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Review

Climate Change and Cultural Heritage: Methods and Approaches for Damage and Risk Assessment Addressed to a Practical Application

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Abstract: In the last 20 years, research on the observed and projected impacts of climate change on cultural heritage has led to significant developments regarding damage quantification and risk assessment, which unfortunately are not yet exhaustively transferred to practical applications and to the sector of policy and decision making. One of the major reasons for this still lacking alignment remains with the inadequate handover of quantitative data, which is a prerequisite for the development of measures and strategies for the mitigation of the impacts and risk reduction. In this paper, we focus on the methods and approaches put in place for the production of projections providing quantitative assessments of climate change-induced impacts in the near and far future (up to the 21st century) on outdoor built heritage mainly constituted by stone and stone-like materials. Our critical study found that different approaches have been applied for quantifying slow cumulative damage due to the ongoing variations of climate and air pollution parameters and to risk assessment caused by hydrometeorological extreme events induced by variations of temperature and precipitation. There is clear evidence that efforts are still needed for directing research to provide concrete solutions and tools addressed to meet the requirements of stakeholders and to solve the existing challenges in the field: selected effective models and tools are illustrated. The discussion is structured in order to highlight the driving role of research in supporting the definition of priorities for heritage managers and the development of strategies by decision and policy makers for the prevention and safeguarding of cultural heritage at risk.

Keywords: outdoors built heritage; stone; stone-like materials; slow cumulative damage; extreme events; damage function; vulnerability; projections; downscaling; policy-decision-makers; user-driven approach

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1. Introduction

The risks on cultural heritage imposed by climate change have gained increasing attention during the last 20 years and several efforts have been made in order to assess the projected impacts on different building materials and heritage categories, both for outdoors and indoors [1,2]. In spite of the state of advancements unquestionably achieved in the research, the safeguarding of cultural heritage from climate-induced hazards still suffers from a lack of integration of measures purposely dedicated in the national plans for adaptation to climate change and disaster risk reduction and management [3]. On this aspect, the recent report "Strengthening Cultural Heritage Resilience for Climate Change" (2022) of the EU Open Method of Coordination (OMC) expert group of Member States stresses that only 12 out of the 28 countries participating mentioned the presence of cultural heritage in climate change policies, while merely 7 are the countries with available plans to coordinate climate change and cultural heritage (i.e., Ireland, Greece, Italy, Cyprus, Slovenia, Finland and Sweden) [4]. Additionally, the last report of the Intergovernmental

Panel on Climate Change (IPCC) highlights that cultural policies are still limited, although the integration of culture into policy and planning is recognized as a key step for the development of sustainable and resilient cities [5]. One of the reasons for the still ineffective handover of scientific results to policy and decision-makers in the field of cultural heritage protection is surely an inefficient transfer of research outputs into concrete tools and solutions addressed to meet the stakeholder needs and to solve the existing challenges at a territorial level [6,7].

A most impending requirement from policy and decision-makers is undoubtedly the availability of quantitative data of the observed and projected impacts for different scenarios on cultural and natural heritage, which are fundamental for establishing thresholds of acceptable risk and for setting up strategies of adaption and mitigation. Additionally, the need for improved knowledge about the scale and rates of damage on cultural heritage (both tangible and intangible) and the lack of a coherent methodology for its assessment are claimed as being still existing gaps [4]. Initiatives addressed to bridge these gaps will surely contribute to supporting the correct planning of mitigation and adaptation measures in different countries and, consequently, to define the priorities of intervention and the appropriate allocation of resources for their implementation.

The current article addresses methods and approaches mainly put in place for the development of projections providing impact evaluations in the near and far future of climate change on outdoor cultural heritage, both regarding slow cumulative damage due to ongoing climate/air pollution changes and to the risks associated with extreme hydrometeorological events linked to changes in temperature and precipitation. Focus is given to the methodological approaches applied to attempt a quantification of the damage and to the development of risk indicators in the field of protection and management of built heritage mainly in stone and stone-like materials. Quantifying and/or ranking the damage and risk continue to represent a challenge for the scientific community as they require a selection of prioritized parameters and atmospheric forces, namely, a limitation of the field of reliability and applicability (in our specific case heritage building materials, and cultural heritage categories), an awareness of the impossibility of comprising all the aspects [8], and the establishment of a dose-response link possibly on the basis of experimental work in the laboratory and by performing long-term field exposure tests.

