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Article

A Multidisciplinary Approach for the Vulnerability Assessment of a Venetian Historic Palace: High Water Phenomena and Climate Change Effects

Luisa Berto [1], Diego Alejandro Talledo [1], Greta Bruschi [1], Isabella Zamboni [1], Enrico Lazzarini [2], Chiara Zofrea [1], Paolo Faccio [1] and Anna Saetta [1,*]

[1] Department DCP—University IUAV of Venice, 30135 Venice, Italy; lberto@iuav.it (L.B.); dtalledo@iuav.it (D.A.T.); gbruschi@iuav.it (G.B.); izamboni@iuav.it (I.Z.); chiara.zofrea@libero.it (C.Z.); faccio@iuav.it (P.F.)
[2] Department ICEA—University of Padova, 35131 Padova, Italy; enrico.lazzarini@studenti.unipd.it
* Correspondence: saetta@iuav.it

Abstract: This paper illustrates a multidisciplinary approach aimed at the vulnerability assessment of historic masonry heritage in Venice, focusing on questions of method and practice, which specifically involve the disciplines of restoration, building archaeology and structural engineering. Taking into account the existing standards for the management and assessment of cultural heritage, an integrated methodology is proposed for analyzing and interpreting historic constructions. Particular reference is made to Venetian scenery and its relationship with water, from the worldwide known high tide phenomena to the new perspectives offered by MOSE (i.e., Experimental Electromechanical Module, a system of a series of retractable mobile gates) and the new challenges due to climate change. Within such an approach, the different disciplines, including the building archeology, contribute to obtaining an interpretative model for historic buildings subjected to the high tide phenomena, with the aim of performing a vulnerability assessment and to design possible restoration interventions. The proposed methodology is applied to the case study of a Venetian historic palace facing the Grand Canal. For this palace, all the steps of the knowledge path have been carried out, from historical study to geometrical, Material-Constructive Survey, Crack Pattern and Degradation Analysis to stratigraphic analysis. The interpretative model obtained at the end of this path is enriched with the results of preliminary numerical analyses that investigate, in greater depth, the effects of high water phenomena on the rising damp front in masonry walls. Some previsions on the effects of MOSE activation and of climatic change, in particular in terms of sea-level rise, are presented.

Keywords: Venice; historic building; climate change; high water; restoration; archaeology; structural engineering

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1. Introduction

Reflecting on the future of historic centers and finding strategies for their conservation and protection has become a crucial issue all over the world nowadays, also in view of the new threats represented by climatic change. In this field, it is fundamental to develop tools to support decision-makers and technicians to face this complex problem, and also in the framework of multi-risk approaches, e.g., [1–5]. For this aim, the available technologies and innovations may make a significant contribution, as an example, within structural assessment [6–9].

Venice, with its artistic splendor and its intimate and sometimes dangerous relationship with water, provides an emblematic case. Several studies and projects in the last years have highlighted the necessity to protect Venice from tidal flooding, considering its fragility and the complexity related to managing tourism, e.g., [10–16]. As a matter of fact, the Venetian territory is extremely fragile, and climate change impacts are manifesting their effects in relation to different issues in recent years, ranging from hydrological risk to urban overheating (urban heat island, UHI), to problems of coastal and lagoon defense, up to the degradation of historic buildings. All this has significant environmental, social and economic consequences, which, in the particular case of Venice and its lagoon system (belonging to UNESCO World Heritage sites located in coastal areas), may invalidate the development of economic activities and the well-being of citizens.

From this perspective, there is also a reflection on the role that time assumes in the process of transformation of the architecture. Time has always affected the mechanical characteristics of materials, altered the constructive connections, determined the phenomena of anthropic addition or subtraction (not always with improving outcomes), including calamitous events that distort the assets and can compromise the efficacy of repair works. Until the most recent period, which includes the climate changes that contribute to accelerating the processes of degradation directly—due to the significant variations in temperature and humidity levels—or indirectly—by subjecting the entire building to traumatic episodes (meteorological and extreme weather events). The latter events acquire, for the uniqueness and fragility of the Venetian buildings, even more serious significance.

The close relationship between Venice (and its inhabitants) and the sea-lagoon system is well described by one of the most ancient documents that have come down to us, which dates back to 789 A.D. In his Historia Langobardorum [17], Paolo Diacono writes of the Venetians "*non in terra neque in aqua sumus viventes*" (we live neither on water nor on land). If, on the one hand, the sea is responsible for the greatness and wealth of Venice, has made it one of the greatest maritime powers over the centuries, on the other hand, it is the cause of the worldwide known phenomenon of "*acqua alta*" (literally high water, or high tide), which in some cases may submerge a large part of the city. High tide generally happens when the astronomical tide is combined with a relevant meteorological tide (typically in the presence of adverse weather conditions with low pressure and strong wind blowing from the south-east called "*Scirocco*").

Since 1910, the standard reference for relative sea level in the Venice area has been the so-called "*Zero Mareografico Punta Salute*" (ZMPS), which represents the mean tide level (MTL)—calculated as the mean of the high and the low water measured at the tide station of Santo Stefano in the period 1884–1909 (central year 1897)—and it corresponds to −0.2356 m in the vertical datum Genoa 1942 (EPSG:1051) [18], which is the standard national reference in Italy. In Figure 1, the name of tides in relation to their level referred to ZPMS is reported together with the corresponding flooding percentage of the city areas. As it can be seen, conventionally sea level higher than +80 cm ZMPS is called high tide; in this situation, the water submerges wide zones in the low-lying areas of the city, such as the famous "*Piazza San Marco*". When the sea level exceeds +110 cm ZPMS (very high tide), which corresponds to the threshold level for the activation of the sound alarm, about 12% of the city area is flooded [19].

The maximum high tide phenomenon registered in Venice was on 4 November 1966, with a tide level of +194 cm ZMPS (known as "*Acqua granda*"), and the minimum level of −124 cm ZMPS was on 18 January 1882. Details about the history of tides in Venice can be found in Reference [20].

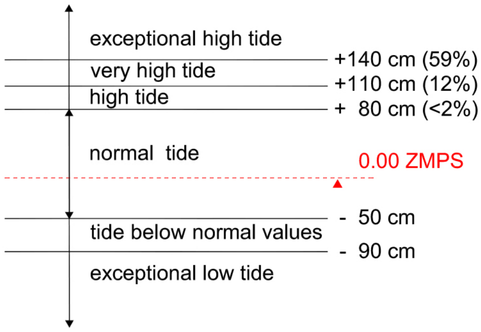


Figure 1. Designation of tide in Venice with reference to sea level referred to as ZMPS [21] and corresponding flooding percentage.

The recurring phenomenon of high water and the consequent flooding of the city accelerate the deterioration of Venetian constructions. In fact, the frequency and intensity increase of this phenomenon can lead to wet–dry cycles that, combined with the presence of salt in lagoon water, can cause different types of problems to masonry structures and, in particular, to those of monumental buildings that are often characterized by decorations, frescoes, etc. (e.g., consider the inside of churches and historic buildings). These problems range from the deterioration of plasters, of the decorative apparatus and of the external parts of the walls, up to significant impairment of the load-bearing capacity of the masonry when the salt penetrates the wall [22–24]. Salt attack is the decay of masonry materials by soluble salts that crystalize within the pore system of the masonry. As the salt crystals grow, the masonry could be damaged due to the force exerted by rapidly crystallizing salts (due, e.g., to a high rate of evaporation).

It is worth noting that wet–dry cycles, which are an important driver of salt attack decay, represent a typical situation of Venetian buildings. Moreover, the rising damp front in Venice is constantly increasing, on the one hand, due to the rise of the medium sea level, and, on the other hand, due to the subsidence of the city [25]. This phenomenon, combined with the characteristics of the very aggressive environment constituted by the lagoon due to the presence of salts and pollutants, aggravates the already precarious state of the Venetian buildings.

For the protection of Venice from high water phenomena, in addition to local interventions (e.g., the reinforcement of coastlines, the raising of banks and pavements) that have always been part of the Venetian tradition, a system of retractable mobile gates called MOSE (Experimental Electromechanical Module) was designed [26]. The project began in 1987 with the aim of protecting the Venetian lagoon together with its historic, artistic and environmental heritage from the effects of exceptional tides up to 3 m ZMPS. Construction began in 2003, and on 10 July 2020, the first full test was successfully completed. Currently, the MOSE operates for tides above 1.10 m ZMPS [26]. What the effects of the operation of MOSE may be both on the lagoon system and on the buildings in terms of control of tidal excursions and, consequently, of the control of the combined salt attack–rising damp phenomenon, which are two separate but interrelated processes, are still being studied. Anyway, this flood defense measure has been considered in the work of Sesana et al. [27], a good example of best practice for climate change adaptation of cultural heritage.

The presented study is part of the "Venice 2021: Scientific Research Program for a Regulated Lagoon" research project on the functioning of the Venice lagoon, considering the effect of the MOSE system against high tides. One of the main goals of the research program is to provide decision-makers with scientific knowledge to protect both the natural ecological functioning of the lagoon and the safety of the built environment. In particular, in this study, the first results of a methodology for the analysis and interpretation of historic constructions aimed at providing a combined quantitative–qualitative assessment of the vulnerability of buildings are presented.

Actually, this approach combines different disciplinary contributions, including historical analysis, geometric and building stratigraphic surveys, the characterization of materials and their degradation and methods of structural engineering.

The proposed multidisciplinary method is applied to the case study of Palazzo Malipiero, located in Campo San Samuele in Venice, focusing on theoretical and operational issues.

Particular attention is paid to the rising damp phenomena in masonry constructions, which, as previously underlined, is of fundamental importance in Venice for the maintenance of the artistic and cultural heritage of the city.

2. Climate Change and Historic Constructions: The Case of Venice

Effects and future scenarios due to climate change have kicked off debates and the elaboration of possible adaptation strategies, measures and policies, which would allow the reduction of the negative impact of global warming on society and the economy, including environmental assets, existing buildings, as well as tangible and intangible cultural heritage. For planning the future of world heritage sites that could be severely impacted by climate change, Seekamp and Jo [3] have recently recommended the adoption of new policies based on heritage resilience combining preservation with transformation. A literature review on the impacts of climate change on tangible cultural heritage, including the interiors of historical buildings, has been recently published in [28].

With reference to the architectural heritage, difficulties relating to its adaptability and transformability occur if the climatic factor changes. The danger is losing the identification characters of historic constructions, such as functional, formal, technological and material characteristics, which are partly closely related to the place and culture, but especially determined by the local climate, e.g., [27]. The objectives of the research "Venezia 2021" are in line with the "*Piano Nazionale di Adattamento ai Cambiamenti Climatici*" (National Plan of Adaptation to Climate Change) that highlights, for the Italian territory, the lack of observational data necessary to correlate material degradation and system, characterizing the cultural heritage with the climatic variables and their changes. In addition, the plan underlines the need for downscaling, which means considering case studies consisting of individual artifacts subject to synergistic interactions in relation to the effects of climate change. Because of this, these interactions are probably more intense compared to those measurable in simple and monomaterial systems.

Actually, the structural damage due to extreme climatic actions assumes particular importance since climatic events (meteorological actions, flooding, geological instabilities and action of the wind) affect the construction elements of buildings in different ways (ground floors, vertical and horizontal closures, roof). Usually, the stress due to these phenomena has a sudden nature and a high intensity and can cause significant damage.

The debate concerning the "safe conservation" of the built historic heritage, characterized by considerations of the recurrence of natural disasters and, more recently with reference to the consequences of climate change, is leading to the reconsideration of the entire process of vulnerability assessment. The combination of several causes determines amplification phenomena, intensified by the performance impairment due to natural decay of the materials, the absence of maintenance and the presence of transformations inconsistent with the cultural heritage. From this point of view, Venice certainly represents an emblematic and particularly significant example, also considering that Venice and its lagoon is one of the UNESCO World Heritage Sites most at risk from coastal flooding and erosion before 2100 due to sea-level rise [29]. The impacts on Venice of climate change have been studied, among others, in [11,30,31].

With regard to climate change resulting from global warming, recorded on a regional (i.e., in the Veneto Region) and local scale, the data confirms an increase in the maximum temperature and daily minimum, connected to an increase in the average temperature and consistent with the increased frequency of heatwaves (tripled in the last years). Currently, a slight decrease in total rainfall and a significant decrease in the number of rainy days has been detected, while the frequency of days with intense rainfalls is increasing, as also in other regions of northern Italy (Triveneto, Piemonte, Lombardia, Emilia-Romagna). In general, the decrease of low-intensity rainfall events and the increase of intense events is the symptom of extremization of the rainfall. In addition to the increasing frequency of intense rainfall (quantities concentrated in brief periods) and heavy rainfall (significant quantities on a daily basis), there are other extreme meteorological phenomena that may have a significant impact on safety: hailstorms, strong gusts of wind, tornadoes, mostly associated with storm phenomena.

