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Safeguarding Our Heritage—The TRIQUETRA Project Approach

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Abstract: Cultural heritage (CH) sites are frequently exposed to natural elements, and their exposure becomes particularly precarious with the onset of climate change. This increased vulnerability places these sites at risk of deterioration or complete destruction. Risks such as land deformation, floods, acid rain, and erosion significantly threaten historic monuments, while water-related hazards, significantly influenced by both climate change and human activities, present a particularly grave risk to these invaluable sites. Considerable research efforts have focused on safeguarding CH sites. However, there remains a deficiency in systemic approaches towards identifying and mitigating risks for CH sites. The TRIQUETRA project proposes a technological toolbox and a methodological framework for tackling climate change risks and natural hazards threatening CH in the most efficient way possible. It aims at creating an evidence-based assessment platform allowing precise risk stratification as well as a database of available mitigation measures and strategies, acting as a Decision Support System (DSS) towards efficient risk mitigation and site remediation. TRIQUETRA is a European project that brings together a diverse group of researchers with varied expertise, encompassing university research groups, research institutes, public entities, as well as small and medium-sized enterprises. In this article, TRIQUETRAs overall methodology is presented, and preliminary results concerning risk identification, TRIQUETRAs knowledge base, as well as novel sensors and coatings, are discussed.

Keywords: cultural heritage; climate change; natural hazards; risk identification; extreme weather; geological hazards; chemical/biological hazards; extreme waves; remote sensing; computational fluid dynamics

1. Introduction

Climate change, as revealed by gradual changes in temperature, precipitation, atmospheric moisture, and wind intensity, as well as sea level rise and changes in the occurrence of extreme events, is already affecting cultural heritage (CH) sites [1]. The impact of several climate factors on CH assets can be further aggravated by future anthropogenic climate change [2]. The United Nations Educational, Scientific, and Cultural Organization World Heritage Convention has recognized the effects of climate change as a significant threat to CH, both in the present and the future, stimulating a growing body of related research [3]. Reliable future climate change data from high-resolution projections based on regional climate models (RCMs) is essential to supporting decision-makers and stakeholders for climate change impacts, mitigation, and adaptation at CH sites. However, little research has been carried out so far to identify the climate hazards faced by the CH sites and assess the climate-related risks either by abrupt changes from climate extreme events or by long-term degradation effects of CH materials due to climate change using single or multi-model high-resolution RCM simulations [4].

In the past decades, many projects and individual researchers have investigated ways in which climate change has affected CH sites, how these can be monitored, and which mitigation strategies can be implemented to combat the deterioration of CH sites. This research was summarized in recent years in two important scholarly works. Firstly, the state of work within the period of 2007 to 2017 was discussed in [5]. This study found that systematic research into climate change-induced risks for CH sites started in 2003 and has increased since then. Most research was found to focus on the US and UK, and most methods employed were quantitative as opposed to qualitative methods such as stakeholder interviews. Another major conclusion was that the mitigation measures for the protection of CH sites were hardly addressed. This is offered as a suggestion for the future of research as well as the increased involvement of the community in the protection and monitoring of CH sites.

In 2021, another literature review article was published focusing on the period 2016–2020 [6]. This article indicated that research has increased significantly since 2015, focusing heavily on specific case studies within the Western world, especially Europe, without the inclusion of detailed models or timelines for climate change. The authors state that more international (global) cooperation is required to investigate and counter the adverse effects of climate change.

Efforts were made to address the above concerns, aiming towards a detailed retrieval of information to evaluate the identification of the potential risks triggered by climatic (mainly) and environmental causes in tandem with the monitoring processes and mitigation measures that have been applied or proposed for specific case studies. This study focused on all climate change-induced threats to exposed archaeological sites, cultural landscapes, and exposed cultural assets in Galleries, Libraries, Archive Collections, and Museums (GLAMs) [7].

It is crucial to comprehend the present hurdles that CH sites encounter to effectively conserve them and ensure their transmission to future generations. While much research has been carried out on protecting CH sites, there is still a lack of systemic approaches for identifying, quantifying, and mitigating risks at the regional and/or country level, aiming to provide the maximum protection possible. The TRIQUETRA research project [8] proposes a toolbox for assessing and mitigating climate change risks and natural hazards threatening CH. In this context, TRIQUETRA aims to: (i) create a repository of knowledge regarding the effects of climate change and natural hazards on CH and lessons learned from existing mitigation measures; (ii) propose a systematic approach towards identification of upcoming risks and hazards to CH; (iii) develop novel technologies that allow efficient and accurate quantification of threats to CH; and (iv) increase awareness of the wider public regarding CH risks and preservation, making citizens part of the solution. The strategic objectives of TRIQUETRA outlined above will be achieved through the implementation of various innovative activities currently in progress within the project, including the following:

- assessing the precision of the flash LiDAR technology for 3D mapping of underwater CH sites and validating its applicability for erosion monitoring;
- developing a novel spectroscopic sensor for water quality monitoring near underwater CH sites;
- further increasing the accuracy of climatic models;
- developing models for risk quantification stemming from extreme water, ice, and snow events;
- developing models for calculating geohazard risks based on in-situ data for CH sites;
- developing models on structural damage risks on CH sites;
- assessing chemical and biological hazards on CH sites based on in-situ sensing;
- analyzing the need for and providing novel techniques for the application of remote sensing at CH sites;
- developing a platform that allows multi-hazard impact assessment and acts as an advanced DSS towards risk mitigation and CH site remediation.

TRIQUETRA is a research project funded by the European Union (EU); it started in January 2023 and ends in May 2025. In this article, TRIQUETRAs overall methodology is presented, and preliminary results are discussed. Specifically, in Section 2, TRIQUETRAs main approach is presented, TRIQUETRAs toolbox is discussed, a brief description of all pilot sites where TRIQUETRA will be validated is given, the novel sensors and coatings that are being developed are outlined, and the Earth Observation (EO) methods applied within the project are discussed. In Section 3, results achieved within the first year of the project are presented, concerning the TRIQUETRA knowledge base and the risk identification framework for climate-related hazards, extreme water hazards, snow and ice hazards, geological and geophysical hazards, as well as chemical and biological hazards, and finally concerning the flash LiDAR, the oxygen sensor, and the protective nano-coatings.

2. Overview of TRIQUETRAs Methodology

2.1. TRIQUETRAs Main Approach

The TRIQUETRA project is dedicated to establishing an evidence-based assessment platform for precise risk stratification, along with the development of a comprehensive database cataloging available mitigation measures and strategies. Serving as a DSS, it aims to facilitate efficient risk mitigation and site remediation. The project's methodology revolves around three core stages: (i) risk identification, (ii) risk quantification, and (iii) risk mitigation, forming what is referred to as the "trifecta" approach (Figure 1), hence the name TRIQUETRA. This approach constructs a robust framework for assessing and addressing a wide spectrum of risks.

TRIQUETRAs primary goal is to precisely quantify the severity level of each identified risk within the CH pilot sites. Leveraging a diverse array of established and cutting-edge methodologies such as remote sensing and laser-based spectroscopy, TRIQUETRA aims to establish the level of different kinds of risk and continuously monitor their evolution. Risks emerge from the intersection of hazards, exposure, and vulnerability. To evaluate this, a combination of risk probability and impact assessment is employed, where risk is determined by the likelihood of a hazard's impact multiplied by the overall consequence of that impact (risk = probability $\times$ consequence). The transition from a hazard to a risk occurs when CH assets are exposed to a specific hazard and display vulnerability. Therefore, a thorough vulnerability assessment is conducted for multiple types of hazards, considering the exposure, sensitivity, and adaptive capacity of CH assets. Furthermore, diverse risks stemming from various natural hazards like flooding, extreme heat waves, heavy rainfall, etc., are being evaluated concerning different types of heritage assets, such as archaeological monuments, built heritage, and geological heritage sites. Specifically, TRIQUETRA assesses the following types of risks:

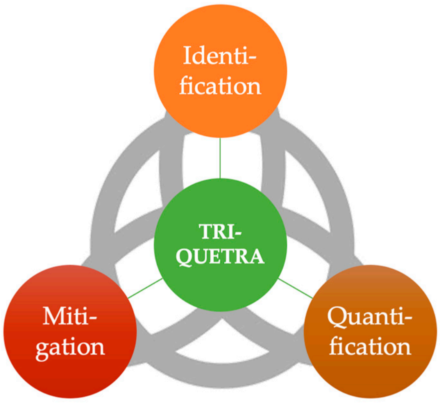

Figure 1. TRIQUETRAs "trifecta" approach.

- climate-related risks, employing high-resolution RCMs, utilizing dynamical downscaling methods from GCM simulations within the CORDEX initiative, focusing on diverse hazards and climate parameters to predict potential damage and flood risks, and integrating RCM output to model impacts on river and coastal flood levels at CH sites;
- extreme water, snow, and ice hazard risks by leveraging optical sensors to identify erosion-sensitive areas, predicting water fluxes during various events like floods or heavy rains using Digital Elevation Models, and assessing water constituents like CDOM, phytoplankton, and non-organic materials to detect potential threats to submerged CH sites, quantifying hydrodynamic forces on CH structures during water hazards, and utilizing computational fluid dynamics with mesh and particle-based methods to model chaotic wave breaking, extreme floods, and 3D effects around monuments;
- geological and geophysical risks, by integrating high-resolution seismometry with terrestrial thermographic surveys to measure dynamic behavior in disconnected rock elements, enabling 4D visualization of thermal measurements, sizing of rock portions involved in geological processes, and precisely projecting vibrational data obtained from seismic sensors onto a 3D model, thus allowing for conceptual modeling of processes, identification of sectors with intense geomorphological dynamics, and detection of precursor signals for potential collapse episodes; using advanced processing to detect microseismic events linked to fractures or coastal detachments; and
- chemical and biological hazard risks, utilizing Advanced Quantum Cascade Lasers (QCLs) and molecular imprinted polymers (MIPs) technology, which facilitate real-time monitoring of significant water-based threats to CH sites, including tracking eutrophication indicators such as nutrients, harmful pollutants like hydrocarbons, and specific biological species like bacteria.

Furthermore, it assesses the damage and failure modes of CH structures by identifying and quantifying various types of damage—be it aesthetic; non-structural; or mechanical—caused by long-term pollutant risks and climate change; while also investigating failure modes in diverse CH structures due to sudden water hazards. High-end nonlinear numerical models will pinpoint stress levels, cracks, and potential collapse in CH structures, complemented by simpler analytical models calibrated with complex model data to efficiently assess risk severity and develop novel damage threshold matrices based on hazard intensity and type.

Last but not least, TRIQUETRA focuses on assessing the compounded impact of various environmental stressors on CH, exemplified by considering sea level rise, intensified storm surges, and increased ship-induced waves on coastal sites. Understanding cascading events like landslides due to extreme rainfall, influenced by climate change, demands refined climate models and sophisticated remote sensing to predict risks accurately. Investigating water-borne debris impact during flash floods or coastal storms requires interdisciplinary methods, where particle-based approaches like SPH-FEM or SPH-DEM show promise in modeling debris motion's impact on critical infrastructure.

As far as the mitigation strategies are concerned, TRIQUETRA aims to implement two adaptation strategies for CH: (a) "small-scale" strategies for the protection of individual components of CH sites and (b) "large-scale" mitigation measures for entire CH sites. Conventional and innovative "small-scale" mitigation measures like new coatings for CH component protection will be investigated. "Large-scale" approaches encompass traditional flood defenses like walls and dykes, modern solutions like adaptable floating breakwaters, and hybrid nature-based options such as reinforced core dunes to evaluate their efficacy against diverse environmental stressors on different CH structures and landscapes, emphasizing the preservation of heritage values in disaster-protection system design.

2.2. TRIQUETRAs Toolbox

One of TRIQUETRAs key outcomes is a platform for storing all knowledge on CH risks as well as relevant previously applied mitigation measures. This is the TRIQUETRA knowledge base, the preliminary results of which are discussed in Section 3.1. In TRIQUETRA, a DSS is also being developed, which will enable stakeholders and decision-makers to make the most educated decisions related to risk mitigation and remediation of endangered CH sites. The DSS platform will include two modules: (i) a risk severity quantification module, and (ii) a mitigation measure selection and optimization module. The dataflow of TRIQUETRAs toolbox is illustrated in Figure 2.

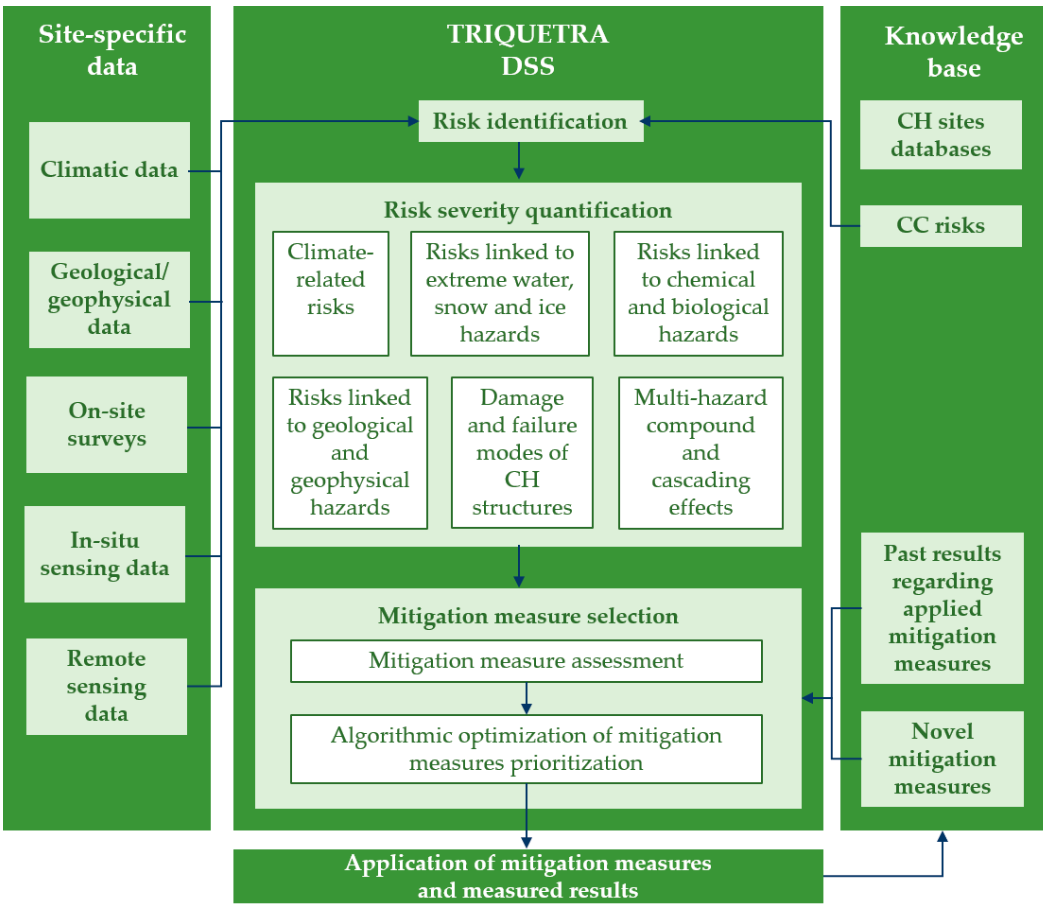

Figure 2. Data flow of TRIQUETRAs toolbox.