The contents are provided with the additional objective to support heritage managers and non-technical experts in prioritizing climate and pollution parameters to monitor and select a more adequate time frequency and space scale of their measurement, in order to adequately support the methods and approaches for damage quantification and risk assessment. Major focus is given to the methods and approaches addressed to assist policy-decision-makers and operational bodies in dealing with setting up and putting into practice measures for the protection of cultural heritage in danger.

2. Dealing with Projected Impact and Risk on Cultural Heritage: Methods and Approaches

2.1. Slow Cumulative Damage Due to Ongoing Variations of Climate/Air Pollution Parameters

Research on the climate change impact on cultural heritage started by focusing on, and has been more exhaustively dedicated to up to now, to the evaluation of the impacts of gradual changes of climate and air pollution parameters on cultural heritage both outdoors and indoors [1,6,9–11]. It is within this framework that we can count on the higher number of efforts aiming at developing projections up to 2100 of the quantitative evaluations of damage at a European and Mediterranean level. Of major interest for this article is the research conducted on the damage processes of subaerial outdoor built heritage, specifically: soiling/blackening and surface recession of carbonate stones (namely, marble and compact limestone) due to air pollution and rain (both clean and acid); biological degradation; decohesion/fracturing caused by salt crystallization and thermoclastism.

This focus is motivated by:

1. Science-based evidence that monumental complexes, archaeological sites and historic buildings are likely to continue to undergo the effects of these damage processes in the near and far future, particularly in urban and coastal areas [1,2,9,11,12];

2. The availability of studies on the quantification of damage on heritage building materials by the development and application of damage functions in combination with outputs from climate projections [13–18].

Table 1 reports the available key equations utilized for damage quantification related to the processes taken into consideration (i.e., the outdoors, stone and stone-like materials), with materials for which the function and, therefore, the evaluation is valid and a list of the climate and pollution parameters recommended to be monitored.

Table 1. Key equations mainly utilized for the damage quantification of heritage building materials (i.e., stone and stone-like materials) exposed outdoors.

Damage Process	Damage Function/Risk Expression	Valid For	Climate/ Pollution Parameters
Surface recession	■ Lipfert (1989) [19]; Bonazza et al; (2009) [13] $L = 18.8 \cdot R + 0.016 \cdot [H^+] \cdot R + 0.18 \cdot (V_{dS} \cdot [SO_2] + V_{dN} \cdot [HNO_3])$ L = surface recession per year ($\mu m \cdot year^{-1}$); 18.8 = intercept term based on the solubility of $CaCO_3$ in equilibrium with 330 ppm CO_2 ($\mu m \cdot m^{-1}$); R = precipitation ($m \cdot year^{-1}$); 0.016 = constant valid for precipitation pH in the range 3–5; $[H^+]$ = hydrogen ion concentration ($\mu mol \cdot l^{-1}$) evaluated from rain yearly pH; 0.18 = conversion factor from ($cm \cdot s^{-1}$) ($\mu g \cdot m^{-3}$) to µm; V_{dS} = deposition velocity of SO_2 ($cm \cdot s^{-1}$); $[SO_2]$ = SO_2 concentration ($\mu g \cdot m^{-3}$); V_{dN} = deposition velocity of HNO_3 ($cm \cdot s^{-1}$)and $[HNO_3]$ = HNO_3 concentration ($\mu g \cdot m^{-3}$). ■ Kucera et al. (2007) [20] $R = 3.95 + 0.0059 \cdot [SO_2] \cdot RH_{60} + 0.054 Rain \cdot [H^+] + 0.078 \cdot [HNO_3] \cdot RH_{60} + 0.0258 \cdot PM_{10}$ R = surface recession per year ($\mu m \cdot year^{-1}$); $[SO_2]$ = SO_2 concentration ($\mu m \cdot m^{-3}$); RH_{60} = is the measured relative humidity when RH = 60% otherwise 0; Rain = amount of rainfall (mm) and $[H^+]$ = H^+ concentration (0.0006–0.13 $mg \cdot l^{-1}$); [HNO3] = HNO_3 concentration ($\mu m \cdot m^{-3}$); PM_{10} = particulate matter concentration ($\mu g \cdot m^{-3}$).	Marble and limestone with porosity lower than 25%	• Rain amount • Rain pH • Temperature (T) • Relative humidity (RH) • Sulphur dioxide (SO_2) • Nitric acid (HNO_3) • Carbon dioxide (CO_2) • Particulate matter (PM)
Soiling/ Blackening	■ Kucera (2005) [21] $R = R_0 \exp(-k_s \cdot PM_{10} \cdot t)$R = reflectance after time t; t = time; R_0 = initial value of reflectance; k_s = rate constant for blackening and PM_{10} = particulate matter concentration = 10 ($\mu g \cdot m^{-3}$). ■ Brimblecombe and Grossi (2009) [16] $-dR/dt = (R_0 - R_p)\, Vd_{EC} \cdot EC/\tau$ dR = rate of change in reflectance of the material (clean stone); t = time; R_0 = reflectivity of the clean stone; R_p = final reflectance of the crust; Vd_{EC} = deposition velocity of elemental carbon; EC = elemental carbon concentration ($\mu g \cdot m^{-3}$); τ = folding density (surface concentration of elemental carbon required to reduce the reflectivity by a factor e). ■ Brimblecombe and Grossi (2009) [16] $R_t = (R_o - R_c) \cdot exp(-k_s t) + Rc$ R_t = rate of reduction in reflectance; R_0 = initial reflectance of the clean stone; R_C = reflectance of the deposited material; t = time; k_s = soiling constant.	Carbonate stones in general (sedimentary and metamorphic), mortars	• Rain amount • Temperature (T) • Relative humidity (RH) • Sulphur dioxide (SO_2) • Particulate matter (PM) • Carbon fractions of particulate matter (PM): elemental carbon (EC) * and organic carbon (OC) *
Biodeterioration/ Biomass accumulation	■ Gòmez-Bolea et al. (2012) [15] $B = \exp(-0.964 + 0.003P - 0.01T)$ B = biomass accumulation ($mg \cdot cm^{-2}$); P = annual precipitation (mm); T = annual mean temperature (°C).	Siliceous stones	• Rain amount • Temperature (T)

