imagery from ESA for land cover, NDVI, change detection and coastal monitoring.	Open access	https://dataspace.copernicus.eu/explore-data/data-collections/sentinel-data/sentinel-2 (accessed on 2 August 2025)
Landsat-8	Multispectral satellite imagery.	Long-term EO archive from NASA for environmental monitoring, vegetation analysis and land change.	Open access	https://landsat.gsfc.nasa.gov/ (accessed on 2 August 2025)
Hellenic Cadastre	Property boundaries, legal parcels, zoning plans.	National cadastre platform offering planning and ownership data.	Restricted access [3]	https://www.ktimanet.gr/ (accessed on 2 August 2025)

Table 1. *Cont.*

Dataset Name	Type	Description	Access	Access Link
Archaeological Cadastre	Archaeological protection zones.	Digital registry of legally protected archaeological zones in Greece.	Open access [4]	https://www.arxaiologikoktimatologio.gov.gr/ (accessed on 2 August 2025)
E-OBS Gridded Dataset	Climate observation.	Gridded daily observations of temperature, precipitation, humidity and more across Europe.	Open access	https://cds.climate.copernicus.eu/cdsapp#!/dataset/insitu-gridded-observations-europe?tab=form (accessed on 2 August 2025)
EURO-CORDEX	Regional Climate Models (RCMs).	High-resolution RCMs for future climate scenarios.	Open access	https://esgf-data.dkrz.de/search/cordex-dkrz/ (accessed on 2 August 2025)
NASA Earthdata	NASA's archive of earth science data.	Data related to atmosphere, biosphere, climate indicators, cryosphere, human dimensions, land surface, ocean, solid earth, sun-earth interactions and terrestrial hydrosphere.	Open access	https://www.earthdata.nasa.gov/ (accessed on 2 August 2025)
NASA Sea Level Rise Projections	Sea level projection.	Sea level rise estimates under RCP scenarios.	Open access	https://sealevel.nasa.gov/ (accessed on 2 August 2025)
SRTM	Elevation model.	30m global DEM from NASA's radar mission.	Open access	https://www.earthdata.nasa.gov/data/instruments/srtm (accessed on 2 August 2025)
EGMS	Surface deformation.	InSAR-derived motion measurements across Europe.	Open access	https://land.copernicus.eu/en/products/european-ground-motion-service (accessed on 2 August 2025)
ETOPO Global Relief Model	Relief model (topography and bathymetry).	It integrates topography, bathymetry, and shoreline data from regional and global datasets to enable comprehensive, high-resolution renderings of geophysical characteristics of the earth's surface.	Open access	https://www.ncei.noaa.gov/products/etopo-global-relief-model (accessed on 2 August 2025)
GEBCO	Bathymetry.	Global bathymetric model.	Open access	https://download.gebco.net/ (accessed on 2 August 2025)
GSHHG	Coastline vector data.	High-res vector coastlines, rivers, borders. The dataset is amalgamated from three data bases in the public domain: World Vector Shorelines (WVS), CIA World Data Bank II (WDBII) and Atlas of the Cryosphere (AC).	Open access	https://www.ngdc.noaa.gov/mgg/shorelines/data/gshhg/latest/ (accessed on 2 August 2025)
UNESCO WHL	Cultural heritage locations.	Global heritage site locations.	Open access	https://whc.unesco.org/en/list/ (accessed on 2 August 2025)
OpenStreetMap	Global open geospatial dataset.	Volunteered geospatial data on infrastructure, land use, cultural heritage sites and more.	Open access	https://www.openstreetmap.org/ (accessed on 2 August 2025)

[1] Some coastal datasets are available free upon request via form. However, systematic bulk download as open geospatial formats is not publicly available, and access is conditional. [2] No centralised open access; data shared upon request or via research collaborations. [3] Public viewing only; no download or reuse permissions provided. [4] Web viewer available, but no export or API access to geospatial data.

4.2. Digital Twins

4.2.1. The Potential Role of Digital Twins in Coastal Land Administration and Cultural Heritage Management

The concept of the Digital Twin originated in the fields of engineering and manufacturing, where it was introduced as a means of optimising industrial systems through the creation of virtual replicas that mirror real-world assets in real time [28–51]. A Digital Twin can be broadly defined as a digital representation of a physical asset, system, or process that is updated in real time with data from sensors or simulations, enabling real time analysis, monitoring, and informed decision-making [51,52]. Over time, the application of Digital Twins has expanded beyond industrial domains, finding relevance in areas like urban planning [53], land use planning [54], smart infrastructure monitoring [55], and transportation networks [56]. Recently, the Digital Twin concept has seen important applications in CH monitoring and management [57–65].

In the context of CH and land administration, Digital Twins provide a dynamic tool for integrating datasets of different sources, such as 3D models, sensor inputs, environmental variables and climate projections, structural assessments, simulation models, and cadastral information into a single environment, which may support monitoring and aid in planning preservation and risk mitigation efforts (Figure 6). Such efforts may denote data-informed and heritage-compatible options that a Digital Twin can screen virtually. For example, such mitigation measures could be, indicatively: (i) preventive conservation and site drainage upgrades to manage pluvial runoff; (ii) early-warning thresholds tied to rainfall, wave, or ground motion sensors that provide continuous monitoring data; (iii) operational measures, such as temporary access restrictions and protective coverings, during adverse events; (iv) nature-based coastal protection (e.g., dune or beach nourishment, vegetated buffers) to reduce wave energy; (v) low-impact structural works, where acceptable, such as detached low-crested breakwaters or revetments; and (vi) localised stabilisation of hazardous cliff sectors (e.g., rock bolting, netting) guided by structural mapping.

Particularly in vulnerable coastal areas, where climate change and natural hazards threaten the integrity of CH sites, Digital Twins allow for stakeholders to simulate future scenarios, assess the potential impacts of different kinds of hazards, and, as a result, design intervention strategies for preserving CH. Within a Digital Twin environment, such intervention strategies can be prototyped and compared by simulating their effects on exposure and vulnerability, spanning soft actions (maintenance, drainage, vegetation management, movable barriers) and hybrid/hard options (revetments, low-crested breakwaters, cliff stabilisation), always subject to statutory approval and conservation principles. As an example, a framework is presented in [66] that integrates coastal Digital Twins with a geospatial dashboard, enabling the visualisation of vulnerabilities of critical infrastructures over time, flood risk awareness, and collective decision-making in adaptation plans. Also, Digital Twins can offer a powerful tool for visualising and understanding the complex interactions between the coastal CH assets, their surrounding environment, and evolving risk factors, such as, indicatively, sea level rise, coastal erosion, ship-induced waves, and extreme weather events. For example, a Digital Twin framework enriched with UAV-based photogrammetric outputs and ocean modelling is presented in [67], enabling effective visualisation and analysis of coastal hazards, such as tidal flooding and shoreline erosion.

