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Digital Prototyping and Regenerative Design Toward Carbon-Neutrality and a Climate Resilient Built Environment: A Multi-Scale Assessment of Environmental Multi-Risks

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Abstract: This study addresses the urgent need to move the construction sector toward carbon neutrality and climate resilience, by considering the increasingly intense impacts of climate change. The research aims to evaluate the application of advanced digital prototyping tools and regenerative design principles to identify environmental risks at different scales, with a particular focus on cultural and natural heritage. The hypothesis is that the integration of climate data and predictive models with regenerative design can overcome existing barriers to sustainable practices and significantly enhance the adaptive capacity of the built environment, particularly in safeguarding cultural and natural heritage against the multi-hazard impacts of climate change. To test this hypothesis, an experimental study is conducted using a combination of climate data, advanced modeling and regenerative design tools to assess and manage multi-hazard impacts on cultural and natural heritage. Two case studies were analyzed: Palizzi Marina, a coastal town vulnerable to sea level rise and flooding, and Palazzo Mesiani in Bova, a historic building exposed to increased solar radiation and temperatures. This type of analysis has enabled a comprehensive multi-scenario and multi-hazard assessment that offers a detailed overview of the risks to be considered in the design phase. In conclusion, the research underscores the importance of interdisciplinary approaches and emerging technologies in resilient design frameworks. By integrating climate data and predictive models with regenerative design methodologies, this study can significantly contribute to enhancing the adaptive capacity of the built environment. This approach aids in the transition of the construction sector toward sustainability and climate resilience, particularly in protecting cultural and natural heritage.

Keywords: digital prototyping; regenerative design; climate resilience; multi-scale environmental risk assessment; heritage; multi-risk impact mitigation

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Citation: Lucanto, D.; Nava, C.; Mangano, G. Digital Prototyping and Regenerative Design Toward Carbon-Neutrality and a Climate Resilient Built Environment: A Multi-Scale Assessment of Environmental Multi-Risks. *Buildings* **2024**, *14*, 3934. https://doi.org/10.3390/buildings14123934

Academic Editors: Bruno Barroca, Maria Fabrizia Clemente, Jeffrey Raven and Gwenaël Jouannic

Received: 8 November 2024
Revised: 2 December 2024
Accepted: 4 December 2024
Published: 10 December 2024

1. Introduction

In the current international context, climate challenges require rapid and innovative responses, making it necessary to develop effective strategies for the protection of cultural and natural heritage. However, the adoption of sustainable practices in the construction sector faces numerous obstacles, including economic, technical and regulatory barriers [1]. Overcoming these obstacles requires an integrated design approach oriented toward the adoption of advanced and regenerative design principles that, by promoting new operational processes, can mediate between the various actors in the construction sector: professionals, technicians, policy makers, etc.

The challenges posed by climate change are constantly increasing. The effects of global warming are manifesting themselves with increasing intensity and frequency, often exceeding the adaptive capacity of natural systems and existing infrastructures. According to UNESCO [2], over 30% of the sites identified as cultural heritage are currently threatened by phenomena such as sea level rise, coastal erosion, flooding and extreme temperatures. At the same time, natural heritage is suffering serious consequences, with estimates from the Intergovernmental Panel on Climate Change (IPCC) [3] indicating that up to 50% of the world's sandy coastlines could suffer significant erosion by 2100 due to rising sea levels and increased extreme weather events.

Architectural and environmental design, especially technological design, plays a key role in the development of adaptation and mitigation strategies for the protection and conservation of natural systems. De Santoli [4] highlights that the integration of advanced and sustainable technological solutions in architecture is essential to address the challenges posed by climate change, while promoting energy efficiency and heritage conservation [5]. An interesting starting point comes from the strategic theories adopted in post-disaster contexts, which interpret principles such as immediate response, detailed damage assessment and reconstruction planning [6]. The practical application of the methodologies developed and validated in the case studies of Palizzi Marina and the historic center of Bova allows an underlining of how necessary it is to guide the transition of the construction sector toward carbon neutrality and climate resilience, and how essential it is to anticipate and mitigate the risk of natural disasters through predictive scientific approaches. As highlighted by Lehmann [7], the adoption of interdisciplinary approaches and the integration of emerging technologies are key to effectively addressing the impacts of climate change on the built environment [8].

By integrating climate simulations and geospatial data with site-specific characteristics, a multi-hazard overview is provided in which different hazards such as flooding, coastal erosion, thermal stress and material degradation are contextualized. Contextualizing the multi-hazard scenario is essential, since different natural hazards can act simultaneously or sequentially, amplifying impacts on structures and ecosystems [9]. They interact with each other in complex ways (Figure 1), and their combinations can lead to different damage response mechanisms than when the risks are considered individually. The understanding of complex adaptive systems, necessary for a socio-ecological transition [10], must be entrusted to advanced frontier research methodologies [11].

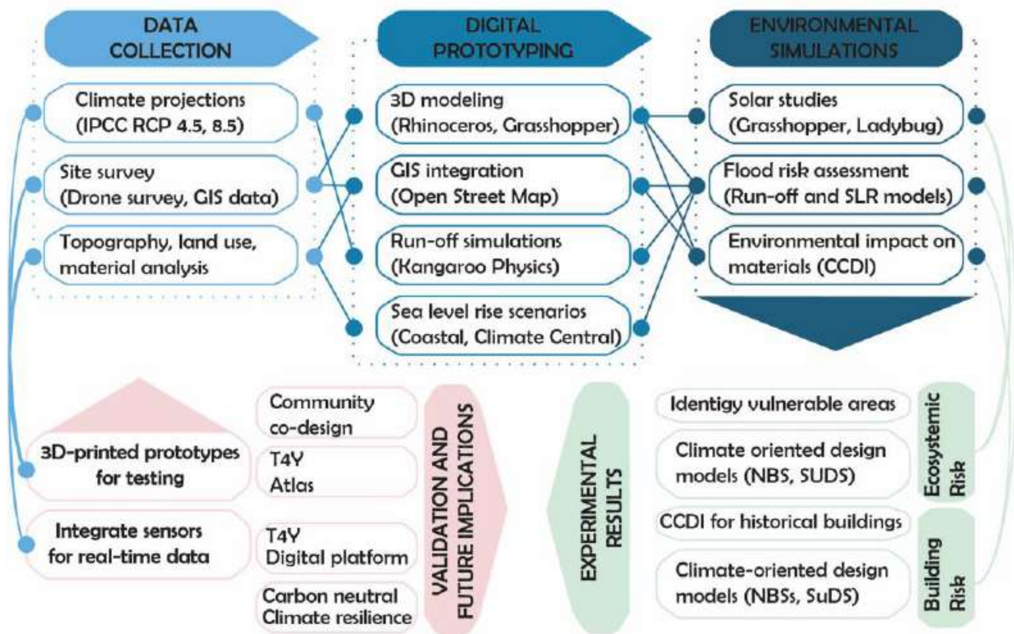

Figure 1. Climate change-oriented design workflow.

1.1. Research Objectives

This present study aims to provide a significant contribution to the assessment and management of the multi-risk impacts of climate change on built, cultural and natural heritage. The application of advanced digital prototyping tools and regenerative design principles allows the development of an integrated methodology that can guide effective design interventions, oriented toward carbon neutrality and the climate resilience of the built environment. The objectives of the experimentation proposed in this text are closely linked to the macro-objectives of the TECH 4 YOU–PP 4.7.1 project [12], which focuses on the development of innovative technologies for climate change adaptation and the improvement of quality of life. The TECH 4 YOU contribution consists in the acquisition of data, models and prototypes that will feed the project's digital platform and the atlas of adaptive solutions. This platform will collect structured information, including climate data, simulations and case study analyses. Atlas will serve as a framework for data collection, analysis and visualization, including the study of adaptive technological alternatives (materials and integrated systems) oriented toward climate and carbon neutrality. In this context, this study, in addition to filling gaps in current practices and contributing to the advancement of knowledge in the field of technological and environmental design, especially in iterative processes between digital and physical models, contributes to the advancement of the project through the achievement of the following specific objectives:

- Development and validation of a Scalable Experimentation Framework: development of an integrated workflow that will allow the integration of specific climate scenarios with the characteristics of the studied sites, allowing an accurate assessment of multi-risk climate impacts at local scale.
- Application and testing of the method in case studies: the practical application of the framework will allow the validation of the effectiveness of the methodology in real contexts, providing empirical data for the optimization of adaptive strategies.

1.2. Theoretical Background

A significant part of the debate on climate change revolves around the risk and uncertainty associated with the predictive ability for these phenomena, compounded by uncertainties about the magnitude and likelihood of these events occurring. As Nava points out [13], "It is therefore necessary to have an approach that is not exclusive with respect to the relationship between impact and risk, but that considers an approach to a risk balance capable of assessing direct and indirect effects on the systems concerned, with the best overall performance, local and global". The most common danger becomes, in fact, that transferring the meanings of the term "risk" from other disciplines makes reductions in the field or assimilations of context that forget the reference condition of the causal scenario of interest: "the aggregate vectors of risk, exposure and vulnerability to which we refer any mitigation or adaptation action in relation to climate change" [13].

The theoretical field of application of experimentation emphasizes, in fact, the contribution of technological and environmental design in climate change studies. In the field of the technological design of architecture, in fact, the principles of sustainability, resilience and innovation are fundamental to developing effective solutions [14]. Resilience, in particular, is defined through three interconnected profiles: ecological, technical and psychological. These profiles are closely integrated whenever there is a need to intervene both in the impact reaction phase and in the prevention and planning phase of adaptation conditions of natural and artificial systems [15].

By utilizing orient adaptation and mitigation strategies based on a multi-hazard analysis, it is possible to develop more resilient design solutions that improve the ability of the proposed solutions to regenerate the environmental context within which they are inserted (ecological aspect), increasing the capacity of infrastructures to withstand adverse conditions (technical profile) and supporting communities in adapting and innovating in response to changes (psychological profile). By integrating these principles with advanced digital prototyping and regenerative design methodologies, this study aims to bridge the gap between theoretical models and practical applications. The use of predictive parametric modeling technologies allows the development of a workflow capable of integrating climate scenarios and their specific effects on local ecosystems. This approach allows for an integrated assessment of the direct and indirect effects on the systems involved, ensuring the best overall performance, both locally and globally.

Together with the relevant theoretical assumptions from Hoseinzadeh's study [16], the concept of carbon neutrality is linked to the proposed experimentation, emphasizing the importance of design strategies aimed at reducing global CO_2 emissions. The concept of carbon neutrality is central to the transformation of the built environment. Recent studies [17–19] have shown that integrating the principles of regenerative architecture with sustainable design can lead to a significant transformation in building practices, promoting the reduction of waste and environmental degradation, and improving the well-being of communities and ecosystems. A further fundamental aspect is represented by regenerative design [13], using computational techniques to optimize projects according to specific criteria. The use of regenerative design software allows the development of parametric models to simulate the effects of different climate scenarios. This approach addresses the development of sustainable solutions, but also enhances the data collections necessary for exploring and validating the elaboration of design alternatives that may not be immediately apparent with a "traditional" design approach [20].