Table 1. *Cont.*

Damage Process	Damage Function/Risk Expression	Valid For	Climate/ Pollution Parameters
Thermoclastism	▪ Bonazza et al., (2009) [14] $\sigma_T = E \cdot \alpha \cdot (daily\Delta T_{air} + 20°C)/(1 - v)$ σ_T = maximum thermal stress (MPa); *E* = Young's modulus (GPa); α = thermal expansion coefficient (K^{-1}); $\Delta T_{air} = T_{airmax} - T_{airmin}$ (°C); ν = Poisson's ratio.	Marble	• Surface temperature • Temperature (T)
Salt crystallization	▪ Evaluation based on cycles per year/season of temperature and relative humidity (Sabbioni et al, 2010; Grossi et al., 2011; Menendez 2018) [9,12,22]	Porous stones in general	• Relative humidity (RH) • Temperature (T)

* rarely available from air quality monitoring networks. Specific aerosol monitoring campaigns are necessary in proximity of the sites.

Among the listed equations, those employed for surface recession and biomass accumulation offer a direct quantification of the damage, while the functions provided for soiling/blackening, thermoclastism and decohesion caused by salt crystallization require the establishment and adoption of the acceptable thresholds of damage and/or formulation of risk expressions determining the frequency of events likely to cause deterioration.

The majority of the European-based projections for the near (2021–2050) and far future (2071–2100) for the deterioration processes listed have been produced in the framework of the EC Noah's Ark Project by applying the Global and Regional Hadley climate models (i.e., a grid resolution of 295 × 278 km and 50 × 50 km, respectively) under the A2 scenarios (i.e., IPCC SRES Emission Scenarios used in TAR and FAR) [9]. Ciantelli et al. 2018 [18] provided downscaled projections covering the Panamanian isthmus for surface recession, biomass accumulation and deterioration due to salt crystallization at a grid resolution of 25 × 25 km, by using the climate model EC-Earth for the middle-future period (2039–2068). The available downscaled analyses are mainly at a local level and are focused on case studies [12,17,22–24].

Undoubtedly, downscaling in the resolution remains a still-existing gap in dealing with projections of the slow cumulative damage processes induced by climate changes [25].

Additionally, projections produced by the application of damage functions such as those listed in Table 1 do not account for the different rates of vulnerability or for the exposure of cultural heritage sites, and they consider the whole area investigated as constituted by the building materials for which the functions are valid. On the other hand, in spite of the recognized limits, these equations find concrete current examples of practical application from the actors and institutions in charge of the protection and management of cultural heritage, such as the Italian Risk Map of Cultural Heritage system coordinated by the *Direzione Generale Sicurezza del Patrimonio Culturale* of the Italian Ministry of Culture, which exploits climate and air pollution data from a monitoring station network [26]. In addition, they continue to be applied for site-specific analyses and for substantially improving evidence-based scientific data in support of the measures and policies of air pollution reduction and climate change mitigation, with benefits for cultural heritage [27].

