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RESEARCH

Management of risk assessment for cultural heritage on GIS based solution for the historic center of Venice

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Abstract
This contribution aims to analyze the specific vulnerabilities of the historic center of Venice and to develop an evaluative method capable of taking into account both the intrinsic and extrinsic characteristics of the built environment through the use of georeferenced information systems. In particular, the study focuses on the analysis of vulnerabilities related to the gradual phenomenon of mean sea level rise and on an approach for the identification of site-specific surface temperatures based on remote sensing data. Finally, the work addresses the integration of the different types of datasets into a single spatial management platform (GIS), referenced to individual historic buildings.

Keywords Risk management · Geographic information system · Architectural heritage · Venetian built heritage

Introduction

In order to fully understand the methodological choices adopted, it is first necessary to refer to the research questions that guided the work and to which we sought to provide answers through the use of tools considered appropriate and comprehensive, among which the contribution of this article is situated.

The research aimed to construct a knowledge framework of the built heritage of the historical centre of Venice, with the objective of identifying homogeneous macro-categories characterized by shared technical, material, and morphological features (Trovò and Bruschi 2025a, b). The definition of these categories formed the basis for the subsequent phases of the work, which were oriented toward the development of an approach to risk assessment for the Venetian built heritage, structured according to criteria capable of evaluating risk as a function of homogeneous classes. In this context, the use of Multiple-Criteria Decision Analysis (MCDA) emerges as an effective tool for synthesizing complex evaluations and for comparing and prioritizing different alternatives (Chen et al. 2001; Cinelli et al. 2014).

The analysis of impacts and risks to cultural heritage is provided both in terms of the effects of gradual changes in climatic parameters (temperature, precipitation, relative humidity, etc.) and to the potential damage caused by extreme hydrometeorological events (floods, intense rainfall, prolonged drought periods). For both analyses, currently available knowledge and tools were employed (Sesana et al. 2021; Bonazza 2022; Bonazza and Sardella 2023; Bonazza et al. 2018; Di Ciaccio et al. 2025).

In collaboration with the Municipality of Venice, the risk assessment was developed for the city's historical building stock, targeting three main categories: palaces, churches, bell towers. A total of 802 buildings, all belonging to the Cultural Heritage (CH) assets of the historic center of Venice, were identified for this analysis. As detailed further in the risk assessment section, the specific type of legal protection to which each asset is subject was evaluated as a fundamental intrinsic characteristic for the overall risk definition.

For the specific purposes of this study, the construction of the GIS-based informative database focused on the

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Dorsoduro district, analyzing a total of 151 elements. For this district, the detailed analysis specifically addresses three categories: palaces (110), churches (24), and bell towers (17).

The risk definition is based on a multi-criteria model evaluating both intrinsic and extrinsic factors. Intrinsic factors include construction and connotative features, the state of conservation[1], and the specific type of legal protection or restrictions[2] to which each building is subject. Extrinsic factors were evaluated in relation to urban location and environmental exposure. Specifically, the building stock was divided based on its positioning: marginal areas exposed to winds (bora and sirocco) and rain; water frontage threatened by wave motion and water absorption; and properties within the urban fabric, which are more protected from direct extreme events. The use of multipliers, differentiated by material and construction, allowed for the modulation of vulnerability and resilience scores (Trovò and Bruschi 2025a).

The selection of these specific parameters - including solar exposure, wind regimes, and sea level rise - is dictated by their significant impact on the vulnerability of Venetian built heritage (Bruschi 2020). It is now widely recognized that tangible cultural heritage is threatened both by the progressive alteration of climatic conditions and by the increase in extreme events. As noted by Cinelli et al. (2014), rising temperatures, combined with variations in precipitation and relative humidity, accelerate the degradation of the materials constituting cultural assets. Within the jurisdiction of the Municipality of Venice, these impacts are particularly acute; the entire territory is directly exposed to hazards such as heatwaves, river flooding, urban inundation, exceptional tides (high waters), and intense winds - phenomena identified by the European Environment Agency (EEA 2017) as the primary climate change threats for the Mediterranean region. Referring back to the broader framework, it is important to clarify that the definition of risk 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» (Bonazza and Sardella 2023). In this context, the use of vulnerability values derived from quantitative data is not always feasible; consequently, most of the models currently in use are based on methodologies of a predominantly qualitative nature (Bonazza and Sardella 2023).

For the analysis and management of risk in the city of Venice, the main challenge lay in combining information across different scales and heterogeneous levels in order to integrate them into a single system. The implementation of a unified GIS-based project applied to the Dorsoduro district made it possible to systematically organize multi-scale data, including vulnerability parameters and spatial information such as thermal and altimetric data. Its use also enabled the identification and visualization of data through thematic maps, produced by analysing the different informational layers and performing spatial *queries*.

In the field of management, control and intervention planning, GIS technology has been a valuable ally to public bodies and administrations in recent decades (Jones 2019), specifically in obtaining thematic and stable data for the formulation of large-scale intervention strategies. UNESCO recognizes that the duty of ensuring the identification, protection, conservation, presentation, and transmission to future generations of cultural and natural heritage (UNESCO 1972) lies with each Member State, with the aim of establishing a unified process for heritage conservation. Accordingly, «to ensure that effective and active measures are taken for the protection, conservation and presentation of the cultural and natural heritage situated on its territory, each State Party to this Convention shall endeavour, in so far as possible» (UNESCO 1972), encouraging States Parties to: «(a) to adopt a general policy which aims to give the cultural and natural heritage a function in the life of the community and to integrate the protection of that heritage into comprehensive planning programmes; (b) to set up within its territories, where such services do not exist, one or more services for the protection, conservation and presentation of the cultural and natural heritage with an appropriate staff and possessing the means to discharge their functions; (c) to develop scientific and technical studies and research and to work out such operating methods as will make the State capable of counteracting the dangers that threaten its cultural or natural heritage; (d) to take the appropriate legal, scientific, technical, administrative and financial measures necessary for the identification, protection, conservation, presentation and rehabilitation of this heritage; […]» (UNESCO 1972).

In light of the above, it is clear that the use of GIS applied to cultural and natural heritage offers real opportunities to respond to the recommendations and objectives defined by the World Cultural and Natural Heritage Convention (Garzulino et al. 2021).

Assessment of quantitative vulnerabilities

This article initially proposes a possible approach for the identification of vulnerability of a quantitative nature with respect to the gradual phenomenon of mean sea-level rise. To this end, a Digital Terrain Model (DTM) with a spatial

[1] Properties that are abandoned were considered higher risk than those characterized by recent interventions.

[2] Buildings that are protected by historic preservation provisions were considered higher risk than those that are unregulated.