The risk severity quantification module will be responsible for the quantification of the severity of each identified risk for each CH site of interest, in accordance with the needs of the decision-makers. Within this module, the severity of the risks will be ranked on an appropriate scale (e.g., catastrophic, critical, marginal, or negligible). At first, the risk severity quantification module will comprise tools for describing each risk in detail, allowing a better understanding of the risks and a more effective evaluation of their potential impacts on each CH site. Secondly, it will encompass tools for defining the nature of the risks affecting each CH site (both natural and man-made hazards), their probability of causing harm to CH sites, and their consequences, through a combination of quantitative and qualitative methods. Thirdly, it will comprise a variety of analytic techniques for risk severity quantification, depending on the nature of the risks, taking into account all the available studies, surveys, and relevant data from the TRIQUETRA knowledge base for characterizing their consequences. The risk severity quantification module will establish a way of arranging the risks in order of importance. The methods that will be implemented in this module for risk severity quantification will encompass systematic and evidence-based approaches for describing and quantifying the nature as well as the magnitude of each risk associated with each CH site of interest. Both qualitative and quantitative assessments will be hosted by the module. In the context of qualitative assessments, the risk severity quantification process will generate non-numerical estimates of the severity of each risk. The quantitative tools that will be hosted by the module will rely on state-of-the-art analytic models (both simple models and complex ones) in order to express the severity of each risk, yielding transparency in the risk assessment process and improving the validity and reliability of the analysis.

The mitigation measure selection and optimization module will incorporate mitigation measures into the DSS, allowing the best mitigation measure to be selected for each particular case study. Those measures will be categorized in terms of interoperability, areas of application, mitigation potential, and ease of deployment. This module involves the selection of optimal mitigation measures that will be incorporated into an optimization process, which will also tackle possible combinations of responses for the mitigation of risks to CH and will take into account the underlying topology of the CH models. The overall module focuses on the zero emissions part of the Paris agreement [9], providing insights into the organizational risks and opportunities incited by climate change and leading the transition to net zero emissions, including Zero-Emission Vessels (cars/ships, etc.) that provoke events such as sea level rise, global warming, etc. Ultimately, the module aims to reshape the CH—climate change model towards long-term value and resilience by highlighting the impact and dependencies of climate change on CH and the global economy.

The TRIQUETRA DSS covers a holistic approach and, in parallel, evidence-based policymaking with multi-stakeholder involvement in order to give reliable recommendations to end-users regarding the assessment and mitigation of climate change risks on CH. The TRIQUETRA DSS will be integrated with the aforementioned modules, the datasets, and the knowledge base so as to improve reliability in decision-making. In this direction, recommendation engines, DSS tools, and relevance feedback mechanisms will be developed. For the recommendation engines, we will exploit multi-criteria analysis and dynamic programming methods. These tools will give different rules and weights to different criteria so that a reliable recommendation map will be developed. For the DSS tools, the TRIQUETRA DSS will integrate artificial intelligence tools, including deep machine learning algorithms. Finally, it will support a set of relevant feedback mechanisms that can automatically update the response of a system to users' wishes and preferences, as implicitly described by the users. The TRIQUETRA DSS platform will be interconnected with the Digital Twin concept, which uses simulation, machine learning, and reasoning to help with decision-making. The TRIQUETRA DSS Platform, which is at the nexus of CH, climate change, natural hazards, digital technologies, and big data, are expected to have a major impact on the state-of-practice and result in a paradigm shift in the risk management and protection of CH.

2.3. Pilot Case Studies

TRIQUETRA will be validated at eight different CH sites across Europe (Figure 3), i.e., one site in Italy, three sites in Greece, one site in Germany, one site in Switzerland, one site in Cyprus, and one site in Poland, spanning a wide range of archaeological periods, CH typology, structures, and materials. In the following sections, a brief description is provided for each pilot site.

Figure 3. TRIQUETRAs pilot sites.

2.3.1. Kalapodi

The sanctuary of Kalapodi, located in Ancient Phokis, Central Greece, showcases a remarkable variety of materials and building methods. It includes natural stone (such as soft limestone and sandstone), Roman cement, and various metals like bronze, iron, and copper, along with pieces of plaster in its monumental complexes. Excavations conducted by the German Archaeological Institute (DAI) since 1974 have revealed two temple complexes and surrounding structures (dating from ca. 1300 BC to 700 AD). Frost poses a constant danger to the site's materials, contributing to decay issues alongside the vulnerable structural materials. Within the framework of TRIQUETRA, weather and environmental monitoring techniques will meticulously record the micro-climate conditions of the archaeological site. Additionally, a material analysis will document the impact of climate on building materials. An integrated methodological model, inspired by solutions applied to vulnerable agricultural crops like vineyards, aims to protect the monumental complex against frost.

2.3.2. Ventotene

Ventotene, the smallest inhabited island in the Tyrrhenian Sea's Pontine Islands, Italy, recently claimed the title of the historical capital of European morals and intellect. This volcanic island, a remnant of an ancient caldera, along with Santo Stefano, faces risks from coastal cliff landslides due to weather conditions and rising sea levels. Its rocky outcrops are vulnerable to erosion and marine forces. Ongoing instability from a 2020 landslide highlights these risks. The Villa di Giulia archaeological site at Capo Eolo showcases fresco-decorated walls needing reinforcement against wind and sea impact. Deep-sea surveys discovered five wrecks, with ongoing dives gathering geological, geomorphological, and archaeological data. Within TRIQUETRA, activities include gathering geological and meteorological data, conducting geological-technical surveys, creating detailed documentation, studying restoration/consolidation plans, and allowing the design of a monitoring system for site management authorities. Terrestrial monitoring installations under TRIQUETRA transmit continuous geophysical and meteorological data to a central control center managed by local Ventotene authorities.

2.3.3. Aegina

Aegina Kolonna, a significant archaeological site on Aegina Island's north-western tip in the Saronic Gulf, Greece, played a vital role in the Aegean Bronze Age. It includes a prehistoric settlement with an inner area and suburbs on the east side, later transformed into a necropolis during the Iron Age after abandonment around 1200 BC. The site thrived from the Archaic to Roman eras, undergoing continuous archaeological excavations since the 19th century. The application of TRIQUETRA technologies focuses on measuring geological hazards linked to ground instabilities and safeguarding cliffs against wave- and precipitation-induced erosion. Specific geophysical campaigns target the site's terrain. The preparatory phase within TRIQUETRA involves a comprehensive analysis of the site's increasing degradation. Understanding the distinctions between natural waves, ship-induced waves, and alterations in current behavior is crucial. Integrating climate studies to track precipitation changes over recent decades is essential. Methodologically, scrutinizing archival, satellite, and infrared imagery, coupled with chemical and physical assessments of endangered cliffs, will aid in initial risk identification and subsequent quantification. In a subsequent phase, TRIQUETRA will employ both established and innovative methods to mitigate identified risks. This phase will focus on devising strategies to proactively prevent cliff damage.

2.3.4. Choirokoitia

Choirokoitia, a UNESCO World Heritage Site, stands as a remarkably preserved Neolithic settlement in Cyprus, thriving around the early 9th millennium. Located 6 km from Cyprus's southern coast in the Larnaka District, nestled at the foot of the Troodos mountain range within the Agios Minas River valley, it is susceptible to various natural hazards due to climate change. Monitoring these hazards is vital for early risk detection and effective conservation planning. The site faces threats like landslides, earthquakes, rock falls, ground subsidence, and erosion. To address such threats, TRIQUETRA implements multiple techniques. These include data collection from a permanent GNSS station and corner reflector, analyzing multitemporal SAR satellite data to estimate land movement, and simulating rockfalls via 3D modeling with UAV photogrammetry. Focusing on InSAR ground motion data and field surveys, ground deformation from natural hazards is being detected and analyzed. TRIQUETRAs innovative methods integrate SAR monitoring to identify hazards using remote sensing techniques. Starting with InSAR imagery for hazard pinpointing, field verification is employed to measure changes caused by natural or geo-hazards. Persistent Scatterer Interferometry (PSI) analysis will extend this monitoring to assess potential displacements in a wider area. A recent airborne campaign acquired hyperspectral data on the site.

2.3.5. Epidaurus

Ancient Epidaurus, a significant coastal and underwater UNESCO site dating back to the 12th century BC, faces numerous threats. The Sunken City near Ancient Epidaurus confronts bio-erosion and degradation due to water, microorganisms, rising sea levels, coastal erosion, floods, sediment deposits, and illegal mooring of tourist boats. TRIQUETRA implements advanced 3D modeling techniques to preserve and protect the Epidaurus pilot site, utilizing novel surveying, photogrammetric, and remote sensing methods and working closely with local stakeholders and authorities. It aims to create high-precision 3D models of coastal and underwater antiquities using aerial and close-range photogrammetry, laser scanners, LiDAR sensors, and underwater surveys. These efforts establish a common reference network and focus on early detection and monitoring of changes.

2.3.6. Roseninsel

Roseninsel, part of the UNESCO World Heritage Site "Prehistoric Pile Dwellings around the Alps", encompasses archaeological remains spanning from the Roman to post-Medieval periods, alongside historical monuments and a 19th-century garden monument. Within TRIQUETRA, a robotic surface vehicle has captured detailed bathymetry maps and orthophotos of submerged structures and lake floors with high precision. LiDAR measurements complement this data. Integration of satellite data into a GIS will facilitate easy change detection, particularly after weather events, to identify erosion. Satellite data with higher spectral information, like Sentinel-2, DESIS, and EnMAP, will monitor water quality parameters, aiding in evaluating natural and human-induced impacts like turbidity and eutrophication. Further assessments will evaluate factors such as the impact of snow/ice, wave erosion, biological and chemical hazards connected with water quality, and atmospheric hazards in order to understand their relevance for the conservation of the archaeological monument in the context of climate change and human activities.

2.3.7. Argilliez

Les Argilliez, part of UNESCOs "Prehistoric Pile Dwellings around the Alps", is a fully submerged site in Lake Neuchâtel dating back to 3841-3817 BC. Erosion threatens the site, impacting its piles and surrounding area. Regular 3D modeling tracks erosion, which is crucial for preservation efforts. TRIQUETRAs plan involves using a unique bathymetric LiDAR prototype to monitor erosion and measure the height of piles over time with centimetric precision. This data also assesses water depth and tracks changes in mussel proliferation affecting the site's artifacts. The project aims to create a detailed site map using unmanned vehicles, i.e., Unmanned Surface Vehicles (USVs) and Unmanned Aerial Vehicles (UAVs), for regular measurements over six months, assessing data quality and platform suitability. The most effective vehicle will be selected for future campaigns, leading to a comprehensive 3D site map that will be used for ongoing surveys. This approach ensures precise monitoring and preservation strategies for Les Argilliez.

2.3.8. Smuszewo

Smuszewo's fortified settlement from the Late Bronze/Early Iron Age is a protected archaeological site situated between two lakes on an isthmus. It faces threats from climate change and human activities, affecting wooden structures and organic materials due to fluctuating water levels and changing farming practices. TRIQUETRA aims to monitor these impacts using remote sensing data integrated within GIS, allowing real-time tracking of natural and anthropogenic processes. Preparation involves collecting historic meteorological data, conducting aerial surveys, and securing permissions for non-invasive investigation methods. The project seeks to utilize the gathered data to propose strategies for risk mitigation, protection, and management of the site, potentially applicable to similar heritage sites in the region.

2.4. Novel Sensors and Coatings

In the frame of the TRIQUETRA project, a new-generation flash LiDAR sensor is being developed. This new flash imaging LiDAR will be capable of acquiring 3D images of a scene in a single snapshot and dealing with multiple reflections ("echoes") such as those generated by the air-water interface. This technology is considered a key enabling technology for applications such as autonomous navigation (e.g., airborne, space), mapping (e.g., geology, archeology, etc.), object detection, and underwater inspection, especially in shallow waters. It confers the following advantages over a traditional scanning architecture: better integration (volume), longer lifetime (no moving parts), and no compromise on angular resolution, measurement rate, or platform stability. Moreover, thanks to dedicated electronics embedded at the pixel level (active gating), 3D mapping can be performed even when visibility is reduced (e.g., in turbid waters).

Furthermore, in the context of TRIQUETRA, a swarm system will be developed to monitor turbidity, with the main goal of improving 3D mapping of shallow water using the novel flash imaging LiDAR technology. This system will provide meaningful data for optimizing LiDAR data. First, in-situ real-time monitoring of tilt and turbidity will enable selecting the right time window for LiDAR test campaigns in function of local weather conditions. Second, in-situ turbidity measurement will be used to optimize the LiDAR data acquisition (i.e., time gating distance) and post-processing (i.e., removal of parasitic reflections) to extract higher-quality information. At the same time, it will permit the evaluation of LiDAR performance as a function of turbidity. The swarm system will be improved with the integration of high-performance oxygen sensors that will allow higher accuracy and longer measurement campaigns, as well as new sensor integration on the buoy, adapted to carry out oxygen measurement in an environment very close to submerged archaeological structures. Similarly, new optical sensors are being developed for monitoring pH and different nitrogen derivatives (i.e., nitrate and ammonium).

Furthermore, novel nanotechnology-based coatings are being developed to contribute to preserving CH sites without compromising their authenticity. According to the chemical composition of the surfaces and the specific needs arising from each pilot site of TRIQUETRA, products will be developed to act as hydrophobic agents, corrosion inhibitors, chemically resistant barriers, UV-blockers, and anti-soil preventers. The above-mentioned characteristics, individually and/or synergistically, can act both in the repair and maintenance processes of CH sites. Materials for consolidation, cleaning, joining fragments, and filling that meet all relevant internationally existing criteria will be applied to sound and artificially weathered specimens. Treated and untreated specimens will undergo accelerated weathering (wet-dry cycles, soluble salt crystallization, and freeze—thaw cycles) in order to assess their suitability and effectiveness. The identification of the organisms and microorganisms that have been developed on ancient materials, their possible evolution due to changes in the conditions in the environment of the monuments, the selection of suitable biocides, and the evaluation of their suitability and effectiveness are of particular interest and constitute a challenging task. Based on the results of the laboratory examination, the current criteria in the field, and the long-term relevant experience, possible future further risks will be investigated, and proposals will be made, in the context of the TRIQUETRA project, for effective interventions.