The recommended/suggested optimal frequency of the measurements for all climate and pollution parameters listed in Table 1 for each damage process is daily (i.e., averages and for specific cases, such as thermoclastism, maximum and minimum values), in order to obtain data for representative evaluations of the monthly, seasonal and yearly values. These values are the most commonly used in dose-response functions for slow cumulative damage processes, of which the rate of degradation is in general subtle and can be evidenced only over time.

Air quality networks with free and open-access data play, in this framework, a very important role, even though they do not always offer all the required parameters (for example, elemental carbon is quite difficult to find in spite of its recognized driving role in blackening), as well as measurements at a proper distance of the heritage site under study. Nevertheless, the accessibility and the certainty in a standard method of measurement make the use of climate and air pollution data from these sources highly recommendable.

Data and products from Copernicus services, specifically, Climate Change (C3S) and Atmosphere Monitoring (CAMS) also represent a significant source of data for the damage assessment of cultural heritage by providing climate and pollution data at 10 × 10 km of spatial resolution [28]. The Copernicus services ensure coverage of remote areas or those not accessible (such as areas under armed conflict) and where there is the lack of an in situ environmental monitoring network. The examples of exploitation of data from the CAMS and C3S services for cultural heritage protection are still sporadic and the potential offered is still far from being fully explored.

2.2. Risks Associated with Extreme Hydrometeorological Events Related to Climate Change

Research has only recently started to focus on the development of projections of the impacts and risks imposed on cultural heritage by extreme events linked to climate change. Basically, the methodological approach builds on the concept of risk as the combination of three components: hazard, vulnerability and exposure. European and Mediterranean-based projections up to 12 × 12 km in spatial resolution for climate-induced extreme hazards under different scenarios are available. They are produced by applying individual regional climate models and ensemble climate simulations to reduce the uncertainties and provide outputs and tools for practical solutions in response to the challenges faced by the cultural heritage community in protecting and managing cultural heritage at risk [29–31]. The pursued approach goes beyond the analysis of damage for a single material or materials group, as adopted for the damage quantification caused by ongoing variations of climate and air pollution parameters (Section 2.1). It instead embraces the complexity of diverse categories of cultural and natural heritage by attempting to include the criticalities that increase its vulnerability by a physical and managerial point of view [32]. Vulnerability assessment still remains a complex issue and the selection of the more appropriate method to be employed continues to be under debate. Empirical and analytical methods have been applied and the majority of the evaluations available for cultural heritage are hazard-oriented (such as for flooding, and fire) and are sporadically combined with climate projections of the likelihood of an increase or decrease in a hazard for a comprehensive evaluation of the risk [30,33–35].

Empirical methods lend themselves to a more direct practical application being based on the analysis of observed damage, expert opinion and, consequently, a score assignment. The application of this method ensures a full understanding of the critical factors which influence the vulnerability in the field at an operational level from the experience gained by non-technical users, such as owners and managers, who are actively involved in the overall assessment. The adoption of a more accessible and comprehensive method for vulnerability evaluation entails an improved potential for practical application.

Figure 1 sets out the overall concept underlying the pursued approach in the framework of the Interreg Central Europe Projects ProteCHt2save and STRENCH [36,37] for the risk assessment of cultural heritage exposed to climate extreme events, while explaining the methods and tools applied for the hazard mapping and vulnerability assessment, with the final aim of setting preparedness strategies for the resilience of cultural heritage at a local level.

For the hazard analysis, the methodology focuses on events linked to climate change associated with precipitation and temperature extreme variations, such as heavy rain, flash and large basin floods, and prolonged drought periods.

The elaboration of hazard maps at a territorial level linked to a hydrometeorological extreme event has been conceived as a key step to identify the hazard prone areas in Europe and the Mediterranean Basin, that are exposed to calamitous events (i.e., a flood of a large basin, flash flood, heavy rain, etc.). The identification of the hazard-prone areas, together with the vulnerability assessment carried out at a local and building scale, allow the users to set up mitigation and preparedness measures in order to increase the resilience of diverse categories of cultural and natural heritage, among them archaeological sites, small, ruined villages, monumental complexes, historic buildings, and cultural landscapes.