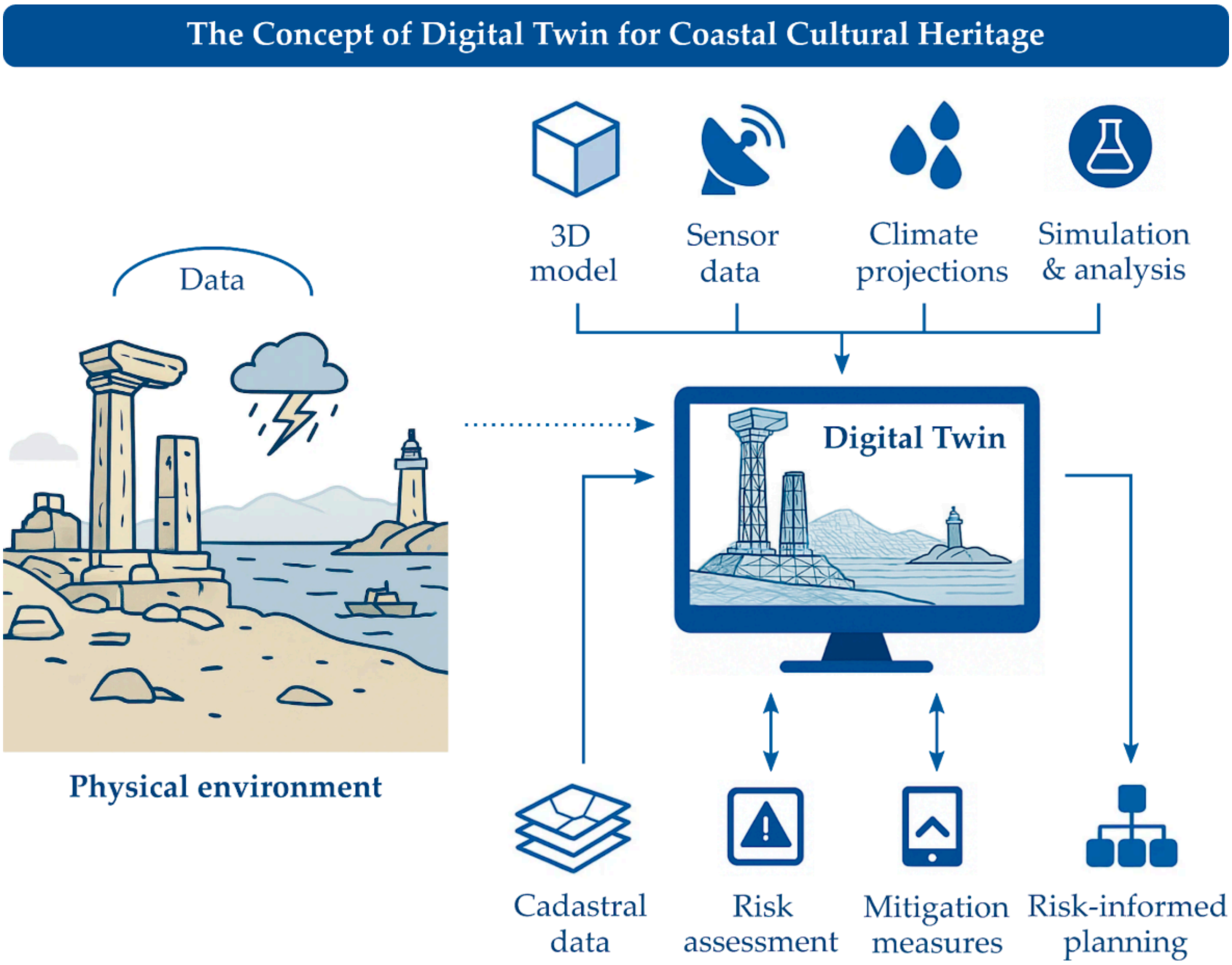

Figure 6. The concept of Digital Twin for coastal CH.

Within the broader land administration ecosystem, Digital Twins can be used as an interface between cadastral data, archaeological records, climate projections, and real time environmental monitoring, providing useful kinds of information concerning the condition and vulnerability of CH sites, aiding decision-making, emergency response, and resilience planning. Operationally, a Digital Twin-enabled workflow translates emergency response and resilience planning into actionable steps. For emergency response, dashboards of Digital Twins can use sensor-driven thresholds (e.g., wave overtopping, rainfall intensity, ground motion, etc.) to auto-trigger temporary access closures, send checklists for cultural-first-aid (e.g., in order to put protective geotextile covers, place sandbag berms, add temporary shoring), and coordinate rapid post-event assessment using a UAV/LiDAR survey to document damages and update the Digital Twin. For resilience planning, the Digital Twin can simulate and compare nature-based options (e.g., dune/beach nourishment, vegetated buffers) alongside low-impact coastal works (e.g., detached low-crested breakwaters, revetments), attempt drainage upgrades for storm runoff, and store trigger–action matrices (who does what, and when) in the site's disaster plan. These practices align with international disaster risk reduction guidance for cultural heritage and with emerging coastal Digital Twin initiatives that focus on early warning, scenario testing, and decision support [68–71].

The advantage of Digital Twins is that they are continuously updated—unlike static records or traditional geospatial tools—and they are capable of simulating future scenarios, facilitating proactive risk management. Moreover, Digital Twins can potentially complement the National Cadastre, the Archaeological Cadastre, and other geospatial ecosystems by providing up-to-date and visually rich representations of cultural landscapes. Their ability to host heterogeneous datasets, ranging from high-resolution point clouds and 3D photorealistic models to sensor data updates and risk indices, can form the basis for a multi-disciplinary approach to CH management, bridging the gap between archaeological, geospatial, and environmental specialties. With this technology, it will be easier for authorities and responsible agencies to act proactively and compile a disaster risk reduction plan and therefore be prepared to act in time and minimise damages. In practice, acting proactively means turning forecasts and sensor thresholds into concrete actions under realistic coastal and pluvial threats. For instance, for coastal flooding and wave overtopping, agencies can set threshold-based early warnings and use them to automatically close access at CH sites [72,73]. Agencies can also pre-position and deploy sandbags or movable flood barriers at vulnerable entrances during events to reduce floodwater ingress [74]. After the event, rapid documentation via UAV photogrammetry and/or LiDAR sensors can update the site's Digital Twin for recovery planning [75,76]. For pluvial flooding, drainage retrofits and water-sensitive urban design (WSUD), such as blue-green measures, can be planned to reduce peak flows and runoff volumes [77,78]. For shoreline change and sea level rise, the Digital Twin can compare nature-based options (e.g., dune/beach nourishment, vegetated buffers) with low-impact coastal works (e.g., detached low-crested breakwaters, revetments) in order to reduce exposure without harming heritage values [79–81]. These actions are consistent with recent Digital Twin frameworks for early warning and decision support in flood and coastal risk management [82]. Of course, the specific selection, design, and implementation of such measures requires specialised site-specific studies that account for local environmental conditions, heritage constraints, and regulatory frameworks.

As an example, in the case of coastal CH management in Greece, and particularly for the archaeological site of Aegina Kolona, such a Digital Twin is under development as part of the TRIQUETRA project [17,18]. The aim is to address the increasing pressure from climate-induced threats by integrating a wide range of risk parameters, including projected sea level rise under different RCP scenarios, coastal flooding, and extreme water hazard events, as well as geophysical threats such as earthquake-induced ground instabilities and ship-induced waves. The Digital Twin in TRIQUETRA integrates diverse spatial datasets and results from photogrammetric documentation, as well as outputs from hydrodynamic and slope stability simulations, geological and geophysical numerical models, and climate projections derived from EURO-CORDEX simulations. As such, this Digital Twin, once its development is completed, may support holistic risk assessment, contributing to informed decision-making for the long-term preservation of the site.