With particular reference to tides, it can be observed in Figure 2 how the mean sea level is rising, and this is one of the main effects of climate change. Over the 20th century, the relative sea level rose by about 25 cm leading to an increase in flood frequency. For this reason, the frequency of very high tide inundating the city during the winter is increasing, as shown in Figure 2. A return period of tide level over 110 cm of approximately 0.25 years was reported in the work of Carbognin et al. [32] now this value is about 0.11 years, while at the beginning of the 20th century, it was about 2.2 years.

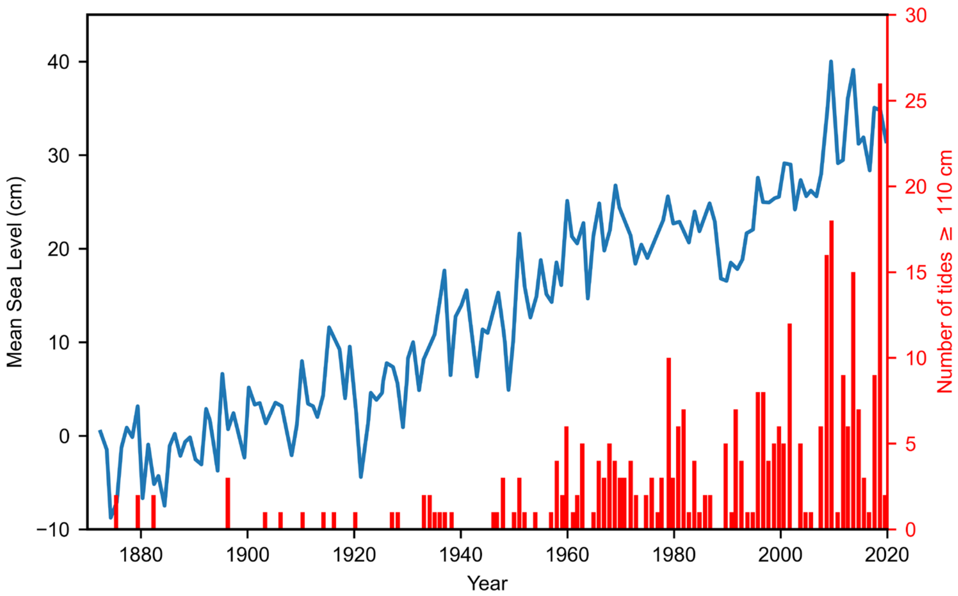


Figure 2. Development of annual mean sea level (blue line) estimated as the mean value between maximum and minimum in Venice, Punta Salute, in the period 1872–2020, and frequency of tides exceeding 1.10 m (red histogram), redrawn from [21].

The variation of the relative sea level in the last 150 years shows a linear trend of about 2.5 mm/year, approximately half of which is due to land subsidence and the other half to sea-level rise. Only for the part related to the sea-level rise, neglecting land subsidence, a higher trend (about 2.8 mm/year) has been recognized in the period from 1993 to 2019 [33]. Future projections of the relative sea-level (RSL) variation are very difficult due to the uncertainty of climate change, and different scenarios have been explored. Considering the five scenarios provided for in the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) [34] (from very low GHG emission to very high GHG emission), the mean sea-level rise in 2050 will vary between 3.2 mm/year (4.1 mm/year considering subsidence) and 5.3 mm/year (6.2 considering subsidence). More details about this hot issue for the Venice lagoon can be found in the works of Zanchettin et al. [33] and Galassi and Spada [35].

Certainly, the combined effect of the rise in the mean sea level and the occurrence of extreme weather events will make very strong and exceptional tidal phenomena even more frequent.

3. Multidisciplinary Approach to Historic Building Analysis

As part of research activities related to the Venice 2021 program "Construction of specific intervention strategies for the conservation of the cultural heritage" [36], a methodology for the study of historic Venetian buildings has been proposed integrating different disciplines involved in the conservation of built heritage.

The proposed methodology, schematically represented in Figure 3, is aimed to develop an interpretative model of historic masonry buildings in a Veniatian context effective for vulnerability assessment. This methodology involves a specific path of knowledge and numerical analyses that allow the effects of climatic change and adopted high tide protection measure (MOSE) to be considered. The core idea of the research is the extension of the principles expressed by the recent Italian standards addressed to the seismic assessment of cultural heritage, including more innovative aspects, such as complex environmental conditions, effects of climate change and of eventual defense actions. This is a key aspect for achieving a level of knowledge appropriate to the vulnerability assessment and to the design of possible interventions in accordance with the requirements of protection and preservation [37,38].

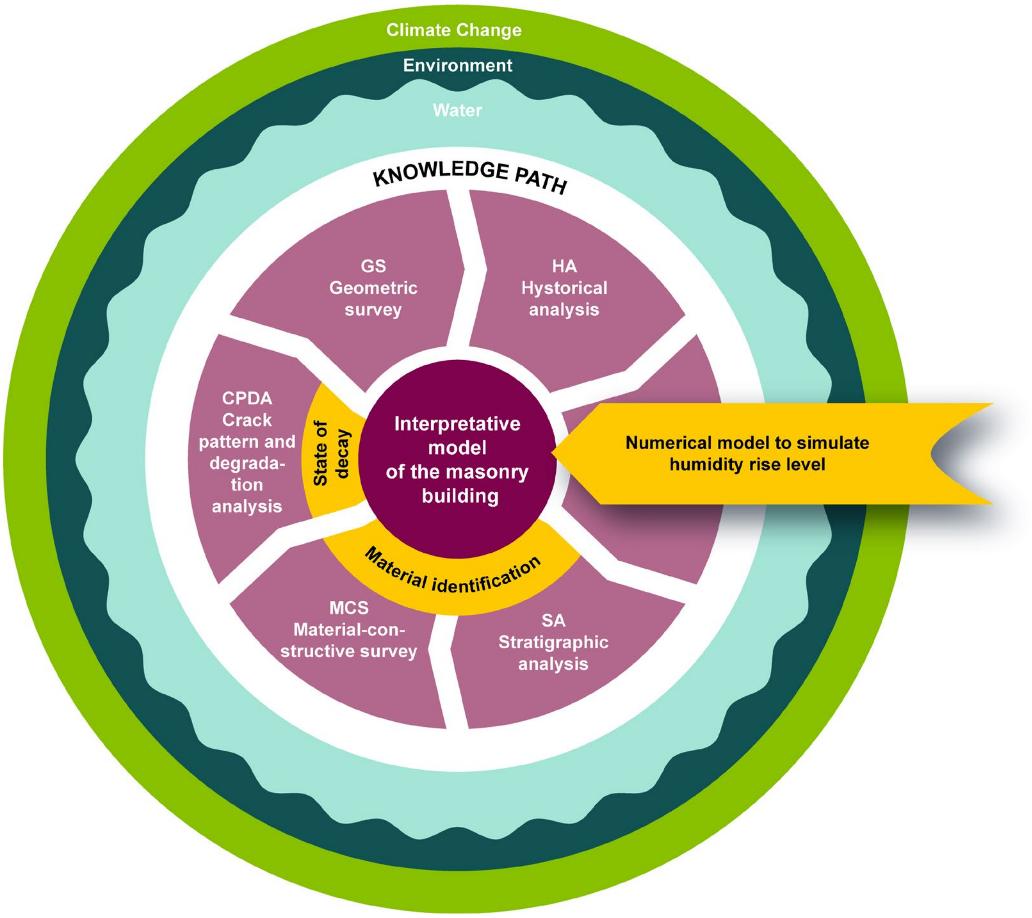


Figure 3. General framework of the proposed methodology for developing an interpretative model of Venetian historic construction for vulnerability assessment.

In this methodology, the path of knowledge is specifically defined for the Venetian case, and consists of a close examination of the ground floor's condition of buildings with reference to the elevation above mean sea level. Historical transformations, including previous restoration interventions, forms of alteration and degradation, in relation to high tide and to their past or planned variations, have to be properly considered. This path, which will be described synthetically in the following, includes various types of analysis paying attention to the multidisciplinarity in the investigation planning and in sharing the results.

The contribution of the Historical Analysis (HA) is performed in the research of natural or anthropic transformations that have affected the historic building and which may have increased the structure’s vulnerability. The analysis of historical data obtained, for example, from cadastral maps, is an indispensable preliminary phase able to guide the planning activity of direct surveys on the artifact. Of crucial importance is the knowledge of Venetian manufacturing features referring, for example, to high tide protection historical tools, which allow, among other things, to conduct correlations between the current state and the past in terms of zero tidal sea level variation. A typical example of a protection tool is represented by the installation of the so-called “*cadene*”, continuous courses of Istrian stone blocks, a low porosity material and very resistant to salt corrosion, Figure 4. These elements, at the time of construction, were collocated at a regular height interval in order to create a waterproof layer up to a certain level above the mean sea level, but to date, it can be largely exceeded from daily tidal excursions [39–41]. Figure 5 shows an example where the lack of efficacy in the “*cadena*” is underlined by the presence of corrective measures, such as the mechanical cutting of the masonry and indenting of damaged bricks (i.e., the so-called “*cuci-scuci*” technique). In particular, Figure 5a depicts the presence of green-brownish patina of algal vegetation, indicating the level reached by the water during the daily tidal variations, witnessing the lack of efficacy of “*cadena*” on a high tide, as shown in Figure 5b.

Lastly, from indirect sources, such as the historical treatise, it is possible to know the principles that characterize masonry and timber constructions typical of Venetian historic buildings. Such principles deal with the correct use of materials for realizing the construction elements that are placed with a precise hierarchy in the architectural organism, ensuring the unitary behavior [42]. Such an example is represented by Venetian canal-facing facades generally not toothed to the internal transverse walls in order to accommodate the inevitable differential settlements.

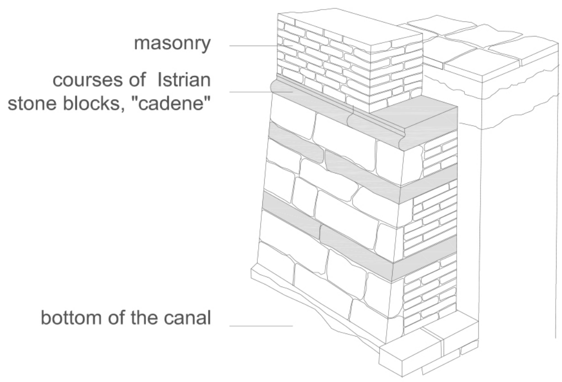
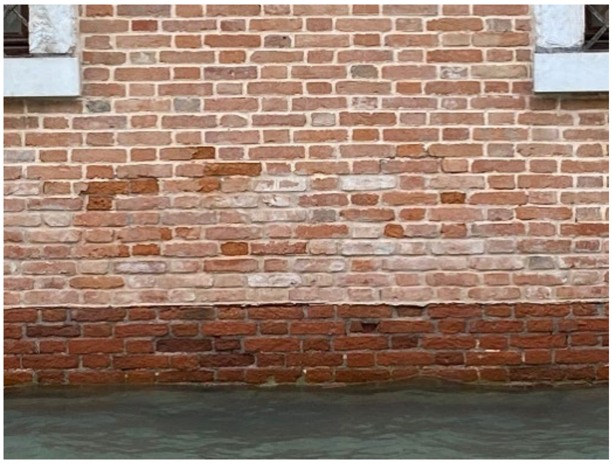


Figure 4. Schematic representation of Venetian masonry foundation detailing the “*cadene*”, adapted from [40].

(**a**)



(**b**)

Figure 5. Venice: Example of building with no more effective "*cadene*": (**a**) low tide; (**b**) high tide.

In parallel with the historical analysis and in direct connection with it, among the first activities to be carried out, there is the geometric-dimensional survey of the construction. The Geometrical Survey (GS) allows the acquisition and graphical representation of information on formal aspects, spatial layout, relations between the different constituent elements and materials, being at the same time a tool to spatially organize all data that will be successively collected. It is fundamental, in the context of Venetian buildings, to introduce specific references to the mean tide level and thus provide preliminary information about potential vulnerabilities in relation to high tide phenomena. Moreover, the detailed analysis of deformed configurations allows us to perform further study on the ongoing or stabilized instability phenomena of the building.