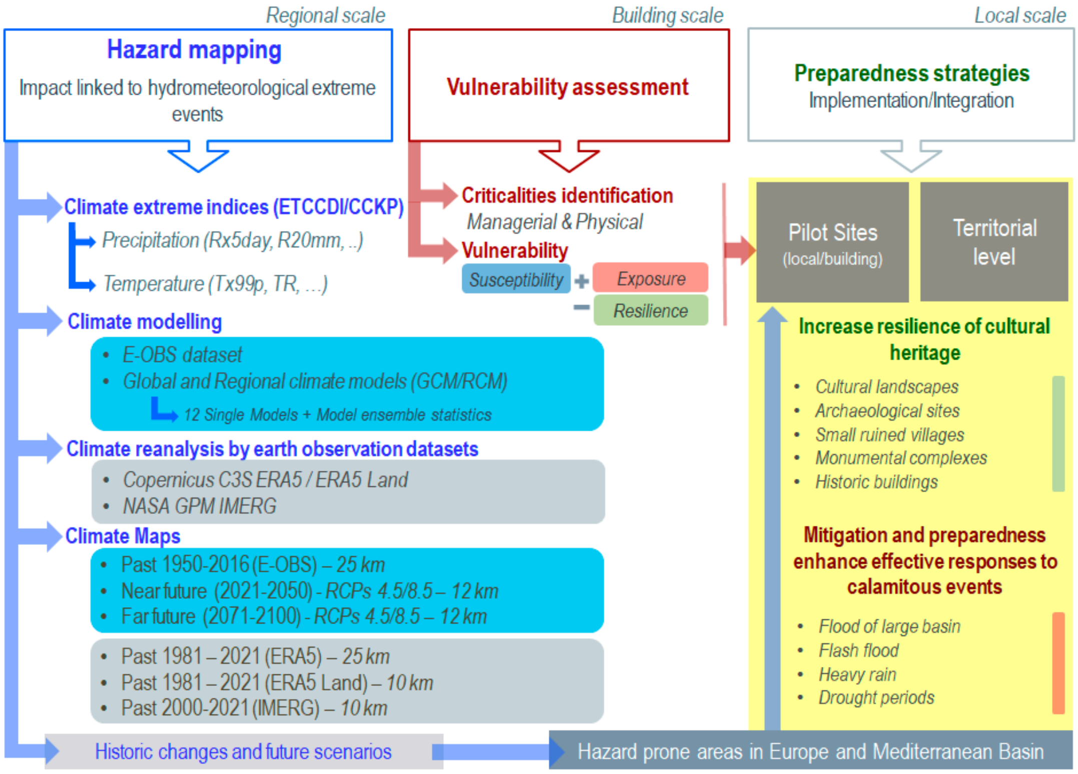

Figure 1. Overall concept of the methodology applied for the risk assessment of cultural heritage categories exposed to climate-induced hydrometeorological extreme events in the framework of the Interreg Central Europe ProteCHt2save and STRENCH. For hazard mapping section, blue boxes refer to data and maps deriving from climate models, while grey boxes refer to data and products from earth observation domain (Copernicus and NASA).

The methodology applied for mapping historic and future climate change referring to extreme variations in precipitation and temperature, basically comprises the following steps:

1. Search and selection of appropriate climate extreme indices and climate variables among the 27 indices defined by the Expert Team on Climate Change Detection (ETCCDI), whose definition can be found at the Climdex Project web site [38], but also among the indices defined by the Climate Change Knowledge Portal (CCKP) [39] (Table 2);
2. Computation and elaboration of selected indices to produce maps and analyses of their historical changes by using:
    a. climate data (T, P) from E-OBS observational dataset, from 1950 to present with a spatial resolution of 25 × 25 km [40] (Table 3);
    b. products provided by the EU Earth Observation program, Copernicus (ERA5 and ERA5 Land form C3S), and NASA (GPM-IMERG), providing climate data and reanalysis at a spatial resolution of 10 × 10 km [41] (Table 3).
3. Computation and elaboration of high-resolution maps of their future projection by using numerical climate model simulations. Twelve different combinations of GCM/RCM ensembles based on the EUROCORDEX initiative (with a resolution ~12 km) have been produced [40] (Table 3). Future projections cover two 30-year future periods, namely, the near future (2021–2050) and the far future (2071–2100), with respect to a historic reference (i.e., 1975–2005). The projections are available under the

two emission scenarios of RCP4.5 (stabilizing) and RCP8.5 (pessimistic). The use of an ensemble approach has been proved to reduce the uncertainty in climate change projections, particularly at a regional level, and it is widely used in climate change impact research, giving more reliable results than individual models [42].