As far as emerging technologies are concerned, technological advances in the field of 3D printing have had a significant impact on future developments in experimentation. The use of 3D printing has made it possible to create detailed physical models of the case studies, facilitating the analysis of the morphological and climatic conditions of the sites. The prototypes developed, thanks to future implementation, will allow the visualization and testing of innovative design solutions, in line with the principles of regenerative design [21].

The elaboration, and in a certain sense the reinterpretation of these concepts, makes it possible to define the scientific boundaries within which experimentation operates.

2. Materials and Methods

The methodology adopted for this experiment is based on the creation of a framework that integrates digital prototyping [22] and regenerative design [21] for a multi-scalar evaluation of environmental risks [23], allowing for an accurate analysis of physical climate risks and their impact on the built environment, thus guiding the transition toward a carbon-neutral [24] and climate-resilient [25] environment. This approach enables the establishment of a one-to-one correspondence between projections of climate change scenarios and the morphological, architectural, and technological characteristics of the analyzed contexts. This section will present the materials and methods used in the study, with the aim of illustrating in detail the approach adopted to assess the impacts of climate change on the sites of interest. The selection of representative case studies allows the emphasizing of the multi-scalar approach used to identify multi-risk factors, ensuring alignment with the context and the specific scale of the cases, representative of both the natural and cultural heritage in the Grecanica Area of Reggio Calabria (Calabria, Italy) (Figure 2).

Figure 2. Map of the Grecanica Area.

Palazzo Mesiani in Bova (Figure 3, left), cultural heritage, on the other hand, is a significant historical building that represents the local cultural heritage; its selection makes it possible to analyze the effects of climate change on a building scale, regarding thermal impacts and the increase in solar radiation on the building envelope.

Figure 3. (**Left**) highlighted map of the historical centre of Bova; (**Right**) highlighted map of Palizzi M.

Palizzi Marina (Figure 3, right), natural heritage, a small coastal town, is particularly vulnerable to coastal erosion, sea level rise, and extreme weather events, making it an ideal case for studying the climate impacts at both the urban and territorial scale.

2.1. Methodological Framework

To effectively address the complex impacts of climate change on the selected sites of interest, an innovative and integrated methodology has been developed that combines advanced sensing techniques, digital modeling and sophisticated tools for climate and environmental analysis. The experimental phases consist of a combination of advanced surveying techniques, digital modeling and sophisticated climate and environmental analysis tools to assess the impacts of climate change on the sites of interest. By integrating photogrammetric drones, climate data-processing software and environmental simulation plug-ins, we were able to overcome the limitations of traditional approaches and provide a multidisciplinary and detailed perspective on the issues addressed.

This methodological approach enables a one-to-one correspondence between various risk factors and the sites' morphological, architectural and technological characteristics. By linking updated climate projections with specific environmental conditions, it is possible to analyze how global and local contexts interact under different climate change scenarios. Figure 4 illustrates the workflow, showing how data—such as climate projections and geospatial information—are transformed into actionable information through risk modeling and analysis. This ensures a direct and reciprocal interaction between climate projections and the built environment's characteristics. The generated information guides the targeted use of resources, steering design decisions toward climate resilience and carbon neutrality.

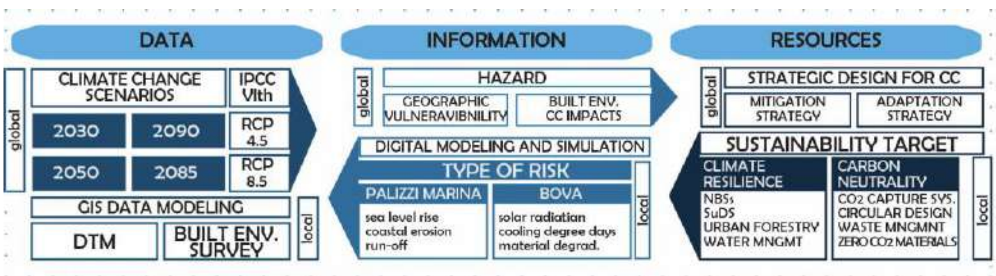

Figure 4. Methodological framework for the climate change-oriented design workflow.

The structure of the data, information, and resources [26] highlights the logical and operational flow of the methodology, facilitating its application in technological and environmental design processes.

By accounting for the inherent uncertainties noted by the IPCC, this approach enhances the understanding of the interaction between risk, uncertainty and climate responses. The framework's ability to represent a holistic and dynamic view of climate risks allows an understanding of how atmospheric phenomena interact with material characteristics, potentially increasing the vulnerability of environmental and historical assets. By transforming climate projections and geospatial data into targeted and applicable information, the operational structure supports design decisions aligned with principles of climate resilience and sustainability.

2.1.1. Digital Prototyping

Detailed digital prototyping was conducted for the case studies using advanced surveying and modeling techniques. For Palazzo Mesiani in Bova, photogrammetric surveying with a drone was employed (Figure 5). This technique acquired high-resolution data of the terrain's orography and morphological features. The collected images were processed using Agisoft Metashape Professional 2.0.4 software, generating detailed 3D models through Structure from Motion (SfM) and Multi-View Stereo (MVS) algorithms (Figure 6). The resulting three-dimensional digital prototype was utilized for subsequent analyses.

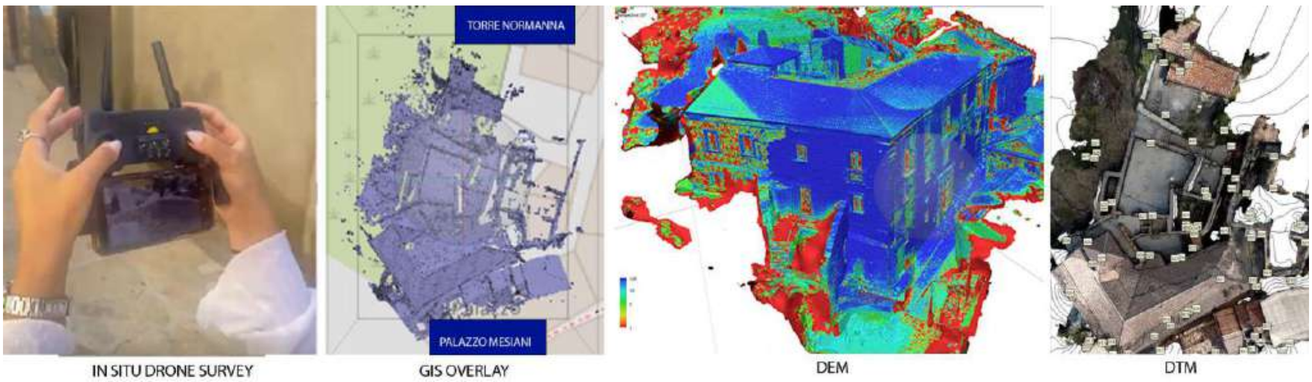

Figure 5. Drone survey process.

Figure 6. Refined digital prototype of Palazzo Mesiani.

For Palizzi Marina, digital prototyping was conducted using Grasshopper within the Rhinoceros 3D environment. Georeferenced 3D models were obtained from OpenStreetMap data, providing a mesh that accurately represents the terrain and built environment of the area. The GHopper GIS plugin was employed to facilitate the integration of GIS data into the 3D modeling environment. This plugin acts as a conduit between extensive GIS databases and the detailed, scalable environment of 3D modeling, enabling a seamless transition from geospatial data to a workable 3D model.

An original Grasshopper script was developed to process and visualize topographical features such as contours, slopes, elevations and other relevant spatial information. The script utilized components such as "Import SHP" for vector data and "Raster to Point" for elevation data, allowing for the direct import and processing of various GIS datasets, including shapefiles and digital elevation models.

The Grasshopper script began by extracting elevation data from the georeferenced mesh obtained from OpenStreetMap, assigning precise height values to various points within the geometry. Subsequently, the terrain surface was subdivided into a grid system to perform comprehensive slope calculations for each grid cell. By analyzing the change in elevation between adjacent grid points, the script calculated slope gradients expressed as percentages. This detailed information on the terrain's steepness will be used to identify the run-off coefficients. Finally, the script automatically generated contour lines and cross-sectional profiles of the terrain, providing a visual representation of the topography (Figure 7).

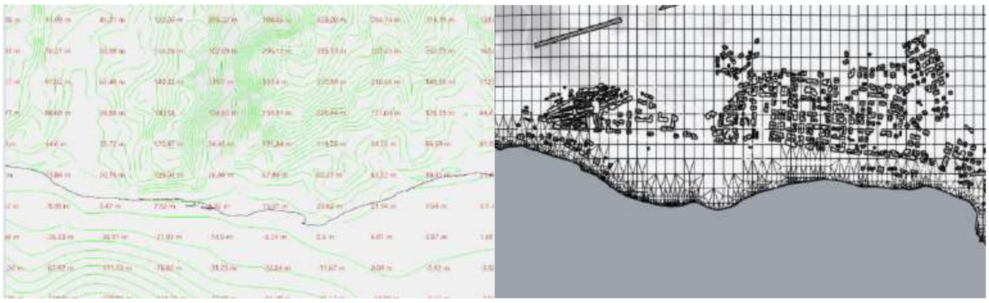

Figure 7. First integrated map for the digital prototype of Palizzi Marina.

2.1.2. Processing of Climate Files Through Meteonorm Software

Site-specific future climate projections for Palizzi Marina and Bova were generated using Meteonorm software vers. 8 [27]. Representative Concentration Pathways (RCPs) 4.5 and 8.5 were selected, representing moderate and high emissions scenarios, respectively. These scenarios were used to generate climate projections for the key years 2030, 2050, 2085 and 2090. Meteonorm produced hourly climate files that include parameters such as air temperature, relative humidity, global solar radiation, wind speed and direction, precipitation and other relevant weather data.

2.1.3. Analysis of Sea Level Rise with Coastal Risk Screening Tool

To assess the impact of sea level rise on Palizzi Marina, the Coastal Risk Screening Tool developed by Climate Central [28] was utilized. This interactive tool allows you to visualize projections of sea level rise and potential coastal flooding risk under different climate and storm scenarios. By inputting precise geographical coordinates, projections of sea level rise under different RCP scenarios were obtained for the key years. The tool identified areas at risk of flooding and coastal erosion, highlighting vulnerable infrastructures, buildings and natural areas.

2.1.4. Rational Methods for Run-Off Calculations

To evaluate the superficial run-off (run-off) in the study areas, an original algorithm based on the rational method [29] was developed, implemented within the Grasshopper visual programming environment. The fundamental equation used is

$$Q = C \times I \times A$$

where Q is the run-off range; C is the run-off coefficient, specific to the type of surface; I is the intensity of precipitation; and A is the area of the surface considered. The development of this original script for the run-off calculation is a significant contribution to the advancement of research. The run-off coefficient C is a parameter that represents the fraction of precipitation that is not absorbed by the soil, evaporated or retained by vegetation, and which therefore flows to the surface [30]. The value of C varies from 0 to 1, where 0 indicates no run-off (all water is absorbed); 1 indicates that the water is not absorbed, so the run-off is maximum.