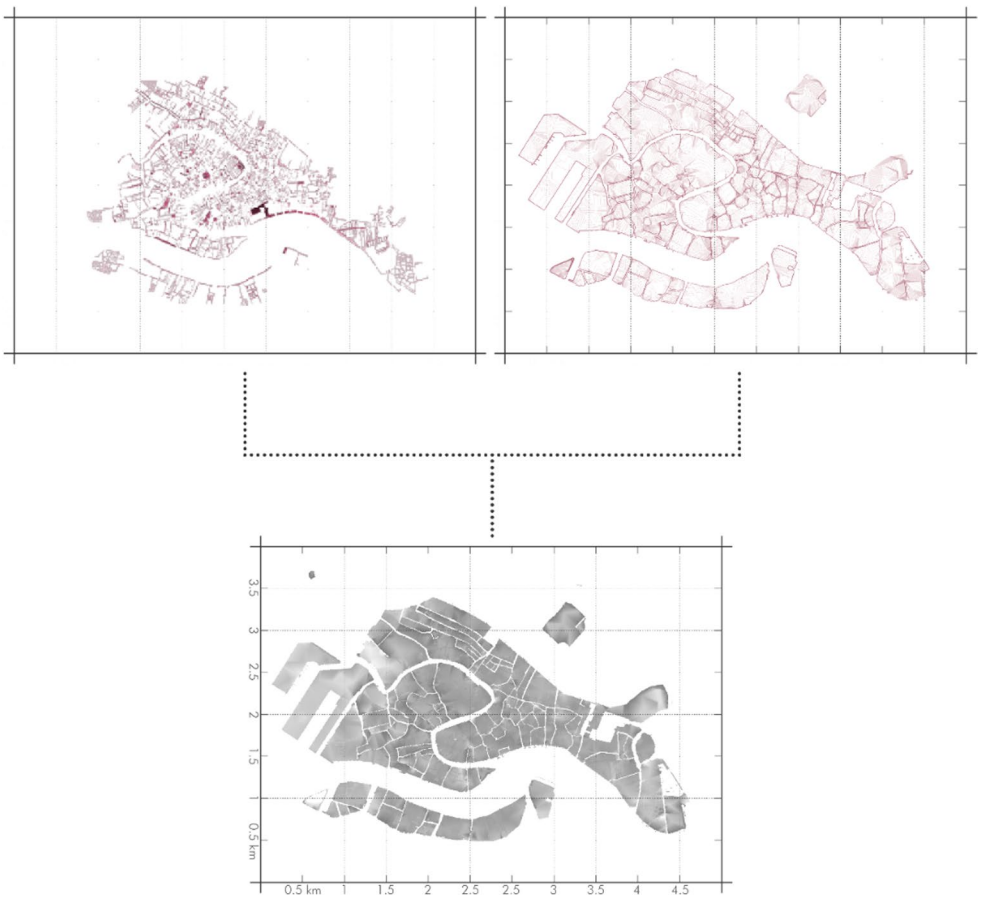


Fig. 1 Workflow diagram for processing the altimetric model used. Specifically, at the top left is the survey carried out by Insula Spa with the extrapolation of elevation points and the processing of a new mesh model. At the top right is the mesh model of the DTM of the Municipality of Venice. At the bottom is the new model in raster format

Table 1 Data used for the definition of the new DTM for the historic center of Venice

Value	Category	Description	Type and Resolution	Workflow
SLR	DTM	Regione Veneto	Raster-Tiff-20 cm	Elevation mesh model
	Elevation contour lines	Survey Insula Spa	Vectorial 1 cm - elevation	

resolution of 25 cm was employed, developed by the Metropolitan City of Venice. The dataset consists of a raster representation of surface elevations, from which it is possible to extract morphological information for the study area, useful for understanding and generating altimetric terrain models that exclude physical–environmental and morpho-vegetational elements present on the surface (Comune di Venezia 2021).

The DTM allows for the identification of urban areas subject to flooding in relation to different forecasted water levels.

To improve the elevation data accuracy in the historic center of Venice, the existing raster datasets were integrated with the pavement survey results conducted by Insula S.p.A. under the RAMSES project (*Rilievo Altimetrico*, *Modellazione Spaziale E Scansione 3D*) (Fig. 1). This project aimed to generate a high-precision digital model of the city, achieving standardized accuracies of ±1 cm (Table 1) vertically and ±2 cm horizontally. The geomatic framework was based on a multi-level integration of surveying methodologies: the primary reference was established via a global GPS/GNSS network of 65 interconnected vertices, further densified by a planimetric network and high-precision geometric leveling across more than 4,400 benchmarks to ensure the metric consistency of the urban surface. Within this rigorous topographic control, a massive static Terrestrial Laser Scanner (TLS) survey of public areas was conducted. The georeferencing of over 22,000 scans was performed using retro-reflective targets tied to the primary topographic network, ensuring centimeter-level precision across the entire urban fabric (Vassena et al. 2024).

This allows for refinement of the DTM in areas such as *calli*, *rive*, *fondamenta*, *campi*, *and campielli* (that is, the different names of Venetian open spaces - streets, squares, banks).

The evaluation procedure involved projecting the raster data into the Roma 40 reference system, Gauss-Boaga projection, known in GIS environments as Monte Mario / Italy

Zone 2 (EPSG authority ID: 3004), which also served as the basis for the subsequent database work.

Subsequently, the raster data were segmented to isolate exclusively the land areas, that is, those areas subject to different conditions of environmental criticality.

At this stage, the data derived from the laser scanner survey were processed, specifically starting from the vector contour lines (with 1 cm vertical resolution). These data are provided as Open Source by Insula S.p.A., the promoter of the RAMSES survey campaign, and are directly accessible for urban studies. Within a GIS environment, a dedicated procedure was implemented to extract elevation points from these contour lines to generate a high-resolution three-dimensional model. This was achieved through the development of a Triangulated Irregular Network (TIN) algorithm using Python, which allowed for the creation of an accurate surface mesh based on the original topographic detail (Fig. 1). The resulting mesh model was then converted into a raster format to ensure compatibility with existing datasets. This raster model, representing the public urban spaces, was subsequently merged with the LiDAR-derived Digital Terrain Model (DTM) of the historic centre. This integration process significantly enhanced the overall accuracy of the final raster product, particularly in the areas covered by the high-resolution laser scanner survey.

Once the new digital model was segmented according to the forecasted elevation levels, it enabled the extraction of different levels of criticality, to be used as the basis for defining flooding scenarios based on predictive forecasts.

The vulnerability analysis was conducted under two distinct operational conditions. The first assessment considers the city's exposure without the mitigation support of the MoSE (Modulo Sperimentale Elettromeccanico) mobile barriers (Fig. 2). This system, operational since October 3rd, 2020, has been raised numerous times. As of August 19th, 2025, it has completed its 100th activation[3], successfully safeguarding the historic center from exceptional storm surges. It was designed to mitigate exceptional tides, with an initial activation threshold of 130 cm, subsequently lowered to 110 cm.