2.5. Earth Observation Methods

Remote sensing has revolutionized CH monitoring, with Earth Observation data acquired from space often exploited to recover previously unknown information following the identification of patterns therein. It is the case of crop marks analysis for the detection of buried structures [10], large area analysis of phenomena such as the nazca lines [11], and the discovery of previously undocumented settlements [12]. On other occasions, the detection of changes in a multitemporal image time series can reveal damage to monuments [13] and phenomena such as looting [14]. Remote sensing relies on a range of sensors and platforms to acquire information in a non-invasive way, without restriction due to the accessibility of the sites or their vulnerability, and with a revisit time and area coverage very difficult to obtain with ground-based systems. On the other hand, data acquired in situ are often more reliable and precisely geolocated and can be used to calibrate, validate, and integrate the information obtained from remote sensing techniques.

In TRIQUETRA, specific focus is given to the monitoring of environmental factors and associated observable consequences that pose potential risks to CH sites and their immediate surroundings. These changes, ranging from ground deformation and coastal erosion to water constituent change and climatic variations, can significantly impact the structural integrity and longevity of the sites. In this context, both active and passive remote sensing technologies play crucial roles in TRIQUETRA for the estimation and mitigation of the associated risks.

Active sensors emit energy and measure the response that is reflected from a target on the ground. Synthetic Aperture Radar (SAR), for instance, utilizes microwaves to precisely detect ground movements in time through a process called interferometry (InSAR), providing detailed information about subsidence, uplift, structural stability, and landscape changes around CH sites (e.g., Choirokoitia site) [15]. Furthermore, SAR is crucial for monitoring floods and tracking water dynamics, providing critical information on the extent and impact of floods on historical sites and artifacts, and observing both short- and long-term changes (e.g., Smuszewo). Both sonar, an active acoustic sensing method, and lidar using laser beams to measure distances [16], can be used for underwater mapping, offering insights into water dynamics, three-dimensional modeling, and bathymetry [12,17].

Their application in TRIQUETRA focuses on underwater CH sites (Epidaurus, Roseninsel, and Les Argilliez).

Passive sensors measure the backscattered solar radiation from a target on the ground. Multispectral systems acquire images in an extended range with respect to the frequencies to which the human eye is sensitive, usually including infrared measurements, and excel in several applications such as mapping of water constituents, ground cover type, vegetation health, and damage in the aftermath of extreme events such as wildfires. In these systems, a tradeoff, depending on the phenomenon to be observed, must be set between the desired revisit time and spatial resolution. As an example, missions such as Sentinel-2 are capable of providing images at the highest resolution of 10 m approximately every five days [18], while the Moderate Resolution Imaging Spectroradiometer (MODIS), as the name suggests, has a maximum spatial resolution of only 250 m but can provide global coverage approximately every 12 h [19]. The former is used in TRIQUETRA to monitor long-term coastline changes and coastal erosion (e.g., Aegina, Ventotene), water quality (Epidaurus, Roseninsel, Les Argilliez), drought analysis (e.g., Roseninsel), and the spread of invasive species on lake bottoms (e.g., Les Argilliez), while the latter yields an extended time series of snow cover characteristics (e.g., Kalapodi). Finally, hyperspectral sensors such as EnMAP [20] or DESIS [21] measure the reflected solar radiation in hundreds of contiguous and narrow spectral bands and naturally excel at detecting water eutrophication and retrieving water constituents and depth with increased accuracy and additional information with respect to multispectral systems, in spite of the limited spatial resolution, usually achieving a maximum of 30 m (Roseninsel, Ventotene). High-resolution hyperspectral data acquired from airborne sensors can instead reach sub-meter spatial resolution and be used to produce detailed wildfire fuel mapping in the proximity of a sensitive site and characterize the present materials and their concentration in each pixel (Choirokoitia). Furthermore, both SAR and optical data can be processed to derive Digital Elevation Models (DEMs) of the sensitive sites and enable a 3D representation of the surrounding area [22].

Remote sensing technologies, therefore, provide continuous and comprehensive data to assess different threats to TRIQUETRA pilot sites. By integrating active and passive sensors and ensuring sufficient spatial and temporal resolution in the resulting multi-modal datasets, the chosen pilot sites can be analyzed holistically. This allows for informed decision-making and proactive conservation measures to help extend, in general, the longevity of CH sites in the face of evolving environmental challenges.

3. Preliminary Results

3.1. TRIQUETRA Knowledge Base

3.1.1. Data

Investing in the knowledge base platform of TRIQUETRA, the consortium focused on two main actions, namely (i) the documentation of numerous culturally significant cases across Europe and the globe, all of which face the looming threat of climate change, and (ii) the gathering of existing environmental and climatic data from the eight European pilot studies of the TRIQUETRA project. Experimentation with innovative monitoring and mitigation approaches addressing the climate change-induced threats of the pilot case studies will also be added in the near future.

The first action concerned the establishment of a comprehensive, easily accessible digital database including vital information concerning CH sites, monuments, artifacts, and landscapes. This initiative was particularly focused on comprehending the diverse range of risks posed by climate change, monitoring techniques employed, and mitigation strategies selected by experts to safeguard these invaluable cultural assets from further future deterioration. A total of 597 pilot case studies were documented and curated from 229 selected published online sources, including European and international projects, books/doctoral theses, national initiatives, and articles in scientific journals. A dedicated section named “Big Projects” was created, focusing on large-scale projects such as European and global initiatives specifically examining the impact of climate change on CH sites across a range of vast regions, including countries, continents, oceans, and even global assessments. This categorization mirrored the approach applied to individual case studies, with a focus on the study areas, types of monument(s), historical period, site characteristics, risk factors, monitoring methodologies, mitigation strategies, and the surrounding natural environment. Twenty types of monuments were reviewed, with historic buildings (149) and archaeological sites (121) being the most frequently reviewed case studies [7].

The above review mapped the status quo of the initiatives taken mainly by the European Union and other national agencies. These, as well as individual studies on this challenging topic, revealed the strengths, weaknesses, and gaps that exist in understanding the vulnerability of our CH assets. It is noticeable that climate change and natural hazards will affect our CH on a global scale, manifesting differently in discrete parts of the world alongside anthropogenic threats and pressures. The analysis of our survey indicated that there is an uneven distribution of case studies globally, with most of them falling within the European continent and North America. However, significant evidence of past anthropogenic activity that has left its imprint on different sites and environments exists worldwide, and we also need to consider it. Therefore, it is essential to continue our efforts in this direction and make our work more efficient for the future.

Archaeological data collection for the TRIQUETRA pilot sites focused on obtaining aerial and satellite images, excavation plans of the pilot sites, digital elevation models, and 3D models. Environmental data included geological maps, concentrations of nutrients and heavy metals in soils, seismic and tectonic activity, hydrological data, isobaths, and other related information. The specific data were organized in a geodatabase, which has been supplemented by a Web GIS application with geographical search capabilities.

3.1.2. Platform

The TRIQUETRA knowledge base platform (KBP), which is part of the TRIQUETRA DSS, incorporates two distinct components: a database containing the outputs of the literature review conducted in the context of the project and a WebGIS platform containing all relevant data for the pilot CH sites of the project (Section 3.1.1). Essentially, the KBP serves as an electronic repository covering a diverse range of data and is also equipped with advanced search tools, enabling users to efficiently search for and discover relevant information within the stored datasets.

The main objective of the TRIQUETRA KBP is to comprehensively integrate and visualize all the data shared by the partners within the project, leveraging both a searchable database of literature and a sophisticated WebGIS platform, adhering to Open Geospatial Consortium (OGC) and Infrastructure for Spatial Information in Europe (INSPIRE) standards.

All data provided by the partners of the consortium is stored in a dedicated secure repository, namely, a NAS Server. This repository aims to enable robust information flow among the various TRIQUETRA components, i.e., the KBP as well as the DSS platform. Then, the NAS Server feeds the WebGIS component of the KBP with all heterogeneous kinds of data related to the pilot CH sites of the project. Moreover, the KBP integrates EU services along with in-situ observation services used by the partners throughout the work carried out (e.g., Copernicus services).

Regarding its architectural design, the KBP adopts a dual-front-end architectural approach, splitting the user interface (UI) layer into two distinct parts: the Bibliography and the WebGIS. The decision to split the UI into two distinct components was driven by the need to conform to the diverse user needs we might face. With this division, varied user preferences are acknowledged when interpreting data, while also recognizing the need for specialized tools for spatial data visualization in the form of a WebGIS platform.

Aiming to establish a data exchange framework that is harmonized with the European directives (e.g., INSPIRE), a Geoserver v. 2.23.1 Docker image has been installed. The connection between the NAS HUB and the GeoServer is achieved by a developed processing engine written in Python3 and using widely used Python libraries (e.g., GeoPandas, GeoServer-rest, SQLAlchemy, etc.) that execute a recurring scheduled processing workflow.

Regarding the interface of the KBP, once the user enters the platform, the loading screen appears, and then the homepage of the platform is accessible, displaying the two components (Figure 4a). Then, depending on the component that the user selects, either the main interface of the TRIQUETRA Bibliography component (Figure 4b) or the main interface of the TRIQUETRA WebGIS (Figure 4c) appears.

Figure 4. The TRIQUETRA knowledge base platform: (**a**) the homepage; (**b**) the main interface of the TRIQUETRA Bibliography component; (**c**) the main interface of the TRIQUETRA WebGIS.

A data table is an efficient format for data analysis and visualization. When handling large amounts of data, it is very important to have a tool that visualizes them and conveys their sense of scale without resorting to displaying them with just a number. At the same time, a graph, a chart, or a visual aid is just as important when handling large-scale data. The bibliography page consists of a tabular view of the data collected and also provides an interactive map to aid in its visualization, thus creating a simple yet effective view of the data. The table contains a detailed description of each paper and its every variation, while the table groups them based on their geographical significance.

A WebGIS provides the user with the right tools to create insights and predictive modeling to support decision-making policies, such as risk assessment and prevention. The TRIQUETRA WebGIS platform uses MapBox GL to display geospatial data and layers gathered by researchers on the project. The platform uses an algorithm to convert data into nested components that simplify the navigation of layers and point clouds for the user and give the platform a more simplified look without any data loss. The platform shares its navigation tools with the bibliography map, like move, zoom, tilt, and search, but offers a plethora of tools to the user that are not available in the Bibliography component.

In conclusion, the KBP will keep being maintained and updated with new datasets throughout the course of the TRIQUETRA project. Taking into consideration that not all the types of data that will be produced throughout the project have been strictly determined, additional tabs and options might need to be integrated into the TRIQUETRA KBP, especially into the WebGIS component. The KBP will also contribute to the TRIQUETRA DSS, which will enable a better decision-making process for risk mitigation and remediation of at-risk CH sites beyond the case studies of the project and become a node of reference for how particular monitoring and mitigation practices have addressed specific climate change threats in different cultural and environmental contexts.

3.2. Risk Identification

3.2.1. Climate-Related Hazards

Recent Past and Future Climate Change at Pilot CH Sites

For the scope of the project, meteorological data from weather stations (observations) as well as simulations from regional climate models (RCMs) have been analyzed in order to assess present and future climate change towards the identification of the related risks on the CH sites of interest (from south to north: Choirokoitia in Cyprus, Aegina, Epidaurus, and Kalapodi in Greece, Ventotene in Italy, Les Argilliez in Switzerland, Roseninsel in Germany, and Smuszewo in Poland). The station data were acquired from different networks, which included stations with long meteorological records at the proximity of the selected CH sites (no data are available for Ventotene) and refer to 7 Essential Climate Variables (ECVs), namely, precipitation (PR), near-surface temperature (TAS), daily surface maximum (TASMAX) and minimum (TASMIN) temperature, relative humidity (RH), downwelling solar radiation (RSDS), and near-surface wind speed (WS).

A multi-model ensemble (11 models) from various RCMs driven by various Global Climate Models (GCMs) was produced based on datasets of 11 sets of EURO-CORDEX (Coordinated Downscaling Experiment—European Domain; https://www.euro-cordex.net/, accessed on 1 December 2023) high-resolution (~12.5 km) RCM simulations covering the historical period 1950–2005 and the future period 2006–2100 for three (3) different future scenarios (a total of 44 simulations) [23,24]. The examined scenarios refer to three (3) different Representative Concentration Pathways (RCPs) of the Intergovernmental Panel on Climate Change (IPCC) with different levels of future mitigation measures for greenhouse gases (GHGs), namely RCP2.6 (strong mitigation), RCP4.5 (medium mitigation), and RCP8.5 (no further mitigation). For the RCM data, the same ECVs are examined with the station data but with specific humidity (HUSS) instead of RH. The grid cell closest to each CH site is selected.

For both the observations and RCM data, 8 relevant climatic indices (hot days—HD; frost days—FD; diurnal temperature range—DTR; very heavy precipitation days—PD20; simple daily intensity for very heavy precipitation days SDII20; highest 1-day precipitation amount RX1DAY; consecutive dry days—CDD; and consecutive dry days periods—CDDP) have been calculated on an annual basis for the period 1971–2100. HD expresses the number of days within a year with TASMAX >35 °C, FD number of days with TASMIN <0 °C, DTR expresses the annual mean of the daily differences between TASMAX and TASMIN, PD20 expresses the number of days within a year with PR >20 mm, SDII20 is the annual mean PR for days with PR >20 mm, RX1DAY is the PR for the day with the highest precipitation in a year, CDD the largest number of consecutive days within a year with PR <1mm and CDDP is the number of dry periods of more than 5 days within a year.

Based on the analysis of ECVs and climate indices produced from the observational and RCM model data at the CH sites, a set of heatmaps are presented here for a holistic assessment of climate change: (a) in the near past by comparing observations of the recent past period 2001–2020 with 1971–1990 on an annual basis (Figure 5), and (b) in the future by comparing modeled data (multi-model means) of the near future period 2021–2050 or the end of the 21st century period 2071–2100 with respect to the reference historical period 1971–2000 for the three difference RCPs (Figure 6). The statistical significance of the results at the 95% confidence level is indicated by using a two-tailed t-test.