The values of C (Table 1) depend on the type of surface and the slope of the land. Surfaces with a steeper slope tend to have higher C values, as water drains off more quickly and has less time to infiltrate the soil.

Table 1. Run-off coefficients.

Surface Type	Run-Off Coefficient (C)
Asphalt, concrete and roofing	0.70–0.95
Cobblestones	0.25–0.50
Compacted soils	0.40–0.70
Sandy sediments	0.05–0.20

2.1.5. Environmental Simulation and Analysis with Ladybug

To process and visualize climate data and conduct environmental simulations, Ladybug [31], an open-source plug-in for the Grasshopper visual programming environment, integrated into Rhinoceros 3D (version 7), was used. Ladybug Tools vers. 1.8 is a suite of components designed to facilitate parametric environmental analysis, allowing users to import climate data and perform a wide range of analyses on aspects such as energy, natural lighting, thermal comfort and solar radiation.

Ladybug allows you to import climate files in EPW (EnergyPlus Weather) format, previously processed with Meteonorm, and to display detailed climate information through interactive graphs and spatial mapping. Thanks to its integration with Grasshopper, Ladybug allows you to create custom scripts to automate complex processes and adapt analyses to the specific needs of the project.

In the context of this study, Ladybug was used for the simulation, calculation and visualization of the hours of direct illumination and the levels of radiation incident on the area of the Bova case study. Thanks to the solar analysis capabilities of the plug-in, it was possible to assess the solar exposure taking into account the local orography, the orientation of the buildings and the shadows cast by the surrounding structures.

2.1.6. Climate Change Damage Index

The Climate Change Damage Index (CCDI) is an innovative composite indicator designed to quantify the impact of climate change on the durability of building materials, integrating climate-specific data with the characteristics of the materials themselves.

The CCDI identifies and classifies the influence of key climate variables, such as temperature, solar radiation, wind pressure and precipitation, assigning each material a vulnerability level on a scale of 1 to 4, with 1 representing minimal impact and 4 being highly damaging impact.

The application of the CCDI on Palazzo Mesiani is based on the methodology developed by Giglio et al. [32]. This index considers three main factors: environmental conditions, analyzing key climatic variables such as temperature, solar radiation, wind pressure and precipitation; material properties, evaluating the sensitivity of materials to climatic factors, based on experimental data and physico-chemical characteristics; and external factors, including geological, biological and anthropogenic hazards that can further influence the vulnerability of materials.

Each factor is divided into specific indicators and classification criteria, assigning each material a vulnerability level on a scale of 1 to 4, with 1 representing minimal impact and 4 a highly damaging impact.

In the specific case of Palazzo Mesiani, the application of the CCDI focused on the calculation of the environmental conditions, for which benchmarking activities had already been carried out. This involved a detailed analysis of local climate variables—such as the intensity of solar radiation and average summer temperatures—cross-referenced with the specific vulnerabilities of the materials present in the historic building.

The methodology involves the cross-referencing of specific climate data with the critical parameters of the materials, as defined by Giglio. For example, for concrete, temperatures above 40 °C are classified as Highly Harmful (4) according to international standards while, for wood, incident solar radiation above 4.5 kWh/m^2 indicates a high risk of photodegradation.

2.2. Data Collecting

The collection of climate and environmental data for the case studies of Palizzi Marina and Bova was carried out in a systematic way, in line with the methodological framework. Data acquisition begins by drawing on the Meteonorm database. Meteonorm was used to carry out climate projections based on RCPs. In particular, two different RCPs were chosen to cover a wider range of possible climate futures and to assess the impact of climate change on different time horizons (Figure 8):

- RCP 4.5: a moderate emissions scenario, used for the projections for the 2030s and the 2090s, representing both a short-term and a long-term period.
- RCP 8.5: a high emissions scenario, used for projections for the 2050s and 2085s, focusing on a medium-to-long-term period.

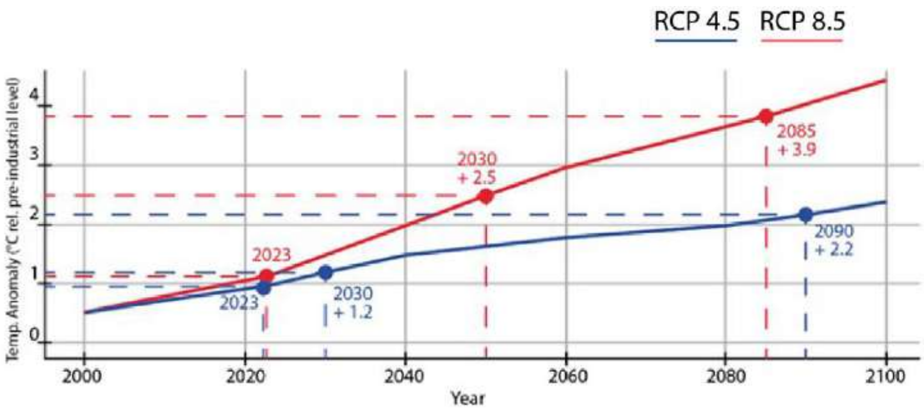

Figure 8. Global temperature projections under RCP 4.5 and RCP 8.5 scenarios with key years. Elaboration on IPCC data by D. Lucanto.

The choice to use RCP 4.5 for the years 2030 and 2090 makes it possible to analyze climate impacts in a scenario in which global emissions begin to decrease from the middle of the century, leading to a stabilization of greenhouse gas concentrations by 2100. This allows for the assessment of both the immediate and long-term effects of more aggressive climate policies and sustainable technologies [31]. On the other hand, the use of RCP 8.5 for the years 2050 and 2085 offers a perspective on a "business as usual" scenario [33], in which emissions continue to grow without significant mitigations, leading to higher greenhouse gas concentrations.

This scenario is particularly useful for assessing climate risks in the medium term, in a context where emission reduction policies may not be sufficiently effective. Moreover, the use of RCP 4.5 for 2030 provides insights into what the climate conditions could be in the next decade under a moderate emissions scenario, while the analysis for 2090 under the same RCP helps an understanding of the long-term effects of mitigation policies.

Similarly, the use of RCP 8.5 for 2050 and 2085 helps highlight the risks associated with a high emissions pathway in the medium term, providing crucial information on the adaptation and resilience of the built environment. In this initial data collection phase, the EPW files generated with Meteonorm were imported and localized using Ladybug. This tool was essential for visualizing and interpreting a series of climate charts related to solar irradiance [34] (Figure 9), enthalpy variations [35], humidity variations, heating degree days and cooling degree days [36] for both study sites, Bova and Palizzi Marina. The analysis of this data allowed for a detailed understanding of the current and future climatic conditions of the two contexts.

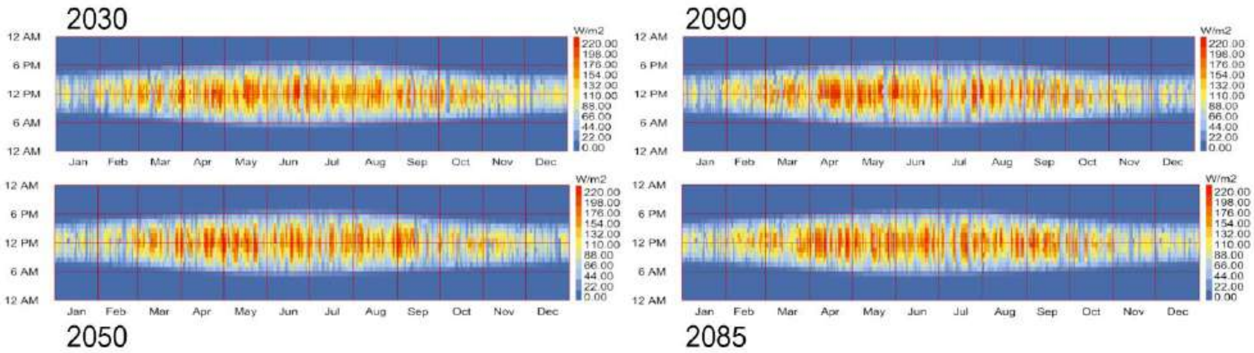

Figure 9. Irradiance graph of the Grecanica Area for different scenarios under RCP 4.5 and RCP 8.5.

Changes in enthalpy and humidity (Figure 10) revealed significant variations that could impact the thermo-hygrometric comfort of buildings and outdoor spaces, suggesting the need for design strategies to control humidity and natural ventilation.

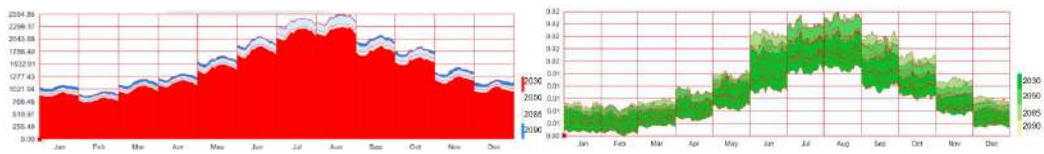

Figure 10. Enthalpy (SX) and humidity (DX) graphs of the Grecanica Area for different scenarios under RCP 4.5 and RCP 8.5.

The graphs related to heating and cooling degree days (Figure 11) revealed a trend toward a decrease in heating requirements and an increase in cooling requirements. This approach, therefore, enabled the establishment of a one-to-one correspondence between future climate projections and the specific morphological, architectural, and technological characteristics of the study sites.

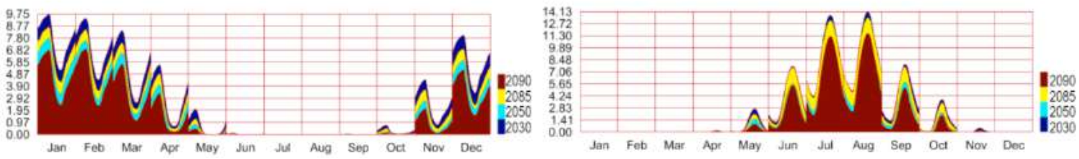

Figure 11. Cooling deg. days (SX) and heating deg. days (DX) graphs of the Grecanica Area for different scenarios under RCP 4.5 and RCP 8.5.

Similarly to the analysis of previous environmental data, an assessment of the intensity of rainfall in Palizzi Marina was carried out, using 2023 data [37] as a reference and considering the maximum hourly precipitation value. Projections based on the RCP 4.5 and RCP 8.5 climate scenarios were carried out using Ladybug. The maximum hourly precipitation value recorded in 2023 was 35 mm/h during an intense event in November. The projections (Table 2) indicate an increase in both annual rainfall and maximum hourly rainfall intensity in Palizzi Marina. In particular, the maximum hourly intensity could increase to 40 mm/h by 2085 in the RCP 8.5 scenario.

Table 2. Projections of annual precipitation and maximum hourly intensity.