The second condition evaluates the mitigation benefits of the MoSE across three specific temporal horizons: the short-term (2030) (Fig. 3), the medium-term (2050) (Fig. 4), and the long-term (2100) (Fig. 5). These scenarios account for



Fig. 2 Mitigation system in action: mobile barriers raised at the Lido inlet. Source: Consorzio Venezia Nuova

[3] Ministry of Infrastructure and Transport, August 3, 2024, available at: https://www.mit.gov.it/comunicazione/news/mit-con-il-centesimo-sollevamento-del-mose-altro-salvataggio-per-venezia (Last accessed: May 12, 2026).



Fig. 3 Raster clipped at the critical water level for the year 2030 scenario, assuming no MoSE intervention

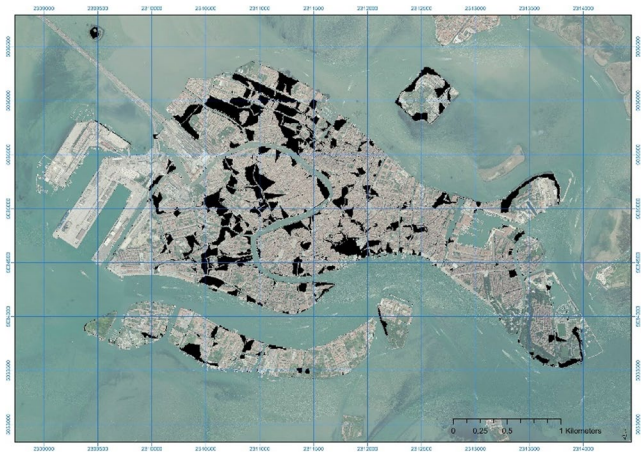


Fig. 4 Raster clipped at the critical water level for the year 2050 scenario, assuming no MoSE intervention

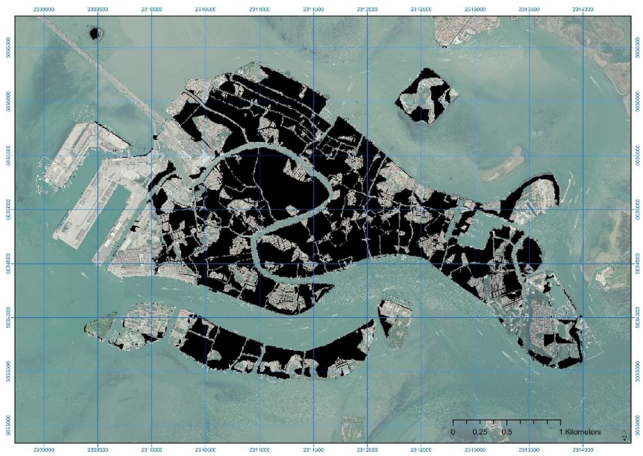


Fig. 5 Raster clipped at the critical water level for the year 2100 scenario, assuming no MoSE intervention

emerging vulnerabilities driven by sea-level rise projections under the RCP 8.5 ensemble model. Specifically, the analysis highlights the criticalities arising when projected sea-level increases are expected to exceed the current operational limits and functional sustainability of the barrier system.

Another area of investigation was dedicated to the assessment of vulnerability through the use of remote sensing techniques as an approach for developing a quantitative temperature analysis. Evaluating the distribution of temperatures at the urban scale allows for an understanding of how these change in relation to differences in exposure. A theoretical subdivision of degradation mechanisms was adopted, assuming a single degradation mechanism as a reference although somewhat artificial, this approach is functional for comprehension (Capponi 2004), while acknowledging that these processes generally act in a combined and synergistic manner.

Temperature assessment represents a valuable tool for identifying, within the built heritage, the areas most exposed and subject to elevated thermal conditions. Stone materials, for example, may experience stress not only from static or dynamic loads, but also from thermal cycles, which induce differential expansion within the material, particularly in anisotropic materials (Fiorani 2009; Bonazza et al. 2009).

In the present study, specific satellite data were selected to analyze surface temperatures and evaluate their effects on the Venetian built heritage, adopting an integrated approach that combines different spatial and spectral resolutions (Table 2).

Spatial resolution is determined by the ground size of the elementary area from which reflected electromagnetic radiation is measured, also defined as the instantaneous field of view. Each elementary area in an image generated by a sensor is represented by a cell within which the radiation value is unique (Brivio et al. 2006).

Initially, images from the Landsat 9 sensor were used. Although characterized by moderate spatial resolution (up to 30 m for multispectral bands and 100 m for thermal bands, recalibrated to 30 m), they offer the possibility of utilizing specific thermal bands. The Thermal Infrared Sensor (TIRS) bands, in particular, allow for monitoring surface temperature due to their sensitivity in the thermal infrared wavelengths (Brivio et al. 2006). Landsat 9's wide spectral coverage makes it a widely used tool for large-scale analyses, enabling the identification of significant thermal patterns, even if spatial precision is lower compared to other sensors.

The second satellite data source used was WorldView-2, a high-resolution satellite capable of providing panchromatic images with a spatial resolution of 0.40 m and multispectral images with a resolution of 1.6 m. The high spatial precision

Table 2 Data used for the definition of the NDVI and NDBI indices and for the analysis of surface temperatures

Value	Category	Description	Type and Resolution	Workflow
SLT	*Remote sensing*	Multispectral Satellite Image (WV2_OPER_WV-110__2A_20110413T102815_N45-358_E012-293_4061)	*Raster* Worldwide 2 Panchromatic resolution: 46 cm Multispectral resolution: 1.84 m	NDBI, NDVI
	Remote sensing	Multispectral Satellite Image (LC09_L2SP_192028_20240825_20240826_02_T1)	*Raster* Landsat 9 Panchromatic resolution: 15 m Multispectral resolution: 30 m	SLT

of the panchromatic images allows for detailed analysis of the urban fabric and building structures, while the eight multispectral bands, covering the visible and near-infrared range, provide additional information for the characterization of surface materials and their responses to thermal variations. The combined use of these two satellite sources allowed the limitations of Landsat 9's spatial resolution to be compensated by the detail of WorldView-2 images, while ensuring a comprehensive multispectral analysis and evaluation of the thermal and structural conditions of the studied heritage.

The Landsat 9 data were integrated into the territorial data management platform, projected into the reference system consistent with the municipal dataset of Venice (Monte Mario / Italy Zone 2, EPSG authority ID: 3004), to ensure correct georeferencing and compatibility with the other datasets already present. For the higher-resolution WorldView-2 data, careful preprocessing was required. In particular, geometric distortion corrections were performed to preserve image accuracy.