In the proposed methodology, the stratigraphic analysis (SA) applied to the discipline of architecture has a fundamental role in the path of knowledge. It consists of a direct archaeological survey, and it is the main tool of building archaeology. This discipline applies the principles of stratigraphy [43] to buildings, which was developed in Italy in the 1970s [44]. It provides the identification of portions of the building with the same material and constructive characteristics. This survey technique, spread in Italy among conservation architects, is particularly useful within a multidisciplinary approach to improve the interpretative model by reducing randomness typical of historical structures through the documentation of the construction phases, the nature of relations between homogeneous parts, as well as the quality of the masonry with reference to the mechanical behavior of the building, also related to degradation phenomena [45–47]. To this end, the Masonry Technique Form, developed by some of the authors, can be used to collect information. The compilation of the Masonry Technique Form is derived from a thorough visual investigation relating to the main geometric-constructive parameters useful for evaluating the mechanical characteristics of the material with a qualitative–quantitative approach [47,48].

In conjunction with the stratigraphic analysis, the Material-Constructive Survey (MCS) is an essential activity to identify the materials used at the time of construction and those introduced in the transformation phases.

Furthermore, Crack Pattern and Degradation Analysis (CPDA) allows the damage state and specific phenomena of material degradation to be determined.

The localization of portions of surfaces affected by the same degradation level and the analysis of the crack patterns, together with the stratigraphic analysis and the essential requirement of masonry quality, are fundamental aspects that can highlight potentially inefficient construction standards; inadequate human intervention that does not allow the unitary behavior of the building. They must be included in the interpretative model of the building since they may have a direct influence on the vulnerability assessment regarding both vertical loads and seismic actions. In particular, concerning this last issue, the results of these analyses allow the identification of the possible formation of macro-elements [45,46] that behave independently from the rest of the building. For this reason, this approach could be properly applied in the field of seismic assessment at the territorial level, for historic centers and for single buildings (e.g., [2,49–53]).

In the proposed procedure, developed with specific reference to the case of Venetian buildings, the interpretative model carried out at the end of the path of knowledge is enriched by means of numerical analyses in order to make the model effective for the subsequent phase of vulnerability assessment and design of the intervention. In particular, the numerical analyses allow for the increase of knowledge on the masonry state with reference to the humidity content, also related to the effects of climatic change and MOSE activation. As a matter of fact, the problem of rising damp due to the presence of salt-containing water represents a major cause of masonry degradation. The water of the lagoon that rises inside the masonry is a saline solution; as a result of the evaporation process, such solution becomes supersaturated, and water-soluble salts start nucleation within the pore system, growing to generate salt crystals. When drying occurs in relatively calm and dry air, salt crystallization and deposition usually affect the superficial part of the wall, and the so-called saline "efflorescence" takes place. On the contrary, in the case of even drier and, locally, very windy air, the evaporation process accelerates, and the salt deposition also affects the inner part of the masonry, causing more serious damage with cracking and detachment of mortar due to the internal pressure produced by the crystallization of NaCl (sodium chloride); this process is known as "subflorescence", e.g., [54]. Moreover, the salts contained in the masonries are usually hygroscopic, attracting even more water. The consequences of continuous cyclic wetting and drying with the subsequent precipitation of salts are not limited to walls of the buildings (with the degradation of bricks, mortar, stones, plaster) but, for example, in cases where the rising damp front reaches or exceeds the first story, may also result in the corrosion of metal rods and the rotting of wooden beams [55].

4. Palazzo Malipiero, Venice

Palazzo Malipiero (12th–17th century), one of the selected case studies within the project "Venezia 2021", called "*la Ca' Granda de' San Samuel*" (literally "the big house of St. Samuel") for the remarkable size, is located in Campo San Samuele in the sestiere of San Marco. This is a typical masonry Venetian palace facing the Grand Canal, Figure 6. The palace is characterized by two main floors; each floor is accessed by its own independent entrance hall, stairway and water door, Figure 7. The monumental courtyards and the adjacent 18th-century garden are annexed to the apartment on the first noble floor. Numerous changes of ownership took place, resulting in extensions, alterations and subdivisions over time, which fragmented the architectural unity.

For this building, the methodology described above and represented in Figure 3 has been applied. In particular, with regard to the path of knowledge, the detailed analyses preparatory focused on the ground floor rooms that, as stated above, are particularly significant in terms of the fragility of the building. After the historical analysis, the activities concerning the geometrical survey (GS), the Crack Pattern and Degradation Analysis (CPDA), the Material-Constructive Survey (MCS) and the stratigraphic analyses (SA) were carried out not as a sequence of separate steps but following a unitary approach. Such analyses concern the detailed examination of surfaces with reference to the damage sustained by masonry, taking into account, on the one hand, the location of the single structural elements and the different altitude with respect to the zero tide level, and on the other hand, of the new tide level at which the Mose is activated.

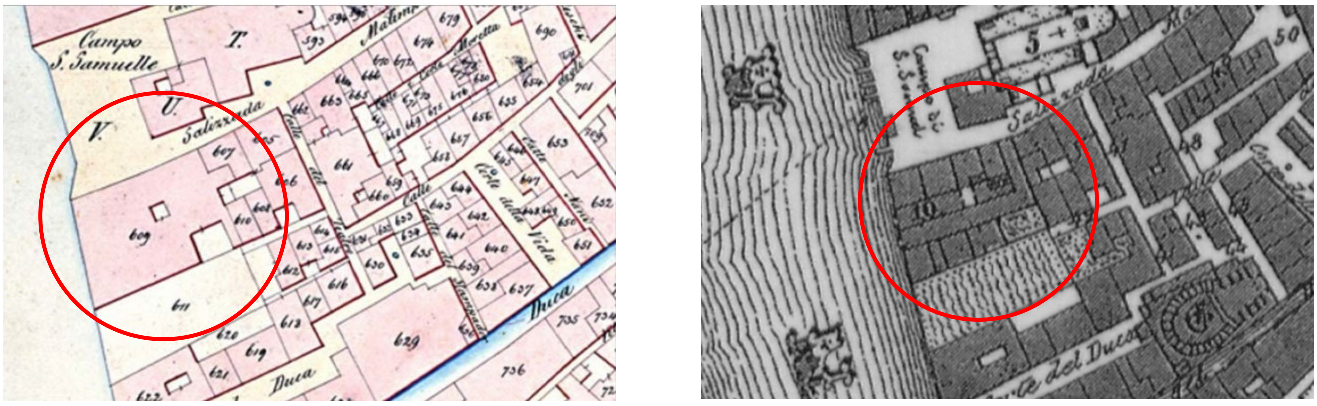
(**a**) (**b**)

Figure 6. Palazzo Malipiero, Venice: (**a**) aerial view; (**b**) building identification.

Figure 7. Palazzo Malipiero, Venice. The façade over the Grand Canal and identification of the water door of room 27.

4.1. Historical Analysis

The analysis of documents and studies edited on Palazzo Malipiero made it possible to build a first interpretative model concerning its main construction and transformation phases. The building, characterized by the continuity of use over the centuries, was erected in the 12th century by the Soranzo family. In the 15th century, the palace was acquired by the Cappello family, whose members added one story to the building [56,57], while later, on the turn from the 16th to the 17th century, the property passed onto the Malipiero family. An inventory of Donata Vendramin describes the palace before the acquisition by Cattarino Malipiero: "The floor is divided into two almost equal parts (as usual in private Venetian buildings) from the vast "*portego*" (a formal hall, characteristic of Venetian palaces) that stands at the front towards the Grand Canal" [56]. Several restorations and alterations occurred in 1622 and then in 1725, due to the Malipiero family, until reaching the current appearance, as can be seen from the two archival documents depicted in Figure 8: the Napoleonic land register (1807) and the famous Combatti plan (1846). The quotation of Cattarino Malipiero of 1631, mentioned in many documents, is also well known: "I acquired two thirds of S. Samuele's downstairs and the entire upstairs, and the ground, and rebuilt it" [56,57]. There are also, in the history of this palace, subsequent changes of ownership that might be indicative of internal transformations of the building (congruous or incongruous) not documentable from the only historical sources, until the acquisition of the palace by the Barnabò family, which commissioned a substantial renovation done around 1951 [56].

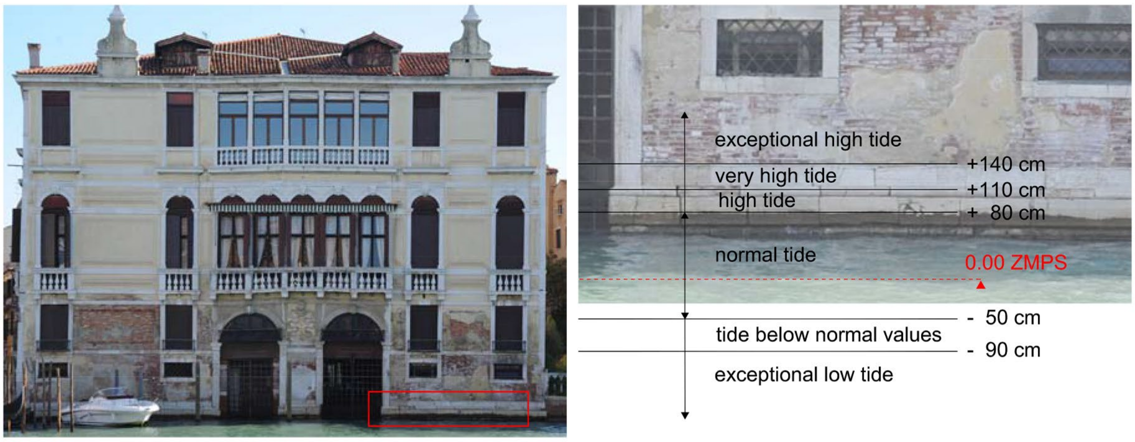


(**a**) (**b**)

Figure 8. Palazzo Malipiero, Venice. Comparisons with historical cartography: (**a**) Napoleonic land register, 1807, sheet 18 and (**b**) "Nuova planimetria della r.[egia] città di Venezia dimostrante le divisioni del caseggiato, i dettagli delle chiese dei pubblici stabilimenti e dei principali palazzi e la nomenclatura stradale: rilevata sul luogo e disegnata nel 1846 da Bernardo e Gaetano Combatti; incisa da G.B. Garlato" (New plan for the royal city of Venice showing the divisions of the building, details of churches, public buildings and most important palaces and the street nomenclature: detected on the site and drawn by Bernardo and Gaetano Combatti in 1846; recorded by G.B. Garlato).

4.2. Geometric, Stratigraphic, Material-Constructive and Crack and Degradation Surveys

Analysis of the rooms on the ground floor of the palace has shown, from the preliminary stages, transformations consequent to continuity of use; frequent replacement of the wall's portions (i.e., the "*cuci-scuci*" technique) at the lowest levels; phenomena of erosion of blocks and mortar joints of the ancient materials but also those most recently employed against rising damp, the phenomena of saline crystallization and related to wave motion. In the facades overlooking the Grand Canal, the presence of "*cadene*" has been detected, the typical technical solution against the high tide for the Venetian palaces described in Section 3, which in this case, appear to be still effective up to a very high tide condition (+1.10 m ZPSM), Figure 9.



(**a**) (**b**)

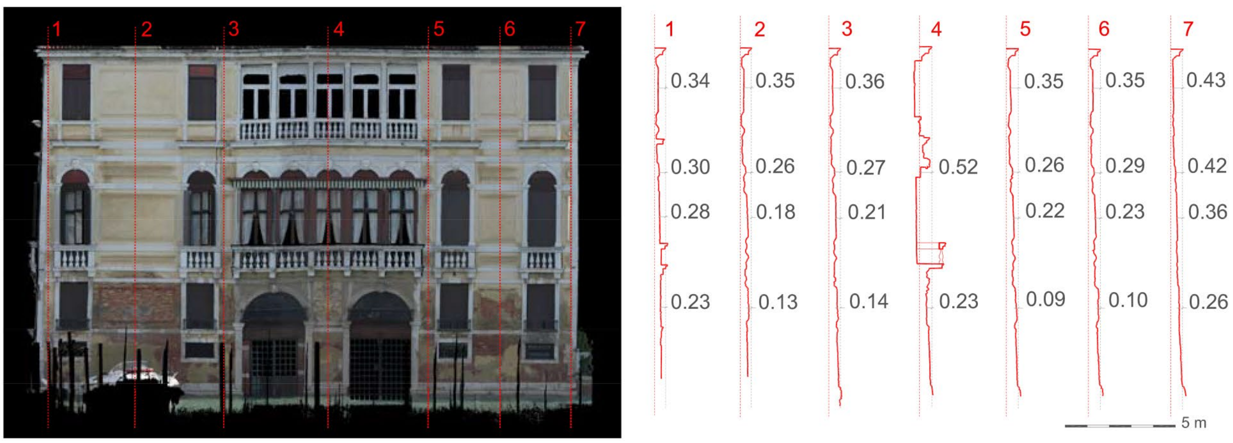
Figure 9. Palazzo Malipiero, Venice. Façade over the Grand Canal: (**a**) photo-rectification with identification of "*cadene*"; (**b**) detail of "*cadene*" with reference to tidal altimetric elevations.