Table 2. List of climate extreme indices selected as the most representative for the extreme events taken into account in the projects computed for the STRENCH WGT.

Extreme Event	Index	Definition and Description
Heavy rain	R20 mm	Very heavy precipitation days *. Number of days in a year with precipitation larger or equal to 20 mm/day.
Heavy rain	R95pTOT	Precipitation due to extremely wet days *. The total precipitation in a year cumulated over all days when the daily precipitation is larger than the 95th percentile of the daily precipitation on wet days. A wet day is defined as having a daily precipitation $\geq$ 1 mm/day. A threshold based on the 95th percentile selects only 5% of the most extreme wet days over a 30-year-long reference period.
Flooding	Rx5 day	Highest 5-day precipitation amount *. Yearly maximum of cumulated precipitation over consecutive 5-day periods.
Flooding	CWD	Consecutive wet days *. Seasonal maximum number of consecutive days with RR $\geq$ 1 mm.
Drought	CDD	Maximum number of consecutive dry days *. Maximum length of a dry spell in a year, that is, the maximum number in a year of consecutive dry days with a daily precipitation smaller than 1 mm/day.
Drought	CDD5	5 days of consecutive dry days **. Seasonal number of events of >5 consecutive dry days with a daily precipitation smaller than 1 mm/day.
Extreme heating	Tx90p	Extremely warm days *. Percentage of days in a year when the daily maximum temperature is greater than the 90th percentile. A threshold based on the 90th percentile selects only 10% of the warmest days over a 30-year-long reference period.
Extreme heating	su30	Strong summer days *. Seasonal count when TX (daily maximum) > 35 °C.
Extreme heating	HWI	Heat waves index **. Seasonal count of days TX >5°C above the monthly average for 5+ days.
Extreme heating	Tx99p	Hot days **. Seasonal N° days above average 99th percentile of TX (on basis of 1986–2005)
Extreme heating	TR	Tropical nights *. Seasonal count of days when TN (daily minimum temperature) > 20 °C.

* [38]. ** [39].

Table 3. Climate dataset, numerical products and re-analyses used for computing the selected climate extreme indices with an indication of time aggregation and resolution.

	E-OBS	C3S ERA5	C3S ERA5Land	NASA GPM IMERG	GCM/RCM Future Projection
R20 mm	✓	✓	✓	✓	✓
R95pTOT	✓	✓	✓	✓	✓
Rx5 day	✓	✓	✓	✓	✓
CWD		✓	✓	✓	

Table 3. *Cont.*

	E-OBS	C3S ERA5	C3S ERA5Land	NASA GPM IMERG	GCM/RCM Future Projection
CDD	✓	✓	✓	✓	✓
CDD5		✓	✓	✓	
Tx90p	✓				✓
su30			✓		
HWI		✓	✓		
Tx99p		✓	✓		
TR			✓		

E-OBS = historical observations for the 30-year-periods of 1987–2016 and 1951–1980. A 25 km resolution from 1950. C3S ERA5 = seasonal. An ~31 km – 0.25° resolution, from 1981. C3S ERA5 Land = monthly, seasonal, and yearly. Resolution ~9 km resolution, from 1981. NASA GPM IMERG = seasonal. A 10 km resolution, from 2000. GCM/RCM Future projections = 2021–2050 and 2071–2100 (reference period 1976–2005) under RCP4.5/RCP8.5. A 12 km resolution.

The final result is the production of climate maps at a territorial level showing historic and future changes and the likelihood of an increase/decrease in climate extremes, with the aim to evaluate the hazard-prone areas in Europe and the Mediterranean Basin.

The likelihood of an increase and decrease in a hazard subsequently needs to be integrated with the vulnerability ranking of the heritage site for a risk assessment (Figure 1).

Risk Mapping Tool for Cultural Heritage Protection

Recently developed in the framework of the Interreg Central Europe Projects ProteCHt2save and STRENCH [36,37], and based on the methodological approach above explained, the "Risk mapping tool for Cultural Heritage protection" [43] has the major objectives of supporting policy and decision-makers in the management of cultural heritage at risk from climate change induced by hydrometeorological extreme events, and fostering the inclusion of dedicated measures for cultural heritage safeguarding in national disaster risk-reduction plans, in the framework of a transnational perspective.