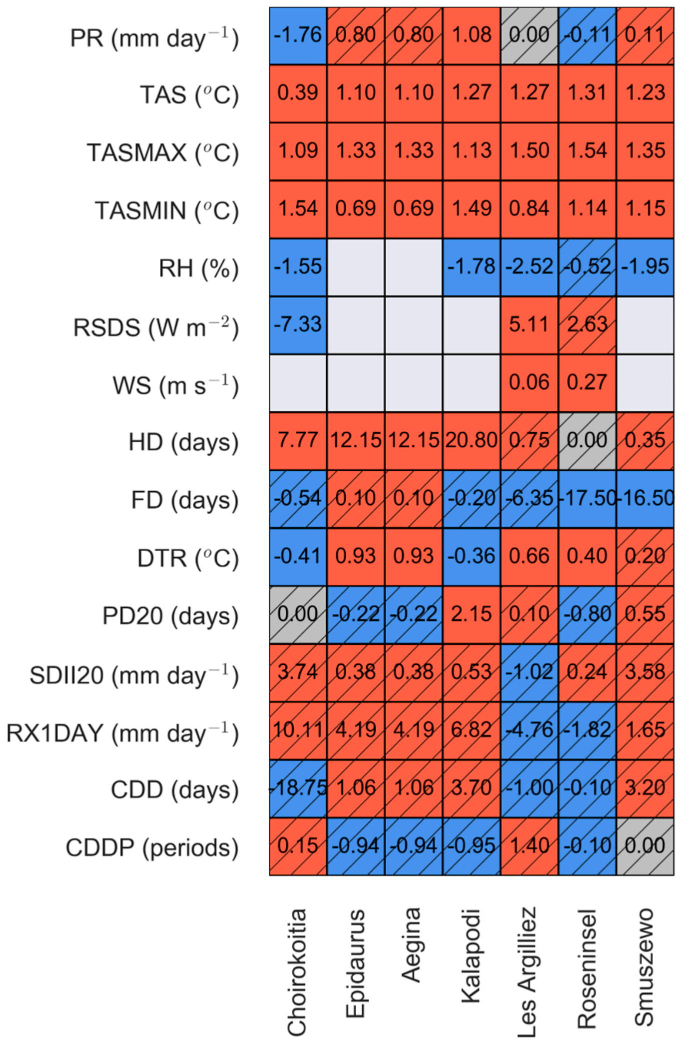

Figure 5. Climate parameters and indices differed between the early (1971–1990) and late (2001–2020) past periods for the examined CH sites. The red color indicates positive, blue negative, and gray zero differences. Non-shaded boxes indicate statistically significant results at a 95% confidence level.

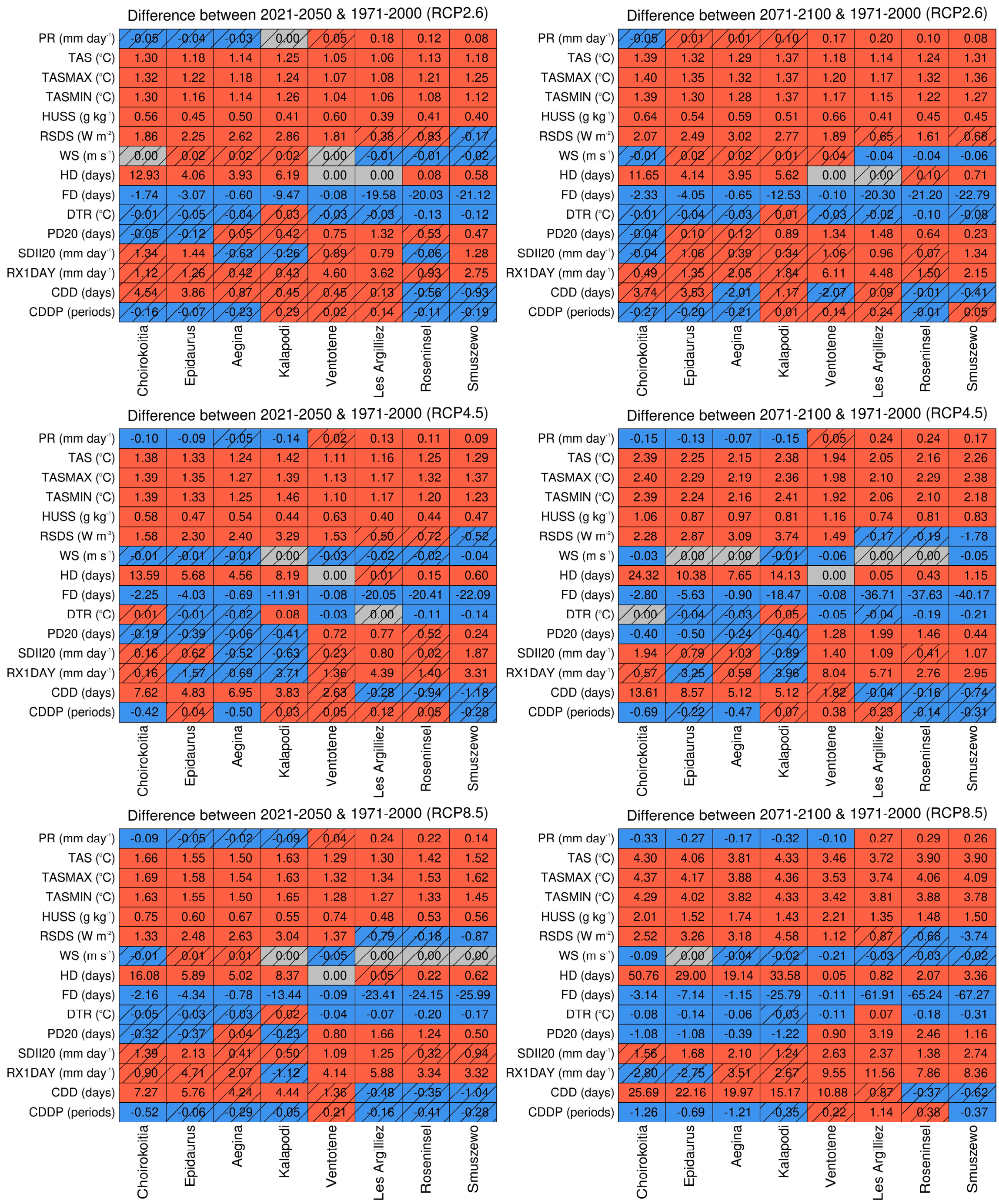

Figure 6. Heatmaps with the differences between the periods 2021–2050 and 1971–2000 (left column) and 2071–2100 and 1971–2000 (right column) under RCP2.6 (upper panels), RCP4.5 (middle manels), and RCP8.5 (lower panels) of all the examined ECVs and climatic indices within TRIQUETRA. The red color indicates positive, blue negative, and gray zero differences. Non-shaded boxes indicate statistically significant results at a 95% confidence level.

According to the weather station observations (Figure 5), an increase in TAS is observed over all the selected CH sites from the period 1971–1990 towards the period 2001–2020. Among the examined CH sites, the highest TAS increase is observed at Roseninsel, reaching 1.31 °C. Overall, the TAS increase at the CH sites ranges from 0.39 to 1.31 °C. Regarding TASMAX, an increase is observed at all CH sites, ranging from 1.09 to 1.50 °C. The highest increase (~1.5 °C) is seen at the Roseninsel and Les Argilliez CH sites. TASMIN increases at all CH sites with a range from 0.69 to 1.54 °C, with the maxima found at Choirokoitia and Kalapodi CH sites. Furthermore, hot days (HDs) have increased at all southern European CH sites, while for the rest of the CH sites, no significant change is observed, as the daily maximum temperature rarely exceeds 35 °C. An increase of about 21, 12, 12, and 8 days within a year is observed at the Kalapodi, Aegina, Epidaurus, and Choirokoitia CH sites, respectively. On the contrary, frost days (FDs) decreased at the central European CH sites due to the TASMIN increase. No significant change is found for the southern European CH sites, as TASMIN rarely falls below 0 °C. A decrease of about 18, 17, and 6 days within a year is observed at Roseninsel, Smuszewo, and Les Argilliez. DTR changes are driven by the extent of TASMAX and TASMIN increases. The highest increase is observed at the Aegina and Epidaurus CH sites (0.93 °C), while a decrease of ~0.4 °C is seen at Kalapodi and Choirokoitia, with the rest of the sites exhibiting increases ranging from 0.20 to 0.66 °C. Overall, the climate analysis (TAS, TASMAX TASMIN, HD) reveals a robust warming and increasing heat stress at the materials of the CH sites during the recent past period 1970–2020. As far as PR is concerned, statistically non-significant changes are observed at the selected CH sites except for Choirokoitia, which exhibits the highest decrease in PR. At the Southern European CH cites, there is a tension for an increase in the most extreme precipitation (the highest 1-day precipitation amount), but the changes are not statistically significant.

The comparison between the ensemble of the EURO-CORDEX RCM simulations and the observations at the selected CH sites indicates a satisfactory performance of the models capturing the observed climatic changes over the period 1971–2000 (not shown here). The EURO-CORDEX ensemble (multi-model mean) shows a clear increase in TAS, TASMAX, TASMIN, and HUSS and a clear decrease in FD across all the CH sites for all the RCPs for both the near-future and the end-of-the-century periods. The largest changes are projected for the end of the century under RCP8.5 (TAS increase of 3.5 °C in Ventotene up to 4.3 °C in Kalapodi, TASMAX increase of 3.5 °C in Ventotene up to 4.4 °C in Choirokoitia, TASMIN increase of 3.4 °C in Ventotene up to 4.3 °C in Kalapodi, HUSS increase of 1.35 g kg^{-1} in Les Argilliez up to 2.21 g kg^{-1} in Ventotene, and a FD decrease of −0.1 days in Ventotene up to −67 days in Smuszewo). DTR generally tends to decrease throughout all the scenarios. PR is generally projected to decrease over the sites in the South and increase over the sites in the North under RCP4.5 and RCP8.5 in the near future and at the end of the century, with the results being statistically significant almost everywhere at the end of the century. The largest changes are projected at the end of the century under RCP8.5, with Choirokoitia exhibiting a decrease of −0.33 and an increase of 0.29 in Roseninsel. PD20 is generally projected to decrease over sites in the South and increase over sites in the North. SDII20 is in general expected to increase under all the RCPs and periods, with some exceptions. RX1DAY in the future follows the increasing trends of PD, PD20, and SDII20 under RCP4.5 and RCP8.5 for stations in the North. CCDs are projected to increase over the sites in the South and increase in the North under RCP4.5 and RCP8.5, but the results are statistically significant at about half of the CH sites. CDDP does not necessarily follow CCD. Overall, the climate analysis points towards a hotter and drier future in the South and a hotter and wetter future in the North.

Towards Risk Identification Due to Climate Change at Pilot CH Sites

In order to assess the suitability of climates hosting heritage and to quantify the damage risk due to climatic conditions, the Heritage Outdoor Microclimate (HMR_{out}) and Predicted Risk of Damage (PRD) indices were applied following the approach of [4]. According to the literature, the Heritage Outdoor Microclimate (HMR_{out}) index is defined as the outdoor microclimate risk of CH and makes it possible to assess the risk related to the microclimate. Further details about HMR_{out} and PRD indices are also provided in the works of [4] and [25]. HMR_{out} is calculated according to Equation (1):

$$HMR_{out} = \left(\frac{HMR_{env.out} + HMR_{fluc.}}{2} \right). \quad (1)$$

Respectively, the PRD index is defined as a "forecast" of damage and assesses the ability of damage caused by the microclimatic conditions [25]. It depends on the microclimate, on the HMR index, and on the type of material. For the outdoor environment, the PRD index is calculated according to Equation (2):

$$\text{PRD} = 1 - 0.95 \times \text{e}(-^{\text{a} \times \text{HMRout\^{}4} - \text{b} \times \text{HMRout\^{}2}}). \quad (2)$$

The indices were applied to inorganic materials at the CH sites made of stone and marble for temperature. Using observational data from the recent past, the years characterized by Minimum-Low, Moderate-Medium, and High-Maximum risk for the temperature parameter were calculated for the periods 1971–2000 and 2001–2020, and their differences are presented in Figure 7. In general, the findings indicate an increased risk of microclimate impact on CH during the period 2001–2020. This is deduced from the reduction in years characterized by Minimum-Low risk and the increase in years with Moderate-Medium and High-Maximum risk. It is crucial to emphasize that the increase in temperature is closely linked to this increase in risk. More specifically, Kalapodi exhibits the highest increase in years with High-Maximum risk (38%) and a 37% increase in years with Moderate-Medium risk. In the regions of Aegina and Epidaurus, the years with High-Maximum risk increased by 18%, with a greater increase observed in years with moderate risk (37%). Similarly, significant increases were observed in the years with High-Maximum risk in Choirokitia, while a smaller increase was noted in Moderate-Medium risk years (5%). Similarly notable increases were observed in the years with High-Maximum risk in Choirokoitia, while a smaller uptick was recorded in Moderate-Medium risk years (5%). Furthermore, the PRD index (not shown here) indicated that the likelihood of damage to CH increased on average by 26.5%. These findings emphasize the vulnerability of CH to the impacts of climate change, underscoring the critical need for additional research on future climatic conditions.

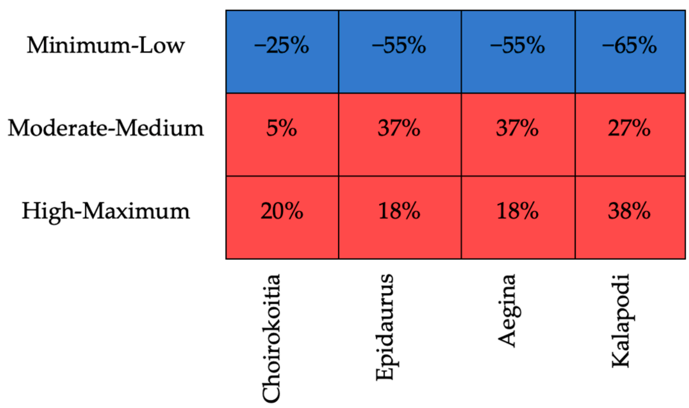

Figure 7. For each risk category, the differences between the early (1971–2000) and late (2001–2020) past periods for the examined CH sites. The percentages represent gains or losses among the total years.

The multi-model ensembles of RCM simulations for the three different scenarios (RCP2.6, RCP4.5, and RCP8.5) will be assessed to evaluate the future HMRout and PRD indices for two climatic variables, Temperature and Relative Humidity. According to the literature, a potential change in these two climatic parameters could have significant impacts on monuments [26,27]. Analyzing the changes in these two critical parameters will provide a more comprehensive understanding of how the resilience of materials and the overall preservation of CH sites constructed from stone and marble may be affected.

Sea Level Rise Effects on Coastal CH Assets

In situ and Earth Observation data show that the global sea level is rising faster than in previous centuries, and its rising rate has accelerated in recent years. On a global level, radar altimeters and tide gauge data indicate an increase from 1.7 mm/yr in the 20th century to 3.2 mm/yr for the last two decades, in coincidence with the rise of global temperatures. Recent sea level rise projections predict an increase of approximately 1 m in sea level globally based on different types of scenarios [28–30]. Because of climate change, the global mean sea level is expected to increase from 75 to 190 cm by 2100 [31].