Survey activities carried out following the approach described in Section 3 and Figure 3 are illustrated in detail below.

Regarding the activity of dimensional-architectural survey, the Geometrical Survey (GS) of Palazzo Malipiero has been carried out. In Figure 10, for example, the façade overlooking the Grand Canal is reported, with the representation in scale of false color; the out-of planes of the walls have also been detected through detail analyses of deformed configurations and reported for seven sections of the facade Figure 11. It can be seen the relevant out of plane of the façade, typical of the Venetian palaces. Particularly focusing on the ground floor of the building, a detailed survey of all rooms was carried out. For example, Figure 12 shows the floor plan of room 27 with wall W03_27 identified, near the water door, which will be the subject of study in Section 4.3. The sections of room 27, identified in the key map, are shown in Figure 13 where also the tidal heights are reported. Photo-rectifications were carried out for all the walls: the one of W03_27 wall is provided as an example in Figure 14.

(**a**) (**b**)

Figure 10. Palazzo Malipiero, Venice. Facade facing the Grand Canal: (**a**) geometric survey; (**b**) processing in false color scale to highlight the overhanging portions (blue, green and yellow). Survey and processing carried out by Circe photo-grammetry laboratory—Iuav University of Venice.



(a) (**b**)

Figure 11. Palazzo Malipiero, Venice. Facade facing the Grand Canal: (**a**) point clouds orthophoto and identification of sections used for the profiles of the deformations. (**b**) Profiles of the deformations (m). Orthophoto carried out by Circe photo-grammetry laboratory—Iuav University of Venice.

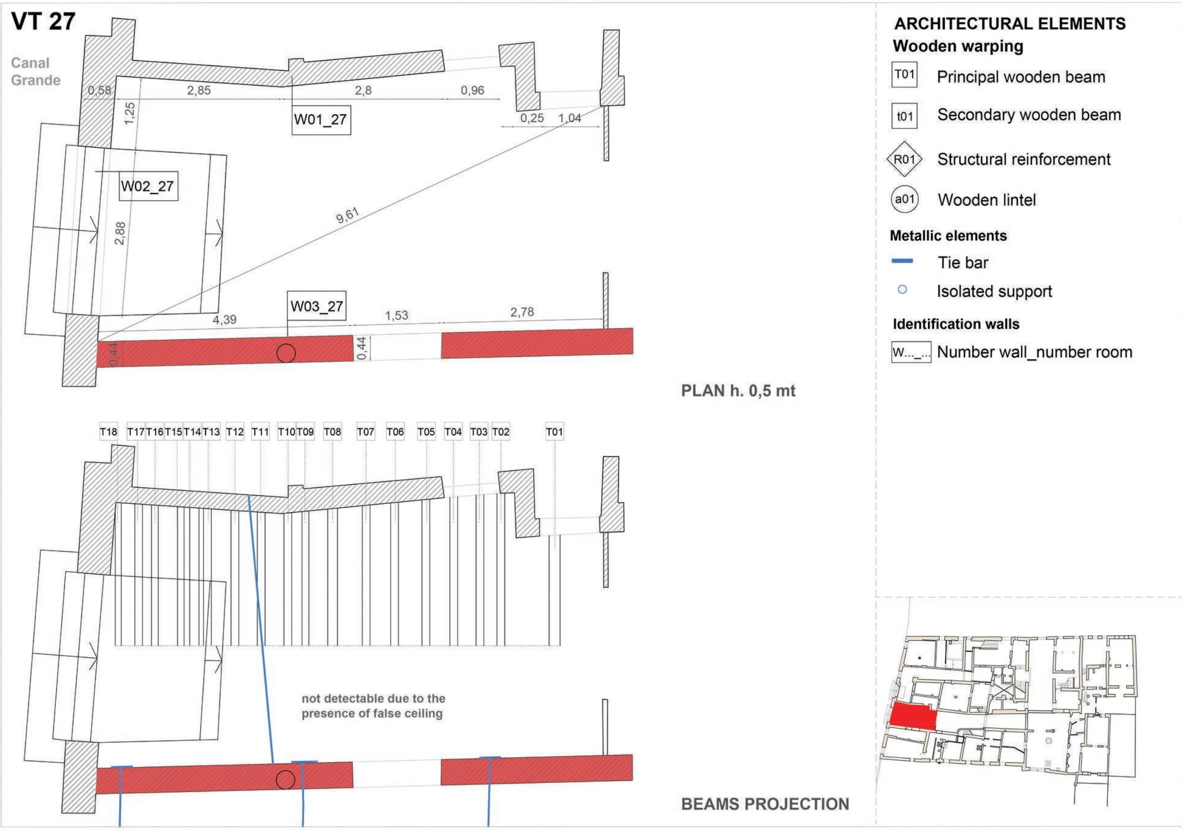


Figure 12. Palazzo Malipiero, Venice. Geometric survey of room 27 with the wall (W03_27) highlighted.

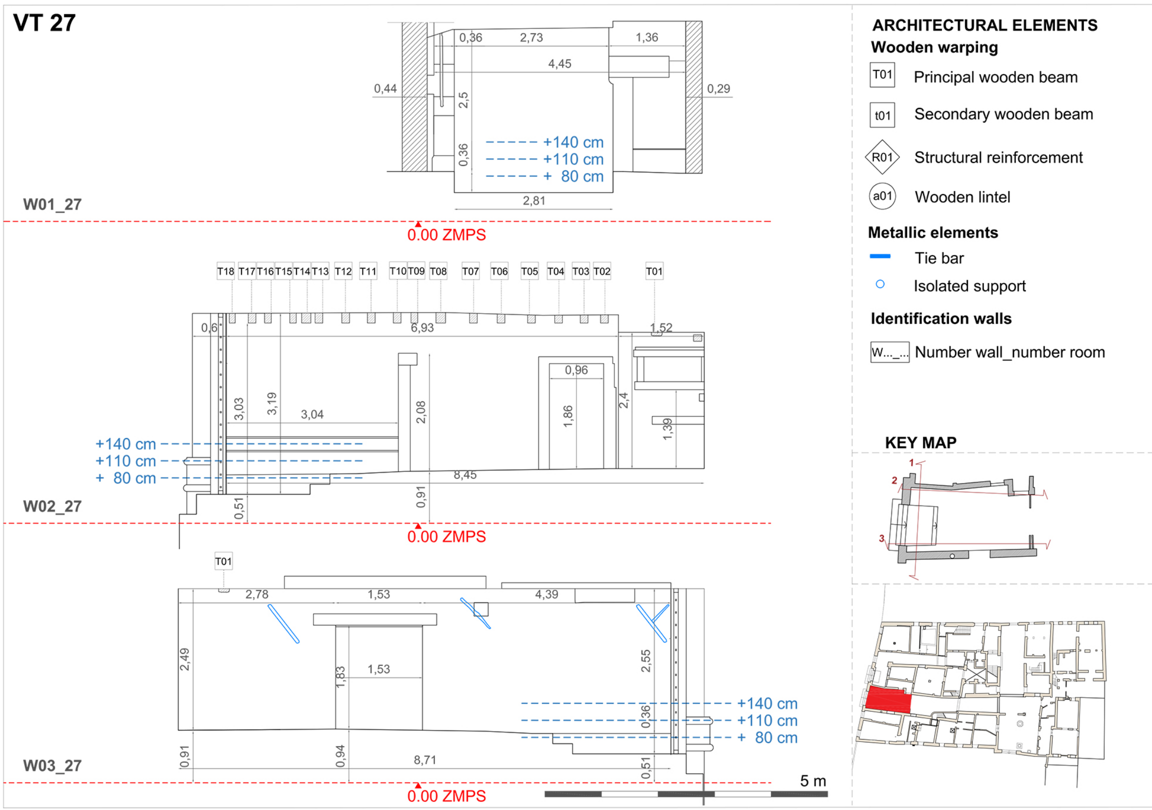


Figure 13. Palazzo Malipiero, Venice. Geometric survey of the walls of a typical room (room 27).

Figure 14. Palazzo Malipiero, Venice. Example of photo-rectification of the W03_27 wall of a typical room (room 27), near the water door, illustration of the transformations that characterize the ground floor of the building.

According to the proposed methodology, Figure 3, material identification, along with the characterization and localization of deterioration (State of Decay) were performed by means of Sratigraphic Analysis (SA), Material-Constructive Survey (MCS) and Crack Pattern and Degradation Analysis (CPDA) with coordination of different experts.

For all the ground floor walls, stratigraphic analysis (SA) was carried out. As an example, the results of the stratigraphic survey for the W03_27 wall has been reported in Figure 15: it can be seen that areas with homogeneous material-construction characteristics that represent traces of different transformation actions over time are identified, such as Masonry Stratigraphic Units (USM), Covering Stratigraphic Units (USR) and Architectural Elements (EA), paying particular attention to Stratigraphic Relationships between them (anteriority, simple support, toothing, overlapping, contemporaneity). All portions of masonry that are based on unitary constructive actions are defined as USM. All the covering layers are USR, such as plaster and stuccos, decorated or not. All vertical connections (e.g., pillars, columns, stairs, ramps) and horizontal connections (ceiling eaves, cornices, etc.), openings, reliving arches, putlog holes, etc., are classified as EA.

Once the construction phases of the ground floor rooms were analyzed, a survey of the masonry was carried out through a detailed visual investigation of the main geometrical-constructive parameters that may affect the strength of the masonry. This investigation was performed for several specimens of masonry which are representative of the more significant USM. As mentioned in Section 3, the information obtained with this activity was collected in specific forms. Figure 16 shows, for instance, the Masonry Technique Form, completed for wall W03_27 of the palace. It is the form STM02, relating to USM 1054 and 1065, given in Figure 15. In this form, after some information on the location of masonry inside the wall, information about characteristics of the block and its geometry, mortar joints (thickness, type of coat, potential state of decay, composition and level of cohesiveness of the mortar), the masonry typology, wall connections, the characteristics of the section and presence of plaster are included. In defining this form, in line with the structural needs, the information that can help to identify any different mechanical behaviors of the masonry was provided [58–61]. The study of all the compiled Masonry Technique Forms, completed by analyzing all the walls of the ground floor of the palace, led to the definition of eight types of masonry on the ground floor of the palace, taking account of masonry quality, state of conservation and mechanical behavior. For example, sample STM02, located on the wall W03_27 in Figure 15 and investigated with the appropriate form in Figure 16, is relevant to the type of masonry identified with M2 (Masonry Code).

Masonry type M2 has the following characteristic: original bricks with some elements of reuse (recurring size 24 × 6 × 11 cm), arranged in the horizontal course (USM 1054); high erosion level of blocks and joints with consequent punctual replacement of bricks with new production elements (construction intervention described by USM 1065); lacing courses with head elements; flush joints (horizontal thickness 10 mm), mixed mortar and punctual remarking of the concrete joints. It was not possible to examine the section, which has a thickness of 0.44 m, but on the basis of the information collected, a good connection of the cross-section can be hypothisized even in the absence of real through stones.