Scenario	Total Annual Precipitation (mm)	Increase 2023 (%)	Maximum Expected Hourly Intensity (mm/h)
2023	729.3	-	35
2030	765.8	+5%	37
2050	802.2	+10%	39
2085	838.7	+15%	40
2090	780.3	+7%	38

3. Results

This section analyzes the results obtained from the experimental application of advanced digital prototyping tools and regenerative design methodologies to the two case studies: Palizzi Marina and Palazzo Mesiani in Bova. The discussion is structured to interpret the analytical results, explore the implications for the design and reflect on the methodological contributions of the proposed approach.

The application of the framework on case studies provided important insights into multi-hazard scenarios affecting cultural and natural heritage in different climate change scenarios. The direct correspondence between future climate scenarios, outlined by the IPCC for the RCP 4.5 and RCP 8.5 pathways, makes it possible to interpret physical risks—such as floods, coastal erosion and heat stress—in a proactive and contextualized perspective, thus guiding adaptation and mitigation strategies. This discussion, therefore, focuses on the results of the experimentation conducted, offering an integrated view of the data and proposing adaptation models that, using advanced digital prototyping and detailed climate analysis, provide the basis for developing innovative solutions that can potentially be replicated in other areas exposed to climate change.

3.1. Palizzi Marina Experimental Results

The experimentation on Palizzi Marina has made it possible to assess the impacts of climate change on the coastal area, focusing on two main aspects: sea level rise (SLR) scenarios and run-off scenarios. Using the climate files generated for RCP 4.5 and RCP 8.5 scenarios, the potential impacts for the years 2030, 2050, 2085 and 2090 are analyzed. To estimate future scenarios of sea level rise in the Palizzi Marina area, the projections provided by the IPCC's Sixth Assessment Report (AR6) were used. These were integrated with advanced modeling tools offered by Climate Central's Coastal Risk Screening Tool, which incorporates IPCC data and uses state-of-the-art techniques for coastal risk modeling.

3.1.1. Integrating Digital Prototyping to Simulate Sea Level Rise Scenarios

Advanced digital prototyping played a crucial role in visualizing and analyzing sea level rise scenarios for Palizzi Marina. Using parametric design software such as Rhinoceros 3D vers. 8 and Grasshopper vers. 2, a high-resolution three-dimensional model of the Palizzi Marina coastline was developed (Figure 12). This approach made it possible to integrate high-resolution GIS data, including topographic information, land use and hydrodynamic conditions, ensuring an accurate geographical representation that could be adapted to different test conditions.

Advanced digital prototyping enables visualization and analysis of sea level rise scenarios for Palizzi Marina. To obtain detailed projections of sea level rise, the Coastal Risk Screening Tool developed by Climate Central was used. By integrating the data provided by Climate Central into the three-dimensional model, it was possible to accurately simulate the effects of sea level rise on the coastal areas of Palizzi Marina. Using projections from the IPCC's Sixth Assessment Report (AR6) and Climate Central's Coastal Risk Screening Tool, sea level rise scenarios for Palizzi Marina were analyzed, considering two Representative Concentration Pathways (RCPs). For each of these scenarios, two probabilities of outcome were considered: medium luck and bad luck. The results (Table 3) show a significant increase in mean sea level over time, with variations that may exceed 1.5 m by 2100 in the worst-case scenario (RCP 8.5 with "bad luck").

Figure 12. Digital prototype of Palizzi Marina coastline data for SLR scenario analysis.

Table 3. Sea level rise projections for Palizzi Marina.

Scenario	RCP	Medium Luck (m)	Bad Luck (m)
2050	4.5	0.60	0.70
2050	8.5	0.65	0.80
2080	4.5	0.70	0.90
2080	8.5	0.75	1.00
2100	4.5	0.70	1.40
2100	8.5	0.75	1.50

The simulations generated a series of detailed visualizations of sea level rise scenarios (Figures 13–16), highlighting areas potentially prone to flooding over different time horizons and emission scenarios.

Figure 13. SLR projections current trajectory (RCP 4.5, medium luck): 2050, 2080, 2100.

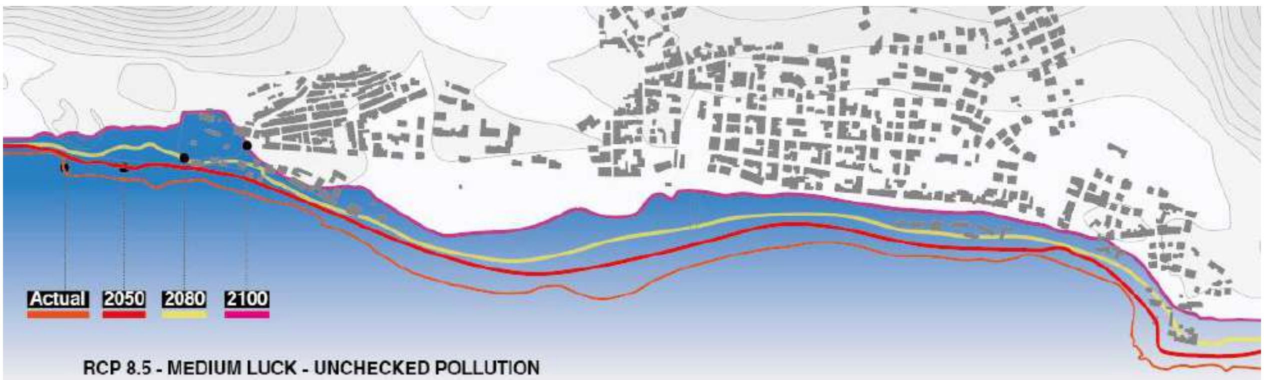

Figure 14. SLR projections unchecked pollution (RCP 8.5, medium luck): 2050, 2080, 2100.

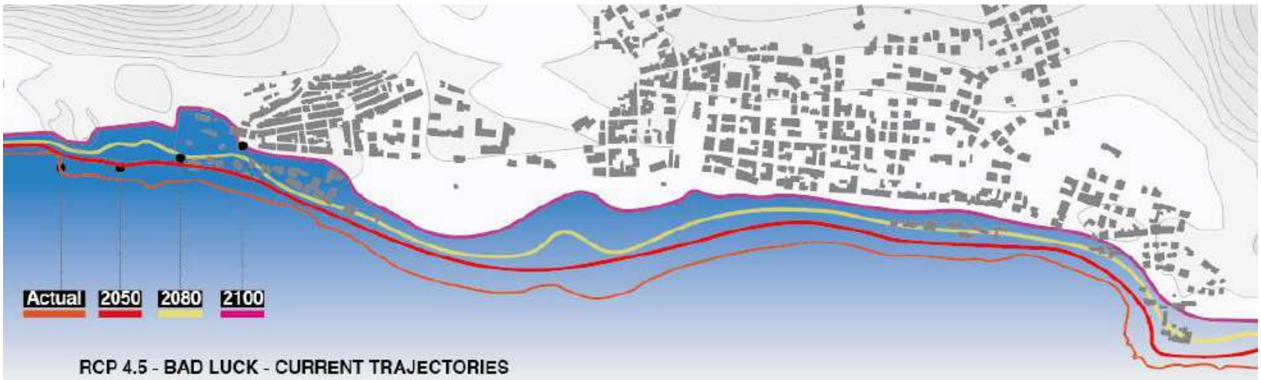

Figure 15. SLR projections current trajectory (RCP 4.5, bad luck): 2050, 2080, 2100.

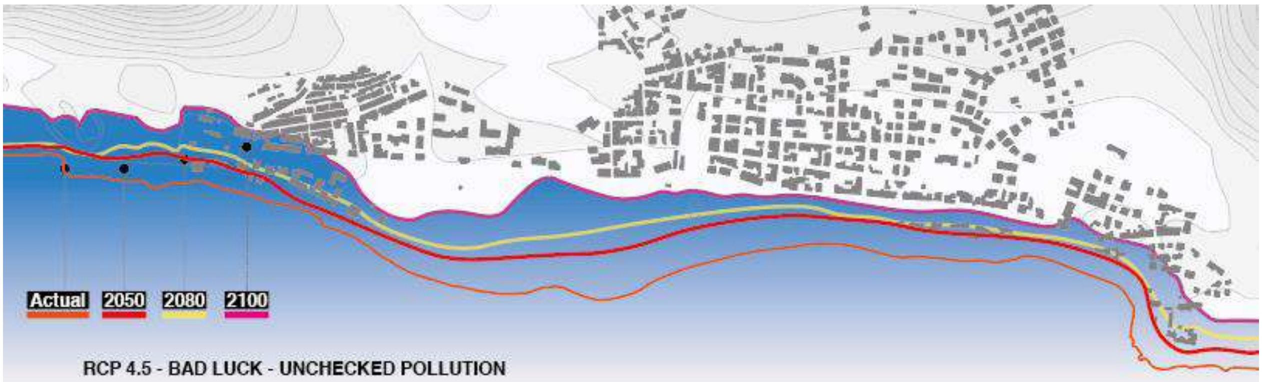

Figure 16. SLR projections unchecked pollution (RCP 8.5, bad luck): 2050, 2080, 2100.

This process can be applied both in the survey phase of physical-climatic phenomena, through the use of predictive digital models, and in the implementation of intervention protocols, through the application of Nature-Based Solutions (NBSs) and Sustainable Urban Drainage Systems, (SuDS) [38], thus supporting the ecological transition and promoting climate resilience for coastal areas. The integration of advanced digital prototyping allows not only to visualize future scenarios in detail, but also to test and optimize innovative design solutions. For example, the adoption of "soft" coastal defence systems, such as the redevelopment of beaches and dunes, can be simulated and evaluated in terms of effectiveness and environmental impact. Similarly, nature engineering interventions can be modeled to understand how they can contribute to the dissipation of wave energy and the protection of the coastline.

3.1.2. Advanced Digital Prototyping for Run-Off Simulation and Flood Risk Assessment in Palizzi Marina

The trial integrated advanced digital prototyping to analyze run-off in different climate change scenarios. Applying the principles of the Regenerative Digital Project, an advanced script was developed in Grasshopper, using the Kangaroo Physics component, to simulate the behavior of water on the topographic surface (Figure 17) of Palizzi Marina and thus identify the maximum flooding capacity.

Using Kangaroo Physics, an interactive physical solver for Grasshopper, made it possible to simulate the flow of water on the surface of the ground, considering its topography. Through this method, it was possible to calculate the volume of water that accumulates in different areas during intense rainfall events and identify the areas at greatest risk of flooding, based on the simulation of water behavior.