To analyze the distribution and composition of the Venetian built environment and to model thermal data according to different territorial conditions, spectral indices were used. These indices are calculated by combining spectral bands acquired from the sensors, each capturing specific wavelengths of electromagnetic radiation reflected from the Earth's surface, allowing for analysis and monitoring of surface characteristics.

Specifically, the Normalized Difference Vegetation Index (NDVI) was employed. This vegetation index is based on the normalized difference of reflectance values (ρ) in the near-infrared (0.75–1.11 μm) and red (0.58–0.75 μm) bands. It allows for assessing the presence, density, and health of vegetation on the surface (Fig. 6).

The Normalized Difference Built-up Index (NDBI) was also employed to analyze urbanized or built-up areas. This index is based on the mid-infrared (MIR) and near-infrared (NIR) spectral bands. Built surfaces reflect more energy in the mid-infrared than in the near-infrared, whereas vegetation reflects more energy in the near-infrared than in the mid-infrared. This contrast allows for easy differentiation between urbanized areas and vegetation.

To evaluate the distribution of temperatures in relation to the island's context, thermal data were processed from the Landsat dataset using a Regression Kriging approach. In this methodology, the Land Surface Temperature (LST) data were used as the dependent variable, while the previously derived NDVI and NDBI indices were used as independent variables. This allowed for the integration of spatial and spectral information in order to estimate the distribution of surface temperatures (Fig. 7).

Structuring of the information system

The GIS information system was used to organize and standardize the data for calculating vulnerabilities and risk parameters. Specifically, the system was aligned with the one already in use by the Metropolitan City of Venice, making the new dataset interoperable with the existing one. As a representative case study, the Dorsoduro district was selected for its relevance in the urban context and its ability to reflect the typological and structural characteristics of Venetian built heritage (Table 3).

As outlined in the introduction, the system allows for the storage of the large amount of data associated with each building, making it comparable and easily inspectable. The adopted configuration includes two main sets of information: the first informational level concerns the intrinsic characteristics of the building, comprising descriptions of its protection status, conservation condition, and maintenance. The second level focuses on extrinsic characteristics, outlining calculated values for different vulnerabilities. These were computed based on the constitutive materials of the



Fig. 6 Calculation of the NDVI index normalized in the range [0–1]

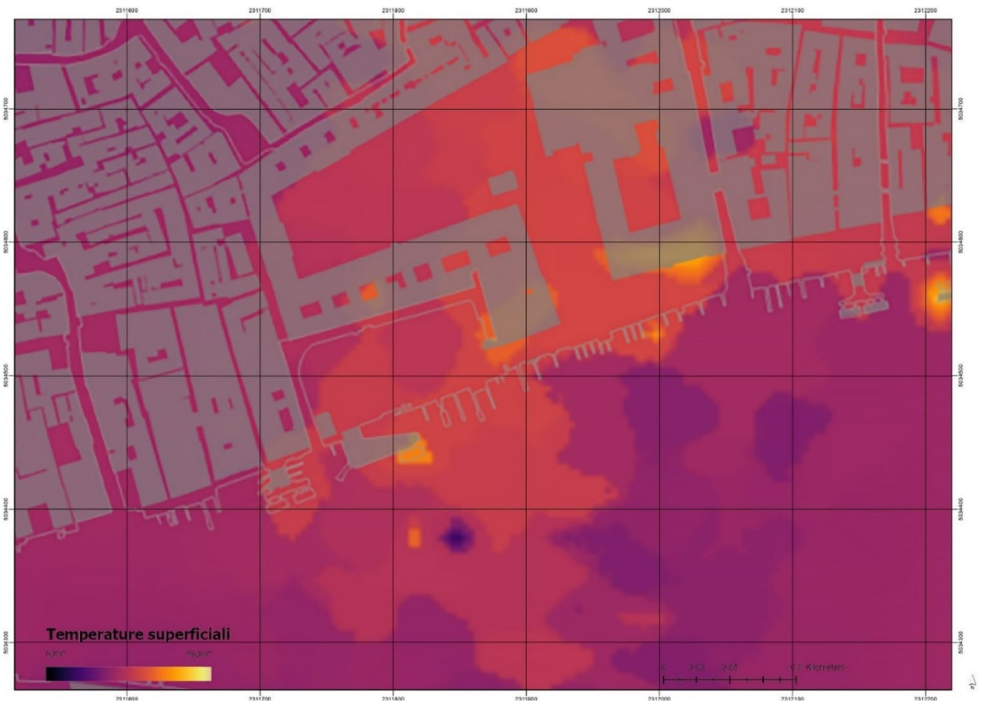


Fig. 7 Surface temperature distribution through Kriging regression

Table 3 Description of the attributes used in the risk assessment for the built heritage of the Dorsoduro district, Venice

COD	Value	Description
EDF_NM		**Building Name**
		Description: Each feature was associated with the building name, allowing for precise spatial positioning of the built heritage.
EDF_TY		**Macro-category of the Building**
		Description: Based on the macro-categories defined during the analysis phase, elaborated by considering building typology and original use (identified within the Dorsoduro district).
A01		Palace
A02		Church
A03		Bell tower
EDF_VAL_ELCON		**Distinguishing Features**
		Description: Presence of specific distinguishing elements of significant artistic value.
0		Absence of Distinctive Features
0,5		Presence of Distinctive Features
EDF_VAL_MAN		**Maintenance Condition**
		Description: Identification and assessment of the maintenance condition of the built heritage, where possible integrated with information from the philological surveys prepared by the Veneto Region.
2		Abandoned
1,7		Not Declared
1,5		Past Interventions
1		Recent Interventions
EDF_VAL_CONS		**State of Conservation**
		Description: Identification and assessment of the conservation status of the built heritage, where possible integrated with information from the philological surveys prepared by the Veneto Region.
2,2		Good
2,4		Moderate
2,6		Bad
EDF_VAL_VNC		**Type of Heritage Protection**
		Description: Identification within the database of the Superintendence for Fine Arts and Landscape for the Municipality of Venice and the Lagoon.
0		DLgs. 42/2004 parte III
2,2		DLgs. 42/2004 parte II
EDF_VAL_AFF		**Facade Orientation**
		Description: Identification of homogeneous macro-areas in relation to their location within the Venetian urban fabric.
2		Urban Fabric
3		Waterfront
4		Urban Edge
EXP_SOL		**Solar Exposure**
		Description: Qualitative assessment of the vulnerability of buildings in relation to sun exposure, differentiated according to their constituent materials.
2		Stone Buildings
1		Plaster and/or Concrete or brick Building
EXP_OMB		**Shading**
		Description: Qualitative assessment of the vulnerability of buildings in relation to shading, differentiated according to their constituent materials.
1,5		Stone Buildings
1,5		Brick Buildings
1,5		Plaster and/or Concrete Building
EXP_PGG		**Rain**
		Description: Qualitative assessment of the vulnerability of buildings in relation to heavy rainfall, differentiated according to their constituent materials and exposure.
2,5		High Building
2		Building Situated on the Edge
1,5		Building Situated on *campo*
1		Building Situated on *calle*
EXP_VNT		**Wind**