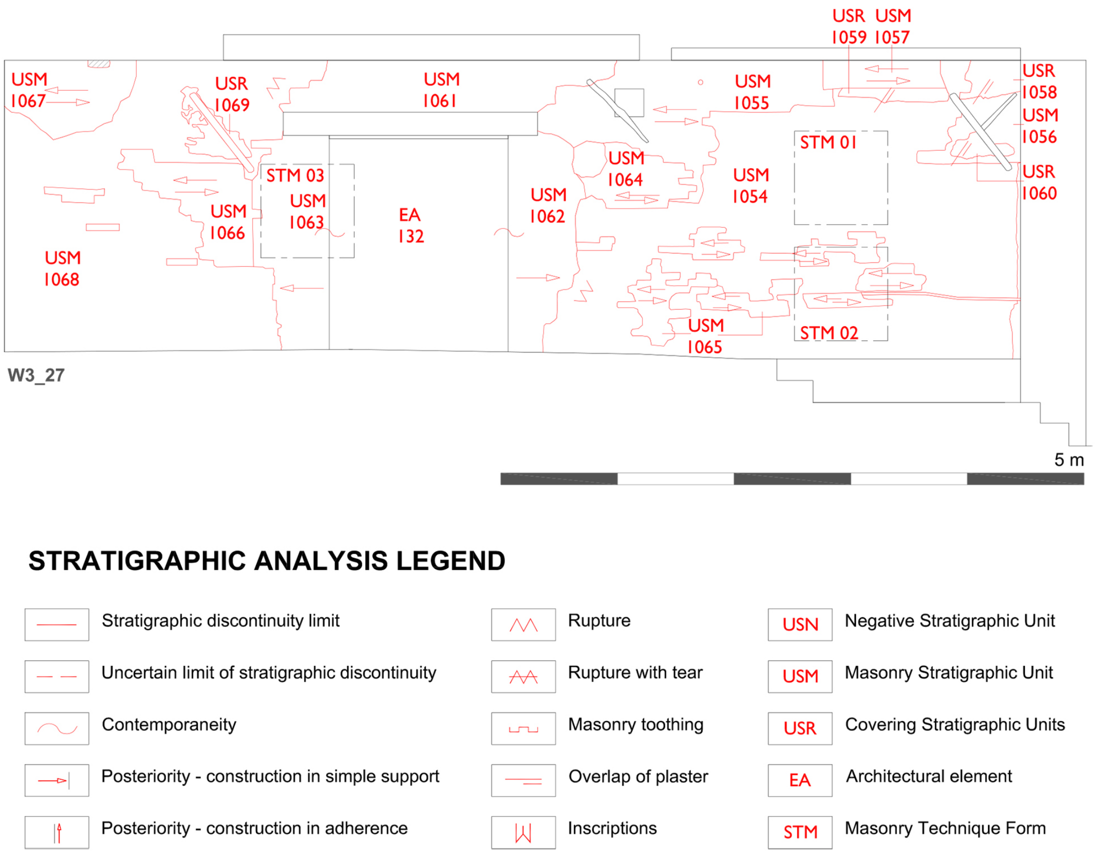
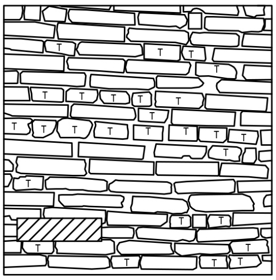


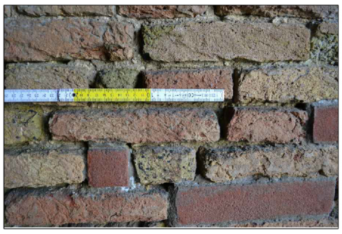
Figure 15. Palazzo Malipiero, Venice. Wall W03_27: stratigraphical survey.

In parallel, the Material-Constructive Survey (MCS) was carried out specifically for the ground floor rooms. In addition to the brick, which is the true protagonist of Venetian buildings, the presence of Istrian stone was identified. It is a very compact organogenic limestone, not very porous, used in corners in the lower base to defend against the rising damp, to guarantee the durability of opening frames (i.e., doors and windows) and to the fastening systems of tie rods and metal chains. Sometimes it was used for the realization of point structures, such as columns. The bricks observed in the analyzed rooms facing the Grand Canal show different mixtures from yellow to bright-red, corresponding to different sources of supply. This is a peculiar characteristic of Venetian masonry, which is characterized by the variety of shapes, colors and sizes of the brick used. In this variety, enriched by time and decay processes, the long and complex economic, productive and transformation history of this palace becomes evident. The variety of composition even within the same wall structure, however, is not always indicative of reuse but, as found elsewhere, also for other ages, it seems rather to relate to different lots of material used during the construction process. This characteristic is perhaps more likely indicative of lagoon production [62].

Among the materials, the punctual presence of reinforced and plain concrete elements was also found, resulting from undocumented previous consolidation interventions. These interventions, mostly carried out to remedy structural deficiencies of the building, not evidenced in the historical analysis of the palace, result in a hybrid architecture, difficult to read and making the topic of safe conservation of these elements particularly complex. Moreover, the solution to this problem often involves the replacements of these elements with more compatible materials. The diffused modality of "*de-restoration*" procedures thus determines the loss of evidence related to cultural context and construction techniques of a transformative phase of architecture.

MASONRY TECHNIQUE FORM	PALAZZO MALIPIERO (Venezia)	STM 02
Room: 27 Floor: 0 Wall code: W3_27	Sample location: [X] wall face [ ] corner Masonry code: M2	USM 1054,
Masonry distribution on the façade: [ ] > 70% [X] < 70% and > 30% [ ] < 30%		1065





	MATERIALS	FEATURES		DIMENSIONS
BLOCK	Lithology:	Shape and Block processing technique:		Block (l x h x w):
	bricks of first use, reuse	[ ] irregular [ ] moderately irregular [X] regular		- Major block: 25x6x12 cm
		[ ] not worked [ ] op. incertum [ ] op. vittatum [ ] op. quadratum		
		[ ] rustication [ ] leveled [ ] smooth [X] reuse		- Minor block: 23x5x10 cm
		Surface finish:		
		[ ] peak [ ] mallet [ ] tooth chisel [ ] chisel [ ] ax		- Recurring block: 24x6x11 cm
		[ ] tooth chisel [ ] point [ ] bush hammer [ ] abrasive [ ] other		
		Colour:	red, orange, yellow	
JOINT	Mortar description:	Joint finish:		Head joints thickness:
	lime and sand, with lumps and partial restoring with cement	[X] flush [ ] racessed [ ] extruded [X] deteriorated		- Major thickness: 10 mm
		[ ] concave [ ] vee [ ] struck [ ] weathered [ ] colouring		- Minor thickness: 8 mm
		Binding agent:		- Recurring thickness: 10 mm
		[ ] aerial lime [ ] lumps [ ] mixed [X] cement		
		Aggregates:		
		[X] fine sand (< ½ mm) [ ] Coarse sand [ ] gravel (> 2 mm)		Bad joints thickness:
		[ ] crushed gravel [ ] organic material [ ] other		- Major thickness: 10 mm
		Colour of binder:	Colour of aggregates:	- Minor thickness: 5 mm
		grey	grey, black	- Recurring thickness: 10 mm
		Consistency of mortar mix:		
		[X] pulverized [ ] very crumbly [ ] crumbly [X] strong		
MASONRY ORGANISATION	[ ] random courses [ ] sub-horizontal course	[ ] parallel sub-horizontal course [X] shorizontal course [ ] recurrence		
	[ ] wedges [ ] "L" joints [ ] lacing courses	Staggered head joints: [X] > 70% [ ] < 70% and > 30% [ ] < 30%		
	[ ] header and stretcher [ ] > header [X] > stretcher	[ ] sailor [ ] soldier [ ] 45° [ ] fish bone [ ] other		
MASONRY CONNECTION	[ ] toothing [ ] incomplete [X] absent/missing	Corner elements: [ ] big dimensions [ ] ashlars [ ] deteriorated		
	[ ] toothing [ ] incomplete [X] absent/missing	Corner elements: [ ] big dimensions [ ] ashlars [ ] deteriorated		
CROSS SECTION	Composizione:	[ ] 1 wythe [ ] 2 wythe [ ] 3 wythe		Total thickness:
	-	[ ] timber frame element [ ] mortar injections [X] n.d.		0.44 m
	[X] n.r. [ ] 1 brick wall	[ ] 2 brick wall [ ] 3 brick wall [ ] wythe without connection [ ] other		Filling thickness:
	[ ] point element / weak connection	[X] through stone / good connection		-
PLASTER	[ ] lime [ ] marmorino [ ] cement	Colour:		Thickness:
	[ ] uniform layer [ ] thin layer [ ] multi-layered	-		-
REMARKS	Replacement of deteriorated elements with newly produced bricks.			

Figure 16. Masonry technique form for the wall W03_27: STM 02, relating to USM 1054 and 1065 and indicative of the type of masonry (Masonry Code) M2.

According to the proposed multidisciplinary procedure, the results of the stratigraphic analysis (SA) have been integrated with those of the Material-Constructive Survey (MCS) in order to identify homogeneous area of materials (according to Material Identification). Similarly, the Crack Pattern and Degradation Analysis (CPDA) allow the identification of the homogeneous area of degradation (Sate of Decay) for masonry and other elements, as well as the presence of cracks and their characteristics. As an example, Figure 17 represents an effective output of this integrated approach for wall W03_27. The legend includes all the materials, material state of decay, beam decay, previous intervention on beam and architectural elements recognized in all of the ground walls of Malipiero Palace. For each of the masonry types, the corresponding Masonry Technique Forms are available.

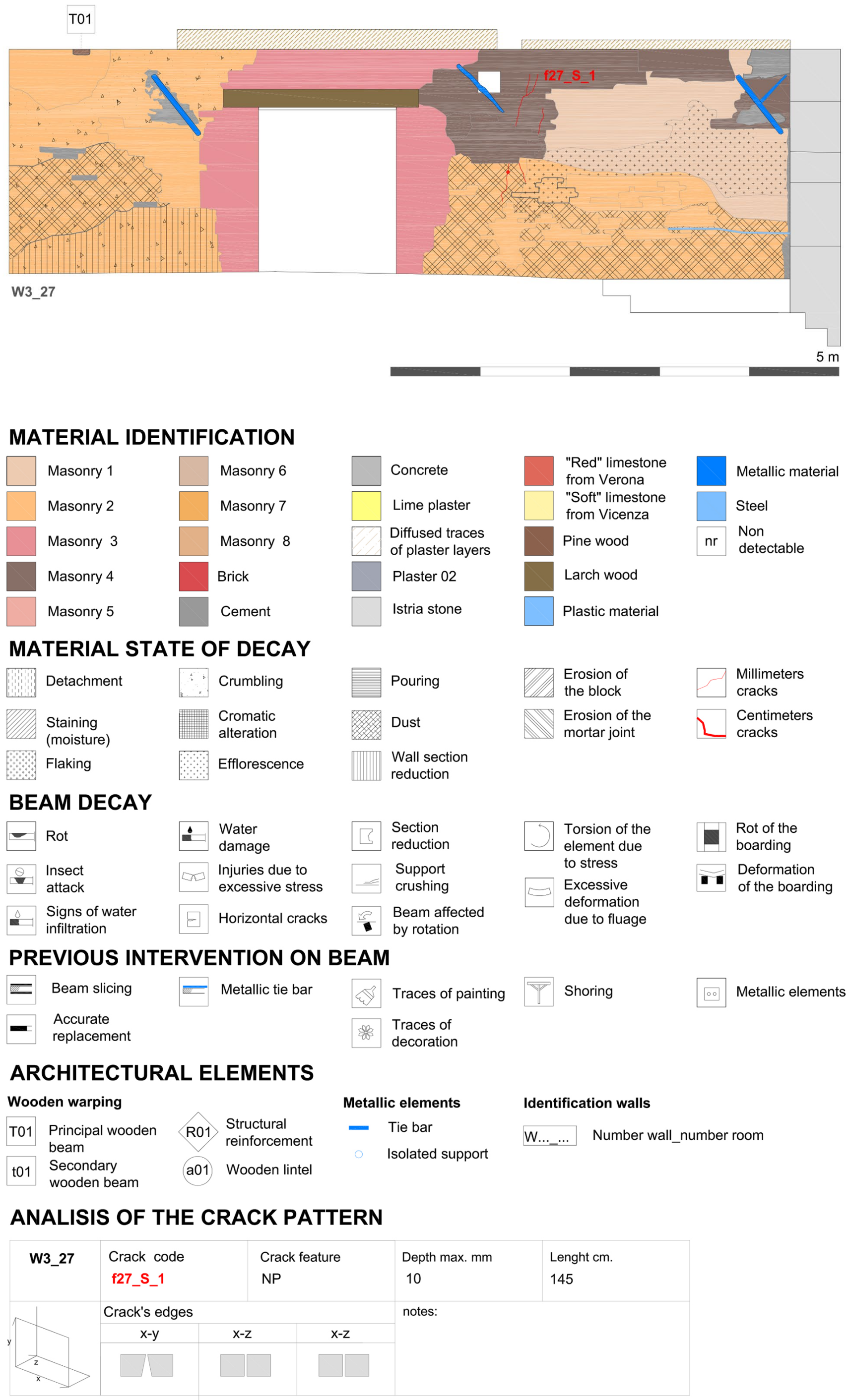


Figure 17. Palazzo Malipiero, Venice. Wall W03_27: material and degradation survey and crack pattern.