Global climate change is a main factor of risk for infrastructure, CH, and people living along the coasts around the world. Sea level rise poses serious threats to coastal zones. In order to assess the expected coastal changes for the next few decades, detailed knowledge of each site's topography (coastline position, DTM-Digital Terrain Model, bathymetry) is needed. In addition, in order to enhance the estimation of the affected areas of a site, local vertical land movement should also be taken into account.

As a result, the production of maps estimating the effect of sea level rise on coastal areas highly depends on the accuracy and resolution of the DTM, the coastline, the vertical land movement, and the sea level rise prediction scenarios. In the development of our approach, open datasets are being used for the creation of maps showing the effect of sea level rise. With respect to DEM (Digital Elevation Model), we are mainly using the Copernicus EU-DEM, while for regions that are not covered by it, we are using the NASADEM [32]. Regarding the local vertical land movement, we are currently exploring how we are going to exploit the data provided by the European Ground Motion Service (EGMS), which provides ground movement across Europe with millimeter precision using Synthetic Aperture Radar Interferometry (InSAR) data derived from Sentinel-1. In addition, the predictions provided by the IPCC 2022 report [33] for the scenarios of RCP 2.6, RCP 4.5, and RCO 8.5 are being used for the estimation of sea level rise in 2050 and 2100. Finally, using high-resolution and accuracy DEM and coastline models, along with the information provided by the EGMS, we will produce maps of the sea level rise-affected areas in the pilot sites of Aegina and Ventotene.

3.2.2. Extreme Water Hazards

One of the identified water hazards for the coastal pilot sites are extreme waves that can intensify due to stronger winds affected by climate change. Such waves can cause gradual erosion of sandy shorelines, failure of rocky cliffs, like the one observed at the CH site of Ventotene, or inundation of whole coastal sites and damage to the structural components (e.g., potentially at the site of Aegina). In order to decipher the observed geological damage of the Ventotene cliff, preliminary computational fluid dynamics (CFD) models were developed using two-dimensional cross-sections, as shown in Figure 8. As a first step, the closest gauge of the National Tidegauge Network [34] was identified, which is referred to as the Ponza station. This gauge is located about 40 km from Ventotene and was installed in 2021. In fact, post-processing of the measurements revealed that the tide was brought into operation on 24 May 2021, and had about 35,600 data points. Using the recorded time histories of wave heights (Hs) and wave periods (T), the maximum values were determined, which corresponded to approximately 6.8 m and 11.5 s, respectively. In addition to the maximum values, several other combinations of (Hs, T) were determined (see Figure 8, center) in order to identify the potentially most threatening conditions. It is noteworthy that although intuitively the maximum waves are the ones with the largest expected probability of damage, this might not be the case since the actual local damage will be affected by the wave type, the location of wave breaking, the soil type, the cliff geometry, and even the combination/sequence of waves that reach the cliff. In the preliminary analyses, a few combinations of (Hs, T) were used as a boundary condition for the CFD model; however, more wave conditions are currently being investigated.

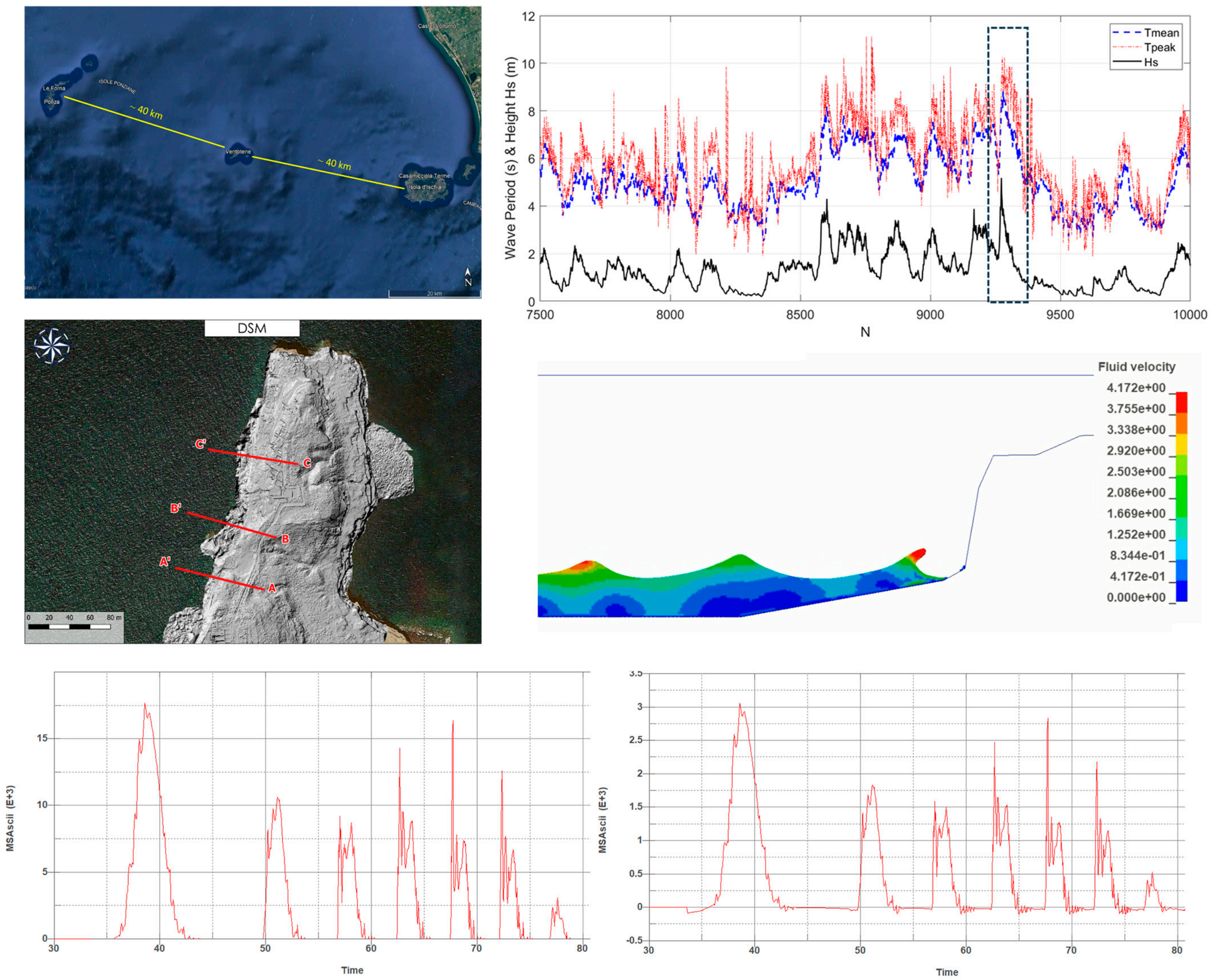

Figure 8. Location of wave measurements at Ponza Station and identified wave heights with respective wave periods (**top**), digital surface model with three critical cross-sections (A'A, B'B and C'C) and computational fluid dynamics model for cross-section A'A (**center**), and numerically predicted hydrodynamic forces on the Ventotene Cliff (**bottom**).

For the hydrodynamic modeling of this study, a mesh-based high-fidelity CFD method that uses an incompressible fluid assumption and has been validated in [35] is utilized. The hydrodynamic solver is based on the Finite Element Method (FEM) and solves the Navier–Stokes (NS) equations together with the continuity equation, which can be represented by the set of Equations (3) and (4):

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial p}{\partial x_i} + \mu\frac{\partial^2 u_i}{\partial x_j \partial x_j} + \rho f_i \quad \text{in } \Omega \tag{3}$$

$$\frac{\partial u_i}{\partial x_i} = 0 \quad \text{in } \Omega \tag{4}$$

where u_i is the velocity in the i-direction, p_i is the pressure in the i-direction, ρ is the density of fluid, and μ is the fluid dynamic viscosity. To solve the above set of differential equations, boundary conditions and initial conditions are specified based on prior analyses or existing measurements. Moreover, additional equations are used to describe the turbulence models. For the time integration of the above equations, the code uses the fractional step method, a projection method in which the pressure and velocity are uncoupled. In free-surface and multi-phase problems, the moving interface is simulated via a level-set method. This type of CFD model can capture transient wave propagation and the most complex physical phenomena that include the nonlinear transformation of the waves as they approach the coast and interact with the bathymetry (shoaling process), the reflection phenomenon, the wave-breaking process, and the wave-structure interaction.

Using the CFD solver, two-dimensional models were built for three cross-sections (AA′, BB′, and CC′) of the Ventotene cliff that were pre-identified as essential. Preliminary results are shown in Figure 8. Interestingly, the wave impact process seems to present different trends, with the wave impacting violently the cliff in some cases and, in other cases, just propagating smoothly over the slope of the cliff, generating different hydrodynamic effects. This can also be observed in the force histories, which consist of both high-impulsive peaks and longer-duration components. These high-magnitude and short-duration peaks are expected to cause different internal stresses inside the rock than the longer-duration forces and therefore will require different types of mitigation. Interestingly, the cliff witnesses both horizontal and uplift forces, the combination of which could exacerbate the overall effects and risk for the coastal site and therefore should be considered in risk assessment frameworks and decision support tools. It is expected that the ongoing CFD analyses and careful post-processing of the data will help decipher the hydrodynamic effects in relation to the incoming wave conditions and the geometry of the cliff (cross-section). Moreover, the same CFD method is currently being used for assessing the wave and tsunami impact on the other coastal site (Aegina) and the underwater site (Epidaurus), while more advanced particle-based and coupled methods like the explicit Smoothed Particle Hydrodynamics—FEM [36] will be used to investigate the cascading effects of water hazards; and particularly the water-borne debris.

3.2.3. Snow and Ice Hazards

Snow cover is crucial in determining local water availability and river runoff [37]. However, it also presents challenges for the preservation of archaeological sites, often characterized by fragile materials and structures, making them vulnerable to erosion and erosive forces caused by rapid snowmelt and snowmelt runoff. In the face of climate change and unpredictable weather extremes, a comprehensive understanding of the relationship between snow cover (snow melt) and erosion is essential for sustainable conservation practices. Anticipated significant changes in snow cover, such as declines or increases in snow cover duration and snow depth, are expected due to global warming, an increase in temperature anomalies, and extreme weather events [38].

Against this background, monitoring snow cover can deliver routine information for developing effective site management, thus ensuring the resilience of archaeological sites as a result of snowmelt-induced erosion. In this context, space-borne Earth Observation (EO) provides valuable continuous monitoring capabilities for large-scale mapping of snow cover and the analysis of long-term trends. Therefore, EO methods and optical satellite time series imagery are used to examine long-term seasonal characteristics for a CH site in order to identify interannual changes in snow cover extent and determine whether there are seasonal patterns of trends in the snow cover area.

For the CH site of Kalapodi, Greece (Figure 9), high-resolution snow cover time series were collected and pre-processed over a larger area of the archaeological site. Initial analyses of the snow cover area were conducted utilizing daily snow cover products from the DLR Global SnowPack processor. This processor generates cloud-free binary masks for snow-covered areas by utilizing time series data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on Terra (MOD10A1.006) and Aqua (MYD10A1.006), offering a spatial resolution of 500 m and daily temporal resolution. In a second step, the daily binary snow cover products were pre-processed, reprojected, and aggregated into composites for each month and year, covering the period from 2000 to 2022. The monthly and annual composites characterize fractional snow cover areas in percent.

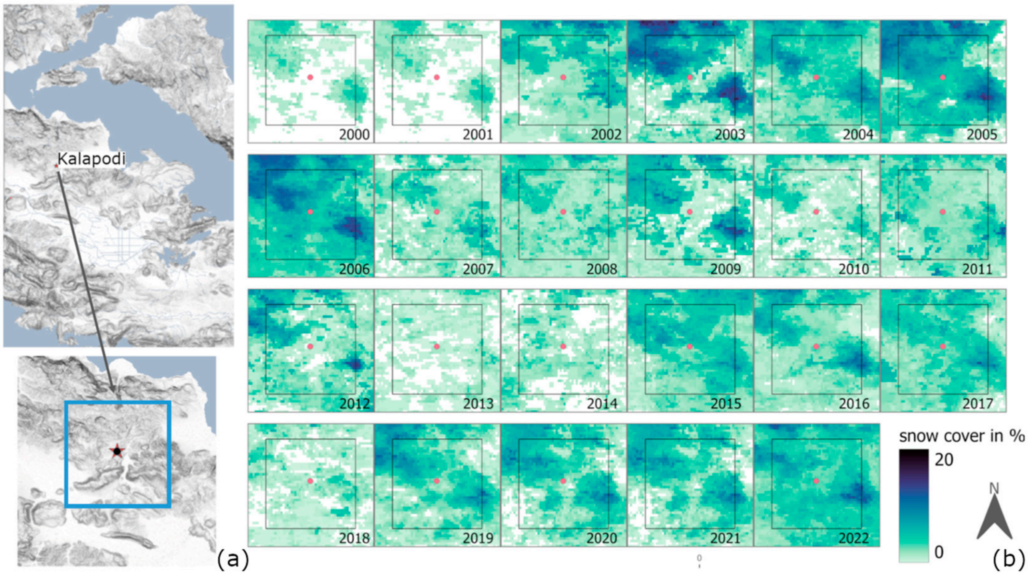

Figure 9. (**a**): Location of the CH site Kalapodi; (**b**): Preliminary results: Mean annual snow cover for the Kalapodi site (red point; incl. surrounding area: 260 km^2) for the period 2000–2022.

Figure 9 illustrates snow cover area progression through annual averages from 2000–2022, revealing a higher occurrence of snow cover in the northwest and eastern regions of the greater site. Utilizing long-term snow cover data at various temporal (e.g., daily, monthly, yearly) resolutions, multidecadal daily and monthly averages of snow cover data were calculated to identify temporal trends of snow cover means (Figure 10) and long-term monthly means of snow cover (Figure 11a,b). The site encompasses not only the CH site but also its surroundings, covering a total of 260 m^2. During the months December to February, the mean monthly snow cover area accounts for 30% to 35% (in the months February and January), while the dry, hot summer months show no snow cover.