Table 3 (continued)

COD	Value	Description
		Description: Qualitative assessment of the vulnerability of buildings in relation to strong winds, differentiated according to their exposure.
2,5		High Building
2		Building Situated on the Edge
1,5		Building Situated on *campo*
1		Building Situated on *calle*
EXP_SLR		**Vulnerability to Gradual Variation – SLR**
		Description: Quantitative assessment of vulnerability in relation to gradual changes due to mean sea-level rise.
2		SLR_2030 With MoSE activation
6		SLR_2050 With MoSE activation
5		SLR_2100 With MoSE activation
4		SLR_2100 + With MoSE activation
EDF_VAL_BN		**High-value materials such as library materials or permanent works.**
		Description: Presence of library materials or permanent works within the building.
0		No presence
1		Presence
VAL_TOT		**Built Heritage Risk Value**
		Description: Risk value classified into five categories.
> 24,1		Vert High
24 < x < 21,2		High
21,1 < x < 18,2		Medium
18,1 < x < 15,3		Moderate
15,2<		Low

historic buildings and their varied responses to climatic factors, such as mean sea-level rise, stresses from strong winds, precipitation, and solar exposure.

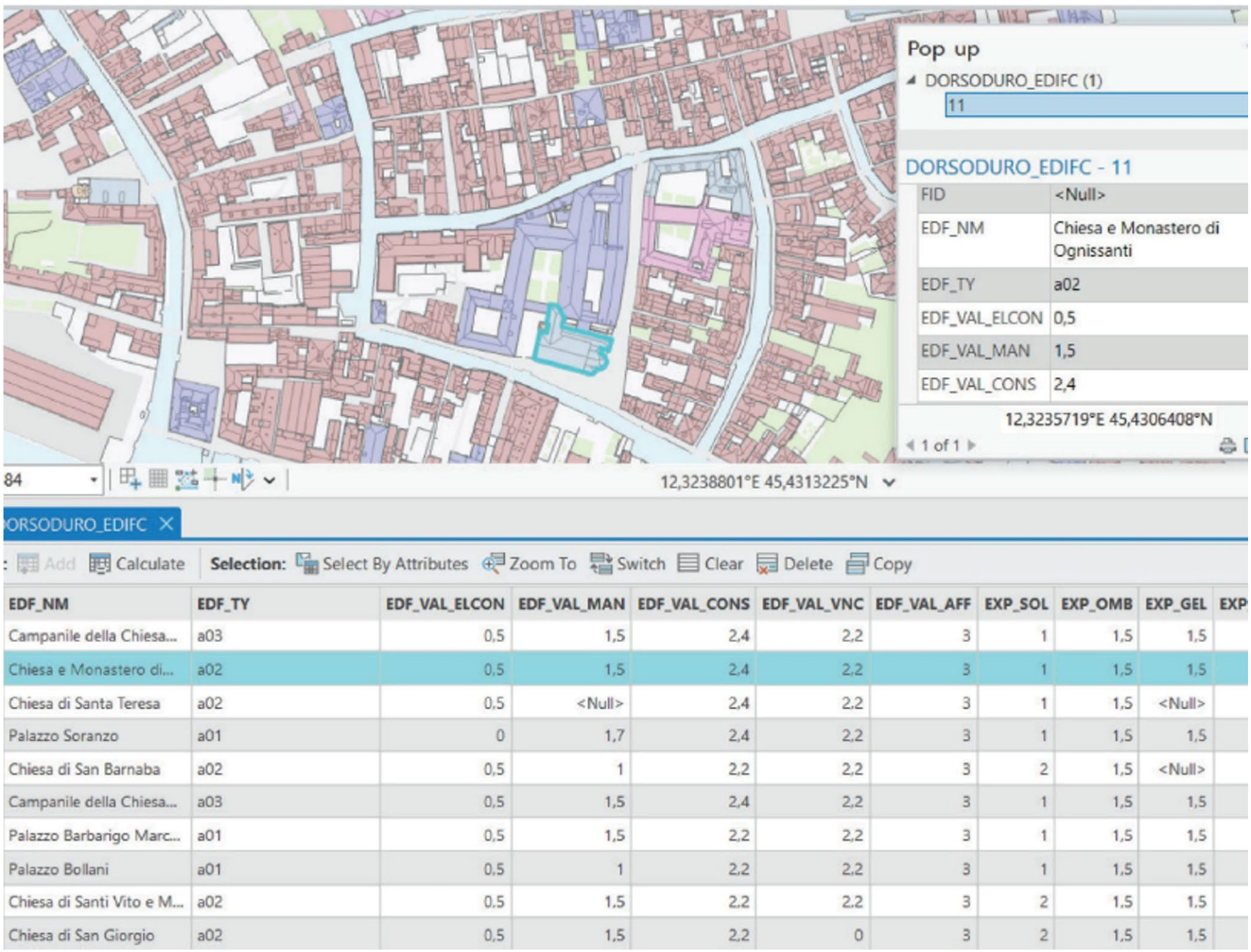
To ensure integrability, the new attributes were coded according to the same structure as the existing dataset. This includes the use of alphanumeric data types with semantic consistency in the naming conventions. Once the update in tabular form was completed, it was associated with the main dataset through a shared unique key (FID). This linkage ensures that each record in the existing dataset corresponds uniquely to a set of values in the new attribute table (Fig. 8).

In a preliminary phase, some features of the municipal database were appropriately modified and reorganized to ensure greater consistency between the available data and the macro-categories of the built environment adopted in this study. This operation allowed the information structure to be aligned with the constitutive elements of the building, which form the basis for the detailed risk analysis. The structured configuration of the dataset offers high flexibility in assigning and updating values over time. As shown in Table 3, the new dataset is integrated with the reference database currently used by the Municipality of Venice, incorporating all the information necessary to determine the overall risk score. This data structure includes both intrinsic and extrinsic factors that define the vulnerability values presented in the second column.

Following the methodology detailed in specific literature (Trovò et al. 2024), the vulnerability calculation employs differentiated multipliers based on the building's construction typology and material composition. This approach allows the risk assessment to account for the diverse structural behaviours in response to climate stressors. Specifically, the methodology considers both the susceptibility of materials their intrinsic predisposition to damage under environmental stress and their resilience, defined as the capacity to adapt and respond to climate forcing to limit adverse effects.