4.3. Numerical Model to Simulate Humidity Rise Level

In order to enrich the interpretative model developed at the end of the knowledge path, some numerical simulations of the humidity rise phenomenon for the studied masonry wall (W03_27) have been carried out. The main results are reported below.

These analyses were carried out using multiphysics software that solves the problem of the diffusion of moisture in porous media. The differential equations that regulate the diffusion of moisture and heat (moisture and heat transfer equation) reported in [63] are implemented in this software. The convective motions generated by gravitational forces have been neglected in order to maintain moisture and temperature, the only potentials responsible for the motion.

For the parameters involved, reference values were assumed for the site under examination. In particular, an average open porosity of 30% was assumed for the masonry. It is important to emphasize that the Venetian typical ancient field-fired siliceous brick could have a great porosity (even more than 40%) [64].

A scheme of the two-dimensional model with the relative boundary conditions is represented in Figure 18, where reference is made to the ZMPS elevation for the altitudes. The computational domain is bounded below by the sea level, so the domain base is assumed to be permanently moist (RH = 100%).

Since the case study wall is located inside the building, but in an unheated place in direct contact with the exterior, the conditions on both sides of the wall are the same.

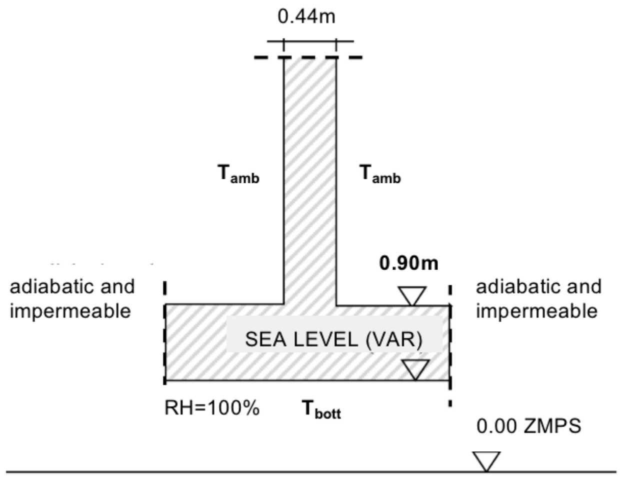
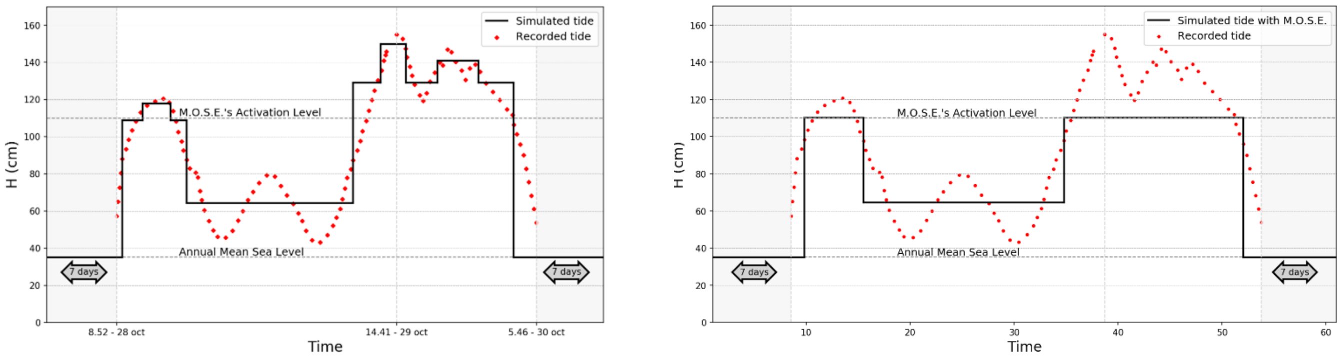


Figure 18. Scheme of the model with the boundary conditions adopted for the numerical simulation of the rising damp in the wall W03_27.

4.3.1. Rising Damp: Medium and Exceptional Tide Conditions: Effect of the MOSE

A numerical analysis was carried out to simulate the height of the rising damp front for the wall W03_27 of Palazzo Malipiero, following a medium tide condition and an exceptional event without and with the activation of the MOSE.

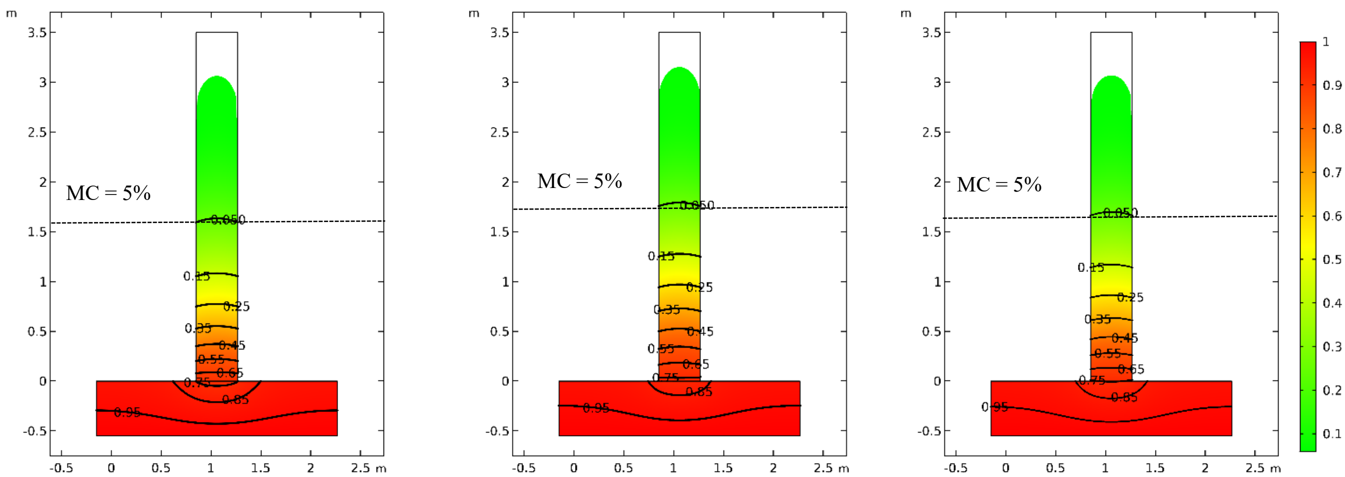
In particular, the exceptional tide conditions recorded on 28–30 October 2018 were considered, with a peak of 156 cm ZMPS and with a consecutive duration with a level above 110 cm ZMPS of 15 h and 50 min. For the numerical analyses, a simplified tide trend was considered, numerically simulated by the square wave superimposed to the actual tide profile in Figure 19a. The simulated tide trend reported in Figure 19b was also considered, obtained by assuming the activation of the MOSE. Historical hourly data on observed tide in Venice can be found in [65].



(**a**) (**b**)

Figure 19. Tide level detected between 28 and 30 October 2018, recorded at Venezia (Punta Salute) [66] and simulated tide: (**a**) without the activation of the MOSE (**b**) with the activation of the MOSE.

For the medium sea condition, sea level = +0.35 m ZMPS (mean sea level in 2018, Figure 2) was assumed. With reference to the temperatures recorded in the period considered, an environmental temperature T_{amb} = 288.15 K, and a base temperature T_{bott} = 283.15 K were assumed. In the analyses, since this is the simulation of a short-term event, the external temperature was considered constant over time. Figure 20 shows the results of the contour of Moisture Content (MC)—defined as the ratio between water content and its saturation value—for the different tidal conditions: average sea level, 7 days from the exceptional tide without the activation of the MOSE and with the activation of the MOSE. It can be observed how the MC level decreases moving from the bottom part along the height of the wall and moving from the internal part to the external part due to the evaporation.

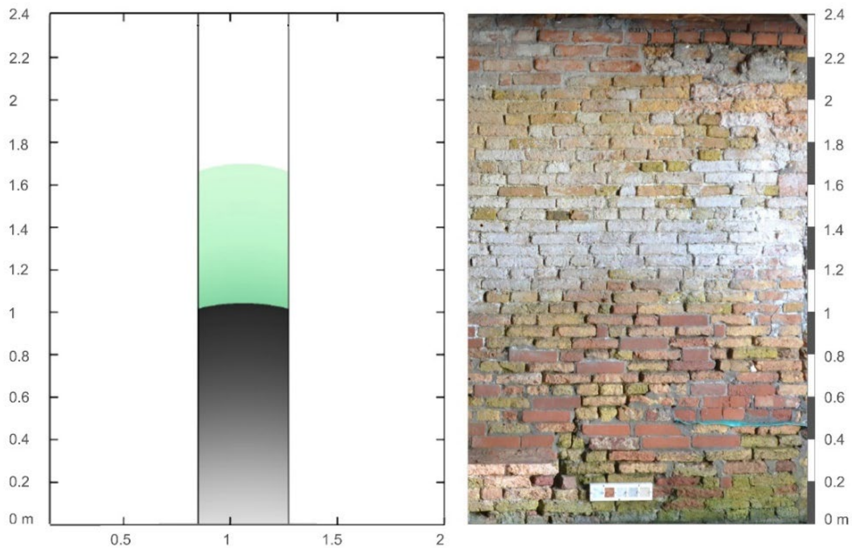


(a) **(b)** **(c)**

Figure 20. Contour of Moisture Content (MC): (**a**) in equilibrium conditions for moisture inside the wall with an average sea level at 0.35 m ZMPS; (**b**) Maximum rising damp front (MC = 5%) after an exceptional event, 7 days after the restoration of the average conditions; (**c**) Maximum rising damp (MC = 5%) after the exceptional event with MOSE activation, after 7 days from the restoration of the average conditions.

The same figure also indicates the rising damp front, which in this study was identified with the isoline corresponding to a water content MC = 5%, since for lower values the salts do not have the possibility of nucleation. In average sea level conditions, the rising damp settles at around 1.63 m from the ground level, which is a quite high value as this is an internal wall for which evaporation per unit of volume is limited, given the thickness and the absence of solar radiation. In the case of an exceptional event not regulated by the MOSE (Figure20b), there is an increase in the rising damp front of 0.15 m, which, therefore, settles at approximately 1.80 m ZMPS. Assuming the activation of the MOSE (Figure 20c), the maximum level reached from the rising damp front settles at around 1.70 m from the floor, with a lowering of about 10 cm compared to the previous case. The effect of MOSE activation, therefore, produces an improvement of the effects of rising damp, albeit in this case limited.

The analyses carried out show how three different moisture zones can be identified along the height of the wall: the lower zone is significantly soaked in water, then there is a zone in which the water content drops due to evaporation until it reaches an area where moisture is balanced by the environmental conditions. The intermediate zone is often associated with the maximum salt concentration for the nucleation of the salt crystals after precipitation. In particular, according to Biscontin [67], the zone of greatest crystallization varies between the permanently humid front and the sporadically humid front. Accordingly, the zone of possible salt formation was evaluated as the one corresponding to MC val-ues in the range 5–15% (MC = 5% in exceptional tide conditions–MC = 15% in average sea conditions), given that MC = 5% was assumed as the limit of the rising damp front and MC = 15% as a value beyond which there is a limited crystallization confirmed also by the results of Rirsch [68]. On the basis of the numerical results shown in Figure 20a,b, the area of possible precipitation of salts represented in Figure 21a was thus ob-tained, which affects a zone between 1.00 m and about 1.70 m ZMPS. This result is in good agreement with what has been observed in-situ on the considered wall which features a diffuse efflorescence on a band between 1.10 m and 1.80m from ground level, as shown in Figure 21b.



(**a**) (**b**)

Figure 21. Area of possible precipitation of salts in the wall W1_27: (**a**) results of the numerical simulation (in green), (**b**) saline efflorescences detected on 23 September 2019.

4.3.2. Climate Change Effect

In order to investigate how climate change can affect the increase in rising damp, some numerical simulations were carried out for the masonry wall under study by varying the average sea level and the temperature in accordance with the scenarios envisaged in the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) [34], with reference to median values at 2050, Figure 22.