The tool combines, for the first time, the outputs from 12 climate models, a historic data set and data from the Earth Observation domain. Past and future projections of purposely-selected climate extreme indices (e.g., maps and time series) with a high spatial resolution and addressed to the safeguarding of cultural heritage are provided for the first time in a unique point of access. An user-driven approach has been adopted since the beginning in order to foster the use by non-technical experts and stakeholders of the cultural heritage field.

By accessing the "Risk mapping tool for Cultural Heritage protection" (shortened to "STRENCH WGT" in Figure 2) and applying the tools available in its "Maps" section, users can directly identify hazard prone areas and download the related historic and future maps [43]. The historic time series at specific locations of the climate extreme indices listed in Table 2 can be also visualized by using the products of Copernicus (from 1981 to present) and NASA (from 2000) (Figure 1).

The "Risk mapping tool for Cultural Heritage protection" also includes a methodology for a vulnerability ranking at a building scale, considering the vulnerability as a result of the interaction among the susceptibility, exposure and resilience. Starting from these requirements, a hierarchy tree is introduced including various branches (referred to as criterion or sub-criterion) which help in conceptualizing the evaluation. The vulnerability is ranked from 0 (low) to 1 (high). Details of the procedure are given in [44]. By using this methodology and following a guided procedure, users can then rank the vulnerability of the site under investigation. The overall aim is to enable the assignment of the values for each criterion or sub-criterion necessary for the evaluation of the three identified requirements.

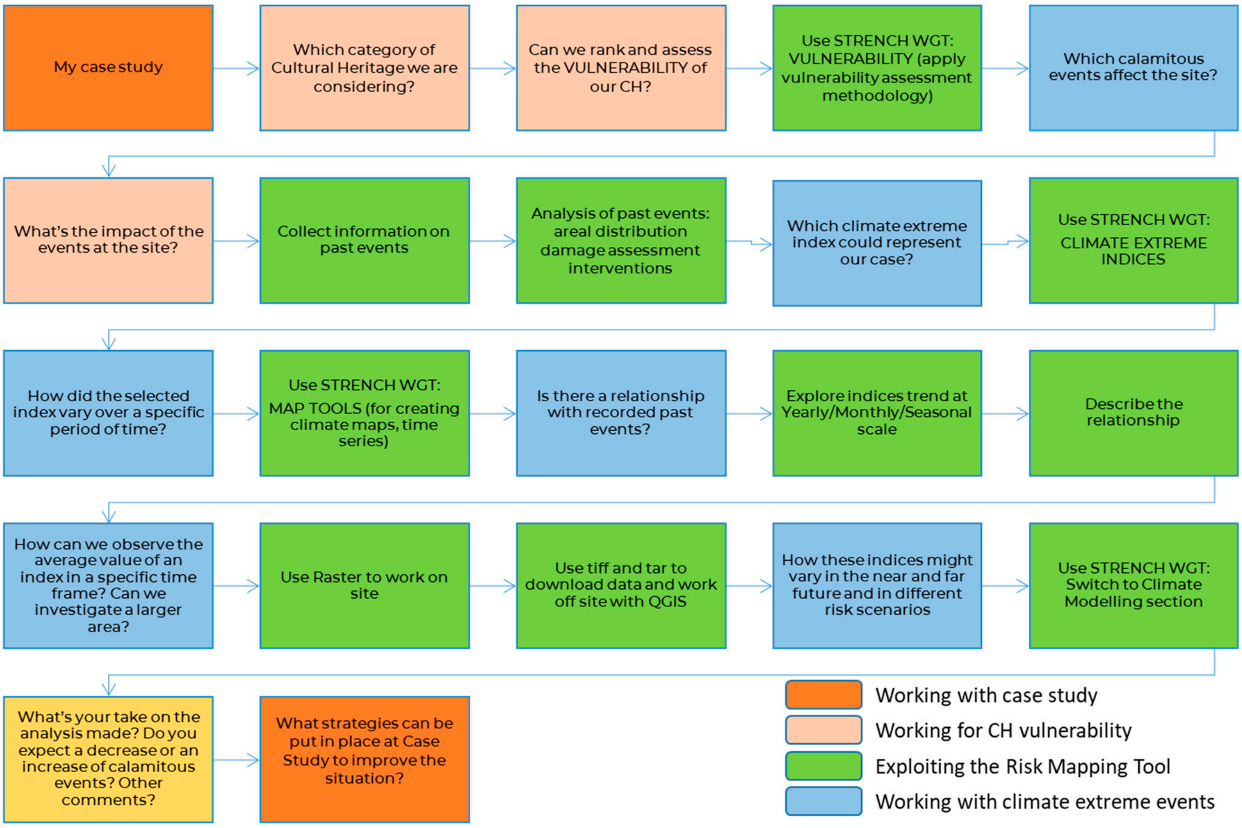

Figure 2. Guided procedure for the application of "Risk mapping tool for Cultural Heritage protection".