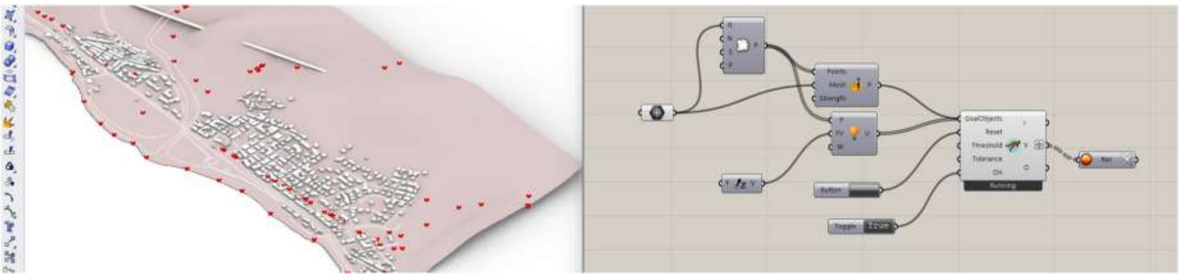

Figure 17. Simulation on Palizzi Marina using Kangaroo Physics.

This made it possible to identify three main areas at risk of flooding (Figure 18):

- Area A—located in the central part, with a low slope and proximity to watercourses, with a volume of water to be managed equal to 4.5 m^3/m^2 for a total of 161,248 L.
- Area B—located in a built-up urban area with waterproof soil, with a volume of water to be managed equal to 1.8 m^3/m^2 for a total of 69,300 L.
- Area C—located in the coastal zone, subject to the combined influence of run-off and sea level rise, with a water volume to be managed of 0.5 m^3/m^2, totaling 62,750 L.

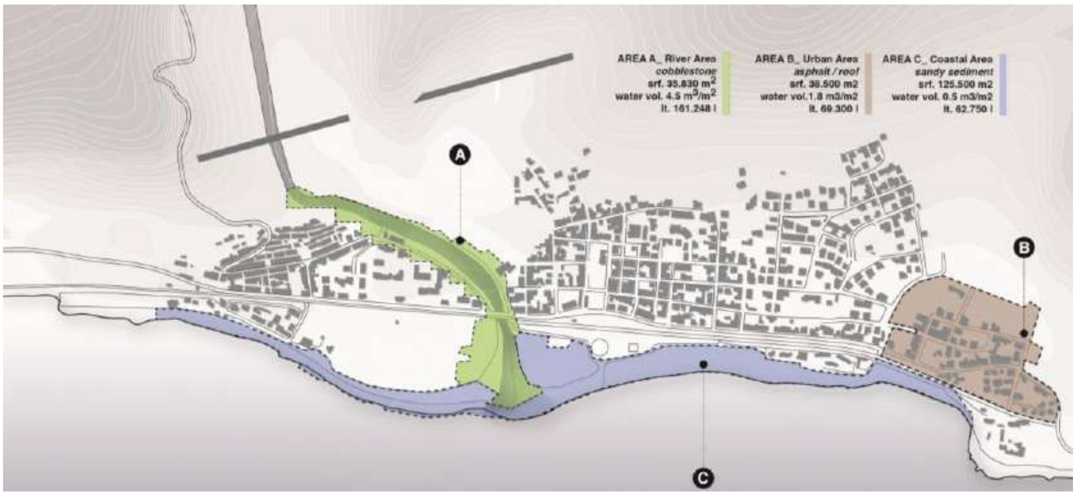

Figure 18. Simulation results identifying key flood-prone areas in Palizzi Marina during intense rainfall events.

To evaluate the run-off in the study areas, the rational method was applied using the run-off coefficients specific to each area, the areas involved and the precipitation intensities expected in the different climate scenarios (Table 4).

Table 4. Results of the run-off experimentation.

Area	Run-Off Coefficient (C)	Surface (A) m^2	Q (m^3/h) 2023	Q (m^3/h) 2030	Q (m^3/h) 2050	Q (m^3/h) 2085	Q (m^3/h) 2090
A	0.30	35,833	376.2	397.7	419.2	429.9	408.5
B	0.80	38,500	1078.0	1139.6	1201.2	1232.0	1169.6
C	0.10	125,500	439.3	464.4	489.5	502.0	476.9

- Area A (35,833 m^2): Characterized by a cobblestone surface; a run-off coefficient of C = 0.30 was chosen. This value reflects the moderate permeability of the pebbles, which allow partial water infiltration into the soil.
- Area B (38,500 m^2): Includes impermeable surfaces such as asphalt and roofs. For this area, a run-off coefficient of C = 0.80 was used, representative of the high impermeability of such materials, where most of the rainwater becomes surface run-off.

- Area C (125,500 m^2): Consisting of sandy sediments; a run-off coefficient C = 0.10 has been adopted. The sand has a high permeability, allowing significant water infiltration and therefore low surface run-off.

3.2. Palazzo Mesiani, Bova, Experimental Results

The experimentation on Palazzo Mesiani has highlighted how climate change can intensify the risks associated with overheating and the degradation of materials in historic buildings. These results underline the importance of integrating climate considerations into cultural heritage conservation strategies, promoting design solutions that increase the resilience of historic buildings in the face of the challenges posed by climate change. As mentioned in Section 2.1.3, detailed analyses were carried out on the hours of direct sunlight and incident solar radiation. These analyses made it possible to identify the periods of the year and the surfaces most exposed to solar radiation, highlighting the areas most subject to environmental stress. Several climate scenarios, both current and future, based on Representative Concentration Pathways (RCPs) 4.5 and 8.5, were considered for the key years 2030, 2050, 2085 and 2090. The analysis quantified the increase in solar energy incident on building surfaces in different scenarios, making it possible to objectively assess the potential overheating and degradation of materials over time.

3.2.1. Preliminary Results of the Experimentation on a Territorial Scale

To apply the multi-scalar approach described in the article, a territorial-scale analysis of the Bova area was conducted, with the aim of understanding the environmental and climatic dynamics that influence the local historical heritage. Through digital prototyping, environmental data has been integrated to predict the impacts of climate change on vulnerable sites. The parametric design methodology made it possible to precisely manage and manipulate this data, facilitating an adaptive response to changing environmental conditions. Digital models of the historic center of Bova were used to analyze the effects of climate change on historical structures, improving understanding of impacts and conservation planning. The irradiance maps (Figures 19 and 20) provide a clear visualization of the intensity of solar radiation and the duration of sun exposure in different climate scenarios, respectively, for the RCP 4.5 and RCP 8.5 pathways (Table 5).

Table 5. Results of radiation analyses.

Scenarios	**Rcp Scenarios**	**Annual Medium Radiation (kWh/m^2)**	**Increase (%)**
2023	Actual	1400	-
2030	RCP 4.5	1450	+3.6%
2050	RCP 8.5	1480	+5.7%
2085	RCP 8.5	1550	+10.7%
2090	RCP 4.5	1480	+5.7%

As can be seen, in the RCP 8.5 scenario for 2085, the average annual solar radiation increases by 10.7% compared to the current value in 2023. This significant increase can have significant impacts on the built heritage, accelerating the degradation of materials and affecting the thermal comfort of buildings.

Seasonal analysis showed that the increase in solar radiation is not uniform throughout the year, showing significant variations between the different seasons. In spring, for example, an increase of 4% is observed in 2030 according to the RCP 4.5 scenario (Figure 19), rising to 8% in 2085 under the RCP 8.5 scenario (Figure 20).

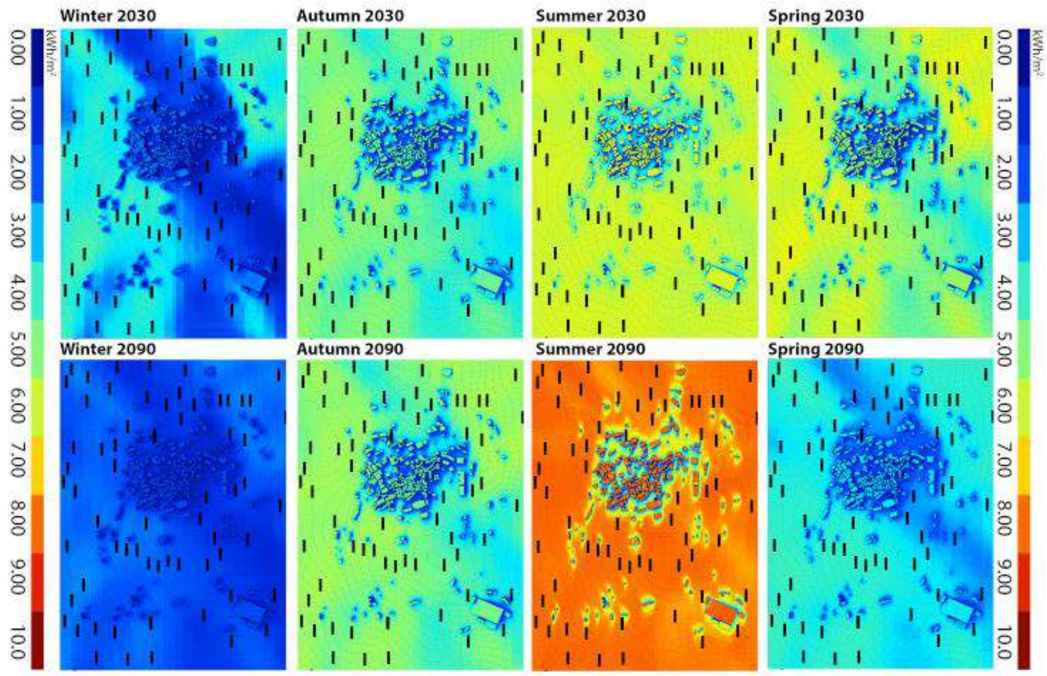

Figure 19. Inc.radiation maps of Bova for RCP 4.5 climate change scenarios.

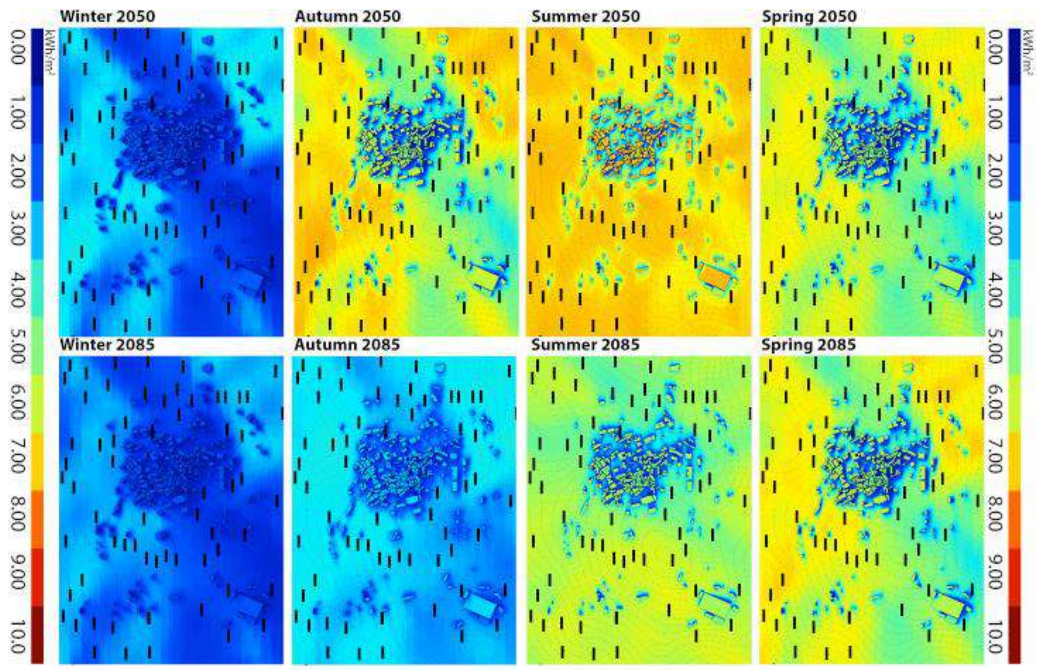

Figure 20. Inc.radiation maps of Bova for different climate change scenarios.