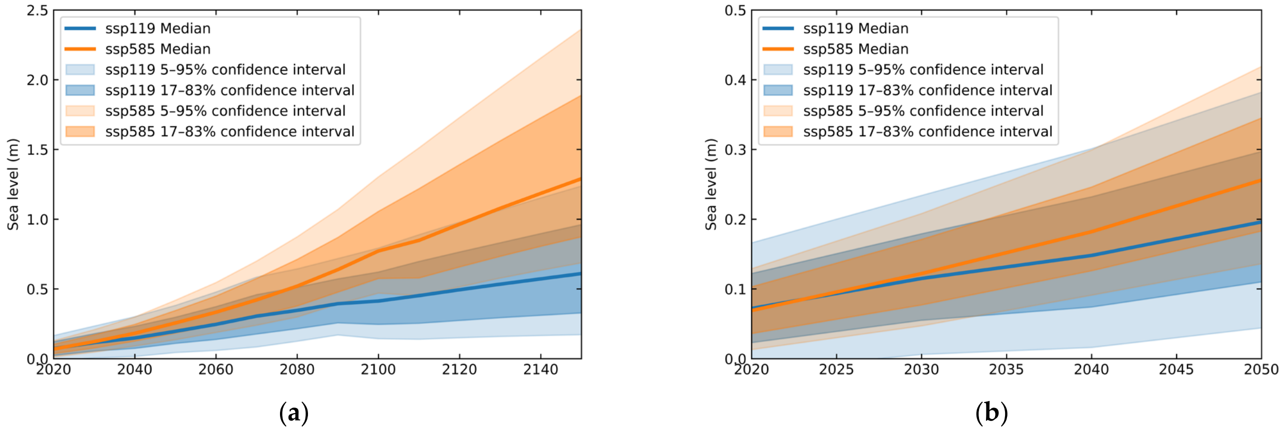


Figure 22. IPCC AR6 Sea-Level Rise Projections indicating best and worst-case scenarios (respectively, SSP1-1.9 and SSP5-8.5): (**a**) projection up to 2150; (**b**) zoom of the same data up to 2050, projection for Venezia (Santo Stefano), data from [69].

The results of the worst-case scenario SSP5-8.5 are provided below, as it is considered the most significant. Specifically, this corresponds to an average sea level increase of +18.7 cm (including subsidence) [69], and a temperature increase of about 1.5 °C. In particular, as regards the subsidence, in [69] it is estimated to be 2.7 cm corresponding to 0.9 mm/yr, which is in fair agreement with other literature studies (a review about the evolution of the land subsidence in the historic city center of Venice can be found, e.g., in [33]).

The results obtained from the numerical simulation assuming a sea level equal to + 0.537m are reported in Figure 23a. Adding also the effect of the temperature increase, the rising damp settles around 170 cm as can be seen in Figure 23b, slightly lower (about 5 cm) than the case with only sea level rise.

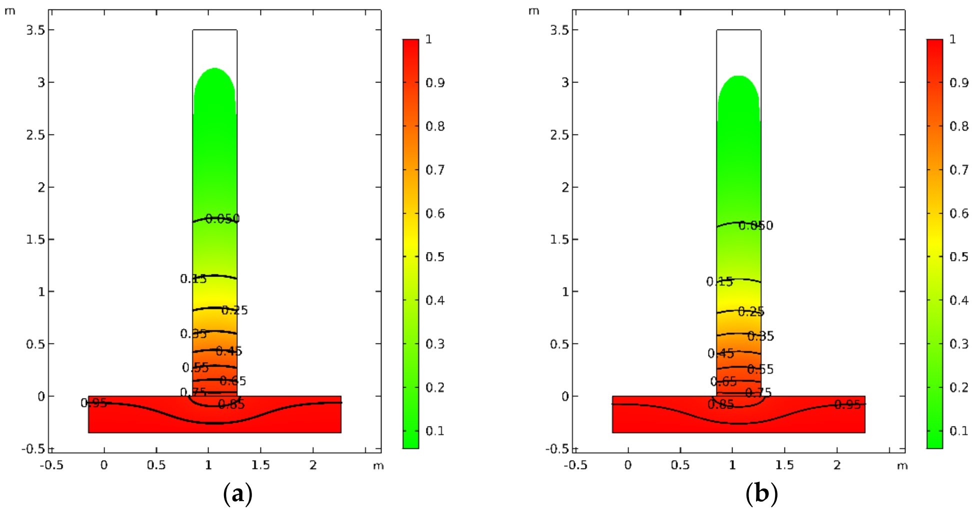


Figure 23. Prediction of capillary rise with reference to the scenario SSP5-8.5: (**a**) effect of sea-level rise; (**b**) combined effect of both sea level and temperature increase.

5. Discussion and Conclusions

The analysis of constructive characters plays an essential role both in the definition of possible interventions of risk mitigation and in the improvement of resilience, especially where risk levels are higher and built historical constructions are more vulnerable, as in the case of Venice due to its relationship with water. Such analyses require a specific multidisciplinary path of knowledge that allows the definition of an interpretative model capable of summarizing what was deduced from the investigations carried out directly on the building and to associate it with the analysis of iconographic and archival sources.

Moreover, considering the transformations over time, a whole comprehension of the current preservation status is possible, bearing in mind all the events that have occurred. In this way, all the collected information, at various levels of detail, contributed to improve the interpretative model by reducing randomness typical of historical structures in order to carry out vulnerability assessments.

In this work, a multidisciplinary methodology combining the specific path of knowledge with proper numerical analyses was presented in order to develop an enriched interpretative model for the vulnerability assessment of historic masonry buildings. The proposed approach, ideated specifically for Venetian-built heritage, focuses in particular on the problem of rising damp, which, due to the presence of salt-containing water, may have detrimental effects on Venetian masonry, in particular in relation to the effect of the high water phenomena [19,66]; considering on the one hand, the MOSE activation [26], and on the other hand, the effects of climate change according to different predicted scenarios.

This approach was applied to Palazzo Malipiero, which thus becomes a methodological example for the studies of other Venetian historic constructions. Furthermore, the Venetian case, while configured as an exception from a constructive point of view, it is also an extremely significant case due to the fact that the main issues affecting the themes of the study of conservation are concentrated and exalted here. Finally, even if Venice presents unique characteristics in the international panorama, the proposed approach could be conveniently applied to buildings belonging to coastal areas subjected to high tide phenomena.

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Abbreviations

The following abbreviations are used in this manuscript.

Abbreviation	Meaning
AR6	Sixth Assessment Report
CPDA	Crack Pattern and Degradation Analysis
EA	Architectural Element (in Italian Elemento Architettonico)
EPSG	European Petroleum Survey Group
GHG	Green House Gases
GS	Geometrical Survey
HA	Historic Analysis
IPCC	Intergovernmental Panel on Climate Change
MC	Moisture Content
MCS	Material-Constructive Survey
MOSE	Experimental Electromechanical Module (in Italian: Modulo Sperimentale Elettromeccanico)
MTL	Mean Tide Level
RSL	Relative Sea Level

RH	Relative Humidity
SA	Stratigrapghic analysis
UHI	Urban Heat Island
USM	Masonry Stratigraphic Units (In Italian Unità Stratigrafica Muraria)
USR	Covering Stratigraphic Units (In Italian Unità Stratigrafica Rivestimento)
ZMPS	Tide Level Zero of Punta Salute (in Italian: Zero Mareografico Punta Salute)

References

1. Appiotti, F.; Assumma, V.; Bottero, M.; Campostrini, P.; Datola, G.; Lombardi, P.; Rinaldi, E. Definition of a Risk Assessment Model within a European Interoperable Database Platform (EID) for Cultural Heritage. *J. Cult. Herit.* **2020**, *46*, 268–277. https://doi.org/10.1016/j.culher.2020.08.001.
2. Arrighi, C.; Tanganelli, M.; Cristofaro, M.T.; Cardinali, V.; Marra, A.; Castelli, F.; De Stefano, M. Multi-risk assessment in a historical city. *Nat. Hazards* **2022**. https://doi.org/10.1007/s11069-021-05125-6.
3. Seekamp, E.; Jo, E. Resilience and transformation of heritage sites to accommodate for loss and learning in a changing climate. *Clim. Chang.* **2020**, *162*, 41–55. https://doi.org/10.1007/s10584-020-02812-4.
4. Li, P.; Xiao, X.; Seekamp, E. Climate adaptation planning for cultural heritages in coastal tourism destinations: A multi-objective optimization approach. *Tour. Manag.* **2022**, *88*, 104380. https://doi.org/10.1016/j.tourman.2021.104380.
5. Sabbioni, C.; Cassar, M.; Brimblecombe, P.; Lefevre, A. Vulnerability of cultural heritage to climate change. *Pollut. Atmos.* **2009**, *202*, 157–169.
6. Ambroziak, A.; Haustein, E. Properties of Old Concrete Built in the Former Leipziger Palace. *Materials* **2022**, *15*, 673. https://doi.org/10.3390/ma15020673.
7. Harirchian, E.; Kumari, V.; Jadhav, K.; Rasulzade, S.; Lahmer, T.; Raj Das, R. A Synthesized Study Based on Machine Learning Approaches for Rapid Classifying Earthquake Damage Grades to RC Buildings. *Appl. Sci.* **2021**, *11*, 7540. https://doi.org/10.3390/app11167540.
8. Mężyk, M.; Chamarczuk, M.; Malinowski, M. Automatic Image-Based Event Detection for Large-N Seismic Arrays Using a Convolutional Neural Network. *Remote Sens.* **2021**, *13*, 389. https://doi.org/10.3390/rs13030389.
9. Talledo, D.A.; Miano, A.; Bonano, M.; Di Carlo, F.; Lanari, R.; Manunta, M.; Meda, A.; Mele, A.; Prota, A.; Saetta, A.; et al. Satellite radar interferometry: Potential and limitations for structural assessment and monitoring. *J. Build. Eng.* **2022**, *46*, 103756. https://doi.org/10.1016/J.JOBE.2021.103756.
10. Settis, S. *If Venice Dies*; New Vessel Press: New York, NY, USA, 2016; ISBN 1939931371.
11. Di Sipio, E.; Zezza, F. Present and future challenges of urban systems affected by seawater and its intrusion: The case of Venice, Italy. *Hydrogeol. J.* **2011**, *19*, 1387–1401. https://doi.org/10.1007/s10040-011-0784-4.
12. Horizon 2020—European Union Funding for Research & Innovation—Innovation Programme Hyperion. Available online: https://www.hyperion-project.eu/ (accessed on 2 March 2022).
13. Interreg Italy—Croatia European—Regional Development Fund STREAM Strategic Development of Flood Management. Available online: https://www.italy-croatia.eu/web/stream/ (accessed on 2 March 2022).
14. Interreg Adrion—European Regional Development Fund I-STORMS Integrated Sea sTORm Management Strategies. Available online: https://istorms.adrioninterreg.eu/ (accessed on 2 March 2022).
15. Interreg Italy-Croatia—European Regional Development Fund ADRIACLIM Climate Change Information, Monitoring and Management Tools for Adaptation Strategies in Adriatic Coastal Areas. Available online: https://www.italy-croatia.eu/web/adriaclim (accessed on 2 March 2022)
16. Somers Cocks, A. Venice in Peril. The British Committee for the Conservation of Venice. Available online: http://www.veniceinperil.org (accessed on 2 March 2022).
17. Diacono, P. *Historia Langobardorum*; GBL Grande Biblioteca Latina: Milano, Italy, 2017; ISBN 8822898729.
18. EPSG Dataset. Available online: https://epsg.org/datum_1051/Genoa-1942.html (accessed on 2 March 2022) .
19. Comune di Venezia Le Percentuali di Allagamento a Venezia. Available online: https://www.comune.venezia.it/it/content/le-percentuali-allagamento (accessed on 2 March 2022).
20. Battistin, D.; Canestrelli, P. *La serie storica delle maree a Venezia 1872–2004*; Istituto Veneto di Scienze: Venice, Italy, 2006. Available online: https://www.comune.venezia.it/sites/default/files/publicCPSM2/pubblicazioni/La_serie_storica_delle_maree_a_Venezia_1872-2004_web_ridotto.pdf (accessed on 2 March 2022).
21. Comune di Venezia Centro Previsioni e Segnalazioni Maree. Available online: https://www.comune.venezia.it/it/content/variazioni-livello-medio-mare (accessed on 2 March 2022).
22. Giaccone, D.; Santamaria, U.; Corradi, M. An Experimental Study on the Effect of Water on Historic Brickwork Masonry. *Heritage* **2020**, *3*, 29–46. https://doi.org/10.3390/heritage3010003.
23. Gentilini, C.; Franzoni, E.; Bandini, S.; Nobile, L. Effect of salt crystallisation on the shear behaviour of masonry walls: An experimental study. *Constr. Build. Mater.* **2012**, *37*, 181–189. https://doi.org/10.1016/j.conbuildmat.2012.07.086.
24. Lubelli, B.; van Hees, R.P.J.; Groot, C.J.W.P. The role of sea salts in the occurrence of different damage mechanisms and decay patterns on brick masonry. *Constr. Build. Mater.* **2004**, *18*, 119–124. https://doi.org/10.1016/j.conbuildmat.2003.08.017.