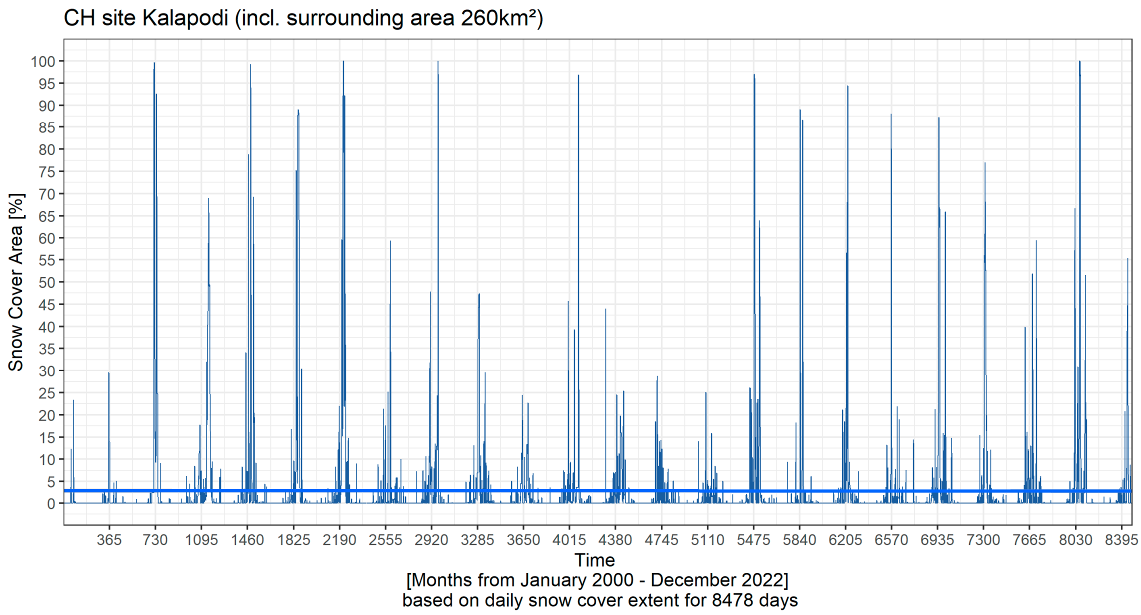

Figure 10. Preliminary results: Trend of snow cover area for the period 2000–2022 based on the daily snow cover for the CH site Kalapodi and its respective surrounding area (260 km^2).

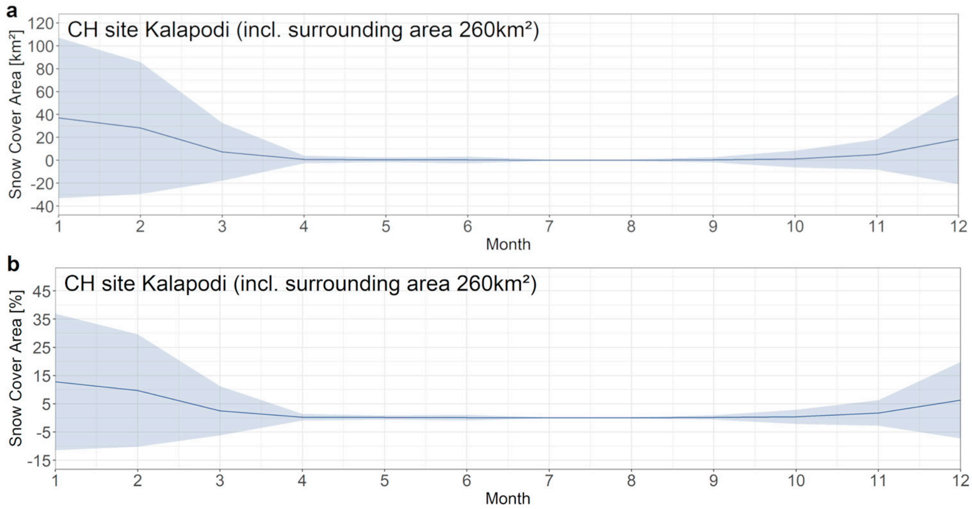

Figure 11. Preliminary results: Mean snow cover area in km^2 (**a**) and % (**b**) derived from daily snow cover extent for the CH site Kalapodi based on monthly means (1 = January to 12 = December) for the period 2000–2022.

The EO time series characterizing snow cover area, combined with further geospatial time series on climatic and hydrological variables, will be further investigated. These can be used to delineate relationships between climate model data and EO-derived snow cover trends.

3.2.4. Geological and Geophysical Hazards

The geological conditions characterizing each CH site have been investigated in order to identify the most relevant geological hazards connected to environments that can pose direct or indirect risk conditions for the safe access and fruition of the historical and archaeological heritage.

Starting from a systematic inventory and review of the available databases at European and national levels, an expert-based evaluation was performed to identify which Type of Process (ToP) (i.e., geology-related hazard) affects the CH sites. A total of nine principal ToPs have been selected. Some of the ToPs are relevant for all the CH sites (e.g., seismic, wind, weather events), while others are only active for some CH sites (e.g., floods, wildfires, tsunamis). Landslides, Geotechnical Subsidence, and Weather Events processes were also subclassified in other secondary ToPs. In fact, these processes deserve special attention since they contain in their meaning of "primary" ToPs a plethora of different subcategories of "secondary" kinds of processes. For these reasons, the landslides ToP was subcategorized considering the secondary ToPs of "Falls", "Slides", and "Flows"; for the Geotechnical Subsidence primary ToP the "Static" and "Dynamic" subsidences were considered secondary ToPs, while for the primary Weather Events ToP "Heat wave" and "Frost days" events were considered secondary ToPs.

A Severity Index (SI) was associated with each ToP in order to express its effect and, therefore, its action. The SI is a parametric characterization index of a geological hazard. It represents a factor to depict the effect related to the occurrence of a specific geological event. In most cases, SI coincides with the unit of measurement that better describes the geological event and its occurrence (e.g., the Peak Ground Acceleration (PGA) for earthquakes or the Wind Velocity for the wind), so it is a quantitative parameter. For some cases, a qualitative index was assigned as SI; this is the case of the Dynamic Geotechnical Subsidence due to which difficulties have been encountered in associating a quantitative parameter to the geological hazard. In any case, the SI was assigned to describe, as best as possible, the effect of the geological event. The SIs were classified into four classes using an expert judgment approach. The SI entity was checked for each CH site, making it possible to evaluate the SI distribution in the context of the different case studies.

The ToP characterization was carried out not only within the boundaries of the archaeological excavations but also considering an Area of Interest (AoI) around each archaeological site. For several processes, like hydraulic risk related to potential flooding, it is not sufficient to focus the hazard analysis on a restricted area since the standard practices of risk identification do not recommend a punctual analysis but a wider observation window. All the AoIs were delimited using a physiographic unit approach (Figure 12). In particular, in a GIS environment, a watershed area analysis was carried out around each CH site; by this way, an area within which the entire drainage network is enclosed was delimited. The AoI is a crucial physiographic unit since it drives, delimits, and controls several geological events, such as floods and landslides. This means, for example, that a landslide activation or a flooding event can affect only the territory bounded by the watershed area (i.e., by the AoI), including the CH site.

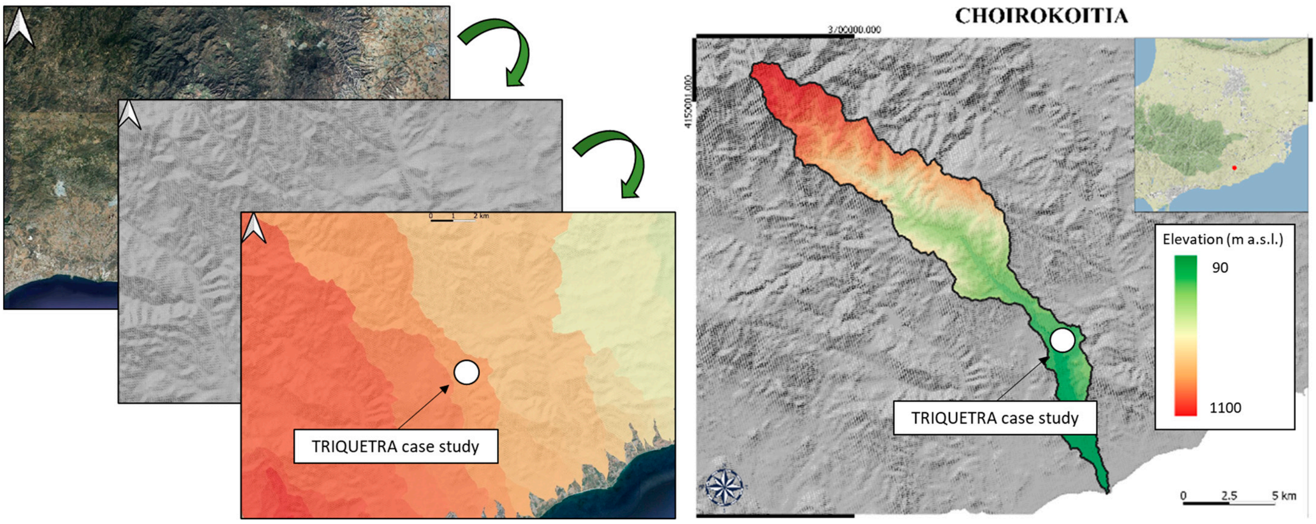

Figure 12. Physiographic unit analysis example framed for the Choirokoitia CH site.

In some cases, in situ surveys were also conducted to further investigate the geological characteristics of some CH sites. This was conducted to identify hazard processes at a large scale of detail, where the size of the produced effects (e.g., minor landslides) is too small to be quantified by regional or national scale studies.

A Geohazard Severity Chart (GSC) was thus drafted for each CH site in order to systematize all the collected information related to the geological hazard conditions of the archaeological sites. The GSCs are designed using a matrix approach where a Type of Process (ToP) and a Time of Recurrence (ToR) are used as input components to describe different geological events' scenarios. The ToR is the GSC component referred to as the time span considered an interval of analysis. ToR has to be intended as the time interval within a geological event that can occur with a magnitude defined by the related Intensity Level (IL). In other words, the ToR strongly influences the hazard of the natural process and, as a result, the probability that a natural event, characterized by a specific magnitude, will strike an exposed element in a defined time window. For the present study, different ToRs have been proposed, varying from decennial to millennial scales, in order to define different severity scenarios for each ToP. By crossing the ToP and ToR components, it is possible to define the Intensity Level (IL) related to the occurrence of a specific geological event.

In the GSCs, four IL classes are defined (low, medium, high, and very high), and they are represented with a semaphoric chromatic scale (green, yellow, orange, and red) (Figure 13). "Not Considerable", "Not Detectable" and "Indirectly" were added as supplementary IL classes. In fact, not all the ToPs are active at each CH site. This is, for example, the case of the sea or lake dynamic-related ToP (i.e., Waves, Tsunamis) that influences only the coastal CH sites. For these cases, the assignment of a "Not Considerable" class has been attributed to the CH site. The "Not detectable" class has been assigned to all the cases for which it was not possible to analyze a specific hazard scenario. This complication has occurred for several ToPs for which defining an Intensity Level (IL) for too many time windows is very difficult at this stage of the study based on the available data. Several scenarios fall into this category, such as the IL associated with landslides, Geotechnical Subsidence, Wildfires, Weather Event Waves, and Wind. Following this approach, it is not necessarily the case that all the ToPs directly involve the CH site. In fact, as mentioned above, around each archaeological site, an Area of Interest (AoI) was defined. So, it is possible that a natural process is activated in the AoI but not directly involved in the CH site. To distinguish this kind of situation from the others where the ToPs influence directly the CH site, the adjective "Indirectly" was associated with all the classes for which the ToPs do not directly involve the CH site; an asterisk (*) was then associated with these cases.

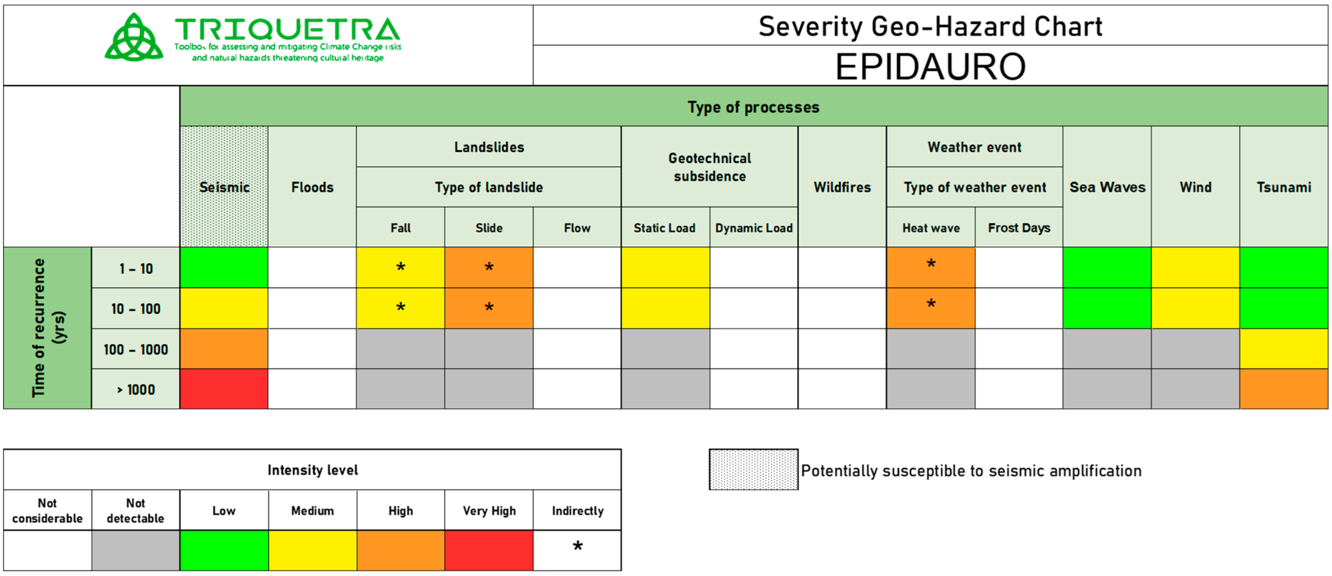

Figure 13. Example of Geohazard Severity Chart (GSC) derived for the Ventotene CH site.

By consulting the GSC, it is possible to qualitatively evaluate the geological process hazard. In fact, combining the ToP with the Time of Recurrence (ToR) gives the hazard of a specific geological process acting on a selected CH site.

Based on the GSCs, for each pilot CH site, the three most relevant geological hazards have been ranked, referring to the time of recurrence with a decennial periodicity (Figure 14).

3.2.5. Chemical and Biological Hazards

Chemical and biological risks to CH sites (a.k.a., chem/biohazards) discussed in this section include those located underwater and near shorelines and/or coastlines. The sites of Les Argilliez, Roseninsel, and Epidaurus are representative examples of this type of CH site within the TRIQUETRA project.

In general, submerged CH sites are exposed to aqueous chemical processes or influences related to metabolic processes associated with aquatic biological species. It should be noted that the chemistry associated with these processes/influences is also dependent on the material characteristics of the CH sites. Hence, the ultimate effects of such processes cannot be generically derived but need to be reviewed in the context of any CH location and its specifics, as indicated in Figure 15. In the remainder, we will briefly discuss carbonate chemistry as an illustrative example of a chemical hazard, the complexity of this, and similar chem/bio hazard scenarios.