The diagram in Figure 2 serves as a guideline to users, including non-technical experts, for the hazard and vulnerability assessment of cultural heritage categories at a local scale (i.e., a case study analysis) by using the "Risk mapping tool for Cultural Heritage protection" and related tools based on the methodological approach outlined in Figure 1.

The procedure requires the active participation of users who operate in an interactive way and is required as a first step to provide a general overview of a case study concerning the geographical location and the main environmental features.

The second step is to focus on an in depth study and description of the cultural heritage category that needs to be protected against one or more environmental hazards linked to climate change.

Then, the assessment of its vulnerability by applying the vulnerability tool/methodology integrated in the "STRENCH WGT" can be performed.

The subsequent step foresees an investigation of the main risks impacting the site and the execution of a detailed research of the past calamitous events that have occurred at the site, while also considering the protective and recovery measures put in place during and after those events in order to highlight the good and bad practices of safeguarding, and to determine the still-existing gaps needing to be overcome. Having once collected all this information, it is then possible to analyze the past and future changes of hazards by selecting the proper climate extreme indices (Table 2). All the procedures are then finally addressed to identify strategies of preparedness and prevention for resilience strengthening of the sites under consideration.

The data and results obtained though the testing of the "Risk mapping tool for Cultural heritage protection" for the 14 case studies in Central Europe involved in the ProteCHt2save (seven sites) and STRENCH (seven sites) projects are available online [43–46]. This activity was addressed in the improvement of the tool on the basis of the active involvement and feedback on use from the partners responsible for the case studies under the guidance of CNR-ISAC, the lead partner of both projects.

3. Concluding Remarks and Future Directions

The safeguarding of cultural heritage, including built heritage such as historic centers, archaeological sites, monumental complexes, and ruined villages, but also landscapes, historic parks and gardens, requires a holistic and multidisciplinary approach in order to identify all the critical parameters and factors that can put it in danger in a changing environment. A paradigm shift is necessary for the proper management of this important heritage. Ambitious policy choices increasingly supported by scientific research are essential for the implementation of strategies and measures to tackle the slow cumulative damage due to ongoing variations in climate and air pollution; however, the impact of short-term events, and emergency situations due to hydrometeorological extreme events, cannot be ruled out. The preparedness, prevention and protection of cultural heritage must be planned carefully, taking into account all the peculiarities of a territory, while analyzing the vulnerability of the cultural heritage assets included in it, and estimating the exposure to a potentially dangerous event in a short- and long-term perspective.

In order to ameliorate the communication between the research sector and practical application in the policy-decision-making process, research focused on the assessment of the climate change impacts on cultural heritage should be, first of all, based on a proper identification of the environmental (e.g., climate and air pollution) parameters to be monitored with a definition of an appropriate spatial and temporal resolution. Adopting the continuous environmental monitoring of prioritized climatic parameters in proximity to the heritage site, and/or planning specific checking with a monthly or seasonal frequency, can support determining the risks as a consequence of climate change effects. It is suggested that cultural heritage managers, owners and non-technical experts in charge of the protection of cultural heritage be reminded that dealing with the identified climate drivers causing deterioration is also dependent upon a comprehension of the vulnerability of a heritage asset, and the environmental context in which it is located. This will allow the scientific community to further explore the potentialities and tailor the damage functions and models with a user-driven approach.

The obtained results in terms of the observed and projected impacts should be translated into pragmatic guidelines for stakeholders, including urban planners, conservation practitioners, cultural heritage owners and managers. The understanding of the synergic effects of related climate change impacts and an improved practical use of outputs will assist in establishing priorities in relation to the protection needs of tangible heritage objects and assets.

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Data Availability Statement: The data presented in this study are available after registering at https://www.protecht2save-wgt.eu/, (accessed on 28 February 2023).

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