4.2.2. Photogrammetric Methods for 3D Documentation of Coastal Cultural Heritage

Photogrammetric techniques are widely adopted for the 3D geometric documentation of CH sites, as they offer cost-efficient solutions for capturing the geometry of monuments and archaeological sites. In coastal environments, where CH sites are exposed to increased vulnerability due to possible marine erosion, wind, salinity, sea level rise, wave effects, flooding, and climate change hazards, photogrammetric documentation can also support risk assessment efforts through the continuous monitoring and change detection of the cultural heritage structures, as well as the updating of the Digital Twin.

A variety of photogrammetric methods can be employed for the documentation of coastal CH sites, including terrestrial photogrammetry, aerial photogrammetry (most commonly, UAV-based documentation or for larger-scale documentation through manned flights), and underwater photogrammetry for the case of submerged structures and LiDAR (Light Detection and Ranging) surveys (terrestrial or aerial laser scanning), either solely or in combination with photogrammetric campaigns. In most cases, topographic measurements (ground surveys) are also required for georeferencing the photogrammetric outputs. A comprehensive overview of image-based and laser-based 3D modelling techniques can be found in [83].

A well-established photogrammetric workflow consists of the application of a Structure from Motion (SfM)—Multi-View Stereo (MVS) pipeline. The stages that are applied include the process of detection of overlapping images, feature point extraction, image matching and outlier removal [84], feature tracking, image orientation estimation, and sparse point cloud reconstruction through SfM, depth map generation, dense point cloud production, 3D surface reconstruction, and texture mapping [83]. This photogrammetric processing pipeline is applied both in aerial and terrestrial documentation workflows. In the case of aerial surveys, except for the acquisition of nadir images, oblique images are also captured for complete site coverage and vertical structure capture [85], while in terrestrial photogrammetry, images are captured from ground-level perspectives using handheld cameras to record close-range architectural details. In the case of underwater photogrammetry, the same general principles of SfM-MVS are applied; however, specific adaptations are required due to the challenges linked to the aquatic environment, such as the different optical properties of water, light penetration, visibility and suspension, radiometric issues, and environmental drawbacks [86].

LiDAR technologies can also be used for 3D documentation either independently or in combination with the photogrammetric methods. Terrestrial laser scanning and aerial LiDAR surveys offer high-density point clouds and are particularly useful in environments with limited texture (e.g., homogenous surfaces), dense vegetation, or where image matching techniques may fail within a photogrammetric processing pipeline. Laser scanners may be distinguished into four basic categories, triangulation scanners, time-of-flight scanners, phase-shift scanners, and structured light scanners [83], all of which are capable of capturing dense and accurate 3D point clouds. In conventional documentation workflows, a common approach is to combine the LiDAR-derived point cloud with a photogrammetrically generated point cloud. After this point cloud fusion, the combined 3D dense point cloud undergoes a surface reconstruction stage for mesh generation, followed by texture mapping using the images captured during the photogrammetric campaign and oriented through the SfM process. Such a process is illustrated in the diagram in Figure 7.

The choice of method or combination of methods depends on site-specific conditions, the required level of detail of the Digital Twin, the accessibility to the CH site, the available equipment, and the scope of the geometric documentation project. In all cases, photogrammetric approaches remain particularly attractive for Digital Twin models due to their low-cost nature. Unlike high-end laser scanning systems, photogrammetric pipelines can be implemented using consumer-grade cameras, open-source software solutions, and minimal field equipment. In this context, repeatable image acquisition campaigns may be applied, allowing for up-to-date documentation of CH sites for long-term monitoring at minimal cost.

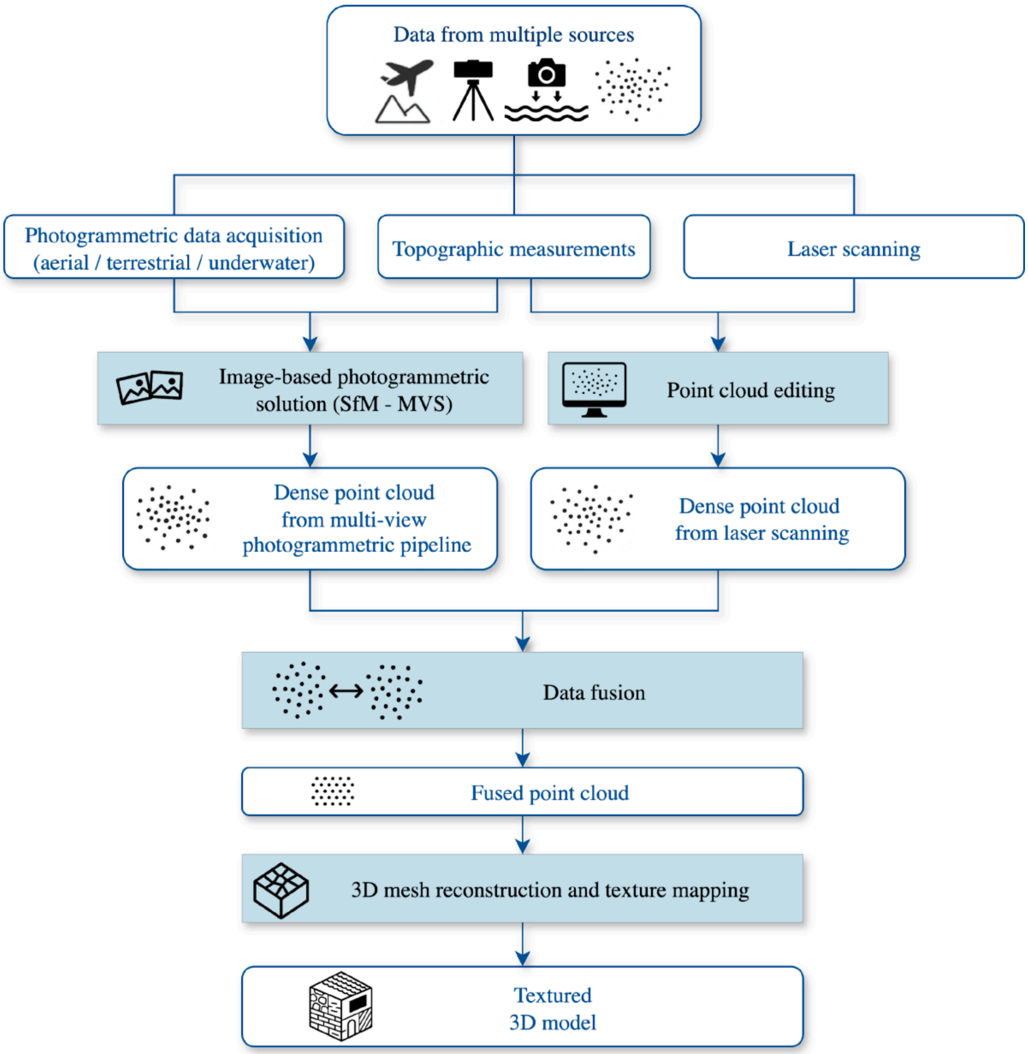

Figure 7. Conventional photogrammetric pipeline for geometric documentation of CH sites, combining image-based and scanner-based acquisition techniques.