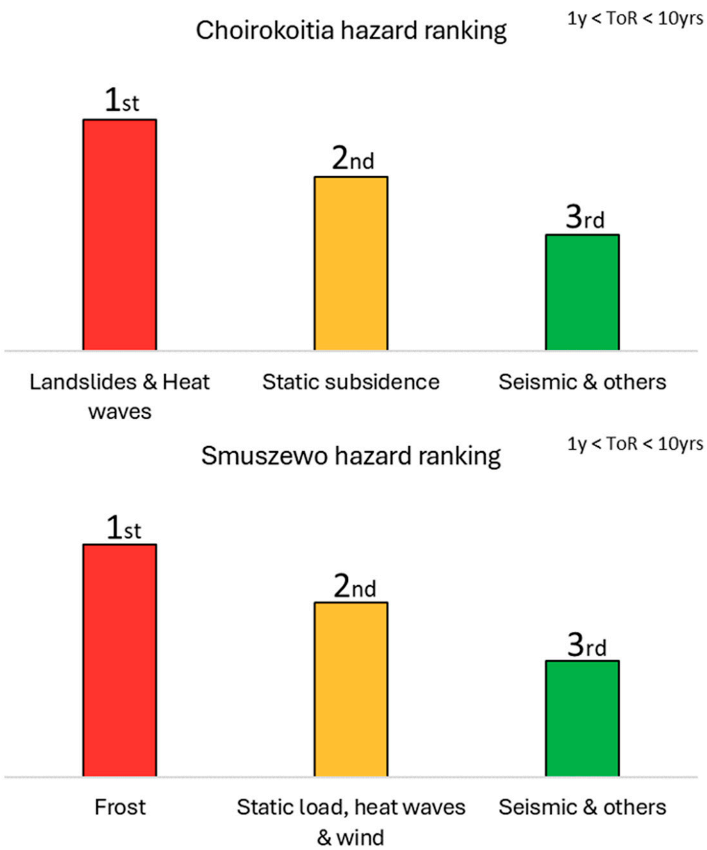

Figure 14. Histograms representing the geohazard ranking for the Choirokoitia and Smuszewo pilot CH sites refer to a Time of Recurrence (ToR) with a decennial periodicity.

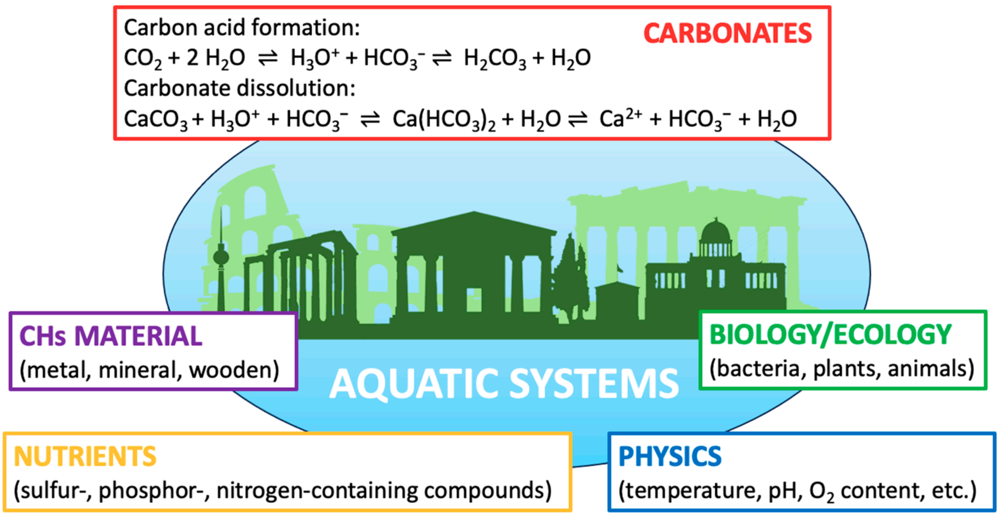

Figure 15. Overview of factors that need to be considered in chemical/biological risk assessment to preserve CH sites in aquatic systems.

Archaeological pile dwellings (e.g., Roseninsel or Les Argilliez) composed of organic structural material respond differently to chem/bio risks/hazards as compared to inorganic structures, i.e., stone-based ruins (e.g., Epidaurus). Without detailing here, particularly in the case of pile dwellings, there is a risk that the wooden organic material will be affected by aerobic bacterial decomposition processes, whereby the microbial species consume the cellulose contained in the wooden material, evidently leading to its decomposition [39]. Thus, sedimentation processes, including but not limited to, e.g., chalk sedimentation, have played an essential role in the preservation of these monuments and provided a natural protective layer resisting bacterial decomposition [40]. As an example of the complexity of assessing chem/biohazards in these particular cases, these hazards may attack, as a "secondary effect", the protective sediment layers in lieu of the original structural material, which in turn may negatively affect the—present and future—conservation of such archaeological pile dwellings.

Since chalk is mainly composed of calcium carbonate, from a chemistry point of view, acidification (i.e., a decrease in pH values of the water phase) impacts this sedimentation process [41]. As carbonate chemistry is also relevant for carbonate-containing stone-based monuments as well as for carbonate-forming organisms, water acidification must therefore be considered among the most relevant generic chemical risk factors for CH sites and the environment. Given the CO_2 emissions nowadays observed (i.e., increasing amounts of CO_2 released into the atmosphere), it is immediately evident that more CO_2 can dissolve within the global water bodies [42]. As CO_2 dissolves in water in the form of carbonic acid, it is immediately conceivable that there is a connection between the greenhouse effect, acidification of water bodies, and the resulting increased impact on CH sites, leading to the need for enhanced efforts in fundamentally unraveling and understanding these processes to facilitate targeted and site-specific CH preservation.

Other chemical factors that are decisive for the ecology/biology around the CH sites are the nutrient content of the aqueous phase, including predominantly but not limited to nitrate, phosphate, and sulfate, and the associated biological cycles responsible for their (bio)availability [43]. Similar to the described processes involving carbonates, in addition to complex associated chemistries and availability within the aqueous system, a series of physical parameters and biogeochemical cycling processes will affect their abundance and activity in a site-specific fashion.

TRIQUETRA aims at identifying relevant chemical and biological processes and hazards associated with selected pilot sites, their impact on the specific CH sites to be preserved, and the development of complementary analyzers and sensors for monitoring target marker chemicals, facilitating the development of long-term mitigation and preservation strategies.

3.3. Novel Sensors and Coatings

3.3.1. Flash LiDAR

Today's commercial LiDAR (Light Detection and Ranging) developments for terrestrial applications are based on infrared light, for eye safety and invisibility reasons, whereas this LiDAR technology relies on a laser at a wavelength of 532 nm (green), maximizing the light transmission through water (gain of about 1000) and hence the measurement distance range. The time-of-flight (TOF) was optimized for this wavelength, offering the highest sensitivity compared to longer wavelengths. Combining this advantage with this LiDARs inherent time-gating feature (measurement starting only after a certain amount of time and hence from a certain distance), the system can detect multiple reflections and can also be used in turbid water, paving the way for underwater applications, especially in shallow waters where sonars are hindered by multiple reflections.

In the frame of background projects, a miniaturized flash LiDAR has been designed, manufactured, and validated for airborne 3D imaging on-board a UAV. The system enables the mapping of shallow-water coastal areas, the monitoring of underwater infrastructure, and the detection of objects beneath the water surface in real-time. TRIQUETRA extends these capabilities to fast 3D mapping underwater, as demonstrated by mapping CH sites on-board a USV combined with other remote sensing methods, aiming to give a more thorough knowledge of these places and offering a fast and low-cost solution for regular surveys.

The designed LiDAR, illustrated in Figure 16, weighs 6.8 kg and holds a volume of $20 \times 17 \times 19$ cm^3, with a peak electrical power consumption of 60 W (usually 15 W in operation). Through the control of a stepper motor, different diffusers and diffractive optical elements can be positioned in the laser beam to modify the illumination Field of

View (FOV). Similarly, a three-axis motorized lens allows adapting the emitter (laser source) to the receiver FOV in a range from 4° to 20°. These features confer increased versatility to adapt to environmental light conditions, obscurant presence, platform velocity, and target reflectivity.

Figure 16. Current version of Flash LiDAR.

The system's core consists of a state-of-the-art embedded processing unit (Xilinx Zynq Ultrascale+) that allows controlling the data acquisition, the actuators' positioning, and communication. Data are acquired by an array of 2 × 2 TOF detectors of 64 × 64 pixels each, featuring a total resolution of 128 × 128 pixels. A new generation featuring a resolution of 256 × 256 pixels is also in development. Each pixel, based on SPADs able to detect intensities down to a single photon, possesses its own TOF electronics (counter and digital converter), enabling precise time stamping of detection events (and hence distance measurement). The processing unit also acts as a master for the fiber-amplified laser that emits nanosecond pulses with high energy (10 µJ). Due to the inherent noise of SPADs (Single Photon Avalanche Diodes), to acquire a single 3D image of sufficient quality, several measurements are required. Each measurement is synchronized to a single laser pulse. By summing measurements, a histogram of photon counts can then be generated, showing the distance traveled by the photons detected (for each pixel). A depth map is then computed by identifying the peak position in the histogram. An intensity image is also obtained from the same data by computing the peak energy.

Within the project, the system's performances were verified on-board of a UAV and from a bridge (fixed position) over the Areuse river in Neuchatel, Switzerland. Results are shown in Figure 17, where underwater rock structures (a and b), a submerged tree trunk (b) located 2–3 m below the water surface, and the river bed (c, 6 m) are clearly visible.

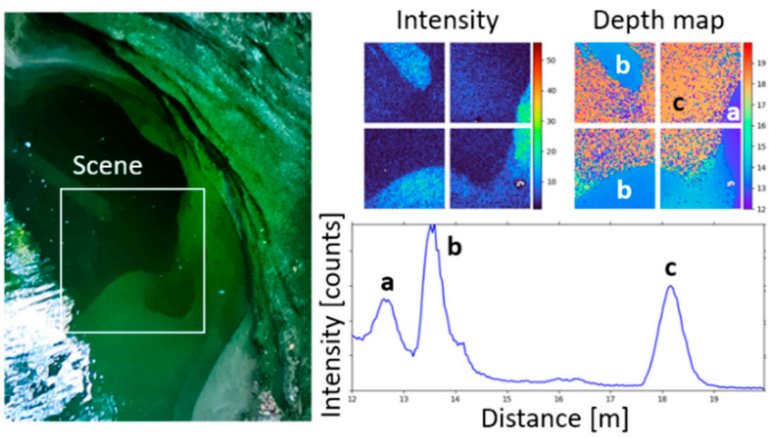

Figure 17. River scene captured with the flash LiDAR. Standard camera image (**left**), flash LiDAR image intensity and depth map (**top right**) and distance histogram (**bottom right**); "a": first reflection peak (rocky structure over water surface), "b": second reflection peak (rock structure and wood trunk underwater), and "c": river bed peak reflection.

TRIQUETRA has new requirements, such as the need for a higher TOF detector resolution (mentioned above), battery-operated, watertight housing, to be as light as possible, and to include geo-positioning information in the generated data and recombined images (mapping).

During the first stage of TRIQUETRA, the low-resolution LiDAR will be used to develop and validate the UAV platform and the image data acquisition and processing. In the second stage, it is foreseen to complete the initial surveys with the higher-resolution LiDAR system. The UAV platform and the new data acquisition firmware reduce the exposure time from 72 ms to 17 ms to limit the sensitivity to motion blur, implement geo-localization, and integrate the waterproof housing.

The LiDAR on-board of the USV was successfully tested close to one of the pilot CH sites on a shipwreck. A second preliminary test will take place on the TRIQUETRAs pilot site, Les Argilliez. The measurement campaigns will continue with the low-resolution system in the forthcoming months to monitor the erosion process over time. Once fully validated, surveys of other CH sites selected in the TRIQETRA project will be performed.

3.3.2. Oxygen Sensor

In the context of TRIQUETRA, the impact of water quality and composition on the preservation of subaquatic CH sites is addressed. The assessment of water quality requires the measurement of a wide range of parameters. Combined, they can give an overview of water composition and seasonal change. Within the project, five different parameters have been chosen for long-term monitoring over several months. These parameters are the oxygen level, the pH, the temperature, the turbidity, the flow speed, and the tilting angle (of a buoy used for the detector's support). These values are collected from individual sensor probes installed on a buoy dipped into water.

As a first case study, the buoy has been installed at Les Argilliez (Figure 18a). The collected data can be interpreted and correlated in different ways. The oxygen level, pH, and temperature are directly linked to the composition of the water. For instance, the oxygen level varies day by day, with an increase in oxygen concentration at night due to a decrease in temperature. In a similar way, oxygenation tends to increase in the winter due to the gradual decrease in water temperature. Figure 18b shows this increase in oxygen level over one month (November 2023).

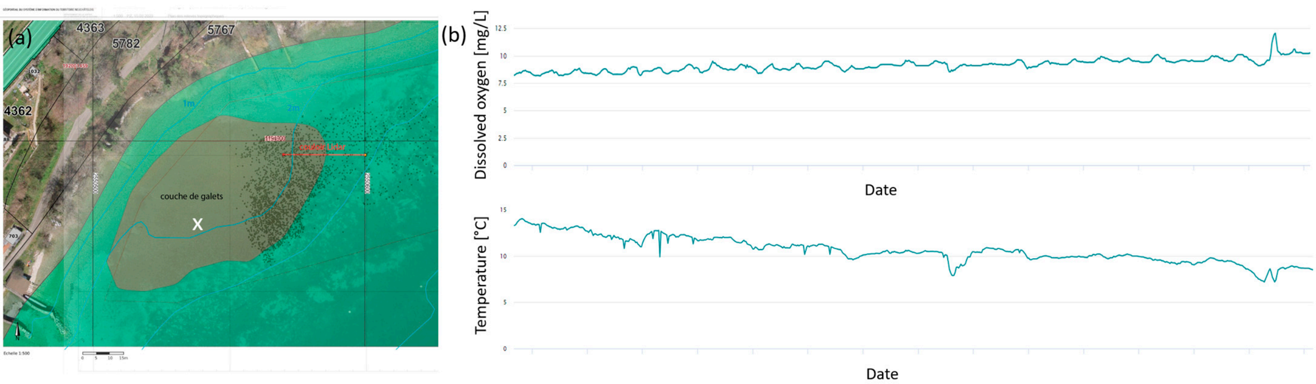

Figure 18. Location of the buoy equipped with sensors in Les Argilliez (**a**) and a set of collected data over a month, showing a gradual increase in oxygen concentration associated with a decrease in temperature (**b**).