During summer, the increase is even more pronounced, rising from 5% in 2030 (RCP 4.5) to 12% in 2085 (RCP 8.5). This significant summer increase in solar radiation can lead to a higher risk of overheating in historic buildings, such as those in Bova, exacerbating material degradation and negatively affecting the thermal comfort of indoor environments. In the autumn, the increase in solar radiation is 3% in 2030 (RCP 4.5) and reaches 7% in 2085 (RCP 8.5). Finally, in winter, there is an increase of 2% in 2030 (RCP 4.5) and 5% in 2085 (RCP 8.5). Although the winter increase is the least significant, it can still lead to changes in the energy balance of buildings, reducing the demand for heating but potentially increasing thermal stress on the structures.

The maps show the increase in solar irradiance in different seasons and scenarios, highlighting the most exposed areas. These are the areas oriented to the south and south-west, which record increases of up to +12% in summer in the RCP 8.5 scenario for 2090.

They also illustrate the variations in the hours of direct sunshine, with an increase in hours of sunshine of up to +10%. The impact on the built environment translates into prolonged exposure to the sun, which can increase the risk of cracks and surface damage to materials.

The inter-scalar approach adopted makes it possible to address the challenges of climate change in an integrated way, combining quantitative analyses on a territorial scale with targeted interventions on a local scale, thus ensuring the resilience of Bova's cultural heritage.

3.2.2. Direct Sunlight Hours Analysis

An analysis of direct sunlight hours was conducted using the "Ladybug_Sunlight Hours Analysis" component. Initially, the entire year was considered, to obtain a comprehensive view of the building's solar exposure. Subsequently, the analysis was divided by season (Figure 21) to identify seasonal variations in solar exposure. The results were visualized directly on the 3D model through a color map, where the colors indicate the number of hours of direct sunlight received by the different surfaces of the building (Figure 3). The analysis revealed that the surfaces exposed to the south and south-west receive the highest number of direct sunlight hours, especially during the summer season. This indicates a potential issue in terms of summer overheating, with possible implications for indoor thermal comfort and the durability of building materials.

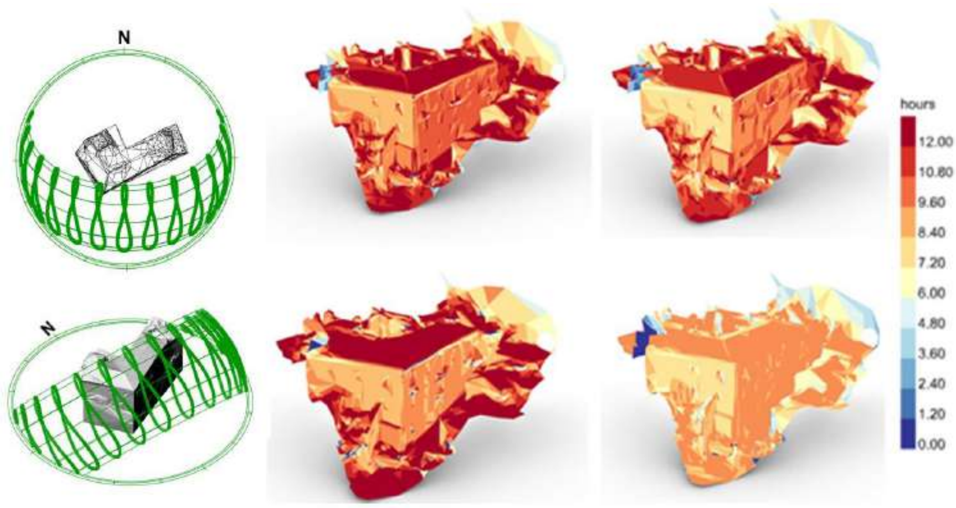

Figure 21. Analysis of direct sunlight hours on Palazzo Mesiani. (**Top left**): spring; (**top right**): summer; (**bottom left**): autumn; (**bottom right**): winter.

3.2.3. Solar Radiation Incidence Analysis

A detailed analysis of incident solar radiation was carried out to quantify the solar energy impacting the building surfaces under different climate scenarios. This analysis highlighted significant differences between the scenarios considered, showing a trend toward increasing radiative power affecting the building.

- Current scenario (Figure 22): During the summer season, the surfaces exposed to the south and south-west record radiation peaks of up to 5 kWh/m^2 while, in the winter and autumn seasons, the average values are around 2–3 kWh/m^2. This situation indicates a potential summer warming that is already present, but relatively limited.
- RCP 4.5 scenarios for the years 2030 and 2090 (Figures 23 and 24): An increase in incident radiation is also observed in the winter and autumn seasons, with values reaching 3–4 kWh/m^2, higher than in the current scenario. In summer, radiation peaks exceed 6 kWh/m^2, highlighting an increase in incident solar energy and, consequently, potential overheating of surfaces.

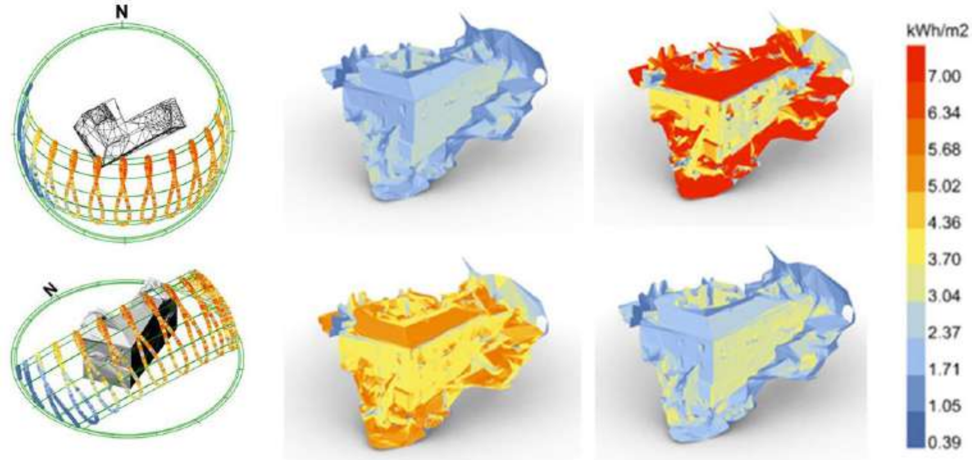

Figure 22. Incident radiation on Palazzo Mesiani—current scenario. (**Top left**): spring; (**top right**): summer; (**bottom left**): autumn; (**bottom right**): winter.

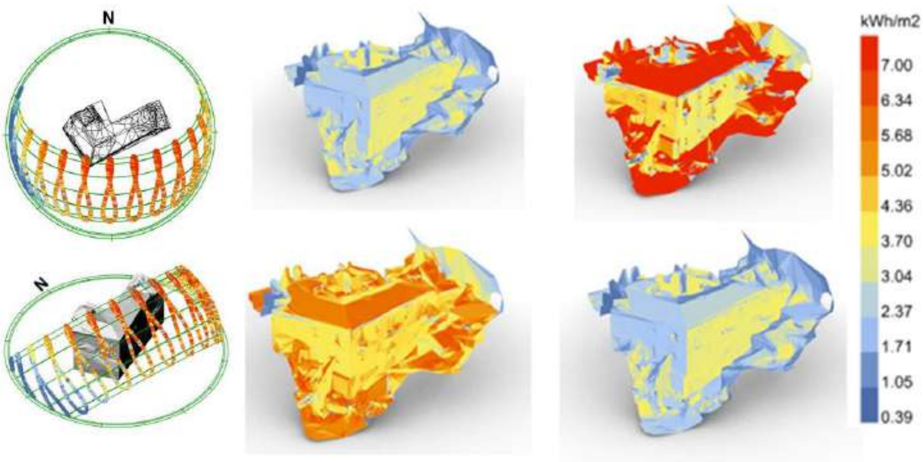

Figure 23. Radiation incident—2030 scenario—RCP 4.5. (**Top left**): spring; (**top right**): summer; (**bottom left**): autumn; (**bottom right**): winter.

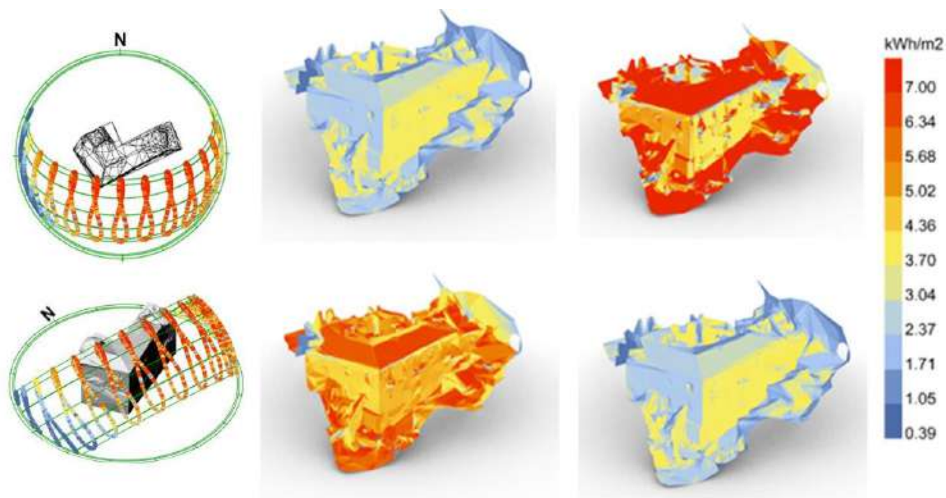

Figure 24. Radiation incident—2050 scenario—RCP 8.5. (**Top left**): spring; (**top right**): summer; (**bottom left**): autumn; (**bottom right**): winter.

- RCP 8.5 scenarios for the years 2050 and 2085 (Figures 25 and 26): The increase in incident radiation is even more pronounced. In the winter and autumn seasons, the values reach 4 kWh/m^2 while, during the summer season, peaks exceeding 7 kWh/m^2 are recorded. This represents an increase compared to the previous scenarios and suggests that the building will be exposed to significantly higher levels of radiation.