The assessment is structured around the interaction between intrinsic factors such as constitutive materials, state of conservation (Fig. 9), and level of heritage protection and extrinsic factors, evaluated in relation to the building's location and its exposure to site-specific environmental conditions (Fig. 10). The integration of these parameters enables a more reliable and representative assessment of the actual vulnerability of historical buildings, leading to a more accurate risk profile grounded in the calibration of climatic factors against the specific physical, material, and historical characteristics of each building.

Risk criteria (Fig. 11) are weighted through specific multipliers that integrate resilience factors related to constitutive materials and building types. These factors are modulated according to different degradation phenomena, which impact the stability and integrity of structures in variable ways.



EDF_NM	EDF_TY	EDF_VAL_ELCON	EDF_VAL_MAN	EDF_VAL_CONS	EDF_VAL_VNC	EDF_VAL_AFF	EXP_SOL	EXP_OMB	EXP_GEL	EXP
Campanile della Chiesa...	a03	0,5	1,5	2,4	2,2	3	1	1,5	1,5	
Chiesa e Monastero di...	a02	0,5	1,5	2,4	2,2	3	1	1,5	1,5	
Chiesa di Santa Teresa	a02	0,5	<Null>	2,4	2,2	3	1	1,5	<Null>	
Palazzo Soranzo	a01	0	1,7	2,4	2,2	3	1	1,5	1,5	
Chiesa di San Barnaba	a02	0,5	1	2,2	2,2	3	2	1,5	<Null>	
Campanile della Chiesa...	a03	0,5	1,5	2,4	2,2	3	1	1,5	1,5	
Palazzo Barbarigo Marc...	a01	0,5	1,5	2,2	2,2	3	1	1,5	1,5	
Palazzo Bollani	a01	0,5	1	2,2	2,2	3	1	1,5	1,5	
Chiesa di Santi Vito e M...	a02	0,5	1,5	2,2	2,2	3	2	1,5	1,5	
Chiesa di San Giorgio	a02	0,5	1,5	2,2	0	3	2	1,5	1,5	

Fig. 8 Visualization of the integrated database, including research data coded to match the structure of the existing dataset

Discussion and conclusions

The topic of specific risk analysis applied to built cultural heritage inherently opens up a multidisciplinary field of investigation, allowing for the integration of aspects related to conservation and mitigation, even at the architectural scale, with those of prevention (Fiorani et al. 2023; Mioli 2023). In this context, the present work sought to develop a largely unexplored research area, namely the quantitative assessment of the vulnerabilities of built heritage, which to date has often been predominantly qualitative. This condition is due both to the scale at which risk assessments are often conducted and to the high heterogeneity of the cultural and natural heritage considered, whose complexity makes it difficult to interpret individual characteristics at the adopted reference scale (Bonazza and Sardella 2023).

The distinction of different categories of the built environment and their respective morphologies in the Venetian context allowed the analysis to be increasingly detailed, placing the individual historic-architectural artifact at the center, with its specific characteristics and intrinsic peculiarities (Trovò 2023). This approach promoted the development of a potential risk monitoring system based on an information system that can be continuously implemented and updated. This aspect is particularly relevant for public authorities, which can regulate and calibrate mitigation strategies according to specific territorial areas, enabling a more conscious and targeted use of resources, especially in relation to the most vulnerable areas.

In this regard, the scale factor of the analysis, initially highlighted, plays a determining role not only in understanding risk but also in implementing intervention policies (Musco and Fregolent 2014), which can range from broad strategies to precise and targeted measures on individual critical elements.

The work also opens the door to potential future developments and integrations. First, expanding the information database to cover the entire historic center would allow a

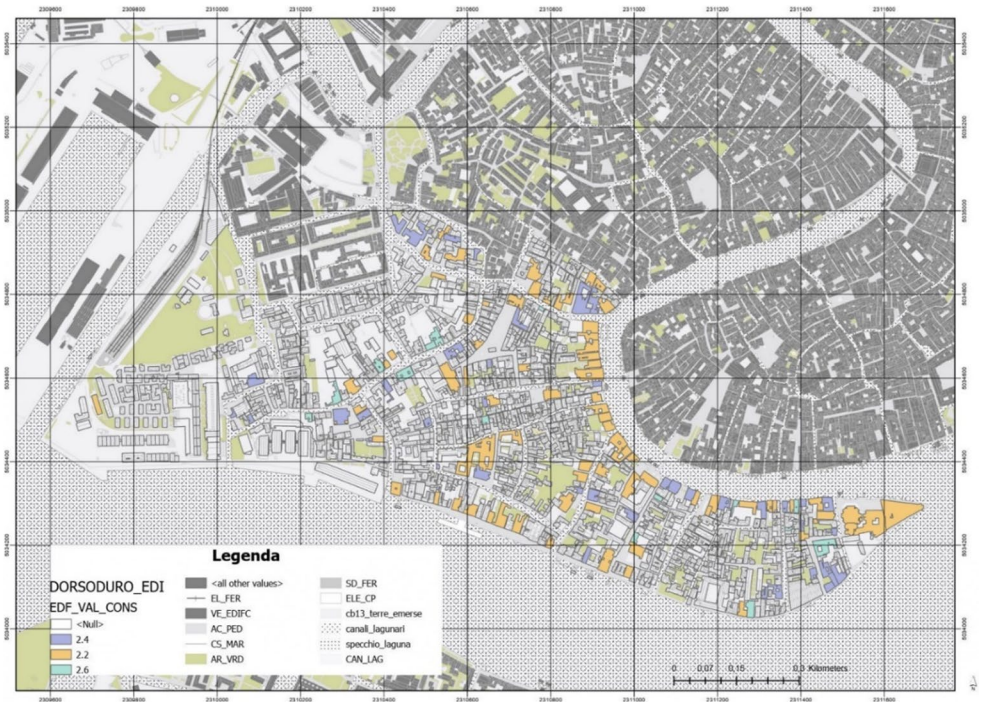


Fig. 9 Dataset map: Conservation Status layer for churches, palaces, and bell towers in the Dorsoduro district, categorized by vulnerability levels: Bad (2.6), Moderate (2.4), and Good (2.2)