5. Case Study: Flood Risk Assessment Under Extreme Events for the Coastal Cultural Heritage Site of Kolona on the Aegina Island, Greece

The archaeological site of Aegina Kolona is located on the island's north-western coast, in the Saronic Gulf, approximately 20 km southwest of Athens. The site lies along a steep coastal cliff and represents one of the most important Bronze Age settlements in the Aegean [87,88]. It was initially developed as a prehistoric acropolis with an inner core and eastern suburbs; it was abandoned around 1200 BC and was reused as a necropolis during the Iron Age. Aegina Kolona flourished through the Archaic and Roman periods and hosted a significant Byzantine settlement between the 6th and 10th centuries AD [89–91]. Excavations have taken place since the 19th century, while extensive restoration efforts started in 2011, mainly to address the progressive degradation of exposed structures, particularly in the western area [92,93]. Figure 8 shows an abstract of the HAC with the Aegina Kolona CH in a red circle, together with all other recorded CH parcels on Aegina island.

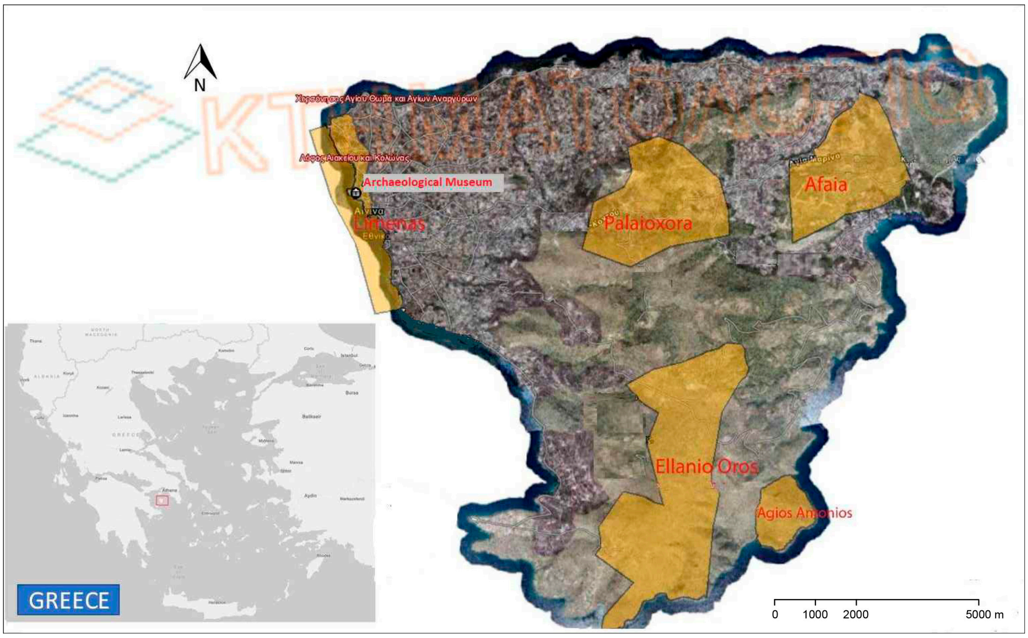

Figure 8. Registered CH parcels in the HAC; the archaeological site of Aegina Kolona is marked by a red circle [27]. The extract of the Hellenic archaeological Cadastre was created using the orthophoto of the official mapping agency "Ktimatologio S.A" and was modified by the authors.

The site is highly vulnerable to environmental hazards such as rainfall-induced floods, marine erosion, wave action intensified by maritime traffic, and poor surface drainage leading to water pooling and damp conditions. Within the TRIQUETRA project, Aegina Kolona serves as a pilot case for assessing climate-related risks and natural hazards to coastal cultural heritage. The TRIQUETRA project applies a multi-disciplinary methodology in the coastal CH site of Aegina Kolona, combining photogrammetry, geophysical surveys, slope stability and seismic analysis, flood risk assessment, and ship-induced waves assessment, alongside climate analysis, to identify and quantify risks and support risk mitigation planning [18,94].

5.1. Photogrammetric Documentation

The photogrammetric survey of the archaeological site of Aegina Kolona was conducted as part of the site documentation activities in the framework of the TRIQUETRA project. A low-cost 3D documentation procedure was followed using commercially available UAV platforms and existing photogrammetric software solutions. The main image acquisition was performed using a DJI Mavic 3 Enterprise drone, which captured 945 nadir images for full-site coverage. In order to accurately document the architectural features of the site, such as walls, slopes, and intricate structural details, an additional dataset of approximately 4900 oblique images was also collected at lower altitudes using the same drone. Furthermore, complementary images were acquired using a DJI Mavic 2 Pro drone, which captured 930 images primarily of the areas surrounding the Kolona.

For the scope of georeferencing, 15 Ground Control Points (GCPs) were measured using a Leica 1200 GNSS receiver operating in the Greek Geodetic Reference System (GGRS '87). Real time corrections were obtained using the Networked Transport of RTCM via Internet Protocol (NTRIP) through the MetricaNet GNSS permanent station network. An additional set of ten checkpoints was surveyed within the site to verify positional accuracy.

Photogrammetric processing was carried out using the Agisoft Metashape Professional software, version 2.2.2, following a conventional SfM–MVS workflow. Initially, the interior and exterior orientation parameters of the images were estimated, producing a sparse point cloud of approximately 2.4 million points. GCPs were measured in the respective images and the SfM outputs were georeferenced. The resulting root mean square (RMS) error was approximately 4 cm for the GCPs and 6 cm for the check points. Subsequently, a dense point cloud was generated through a multi-view stereo (MVS) pipeline, generating a detailed 3D reconstruction of the archaeological site. The final point cloud consists of approximately 61 million points, yielding fine spatial resolution. Based on this dense point cloud, a Digital Surface Model (DSM) of the archaeological site with a resolution of 5 cm was produced. Three-dimensional surface reconstruction and texture mapping were applied for generating a textured 3D polygonal mesh model of about 9.9 million vertices and 19.8 million faces using the dense point cloud and the oriented images. Finally, high-resolution orthomosaics with a ground sampling distance (GSD) of 1 cm and 2.5 cm were produced. Figure 9 shows the photogrammetric documentation results in the archaeological site of Aegina Kolona, illustrating the oriented images, the dense point cloud, the 3D mesh model (both textured and non-textured), and the DSM, as well as the orthomosaic of the site.