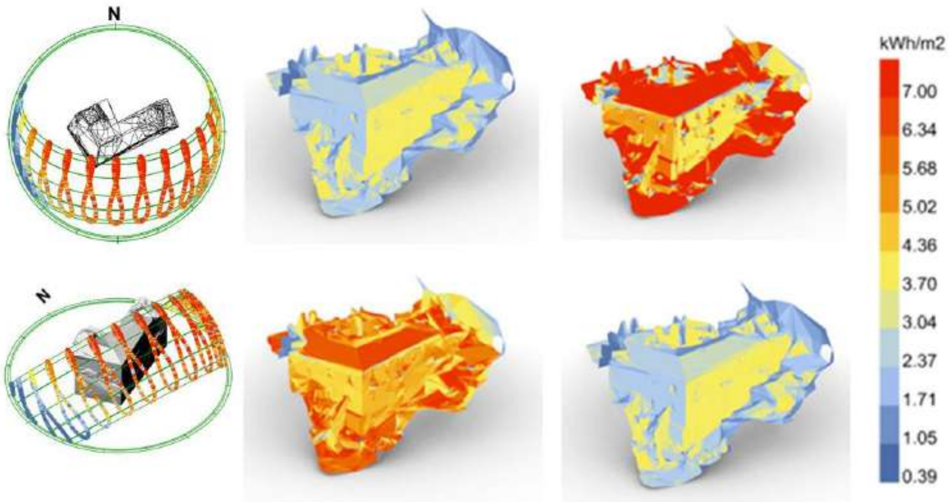

Figure 25. Radiation incident—2085 scenario—RCP 8.5. (**Top left**): spring; (**top right**): summer; (**bottom left**): autumn; (**bottom right**): winter.

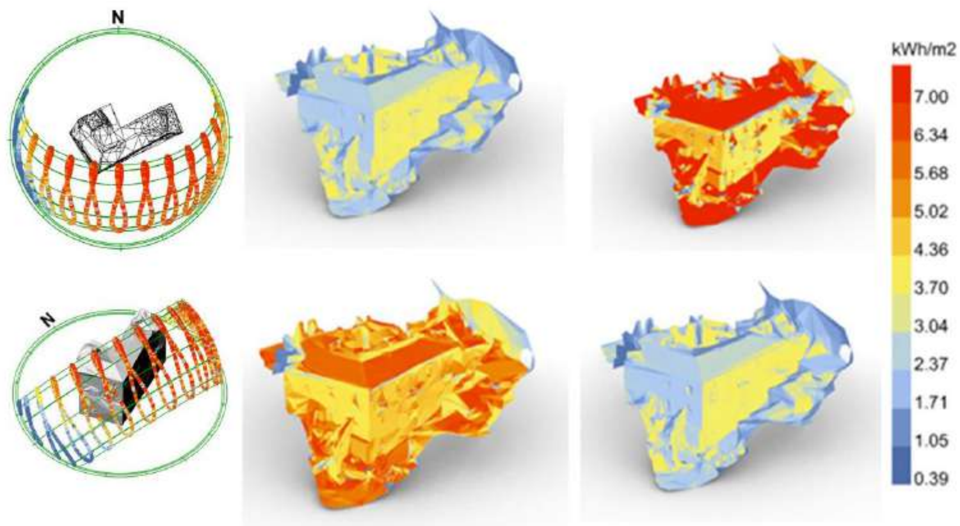

Figure 26. Radiation incident—2090 scenario—RCP 4. (**Top left**): spring; (**top right**): summer; (**bottom left**): autumn; (**bottom right**): winter.

3.2.4. Application of the Climate Change Index (CCI) on Palazzo Mesiani

In the experimentation on Palazzo Mesiani, the application of the CCDI made it possible to cross-reference the data obtained from the analysis of incident solar radiation and hours of direct sunlight with the specific vulnerabilities of the materials present in the historic building. Using the results of the analyses conducted with the Ladybug plug-in in Grasshopper, it was possible to calculate the intensity of radiation on each surface of the building for different climate scenarios (RCP 4.5 and RCP 8.5) and for the key years 2030, 2050, 2085 and 2090.

The application of the CCDI on Palazzo Mesiani has produced significant results, providing a detailed analytical (Table 6) assessment of the vulnerability of building materials to climate change predicted in the different scenarios. By cross-referencing the data obtained from the analysis of incident solar radiation and hours of direct sunlight with the specific vulnerabilities of the materials present in the building, it was possible to identify the surfaces most at risk and quantify the level of exposure to critical climatic factors.

Table 6. Classification of material vulnerability based on CCI and Palazzo Mesiani data.

Climate Factor	Materials	Minimum Impact	Medium Impact	Significant Impact (3)	High Impact (4)	Values Found on Palazzo Mesiani	Reference Legislation
Solar Radiation (kWh/m^2)	concrete	<2 kWh/m^2	2–4 kWh/m^2	4–6 kWh/m^2	≥6 kWh/m^2	<7.5 kWh/m^2 (rcp 8.5–2085)	iso 9050, en 410, uni 10349
	wood	<1.5 kWh/m^2	1.5–3 kWh/m^2	3–4.5 kWh/m^2	≥4.5 kWh/m^2	<7.5 kWh/m^2 (rcp 8.5–2085)	iso 9050, en 410, uni 10349
Temperature (°C)	concrete	<25 °C	25–35 °C	35–40 °C	≥40 °C	>40 °C on the expiosed surfaces	en 1992-1-1,05r, uni 10351
	masonry	<30 °C	30–40 °C	40–50 °C	≥50 °C	35–38 °C (rcp 8.5–2085)	en 1992-1-1, uni 10351

The south-west-facing surfaces of Palazzo Mesiani showed a significant increase in incident solar radiation, reaching values of up to 7.5 kWh/m^2 in the RCP 8.5 scenario for the year 2085 (as highlighted in the previous analyses). This value exceeds the threshold of 6 kWh/m^2, classified as Highly Harmful (4) for materials such as concrete and wood, according to the technical reference standards ISO 9050 [39], EN 410 [40] and UNI 10349 [41].

Similarly, the increase in average summer temperatures, with peaks above 40 °C, places concrete and masonry in a risk class from Significant (3) to Highly Harmful (4), in accordance with EN 1992-1-1 [42] and UNI 10351 [43] standards.

The analytical application of the CCDI on Palazzo Mesiani substantiated the experimentation, providing a quantitative and detailed assessment (Table 7) of the critical issues related to climate change through the cross-referencing of specific climate data with the vulnerabilities of the materials.

Table 7. Summary of the CCI application on Palazzo Mesiani.

Climate Factor	Material	Values Found	CCDI Risk Class	Implications
Solar Radiation (kWh/m^2)	concrete	<7.5 kWh/m^2 (rcp 8.5–2085)	Highly Harmful (4)	high risk of photodegradation
	wood	<7.5 kWh/m^2 (rcp 8.5–2085)	Highly Harmful (4)	accelerated degradation, need for UV protection
Temperature (°C)	concrete	>40 °C	Highly Harmful (4)	possible impairment of mechanical properties
	masonry	35–38 °C (rcp 8.5–2085)	Significant (3)	increased risk of cracking and deterioration

The cross-referencing of experimental data with the CCDI showed the following results:

- Solar radiation: The surfaces of Palazzo Mesiani exposed to the south-west are classified as risk class Highly Harmful (4) for wood and concrete due to the high incident solar radiation expected in future scenarios.
- Temperature: The increase in average summer temperatures, with peaks above 40 °C, places concrete and masonry in a risk class from Significant (3) to Highly Harmful (4).

The integration of the experimental data from Palazzo Mesiani with the CCDI provided a detailed assessment of the vulnerability of the historic building to climate change.

4. Discussion

This study investigated the analytical and experimental capabilities of advanced digital prototyping and regenerative design in facilitating the transition to a carbon-neutral and climate-resilient built environment, with a particular focus on cultural and natural heritage. By conducting a multi-scale and multi-hazard assessment on two case studies—Palizzi

Marina and Palazzo Mesiani in Bova—within a methodological framework that integrates climate change projections with site-specific characteristics, the research provides a comprehensive overview of environmental risks using predictive methods that enhance resilience performance. The results offer a detailed understanding of the critical issues related to climate change in these contexts, reinforcing and expanding upon previous findings.

4.1. Discussion on Palizzi Marina Experimental Results

The findings for Palizzi Marina align with global concerns about increasing risks to coastal areas due to climate change-induced sea level rise and extreme precipitation events. Coastal infrastructures worldwide are recognized as vulnerable to rising sea levels, intensified storm surges and increased flooding. The study extends this understanding by providing localized run-off projections using advanced modeling techniques.

Comparatively, previous studies [44] emphasized the vulnerability of coastal areas to sea level rise and extreme weather events [45]. In this sense, the original contribution of this research succeeds, by integrating climate projections with digital modeling, in assessing the combined impacts of sea level rise and altered precipitation. The integration of high-resolution spatial data and predictive models allows for an improvement in precision in identifying high-risk areas compared to traditional methods. This approach contributes to existing knowledge by offering a scalable framework applicable to the identification and quantification of multiple risk factors in other coastal regions facing similar threats. Considering the contribution to design, the proposed framework supports the development of more effective adaptation strategies, such as the implementation of SuDS and NBSs, which are increasingly supported in contemporary research as adaptive technologies to mitigate flood risks and improve coastal resilience.

Recent results highlight the effectiveness of NBSs and SuDS in mitigating the negative effects of urbanization and climate change. By providing a detailed and site-specific model that incorporates climate projections and local geomorphological factors, this research offers valuable insights to improve the resilience of coastal groundwater systems. In conclusion, the results and the experimental process underscore the critical need to support adaptive design strategies with advanced modeling techniques.

4.2. Discussion of Palazzo Mesiani Experimental Results

The study on Palazzo Mesiani, through the application of the CCDI, provides an experimental assessment of the vulnerability of materials, which complements existing studies on the conservation of historic buildings under climate stress. Research activities conducted so far often focus on qualitative risk assessments considering only intrinsic factors. This study, by integrating environmental factors in climate change scenarios such as rising temperatures and solar radiation, offers a quantitative method that integrates specific climate projections with material properties. The use of environmental simulation tools improves the accuracy of weakness assessments, contributing to more effective conservation practice. This methodological advance aligns with the growing emphasis on data-driven decision-making in heritage conservation, addressing the need for evidence-based strategies to save cultural heritage from climate change.

The experimental investigation can advance the state of the art by offering a precise, data-driven method that combines detailed climate projections with the specific material characteristics of Palazzo Mesiani. This process will enable the investigation of deterioration mechanisms—mechanical, chemical and biological—that are likely to affect the building under projected climate scenarios.

The proposed advancement is thus aligned with research on the development of risk assessment methodologies for historic urban areas. Some recent studies [46], in fact, highlight the need to adopt adequate assessment methodologies that can systematically address the challenges of climate change. By providing a strategy for identifying and quantifying risk factors induced by the effects of climate change, this study contributes to the development of more effective conservation practices. This not only complements existing qualitative studies, but also significantly contributes to the possible evolution of the field of climate risk assessment in cultural heritage conservation.

4.3. Response to Research Objectives

This study addresses gaps in current practices by integrating advanced digital modeling with regenerative design principles to assess climate change impacts at a local scale. This integration responds to the recognized need for context-specific adaptation strategies in a climate change scenario. The main research objectives previously outlined, with oriented and original methodologies, demonstrated the reliability of the experimental setting in contributing to interventions carried out in a carbon-neutral and climate-resilient built environment.