25. Falchi, L.; Slanzi, D.; Balliana, E.; Driussi, G.; Zendri, E. Rising damp in historical buildings: A Venetian perspective. *Build. Environ.* **2018**, *131*, 117–127. https://doi.org/10.1016/j.buildenv.2018.01.004.
26. MOSE: Modulo Sperimentale Elettromeccanico. Available online: https://www.mosevenezia.eu/mose/?lang=en (accessed on 2 March 2022).
27. Sesana, E.; Gagnon, A.S.; Bertolin, C.; Hughes, J. Adapting Cultural Heritage to Climate Change Risks: Perspectives of Cultural Heritage Experts in Europe. *Geosciences* **2018**, *8*, 305. https://doi.org/10.3390/geosciences8080305.
28. Sesana, E.; Gagnon, A.S.; Ciantelli, C.; Cassar, J.; Hughes, J.J. Climate change impacts on cultural heritage: A literature review. *WIREs Clim. Chang.* **2021**, *12*, e710. https://doi.org/10.1002/wcc.710.
29. Reimann, L. Mediterranean UNESCO World Heritage at risk rise. *Nat. Commun.* **2018**, *9*, 4161. https://doi.org/10.1038/s41467-018-06645-9.
30. Camuffo, D.; Bertolin, C.; Schenal, P. Climate change, sea level rise and impact on monuments in Venice. In *Science, Technology and Cultural Heritage*; Rogerio-Candelera, M.A., Ed.; CRC Press/Balkema, Taylor & Francis Group: Sevilla, Spain, 2014.
31. Tagliapietra, D.; Sigovini, M.; Keppel, E.; Guarneri, I.; Palanti, S.; Veronese, N.; Abbate, A. Bioerosion effects of sea-level rise on the Doge's Palace water doors in Venice (Italy). *Facies* **2019**, *65*, 34. https://doi.org/10.1007/s10347-019-0577-0.
32. Carbognin, L.; Teatini, P.; Tomasin, A.; Tosi, L. Global change and relative sea level rise at Venice: What impact in term of flooding. *Clim. Dyn.* **2010**, *35*, 1039–1047. https://doi.org/10.1007/s00382-009-0617-5.
33. Zanchettin, D.; Bruni, S.; Raicich, F.; Lionello, P.; Adloff, F.; Androsov, A.; Antonioli, F.; Artale, V.; Carminati, E.; Ferrarin, C.; et al. Sea-level rise in Venice: historic and future trends (review article). *Nat. Hazards Earth Syst. Sci.* **2021**, *21*, 2643–2678. https://doi.org/10.5194/nhess-21-2643-2021.
34. IPCC. *Summary for Policymakers of the Working Group I Contribution to the IPCC Sixth Assessment Report*; IPCC: Paris, France, 2021. Available online: https://www.ipcc.ch/report/ar6/wg1/ (accessed on 2 March 2022)
35. Galassi, G.; Spada, G. Sea-level rise in the Mediterranean Sea by 2050: Roles of terrestrial ice melt, steric effects and glacial isostatic adjustment. *Glob. Planet. Chang.* **2014**, *123*, 55–66. https://doi.org/10.1016/j.gloplacha.2014.10.007.
36. Saetta, A.; Antonelli, F.; Fabian, L.; Faccio, P.; Peron, F.; Romagnoni, P.; Tosi, M.C.; Zendri, E.; Berto, E.; Bruschi, G.; et al. Piano di adattamento al cambiamento climatico e implementazione di strategie di intervento per la salvaguardia del patrimonio architettonico e ambientale. Primi esisti di una ricerca interdisciplinare. In Proceedings of the Scienza e Beni culturali. XXXVI. Convegno Internazionale, Venezia, Italy, 17–19 November 2020.
37. Moro, L.; Neri, A. (Eds.) *Ministero per i Beni e le Attività Culturali—Segretariato Generale. Linee Guida per la Valutazione e Riduzione del Rischio Sismico del pa-Trimonio Culturale—Allineamento alle Nuove Norme Tecniche per le Costruzioni*; Gangemi: Rome, Italy, 2010.
38. D.P.C.M. Valutazione e Riduzione del Rischio Sismico del Patrimonio Culturale con Riferimento alle Norme Tecniche Per le Costruzioni di cui al D.M. 14/01/2008. In *Direttiva PCM*; Gazzetta Ufficiale: Rome, Italy, 2011; GU n. 47 del 26.02.11.
39. Sagredo, A. Sulle consorterie delle arti edificative a Venezia. *Archivio Storico Italiano* **1857**, *6*, 1. Available online: http://www.jstor.org/stable/44452473 (accessed on 2 March 2022)
40. Piana, M. Accorgimenti costruttivi e sistemi statici dell'architettura veneziana. In *Dietro i Palazzi. Tre Secoli di Architettura Minore a Venezia 1492–1803. Catalogo della Mostra*; Gianighian, G., Pavanini, P., Eds.; Arsenale: Venice, Italy, 1984; pp. 33–37.
41. Gianighian, G. Appunti per una storia del cantiere a Venezia (secoli XVI-XVIII). In *Le Arti Edili a Venezia*; Caniato, G., Dal Borgo, M., Eds.; Edilstampa: Rome, Italy, 1990; pp. 249–250.
42. Faccio, P. Le costruzioni in muratura e legno: Alcune considerazioni sulle metodologie di lettura, restituzione e interpretazione. *Archeol. Archit.* **2015**, *XIX*, 56–65.
43. Harris, E.C.; Edward, C. *Principles of Archaeological Stratigraphy*, 2nd ed.; Academic Press Books—Elsevier: Cambridge, MA, USA, 1989; ISBN 978-0-12-326651-4.
44. Brogiolo, G.P. *Archeologia Dell'edilizia Storica—Documenti e Metodi*; New Press: Como, Italy, 1988.
45. Boato, A.; Lagomarsino, S. Stratigrafia e statica. In *«Archeologia dell'Architettura», Proceedings of the Archeologia dell'Architettura: Temi e Prospettive di Ricerca, Gavi (Alessandria), Italy, 23–25 September 2010*; Brogiolo, G.P., Ed.; All'Insegna del Giglio: Firenze, Italy, 2011; pp. 47–53.
46. Brogiolo, G.P.; Faccio, P. Stratigrafia e prevenzione. In *«Archeologia dell'Architettura», Proceedings of the Archeologia dell'Architettura: Temi e Prospettive di Ricerca, Gavi (Alessandria), Italy, 23–25 September 2010*; Brogiolo, G.P., Ed.; All'Insegna del Giglio: Firenze, Italy, 2011; pp. 55–63.
47. Zamboni, I. Tecniche Speditive di Rilievo Stratigrafico Per la Valutazione della Vulnerabilità Sismica Degli Aggregati Storici in Muratura. Caso Studio: Civita di Bagnoregio (VT). PhD Dissertation, IUAV University, Venice, Italy, 2018.
48. Berto, L.; Faccio, P.; Saetta, A.; Talledo, D.A.; Zamboni, I. Valutazione di vulnerabilità sismica di edifici complessi/in aggregato: Metodi di primo livello. In Proceedings of XVII Convegno ANIDIS—L'Ingegneria Sismica in Italia, Pistoia, Italy, 17–21 September 2017.
49. Dahal, P.; Sharma, G.P.; Patil, S. Seismic Vulnerability Assessment of Lifeline Buildings at Gangtok. In *Earthquakes and Structures*; Springer, Singapore, 2022; pp. 103–112.
50. Formisano, A.; Vaiano, G.; Davino, A.; Citro, S.; D'Amato, M.; Amato, N.A. Seismic vulnerability assessment of two territorial case studies of Italian ancient churches: comparison between simplified and refined numerical models. *Int. J. Mason. Res. Innov.* **2022**, *7*, 172. https://doi.org/10.1504/IJMRI.2022.119890.

51. Işık, E.; Harirchian, E.; Büyüksaraç, A.; Levent Ekinci, Y. Seismic and Structural Analyses of the Eastern Anatolian Region (Turkey) Using Different Probabilities of Exceedance. *Appl. Syst. Innov.* **2021**, *4*, 89. https://doi.org/10.3390/asi4040089.
52. Giuliani, F.; De Falco, A.; Cutini, V. Rethinking earthquake-related vulnerabilities of historic centres in Italy: Insights from the Tuscan area. *J. Cult. Herit.* **2022**, *54*, 79–93. https://doi.org/10.1016/j.culher.2022.01.004.
53. Işık, E.; Harirchian, E.; Arkan, E.; Avcil, F.; Günay, M. Structural Analysis of Five Historical Minarets in Bitlis (Turkey). *Buildings* **2022**, *12*, 159. https://doi.org/10.3390/buildings12020159.
54. Collepardi, M.; Collepardi, S.; Troli, R. Salt weathering of masonry walls, the Venice experience. In Proceedings of the CANMET/ACI International Conference, Salonicco, Greece, 1 June 2003.
55. Chiffi, D.; Faccio, P.; Vanin, A. Anaysis of the structural behaviour of historical venetian buildings through theoretical and experimental models: State of the research. In *Scientific Research and Safeguard of Venice—Research Program 2004–2006 Volume IV*; Campostrini, P., Ed.; Corila: Venice, Italy, 2005.
56. Damerini, G. *La Ca' Grande dei Cappello e dei Malipiero di S. Samuele ora Barnabò*; Edizioni del Grifone: Venice, Italy, 1962.
57. Bassi, E. *Palazzi di Venezia: Admiranda Urbis Venetae*; La Stamperia di Venezia Editrice: Venice, Italy, 1976.
58. Giuffrè, A. *Letture Sulla Meccanica delle Murature Storiche*; Edizioni Kappa: Rome, Italy, 1991.
59. Giuffrè, A.; Carocci, C.F. *Codice di Pratica Per la Sicurezza e Conservazione del Centro Storico di Palermo*; Laterza: Bari, Italy, 1999.
60. Hendry, A.W. *Statica delle Strutture in Muratura di Mattoni*; Patron Editore: Bologna, Italy, 1976.
61. Faccio, P., Foraboschi, P., Vanin, A. La regola dell'arte e il comportamento meccanico dei pannelli in muratura. *Costr. Laterizio* **1990**, *84*, 60–65.
62. Doglioni, F.; Trovò, F. Mutamenti dei laterizi e delle murature veneziane tra XII e XVI secolo. In *Venezia Forme della Costruzione. Forme del Dissesto*; Doglioni, F., Roberti, G.M., Eds.; Libreria Cluva Editrice: Venice, Italy, 2011; pp. 33–36.
63. Künzel, H.M. *Simultaneous Heat and Moisture Transport in Building Components One- and Two-Dimensional Calculation Using Simple Parameters*; Fraunhofer-Institut für Bauphysik, Ed.; IRB Verlag: Stuttgart, Germany, 1995; ISBN 3816741037.
64. Bakolas, A.; Bertoncello, R.; Biscontin, G.; Glisenti, A.; Moropoulou, A.; Tondello, E.; Zendri, E. Chemico-Physical Interactions among the Constituents of Historical Walls in Venice. *MRS Proc.* **1995**, *352*, 771. https://doi.org/10.1557/PROC-352-771.
65. Historical Repository of Hourly Tide Data Venice. Available online: https://www.comune.venezia.it/it/content/archivio-storico-livello-marea-venezia-1 (accessed on 2 March 2022).
66. Comune di Venezia Le Acque Alte Eccezionali. Available online: https://www.comune.venezia.it/it/content/le-acque-alte-eccezionali (accessed on 16 October 2019).
67. Biscontin, G. Indagini sull'umidita di risalita a Venezia. *Recuperare* **1988**, *33*, 78–82.
68. Rirsch, E.; Zhang, Z. Rising damp in masonry walls and the importance of mortar properties | Elsevier Enhanced Reader. *Constr. Build. Mater.* **2010**, *24*, 1815–1820.
69. IPCC AR6 Sea Level Projection Tool. Available online: https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool (accessed on 2 March 2022).