The second set of data, such as the turbidity and water speed, can be linked to the sedimentation or erosion phenomenon at the bottom of the lake. The phenomenon impacts the coverage depth with sediment of the subaquatic neolithic pillars. The collected data will be coupled with LiDAR imaging of the bottom of the lake, which will be carried out in parallel. Both LiDAR and buoys equipped with sensors will be dispatched to other pilot CH sites.

In parallel with data collection, an upgraded version of the optical oxygen sensor is developed and tested first in the laboratory before installation on the buoy in an adapted probe version. This includes the development of a sensing layer based on a patented technology [44,45] and the development of the corresponding read-out system. In brief, the sensing layer (Figure 19a) incorporated a dye that responds to oxygen variation in water. The working principle is based on a change in fluorescence of the re-emitted light of the dye under illumination by a LED (Light-Emitting Diode). When excited, part of the energy can be transferred to the oxygen molecule, as shown in the scheme of Figure 19b. The sensor is based on fluorescence lifetime, which is particularly interesting for sensors dipped into water. As an intrinsic property of the dye, the sensor based on lifetime is less sensitive to fouling associated with a rapid coverage of the working windows by mud. This is a clear advantage over sensors based on absorption.

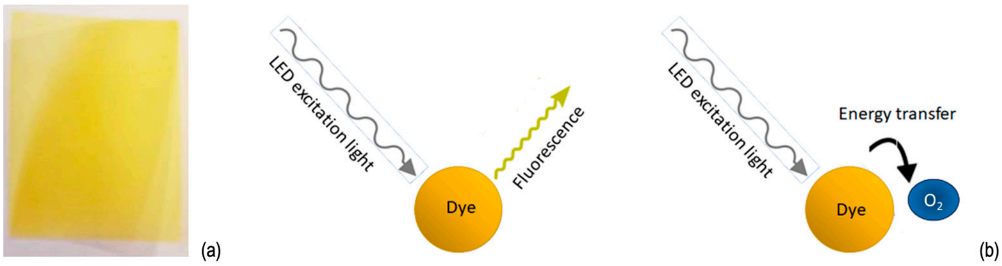

Figure 19. Sensing layer developed (**a**) and the working principle of oxygen detection by fluorescence quenching (**b**).

Following sensing layer development, the read-out system will also be redesigned to be integrated into the current probe geometry. This will include the integration of the light source (LED) and the photodiode, as well as the associated electronics for signal treatment. The last stage is the calibration of the sensor.

3.3.3. Protective Nano-Coatings

CH surfaces are damaged by natural corrosion due to their exposure to outdoor conditions [46,47]. Deterioration is caused by the combined and often synergistic action of many factors, such as air pollution, relative humidity (RH), temperature, acid rain, salt crystallization, ultraviolet radiation (UV), and the growth of microorganisms. These deterioration factors, besides altering the surface's aesthetic appeal, can lead to the destruction of historic structures, with incalculable effects on CH.

Water is among the most aggressive corrosion agents for building materials. In particular, the role of water as a corrosive agent is twofold: (i) it contributes to the washing away of insoluble components found in building materials, and (ii) it contributes to the transfer of salts from area to area of the material. The change in water composition, fragmentation, and increase in surface roughness, as well as the reduction of the mechanical properties of the building material due to the weakening and wear of the connecting units included in the materials, constitute harmful consequences of the action of water. In addition, water favors the growth of microorganisms and the formation of crusts on the surfaces of building materials.

Therefore, the development of products that will be characterized by a multifunctional character, combining either stabilizing, hydrophobic, self-cleaning, and/or antifouling properties, is a promising solution in the treatment of CH structures. An ideal protective coating is expected to be transparent, non-toxic, compatible with the surface, breathable, long-lasting, easy to apply, and resistant to chemicals and UV radiation. Although the production of a coating with all these properties combined is not yet feasible, numerous coatings have been proposed over the last few decades for the conservation, protection, and maintenance of CH.

It is essential to identify the chemical structure of the surface before selecting a protective product for CH preservation. Most CH surfaces are made from metals, glass, and calcareous-based materials, necessitating a unique treatment for each case. The TRIQUETRA project primarily focuses on structures composed of stones, marbles, limestone, and/or calcareous-based materials.

Protective coatings suggested for CH preservation generally can be classified into two main categories [48–50]: (i) polymeric coatings and (ii) nano-based coatings. However, most of these products often exhibit drawbacks and limited performance. For instance, polymeric coatings, such as urethanes, acrylics, and methacrylic resins, widely used for protection, suffer from issues related to durability, removability, photo-oxidation, and reduced water vapor permeability. On the other hand, nano-based coatings, consisting of nanoparticles (NPs) dispersed in a solvent, offer various functionalities. Examples include $Ca(OH)_2$ and SiO_2 NPs for stabilization, silane- and fluorosilane-based NPs for hydrophobicity, TiO_2 NPs for self-cleaning properties, metal oxide-based NPs for anticorrosion properties, and metallic NPs for antimicrobial activity. Combinations of NPs [51–54] can lead to enhanced and multifunctional products. The main disadvantage of the nano-coatings is their low adhesion, combined with the observed phenomenon of the NPs being washed off the application surface.

Our approach to addressing the needs of the TRIQUETRA project involves the development of protective nano-coatings using the sol-gel technique. The matrix of all developed products primarily consists of SiO_2 oligomers/monomers (initiated from tetraethoxy silane, TEOS), widely recognized for stabilizing fragile porous surfaces. These proposed products, owing to their inorganic nature, exhibit a strong chemical affinity with building materials. Post-application, nanoparticles penetrate the substrate due to their low viscosity, chemically attaching themselves to the surface and forming covalent bonds with each other. Consequently, they establish a dense network that enhances the mechanical properties of worn or deteriorated surfaces. Importantly, the treated surfaces retain their natural appearance, water vapor permeability, and porosity while gaining increased durability against acids.

For the consolidation and preservation of heritage stones within the scope of the TRIQUETRA project, it is crucial to undertake comprehensive identification and geological characterization of these stones. This preliminary step is essential to ensuring the preservation of the structural integrity of historical buildings. In essence, the key factors influencing the characteristics of stones are their origin and composition.

Regarding the origin of stones, they can generally be classified into three main categories, as follows:

- Igneous Stone: Granite, originating from igneous rocks formed slowly beneath the earth’s surface, is known for its hardness and density. Some variations, like marble, exhibit veining.
- Sedimentary Stone: Sandstone and limestone fall into this category, formed through the compaction of grains or fragments of existing rock material.
- Metamorphic Stone: Marble and slate, examples of metamorphic stones, are created under extremely high pressures and temperatures below the melting point.

Regarding the mineral composition of stones, they can be classified into two main categories, as follows:

- Silicates: Stones primarily composed of quartz-like silica particles, such as granite, sandstone, slate, and quartzite, are hard, durable, and generally resistant to acids.
- Calcium Carbonates: Stones like limestone, marble, and travertine, characterized by softer properties, are less durable than silicates and sensitive to acids.

It is imperative to note that within the TRIQUETRA project, all stone samples will undergo thorough analytical characterization before any intervention. The proposed product, to be utilized under TRIQUETRA, must meet specific criteria to be deemed suitable for CH preservation, including (i) adherence to the stone substrate, (ii) penetration into the structure, and (ii) avoidance of significant alterations in color and water vapor permeability of the stone.

The innovative development of sol–gel products for stonework within this project is centered around tetraethoxysilane (TEOS) as the initial raw material. Subsequent chemical modifications in the synthesis route aim to achieve hydrophobic, water-repellent, and self-cleaning properties in the final product.

4. Discussion

CH sites are increasingly under threat from climate change-induced risks such as increased precipitation, severe storms, global temperature changes, and changing patterns in sea currents and wave action, to mention a few. Depending on their location, CH monuments are exposed to varying degrees of risks that have increased due to climate change and natural hazards that themselves have been amplified by climate change.

The TRIQUETRA project endeavors to develop an evidence-based assessment platform that enables precise risk identification while building a flexible database of mitigation measures and strategies. Guided by a three-step approach of risk identification, risk quantification, and risk mitigation, TRIQUETRA establishes a robust framework for assessing and addressing a wide range of risks in the most efficient manner possible. The project focuses on 8 pilot sites spread over the European continent: the sanctuary at Kalopodi, the archaeological site of Kolonna in Aegina Island and the Sunken City in Ancient Epidaurus in Greece, the Choirokoitia archaeological site in Cyprus, Villa di Giulia in Ventotene Island in Italy, Roseninsel in Germany, Smuszewo in Poland, and Les Argilliez in Switzerland. In this article, an overview of TRIQUETRAs methodology is presented, with a brief outline of its main approach, toolbox, pilot sites, novel technologies, and Earth Observation methods. Then, preliminary results concerning the knowledge base, the risk identification framework, the flash LiDAR, the oxygen sensor, and innovative nano-coatings are discussed. The TRIQUETRA project envisions achieving the following long-term results:

- advanced understanding of threats in a global and climate change context, enabling novel solutions to protect CH on land and aquatic ecosystems, further enhancing CH site management through better protection, restoration, and promotion of CH;
- promoting intercultural cooperation while engaging citizens and educating young people, continuous engagement with society and economic sectors, as well as better protection, restoration, and promotion of CH;
- enhancing the full potential of the CH and creative sectors as a driver of sustainable innovation;
- enhancing the EU industrial value chains, within the EU and Associated Countries and across borders; and
- innovative monitoring, safeguarding and transmitting CH, fostering the CCIs, and promoting cultural diversity.

The climate analysis over the recent past period 1970–2020 based on observational data from weather stations at the proximity of the pilot CH sites of TRIQUETRA revealed robust warming and increasing heat stress at the materials of the CH assets. Furthermore, the multi-model climate analysis based on high-resolution RCM simulations for three different future scenarios (RCP2.6, RCP4.5, and RCP8.5) points towards a hotter and drier future climate for the CH sites in the South and a hotter and wetter climate for the CH sites in the North. Analysis of the HMR and PRD indices over the recent past period indicates notable variations in microclimate conditions with aggravation of heat stress at CH assets made of stone and marble (Epidaurus, Kalapodi, Aegina, Choirokoitia) and points towards an increase in predicted risk of damage. Analyzing the future changes in HMR and PRD indices based on the multi-model ensembles of RCM simulations for the three different scenarios will feed the risk quantification framework at CH sites by quantifying the damage risk due to future long-term changes in temperature and humidity. The climate-related risks at the CH sites will be further linked with the analysis of future changes in frost days, droughts, precipitation extremes, and sea level rise.

The increase in the frequency and intensity of water hazards, like extreme waves and floods, increases the exposure of coastal cultural heritage sites to hydrodynamic effects that consequently result in higher risks and probabilities of failure. The threat from such risks is not well documented and requires thorough investigation in order to decipher the fundamental physics of the interaction of the waves and floods with different types of cultural heritage sites (cliffs, shorelines, and historic structures). High-fidelity computational fluid dynamics methods represent a very promising approach for deciphering and quantifying the aforementioned complex phenomena and developing next-generation risk assessment frameworks. For example, the CFD analyses conducted herein have already given an insight into the type and magnitude of hydrodynamic forces applied on the Ventotene cliff and revealed the generation of both impulsive and quasi-static components, which will require the development of appropriate mitigation strategies. Future tasks include (i) the two-dimensional CFD investigation of a wide range of wave conditions and wave types (unbroken and broken) impacting Ventotene; (ii) the estimation of not only the total hydrodynamic forces but also the pressures, which can be responsible for local damage; (iii) the development of static and dynamic geological models that will estimate the response of the cliff to the hydrodynamic effects; and (iv) the development of simplified predictive equations and methodologies that will be used later in efficient risk assessment frameworks.

In response to climate change, continuous monitoring of snow cover is crucial for effective site management, ensuring the resilience of archaeological sites against snowmelt-induced erosion. Using Earth Observation methods and optical satellite time series imagery, a study on the Kalapodi site in Greece reveals seasonal patterns and trends in snow cover extent, highlighting the importance of understanding these dynamics and the need for continuous monitoring for sustainable conservation practices in the face of climate change and the increased frequency of extreme weather events. For effective monitoring of changes in snow cover extents, emphasizing the need for upcoming space-borne missions with enhanced temporal and spatial resolutions is essential. Therefore, future monitoring initiatives should prioritize long-term missions that provide continuous observation of our planet's land surfaces to gain a comprehensive understanding of snow cover dynamics over long periods of time.

With respect to the geological hazard analysis, the advance that has been proposed through the GSCs is a synoptic restitution of the geohazards for the individual sites for their comparison from the point of view of the natural dangers to which they are exposed. Based on the GSCs, for each pilot CH site, the three most relevant geological hazards have been ranked. This further synthesis facilitates the evaluation of a choice of strategies to improve knowledge of specific local hazards or can guide the focus of subsequent design activities aimed at quantifying them through more accurate approaches to analysis. Landslides, weather events (such as heat waves and frost events), and seismic shaking are the most significant hazard sources in the case studies examined. Different analysis strategies for these geological hazards may be developed, resulting in a more detailed classification of the hazards' severity. In particular, the forcing of specific geohazards may be quantified in order to define their effects on the environmental context and/or the archaeological artifacts exposed to them. In this regard, the functionality of new technologies, as well as experimental detection and/or monitoring approaches, can be optimized, thereby filling knowledge gaps where they are currently unavailable.

Regarding chem/biological hazards, submerged CHs are exposed to various chem/biological influences. Apart from direct chemical hazards such as increased acidity (due to water acidification), which attacks CHs or protective sediment layers, nutrient levels and oxygen content of the water can influence bacterial decomposition processes, which are particularly important for the preservation of archeological wood. Nutrient levels also determine the surrounding ecosystem. A better understanding of the chem/biological key parameters, which can be obtained and observed using new sensor technologies, can revolutionize future heritage protection and enable more (cost-)effective approaches.

The expected outcome from the above-mentioned risk identification methods applied for climate-related hazards, extreme water, snow, and ice hazards, geological and geophysical hazards, as well as chemical and biological hazards, in association with ongoing work on damage and failure modes of CH structures, will yield a comprehensive approach for an effective risk quantification framework tailored to CH sites. Furthermore, these findings will serve as the fundamental input for the TRIQUETRA DSS platform. The outputs of the TRIQUETRA project are envisioned to advance the long-term preservation of CH sites, serving as a valuable asset in facilitating decision-making and the overall management of CH sites. As researchers extend the application of the TRIQUETRA tools and methods beyond the confines of the TRIQUETRA project to a broader scale, they shall be able to deploy and fuse a diverse range of data, helping them to reach meaningful conclusions and optimal solutions for mitigating a great variety of risks to CH sites. As a conclusion, TRIQUETRAs overarching vision extends beyond the mere preservation of cultural heritage (CH) sites. It aims to foster a deeper understanding of our shared history and identity, enriching our collective appreciation of cultural diversity and historical significance.

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