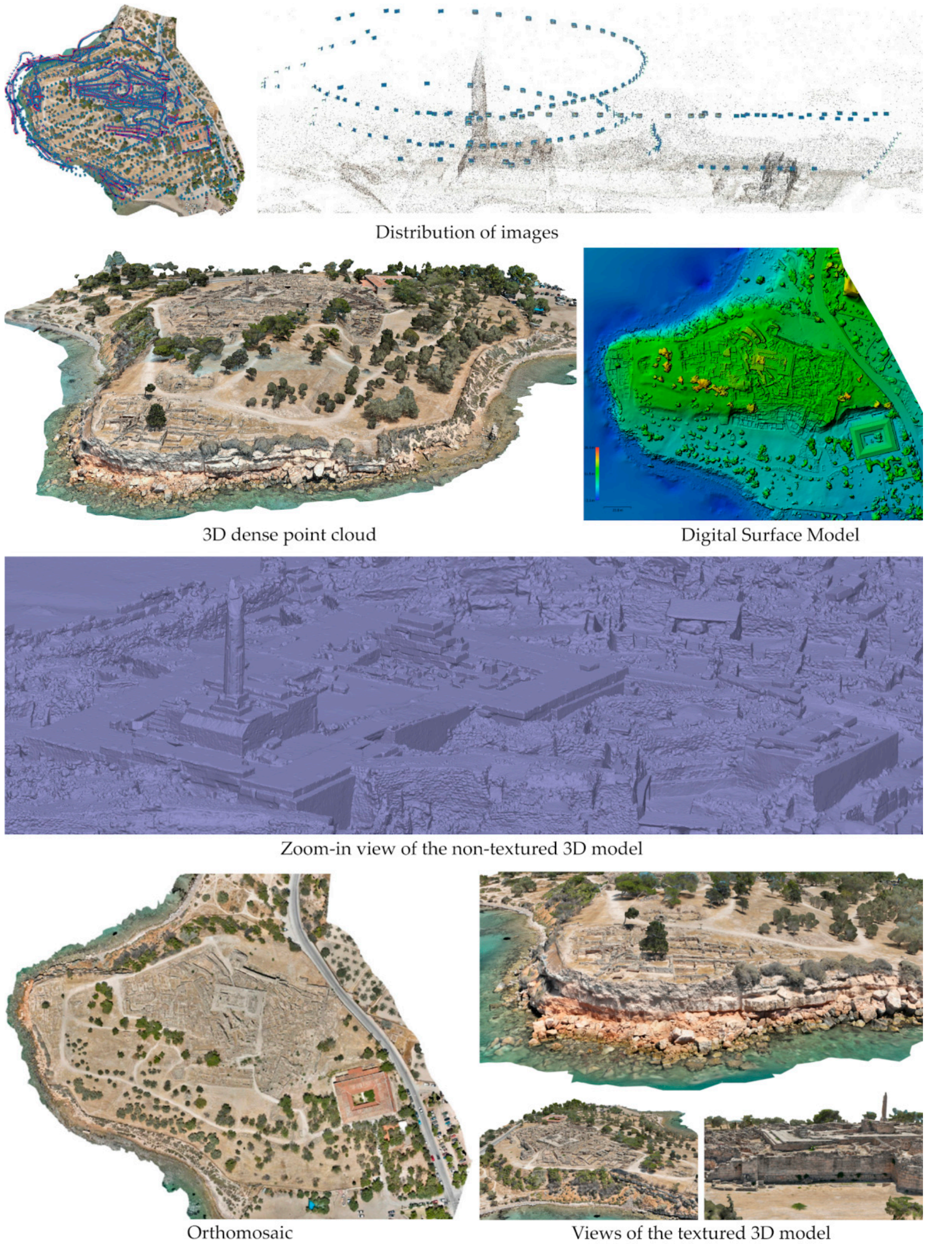

Figure 9. Photogrammetric documentation results in the Aegina Kolona archaeological site.

The overall approach demonstrates the effectiveness of UAV-based photogrammetry as a low-cost non-invasive method for documenting archaeological sites with high accuracy. The generated outputs are the foundation for further risk analysis and Digital Twin generation.

5.2. Flood Risk Assessment Under Extreme Events

The flood risk assessment methodology was built around a multi-scale hydrologic-hydraulic modelling framework that integrates rain-on-grid (RoG) forcing within HEC-RAS 2D, an open source solver developed by the United States Army Corps of Engineers, to capture both watershed-level and site-specific flooding processes. At the island scale, a 5 m resolution DEM from the Hellenic Cadastre was adopted to represent Aegina's topography with detailed drainage patterns. Climate change projections, including CMIP6 ensembles, indicate that Mediterranean regions will experience intensified precipitation extremes, despite overall decreases in mean annual precipitation, with longer return periods becoming more frequent and severe, making the assessment of rare but catastrophic rainfall events (100-, 1000-, and 2000-year return periods) increasingly relevant for long-term coastal cultural heritage preservation strategies under evolving climatic conditions [95]. Extreme rainfall scenarios were defined for 100-, 1000-, and 2000-year return periods using intensity–duration–frequency relationships, with temporal profiles generated using the Alternating Blocks method [95]. In this method, the storm total depth is discretized into rainfall "blocks," with the highest intensity positioned at mid-event to reflect realistic pluviograph structures. This design rainfall was applied directly to grid cells, enabling the solver to internally link runoff production to two-dimensional overland flow routing. Infiltration losses are estimated using the US Soil Conservation Service's approach, allowing for the separation of active (surface-runoff-generating) rainfall from total precipitation, with watershed Curve Number and the storage parameter (S) informing runoff estimation.

For the hydraulic simulations, the Shallow Water Equations Eulerian Method (SWE-EM) solver was selected within HEC-RAS for its robustness in simulating shallow flow over varied terrain. The SWE-EM solver employs a momentum-conservative finite-volume discretization approach with control volumes centred on cell faces, providing improved momentum conservation compared to the Eulerian–Lagrangian method. Stability was maintained via Courant number control ($Cr \leq 1$) and adaptive time-stepping.

Land cover data was obtained from the European Space Agency's 2020 world cover product [96] with a 10 m resolution. Subsequently, the Manning layer (friction coefficient) and curve number layer (permeability) were created according to the land cover. The CH site-scale model was constructed using a 0.05 m resolution DEM from UAV photogrammetry according to the methodology described in the previous section, with the goal of capturing fine-scale terrain variations in and around the Temple of Apollo in the archaeological site of Aegina Kolona. To understand the water flows in the area of interest, three different watersheds were considered, as shown in Figure 10.

Comparison of the three watersheds revealed differences in flooding maps, especially at the level of the individual components of the CH site, as shown in Figure 11. This means that the watershed size and accurate boundaries are important to not miss any potential water mass that is actually contributing to the Temple of Apollo (located close to the outlet) and consequently affecting the flood risk of the CH structures, which necessitated the development of a hydraulic model that considered the whole island. Therefore, in the final simulations, three model configurations were tested: (i) a full-island model including the CH site at coarse resolution, (ii) a standalone CH model driven by upstream hydrographs from the island simulation, and (iii) a nested approach combining hydrograph inflow from the island run with local RoG rainfall on the high-resolution CH mesh. The nesting approach preserved the large-scale hydrodynamic context while resolving detailed topographic influences on water depth, velocity patterns, and flow paths at the site. More details about the modelling approach can be found in [94]. As an indicative structural mitigation experiment within the nested configuration, an impermeable wall with a 1 m crest height was added upstream in the north-eastern sector to deflect shallow overland flow away from the core of the CH site. The intervention was implemented as a linear raised embankment in the DEM. Hydrologic forcing, roughness, and infiltration parameters were identical to the baseline runs so that only the terrain changed. Velocity time series were extracted at a fixed monitoring point immediately downstream of the wall to quantify changes in peak magnitude and duration.