4.3.1. Scalability and Validation of the Experimentation Workflow/Framework

By validating the integrated workflow across different case studies with varying environmental conditions, this study demonstrates its effectiveness and methodological replicability based on principles of comprehensive data integration, adaptability and scalability. The methodology integrates advanced surveying and digital modeling techniques—such as photogrammetric drone surveys and parametric design within Grasshopper—with sophisticated climate data processing and environmental simulation tools like Meteonorm and Ladybug. This integration establishes a direct, one-to-one correspondence between climate projections (including various RCPs) and the specific morphological, architectural and technological characteristics of the sites. By accurately simulating environmental risks like coastal erosion, run-off and the thermal impacts of solar radiation, the methodology bridges the gap between theoretical models and practical applications.

4.3.2. Application and Testing of the Method in Case Studies

The successful application to the case studies of Palizzi Marina and Palazzo Mesiani confirms its scalability and adaptability, thereby providing a replicable framework for multi-hazard assessments. This enhances the capacity for localized climate risk evaluations and facilitates the broader implementation of climate-resilient design practices across diverse contexts.

The workflow developed has been successfully implemented in the case studies of Palizzi Marina and Palazzo Mesiani in Bova, allowing for the assessment and management of the multi-risk impacts of climate change on a local scale. Advanced simulations made it possible to identify the areas at greatest risk, quantify the volumes of water to be managed and assess the vulnerability of building materials, providing a solid basis for the development of effective adaptation strategies.

4.3.3. Populating the Digital Platform

Contributing data and models to digital platforms exemplifies how research can inform tools that support participatory climate risk management. This integration promotes collaboration among stakeholders—professionals, researchers and policymakers—aligning with contemporary approaches to climate adaptation that emphasize shared knowledge and resources. By making data accessible, the study fosters a collaborative environment conducive to developing comprehensive adaptation strategies.

The Atlas serves as a valuable resource to synthesize data, models and adaptive strategies. Providing a centralized repository facilitates access to practical tools and information necessary for implementing climate-resilient interventions, particularly in sites of cultural and natural significance. The Atlas exemplifies how organized information can support decision-making processes, offering reference models for replicating methodologies in other vulnerable locations.

4.4. Implications for Future Research and Practice

The results of this study highlight the importance of adopting advanced digital tools and innovative methodologies in climate change adaptation planning. An important development that has emerged concerns the integration of digital prototyping techniques with the creation of physical prototypes on a territorial scale. The creation of physical prototypes of Palizzi Marina and Palazzo Mesiani, through 3D printing technologies, can represent a fundamental element for the practical validation of the developed methodologies and for the tangible visualization of the effectiveness of the design strategies.

In the case of Palazzo Mesiani, the photogrammetric survey with a drone enabled the creation of a detailed 3D model of the building, subsequently used to create the physical prototype. This allows an in-depth analysis of the incidence of solar radiation and material degradation (Figure 27).

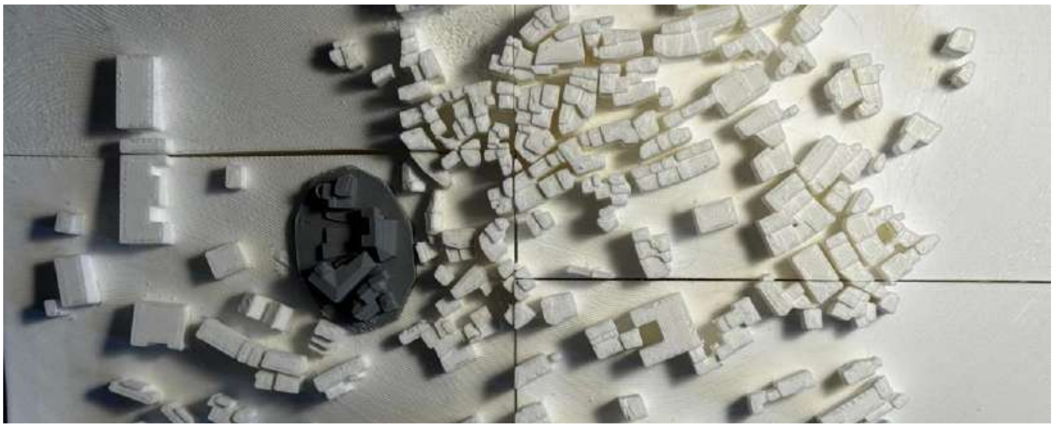

Figure 27. Image of the 3D-printed physical prototype of Bova.

For Palizzi Marina, the use of Grasshopper and the integration of GIS data facilitate the creation of an accurate digital model of the territory, then translated into a physical prototype. This process will allow future researchers to concretely visualize the potential impacts and effectiveness of the proposed design solutions, such as run-off mitigation and coastal erosion (Figure 28).

Figure 28. Image of the 3D-printed physical prototype of Palizzi Marina.

The integration of physical prototypes, starting from the built ones, would complete the validation of the framework, allowing for a comparison of the results of the simulations with concrete observations, and for the evaluation of the proposed solutions in a tangible way. This integration aligns perfectly with the regenerative design approach, allowing the physical testing of design solutions based on sustainable principles. Furthermore, the use of physical prototypes as tools for co-design and community engagement can increase awareness of climate risks and promote a culture of resilience.

Future developments will focus on expanding these methodologies, deepening the combined use of digital and physical prototypes. The following developments are planned:

- The incorporation of advanced technologies and the evaluation of innovative materials and integrated sensors in physical prototypes to collect real-time environmental data on the condition and performance of design solutions.
- The use of physical prototypes as co-design and community engagement tools, to foster more holistic and culturally appropriate adaptation strategies.

This integrated approach opens new perspectives for applied research and contributes to developing effective adaptation strategies consistent with the conclusions previously exposed, emphasizing the importance of sustainable and participatory solutions in mitigating the impacts of climate change.

4.5. Limitations and Recommendations

While this study advances the field, it is essential to acknowledge limitations such as its reliance on specific climate models and emission scenarios, which carry inherent uncertainties. Future studies could incorporate a broader range of scenarios and probabilistic approaches to account for uncertainties in climate projections. Moreover, incorporating real-time monitoring and feedback mechanisms could enhance the responsiveness of the adaptive strategies proposed.

Some limitations emerged during this study. Reliance on climate models introduces inherent uncertainties regarding CO_2 emission trajectories and local climate variations. Although the multi-scenario approach provides a spectrum of possible future scenarios, it may not consider all microclimatic conditions. In addition, the effectiveness of the CCDI depends on existing standards, which may not fully account for the unique properties of historical materials in specific contexts, suggesting the need for further empirical validation and potential refinement of the index.

5. Conclusions

This study has demonstrated that advanced digital prototyping and regenerative design methodologies are effective tools for assessing and addressing the environmental risks posed by climate change, particularly concerning cultural and natural heritage. By employing a multi-scalar approach that integrates climate projections with site-specific data, a replicable framework was successfully validated, contributing to both theoretical understanding and practical applications in technological and environmental design.

The methodology combined advanced digital modeling techniques—such as photogrammetric drone surveys and parametric design within Grasshopper—with sophisticated climate data processing and environmental simulation tools like Meteonorm and Ladybug. This integration established a direct correspondence between climate projections and the specific morphological, architectural and technological characteristics of the study sites, namely, Palizzi Marina and Palazzo Mesiani in Bova.

Significant findings from this study are presented below:

In Palizzi Marina, the identification of critical areas vulnerable to sea level rise (SLR) and intensified run-off events highlights the urgency for adaptive interventions. Projections indicate that SLR could exceed 1.5 m by 2100 in the worst-case scenario, and maximum hourly rainfall intensity could increase to 40 mm/h by 2085 under the RCP 8.5 scenario. These conditions amplify the risk of flooding, coastal erosion and infrastructure damage. Implementing Nature-Based Solutions (NBSs) and Sustainable Urban Drainage Systems (SuDS) emerges as a viable strategy in line with regenerative design principles.

For Palazzo Mesiani, the application of the Climate Change Damage Index (CCDI) enabled precise quantification of material vulnerabilities. Analyses revealed that southwest-facing surfaces could experience incident solar radiation up to 7.5 kWh/m^2 under the RCP 8.5 scenario for 2085, exceeding thresholds classified as "Highly Harmful" for materials like concrete and wood. Additionally, projected increases in average summer temperatures, with peaks above 40 °C, elevate the risk classification for concrete and masonry. These findings underscore the need for targeted conservation strategies to enhance the building's resilience to future climatic conditions.

In conclusion, the integration of advanced digital prototyping tools with projected climate data presents an effective approach to understanding and mitigating the impacts of climate change across different design scales. The successful application of the methodological framework to Palizzi Marina and Palazzo Mesiani demonstrates its adaptability and potential for replication in other regions facing similar challenges. By critically assessing environmental risks and formulating adaptive responses, this approach contributes to global efforts toward carbon neutrality and climate resilience, especially in sensitive yet culturally and naturally significant areas. This study underscores the imperative for proactive and informed strategies to safeguard cultural and natural heritage against the advancing impacts of climate change.

Author Contributions: D.L.: Conceptualization, Investigation, Data Curation, Methodology, Visualization, Writing—Original Draft Preparation. D.L. developed the overarching research goals and aims of the study; conducted all the experimentation, including data collection and evidence gathering; managed and maintained the research data for initial use and future re-use; developed and designed the research methodology and created models; prepared and presented the data visualizations for the published work; and prepared and wrote the initial draft of the manuscript, including all paragraphs. C.N.: Supervision, Conceptualization, Methodology, Writing—Review & Editing, Funding Acquisition. C.N. provided oversight and leadership responsibility for the research activity planning and execution, including mentorship as the scientific supervisor of the postdoctoral fellowship; contributed ideas and assisted in formulating the research goals and aims; assisted in the development and design of the methodology; co-authored paragraphs 1 and 2, critically reviewing and revising the manuscript for important intellectual content; and secured financial support for the project leading to this publication. G.M.: Writing—Review & Editing, Data Curation, Formal Analysis. G.M. conducted critical review, commentary, and revision of the manuscript, specifically co-authoring paragraph 5; verified bibliographic references and ensured the accuracy of data; and conducted supplementary research and analysis to enhance the study findings. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the National Recovery and Resilience Plan (PNRR), Mission 4, Component 2, Investment 1.4, funded by the European Union—NextGenerationEU for the realization of Innovation Ecosystem Tech4You "Technologies for climate change adaptation and quality of life improvement", Actions 8 and 9, lead by Consuelo Nava of the Pilot Project 4.7.1—Open platform "phigital space" (physical and digital) of the type "user profiling" for the advanced and dynamic co-design of interventions on the built and ex novo (project code: ECS_00000009, CUP: C33C22000290006).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would like to thank all the members of the research team for their valuable contributions and support throughout this study.

Conflicts of Interest: The authors declare no conflict of interest.

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