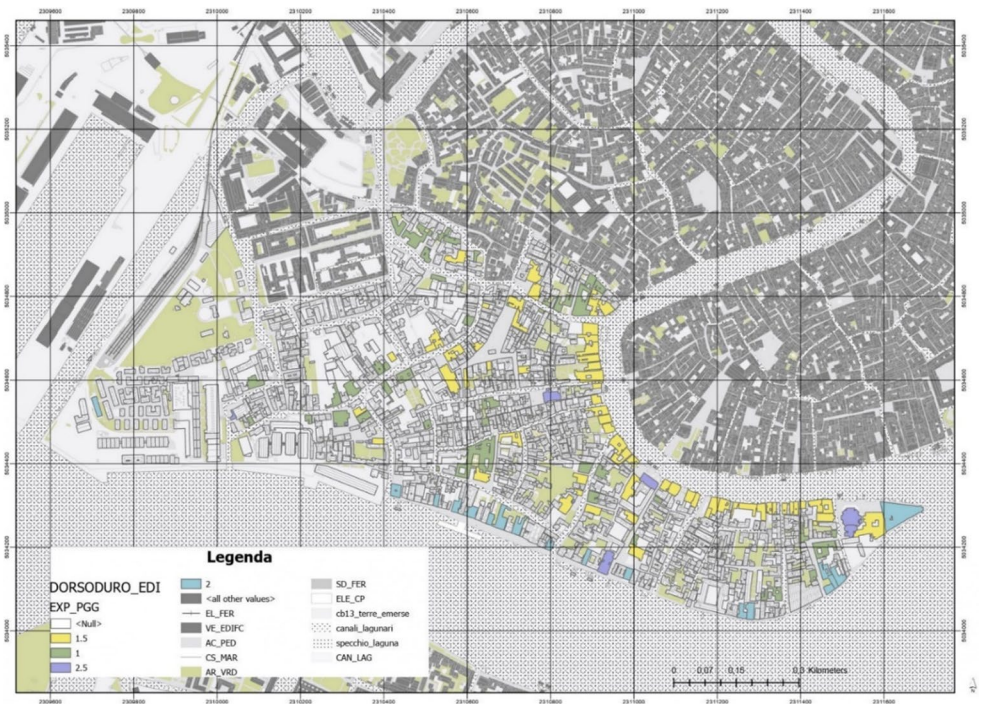


Fig. 10 Dataset map: Rainfall Vulnerability layer for the Dorsoduro district, categorized by urban positioning: High Building (2.5), Building on the Edge (2.0), Building on 'Campo' (1.5), and Building on 'Calle' (1.0)

more extensive testing of the actual applicability and effectiveness of the proposed system. At the same time, the definition of risk values and related multipliers, not explored in detail here, would require an additional phase of review and calibration.

The use of GIS also allows for interpretations in an integrated perspective with the Internet of Things (IoT), introducing processes based on the continuous updating of specific parameters, with the goal of making the analysis dynamic over time and transforming it into an active monitoring tool for the historic center. In this direction, the integration of BIM models within the GIS environment would allow the construction of an even more detailed information system, useful for the knowledge, storage, and management of data related to historic artifacts, directly linking them to the most relevant climatic indices.

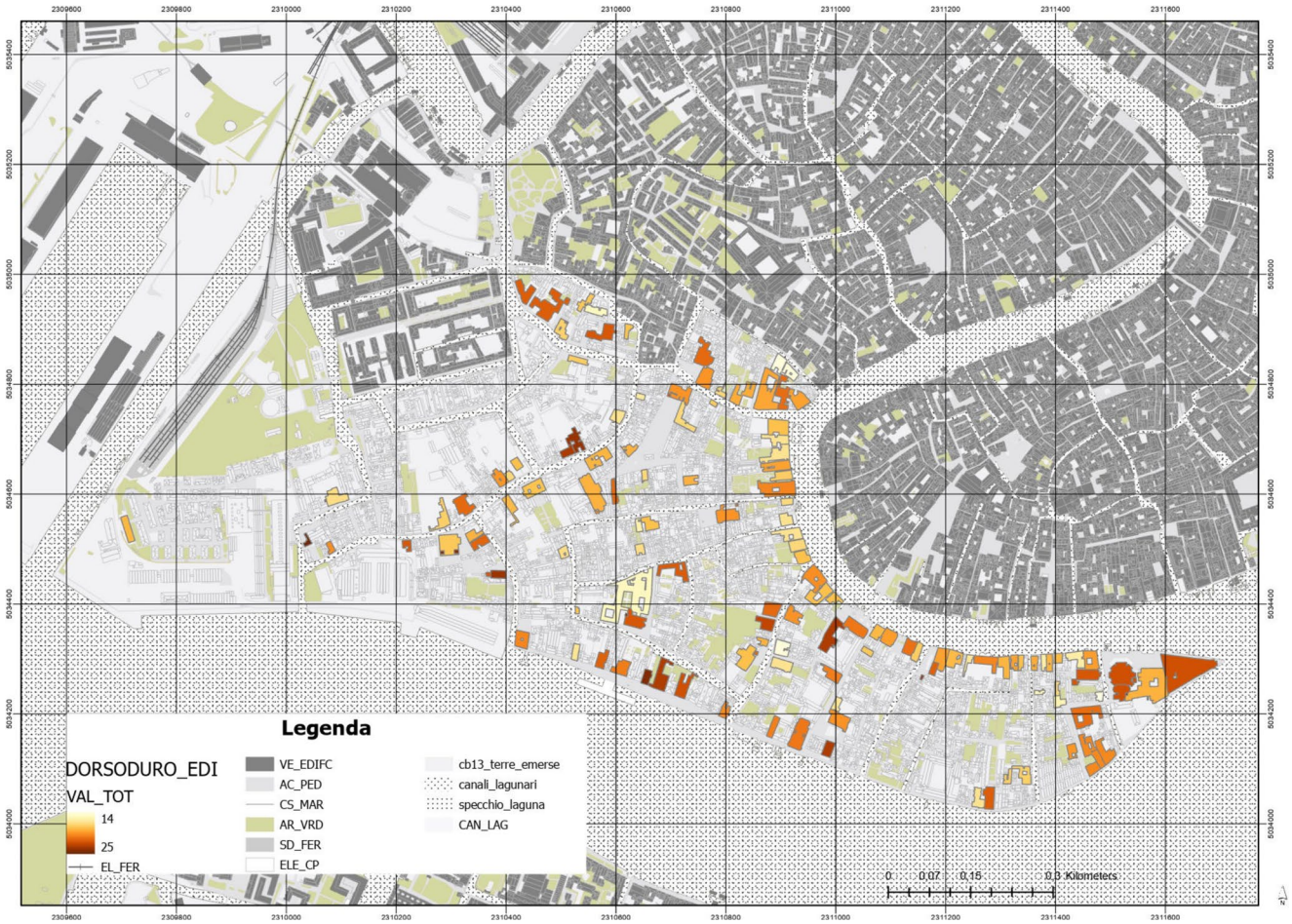


Fig. 11 Dataset map: Built Environment Risk Values layer for the Dorsoduro district. The map displays a gradient representing the risk levels for the three analyzed categories (churches, palaces, and bell towers), based on the following scores: Very High (>24.1), High (21.2–24.0), Medium (18.2–21.1), Moderate (15.3–18.1), and Low (<15.2)

While this work has contributed to a comprehensive understanding of the risks and impacts affecting the Venetian territory, certain methodological challenges remain open and warrant further investigation.