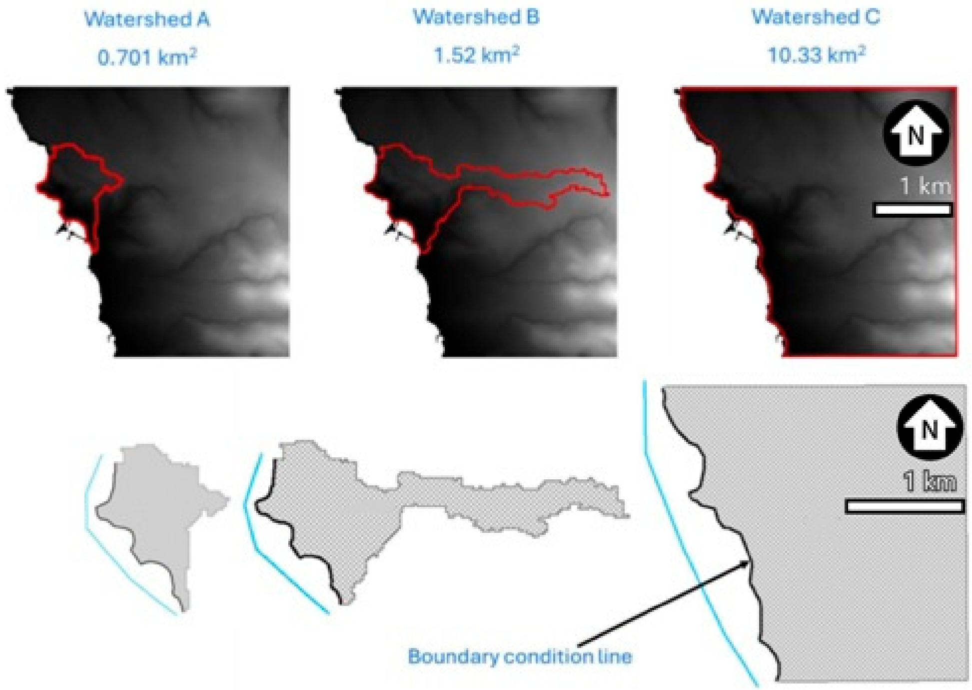

Figure 10. Three different sizes of watersheds considered in the preliminary hydraulic models, GIS (**top**), and geometries in HEC-RAS (**bottom**).

The multi-scale nested approach combining hydrograph inflow from the island-scale run with local RoG rainfall on the high-resolution CH mesh preserved the large-scale hydrodynamic context while resolving detailed topographic influences on water depth and flow paths at the site, all of which are essential for estimating the expected effects on the CH sites like material degradation. Moreover, this approach not only enabled the quantification of the maximum values of the flood characteristics (e.g., CH inundation), but also their evolution during the rainfall event, as shown in Figure 12. Such high-fidelity, component-specific temporal information could potentially provide benefits to stakeholders, archaeological agencies, and ministries of culture, as identified from the Hellenic Cadastre and the Hellenic Archaeological Cadastre, particularly for real time decision-making related to temporary flooding protection (such as protective covering of structures and temporary barriers) and resource allocation, because it reveals the critical instants after the initiation of the extreme events (e.g., when the inundation of a particular structure occurs). For example, knowing that, 3 h after an ongoing rainfall event, five out of the thirty structures of the CH site will be inundated will enable decision-makers to divert their available resources (e.g., by covering the structures or installing temporary inflatable flood barriers) in the most efficient way.

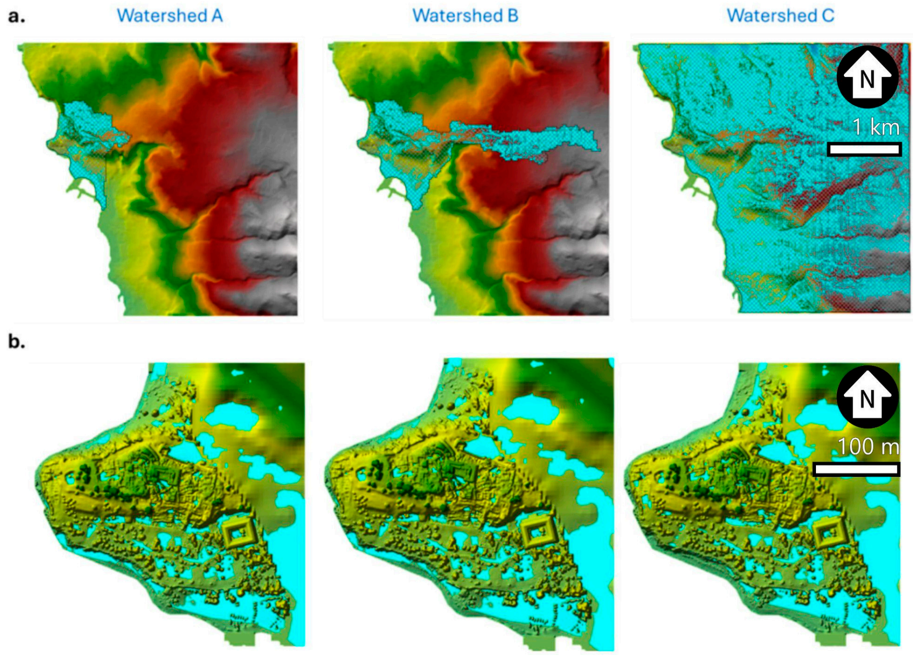

Figure 11. Flood extent from the hydraulic models of the three watersheds at (**a**) watershed scale and (**b**) CH site scale.

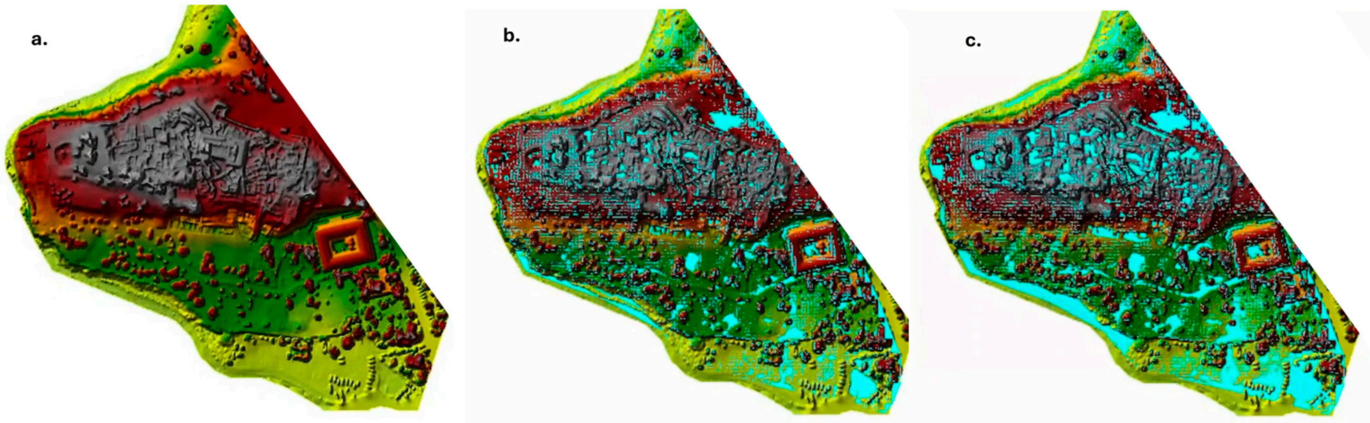

Figure 12. Flooding evolution at the CH site predicted by the multi-scale hydraulic model during the extreme event with T = 1000 years. (**a**) Before rainfall starts; (**b**,**c**) the evolution during the rainfall event progressively.

Finally, the multi-scale computational framework with the high-resolution local DEMs enables the quantification of the velocity patterns around each of the CH structure for different rainfall intensities, which are critical for further estimation of the floods loads, erosion, and scour risk. Figure 13 shows an example of the velocity histories predicted by the computational models at three different locations of the site for three return periods (T = 100 years, 1000 years, 2000 years). Figure 14 shows an indicative mitigation test. As expected, more extreme events result in larger maximum velocities; however, the exact effect is dependent on the location, with some points showing a 15–20% increase between the return periods (e.g., Figure 13 left) and other points showing a negligible difference (e.g., Figure 13 right). Moreover, in the more extreme events (higher return periods), larger velocities were witnessed for a longer duration during the flooding event, which increases the potential risk of erosion and scour around specific structures. Such information enables the development of targeted measures against scour (e.g., protective stone cladding and redirection barriers).

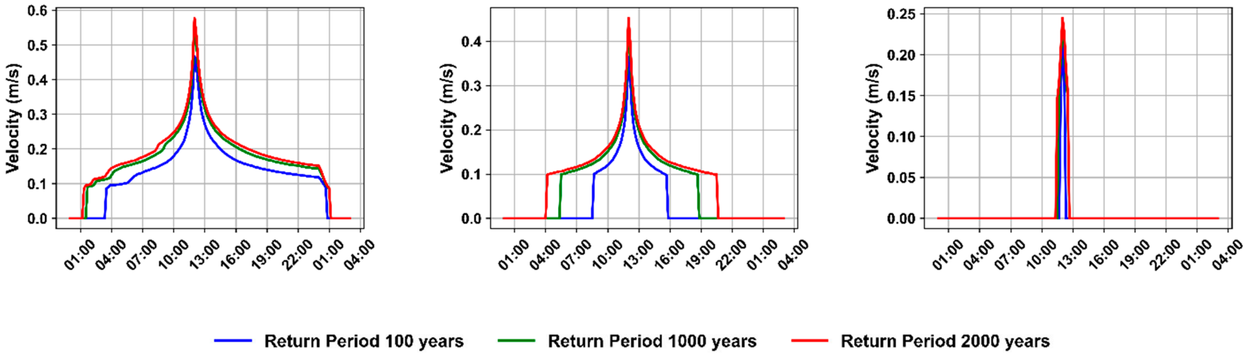

Figure 13. Flood velocities at three selected locations of the CH sites for the duration of the extreme event.

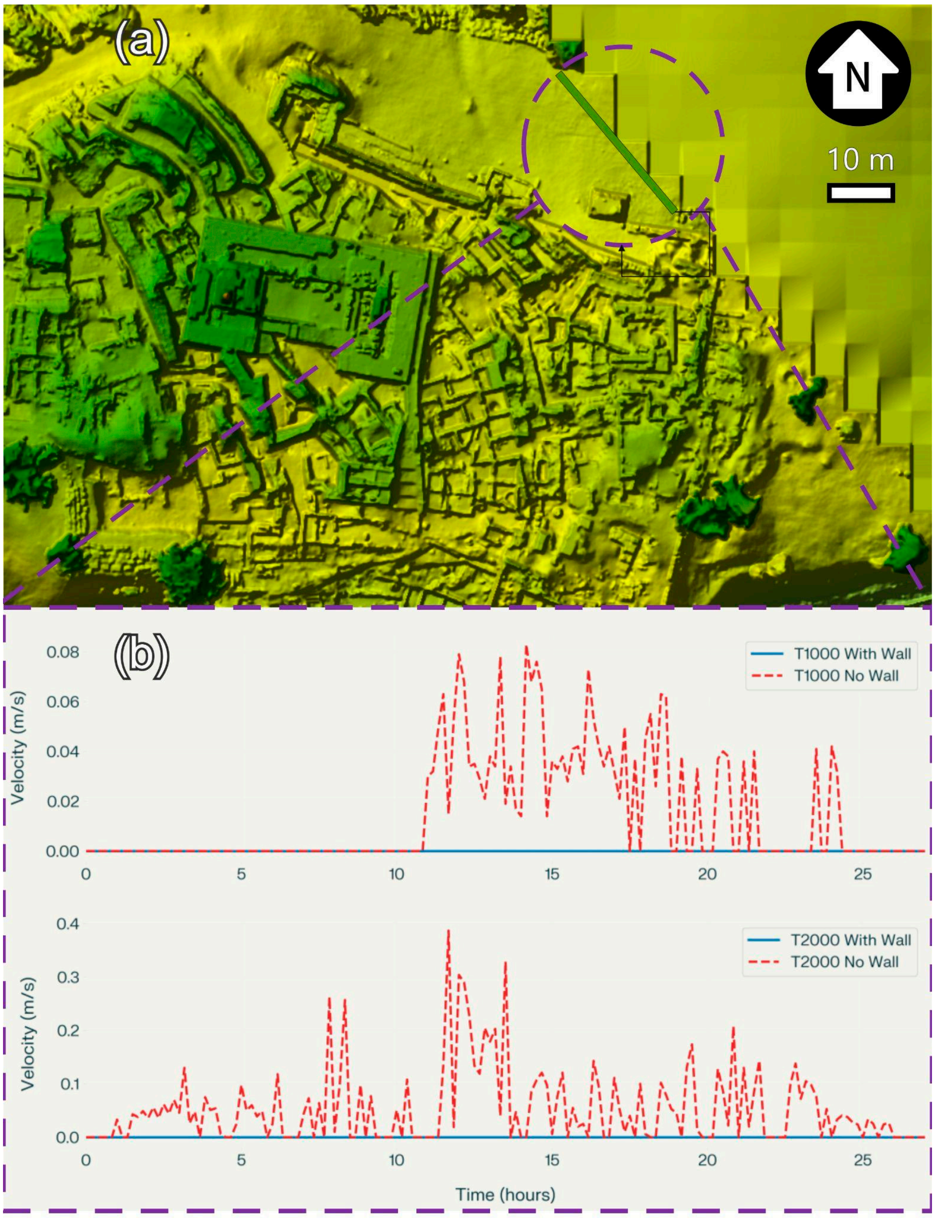

Figure 14. Upstream flow-deflection wall test at Aegina Kolona: location of a 1 m high wall added along the north-eastern sector of the site (**a**), and velocity time series at the downstream monitoring point comparing with wall and no-wall cases for T = 1000 years and T = 2000 years under the nested RoG HEC—RAS 2D configuration (**b**).