A first limitation concerns the assessment of vulnerability within the risk methodology. Although the framework allows for a structured integration of intrinsic and extrinsic factors, the identification and characterisation of the different vulnerabilities still rely on largely qualitative criteria. The transition towards a fully quantitative evaluation capable of expressing vulnerability through measurable and comparable indicators remains a critical area for future development, particularly in order to enhance the reproducibility and transferability of the methodology to other heritage contexts.

A second limitation relates to the temperature data employed in the analysis. The values used are predictive rather than directly measured and are therefore subject to a degree of uncertainty. This is further compounded by potential errors and noise introduced by the spatial resolution of satellite imagery, which may limit the accuracy of localised assessments, especially in dense and morphologically complex urban fabrics such as the Venetian one.

Finally, the use of remote sensing as a tool for analysing specific vulnerabilities represents an additional area of development, particularly if implemented as a monitoring system based on open-source data. A particularly interesting area of experimentation could involve the transposition of raster data through the assignment of values in the form of tabular attributes, thus promoting greater integration between spatial and informational data.

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Data availability The authors declare that the data supporting the findings of this study are available in the document.

Declarations

Competing interests The authors declare no competing interests.

References

Bonazza A (2022) Sustainable Heritage and Climate Change. In: Fouseki K, Cassar M, Dreyfuss G et al (eds) Routledge Handbook of Sustainable Heritage, 1st edn. Routledge, London, pp 263–271

Bonazza A, Sardella A (2023) Climate change and cultural heritage: Methods and approaches for damage and risk assessment addressed to a practical application. Heritage 6:3578–3589. https://doi.org/10.3390/heritage6040190

Bonazza A, Sabbioni C, Messina P et al (2009) Climate change impact: Mapping thermal stress on Carrara marble in Europe. Sci Total Environ 407:4506–4512. https://doi.org/10.1016/j.scitotenv.2009.04.008

Bonazza A, Maxwell I, Drdacky M et al (2018) Safeguarding Cultural Heritage from Natural and Man-Made Disasters. A Comparative Analysis of Risk Management in the EU. Publications Office of the European Union, Maastricht

Brivio PA, Lechi G, Zilioli E (2006) Principi e metodi di telerilevamento. CittàStudiEdizioni, Milano

Bruschi G (2020) La conservazione dell'architettura nel tempo dei cambiamenti climatici: l'analisi come strumento di progetto. In: Biscontin G, Driussi G (eds) Gli effetti dell'acqua sui beni culturali. Atti del XXXVI° Convegno Internazionale Scienza e Beni Culturali. Arcadia Ricerche, Venezia, pp 259–268

Capponi G (2004) L'invecchiamento e il degrado. In: Carbonara G (ed) Atlante del restauro, vol 2. UTET, Torino, pp 433–453

Chen K, Blong R, Jacobson C (2001) MCE-RISK: Integrating Multicriteria Evaluation and GIS for Risk Decisionmaking in Natural Hazards. Environ Model Softw 16:387–397. https://doi.org/10.1016/S1364-8152(01)00006-8

Cinelli M, Coles SR, Kirwan K (2014) Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. Ecol Indic 46:138–148. https://doi.org/10.1016/j.ecolind.2014.06.011

Comune di Venezia (2021) Piano di Azione per il Clima della Città di Venezia. Adattamento – Allegato C1. Comune di Venezia, Venezia

Di Ciaccio F, Russo P, Parisi EI et al (2025) Towards Sustainable Heritage Conservation: Transformer-Based temperature forecasting in the city of Florence. Int Arch Photogramm Remote Sens Spatial Inf Sci XLVIII-M-9-2025:399–405

European Environment Agency (2017) Climate change, impacts and vulnerability in Europe 2016: An indicator-based report (EEA Report No. 1/2017). Publications Office of the European Union, Luxembourg. https://doi.org/10.2800/534806

Fiorani D (2009) Restauro e tecnologie in architettura. Carocci, Roma

Fiorani D, Acierno M, Donatelli A et al (2023) Centri storici, digitalizzazione e restauro. Applicazioni alle ultime normative della Carta del Rischio. Collana Studi e Ricerche, Roma

Garzulino A, Borgarino MP, Del Curto D (2021) When GIS Joins the Conservation Management Plan of a 20th-Century Architectural Heritage. Sustainability 13:3881. https://doi.org/10.3390/su13073881

Jones J (2019) GIS project management approach for implementation of GIS for planning organisations. Dissertation, Northwest Missouri State University

Moioli R (ed) (2023) La Conservazione preventiva e programmata: una strategia per il futuro. Premesse, esiti e prospettive degli interventi di Fondazione Cariplo sul territorio. Altralinea, Firenze

Musco F, Fregolent L (eds) (2014) Pianificazione urbanistica e clima urbano. Manuale per la riduzione dei fenomeni di isola di calore urbano. Il Poligrafo, Padova

Sesana E, Gagnon AS, Ciantelli C et al (2021) Climate change impacts on cultural heritage; A literature review. WIREs Clim Chang 12:e710. https://doi.org/10.1002/wcc.710

Trovò F (2023) Venezia: manutenzione e misure di salvaguardia in una prospettiva storica. In: Mirabella Roberti G, Vieths S (eds) Fra luogo dell'abitare e oggetto museale. Strategie per la cura delle città storiche. Il Poligrafo, Padova

Trovò F, Bruschi G (2025a) The Venice and its Lagoon UNESCO site (Italy): Cultural Heritage and Climate Change. In: Mileto C et al (eds) Historic Settlements. Conservation, Regeneration, Management. Atti del convegno Heritage 2025. EdUPV, Valencia, pp 875–882

Trovò F, Bruschi G (2025b) Patrimonio culturale e cambiamenti climatici. il caso Venezia. In: Driussi G (ed) Le prossime sfide per i beni culturali. Atti del XL Convegno Scienza e Beni Culturali. Arcadia Ricerche, Venezia, pp 205–216

Trovò F, Bruschi G, Umar N et al (2024) Historical cities against climate change. management conservation plans as a possible strategy? In: Driussi G (ed) La conservazione preventiva e programmata. Atti del XXXIX° Convegno Scienza e Beni Culturali. Arcadia Ricerche, Venezia, pp 299–310

UNESCO (1972) Convention Concerning the Protection of the World Cultural and Natural Heritage. Adopted by the General Conference at its seventeenth session, Paris, 16 November 1972

Vassena GPM, Fellin A, Mainardi A et al (2024) Accurate 3D model of Venice: preserving historical data and introducing SLAM IMMS for change detection and updating procedures. In: Fassi F, Remondino F (eds) 10th Intl. Workshop 3D-ARCH 3D Virtual Reconstruction and Visualization of Complex Architectures. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-2/W4-2024, pp 435–442

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