The upstream wall eliminated velocities at the monitoring point for the T = 1000-year event across the full hydrograph. For T = 2000 years, the wall reduced peak velocity from approximately 0.39 m/s to approximately 0.14 m/s and shortened the duration of elevated velocities. The outcomes indicate the attenuation of velocity drivers relevant to scour at the instrumented location. The test is illustrative and serves to demonstrate the screening of candidate works within the established modelling workflow (Figure 14). Overall, the coupling of watershed-scale flood generation with site-scale hydraulic refinement allows for an integrated representation of both upstream contributions and localised hydrometeorological forcing, which is critical for the proper site-specific flood risk assessment of CH structures.

6. Discussion and Conclusions

Climate change poses one of the greatest threats to coastal CH worldwide. Rising sea levels, extreme weather events, coastal erosion, and saltwater intrusion make coastal archaeological sites increasingly vulnerable. In response, the international community—particularly the European Union—has adopted targeted policies, strategies, and legal instruments to promote sustainability and climate resilience in coastal zones, which actually means practical capacity to prepare for, withstand, and recover from hazards. For example, continuous monitoring via sensors and Digital Twins, early-warning and temporary access controls during events, and targeted drainage upgrades for rain-runoff- and nature-based coastal buffers (and, where acceptable, low-impact works) are indicative measures that may be applied within CH and regulatory constraints.

The Hellenic Cadastre and the Hellenic Archaeological Cadastre are central pillars of land administration and heritage protection. These land administration systems ensure geolocation, spatial accuracy, public access to information, and legal clarity regarding land use and ownership rights and responsibilities. Through geospatial integration and the interoperability of platforms, a more efficient, a transparent and data-driven approach to coastal CH protection can be implemented. In practical terms, this means using the Hellenic Cadastre and the Hellenic Archaeological Cadastre as the entry point to overlay protection zones and parcels with flood/erosion/sea level rise layers, automatically flag permit applications in high-risk areas or protected areas, issue targeted notifications during events, and record post-event inspections to keep the site record or the site Digital Twin up to date for decision-making.

The use of open access geospatial datasets and spatial data infrastructures is very important for enabling cost-effective risk-assessment for coastal CH. Through the sophisticated management of available geospatial data and low-cost data collection methods, a 3D geospatial infrastructure may be compiled for important coastal CH sites to create a Digital Twin infrastructure. Open geospatial ecosystems, researchers, and authorities may have real time access to continuously updated environmental variables, land cover, topographic models, sea level projections, and exposure indicators.

This Digital Twin, by using interoperable data, can support continuous monitoring and predictive modelling for climate-related threats and other natural hazards. Building upon such open geospatial layers, the Digital Twin paradigm introduces a very useful tool for the dynamic simulation and analysis of CH sites under severe climate threats. The TRIQUETRA project's implementation of a Digital Twin prototype for the archaeological site of Aegina Kolona exemplifies this. By combining photogrammetrically derived high-resolution 3D models with flood risk assessment, the Digital Twin enables responsible authorities and researchers to simulate several risk scenarios.

Central to this capability is the use of photogrammetric data collection methods as a low-cost, flexible, and highly accurate solution for creating the 3D geospatial infrastructure for building the Digital Twins of CH sites. In contrast to expensive laser scanning systems, image-based 3D modelling via Structure from Motion and Multi-View Stereo (SfM-MVS) pipelines allows for the generation of dense point clouds and surface models using off-the-shelf equipment. This methodological approach was applied in the case of Aegina Kolona, where a high-resolution 3D model of the Kolona and its surroundings was produced using UAV-based photogrammetry. The resulting dataset, comprising over 6000 oblique and nadir images, produced a dense point cloud exceeding 60 million points and a DSM with 5 cm resolution. These outputs not only formed the geometric basis for visual documentation, but also served as core inputs for flood risk assessment.

High-resolution DEMs serve as the foundation for precise flood risk assessment in coastal CH sites, offering critical detail in representing micro-topographic nuances that govern water flow, pooling, and inundation depths. Traditional, coarse-resolution DEMs can underrepresent peak runoff rates and mischaracterize flood extents, leading to unreliable risk evaluations that may overlook local vulnerabilities crucial to heritage preservation. As highlighted in the study of Aegina Kolona, integrating high-resolution site-specific DEMs (order of centimetres) derived from UAV photogrammetry with island-wide DEMs (order of 5 m) from open-sources like the Hellenic Cadastre captures intricate elevation changes and drainage morphologies, resulting in sharper, site-specific flood hazard mapping. Such detail is indispensable for modelling complex built environments where even minor topographic features can significantly influence flood dynamics, particularly in heritage sites, which are often situated in hydrologically sensitive settings.

Equally transformative is the adoption of advanced, multi-scale computational modelling frameworks that couple watershed-scale hydrodynamics with fine-scale, asset-level terrain data. The combination of hydrologic methods with Rain-on-Grid modules enables the simultaneous simulation of rainfall runoff generation and hydraulic propagation across nested spatial scales, effectively bridging regional flood drivers with granular site impacts. This approach permits robust evaluations of how upstream processes and localised terrain interact to affect heritage structures. Collectively, these advances are pivotal in supporting effective, data-driven conservation strategies (e.g., the development of early warning systems or implementation of temporary measures), mitigating uncertainties, informing resilience planning, and ultimately safeguarding irreplaceable cultural assets against escalating flood threats intensified by climate change.

Our case study findings align closely with recent published work on Aegina Kolonna and coastal CH risk, led by partners of the TRIQUETRA project. Firstly, our findings strongly resonate with the work reported in [94], which describes a novel and scalable flood risk assessment framework applied to the Aegina Kolonna site. Using the same UAV-based high-resolution 3D model, the authors in [94] compare three configurations (5 m island-wide Rain-on-Grid model, a site-only model, and a high-resolution nested model coupling UAV-derived DEMs at centimetre scale with coarser models) and show that the nested approach provides more realistic water volume accumulation data and reveals critical micro-topographic controls on flood behaviour. In the present study, we similarly observe that coupling island- and site-scale models significantly strengthens decision support outputs in our Aegina Kolonna case. Secondly, our sea level rise (SLR) screening and the way we suggest ingesting open datasets into a Digital Twin-ready stack are consistent with a recently published TRIQUETRA methodology that maps the exposure of Mediterranean CH assets to 2050/2100 SLR using elevation, vertical ground motion (European Ground Motion Service, EGMS), and IPCC (Intergovernmental Panel on Climate Change)-based projections [97]. Thirdly, recent TRIQUETRA CFD work indicates that SLR amplifies wave pressures and forces on coastal CH under extremes, supporting our emphasis on scenario testing, early-warning thresholds, and temporary access controls at exposed fronts [98]. Finally, the broader approach we follow, linking land administration data (Hellenic Cadastre/Hellenic Archaeological Cadastre), open geospatial ecosystems, and a Digital Twin interface, operationalizes the TRIQUETRA project's DSS vision for risk identification and quantification, situating our Aegina results within an EU-aligned resilience frame [99].

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