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Rising damp in historical buildings: A Venetian perspective

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ABSTRACT

Considering several real case studies, moisture distribution due to rising damp in Venetian brick masonries is discussed and empirical models are developed. Moisture content and soluble salt data of 25 historical buildings in Venice are analysed. Data are scrutinized using statistical methods, obtaining contour plots and estimating the validity of linear and non-linear models. The models confirm that masonries are usually soaked with water till 120–150 cm over sea level, while the evaporation zone ranges in height from 200 cm to 350 cm. In the perpendicular section, moisture distribution depends on several contingent factors such as, among them, the proximity and the exposition of the external façades to the water action.

1. Introduction

Fresh or sea water rising damp in historical buildings is a well-known problem. Soaked masonries often show serious conservation issues. The phenomenon and the resulting decay have been extensively studied [1–4], as well as possible remediation methods [5,6], both from the theoretical point of view [7–11], and on several real case studies all over the world [2,12–17].

To determine quantitatively the rising damp phenomena in buildings and the severity of the related decays, several methods - based on samples collected drilling the masonry - have often been used: gravimetric determination of percentage moisture content (MC%) [18]; evaluation of soluble salts via ion chromatography; determination of hygroscopic moisture content (HMC%) [3,19]. Such invasive sampling, even if is still employed with successful results, is quite impacting. For this reason, it should be limited to the most in the case of ancient and historical masonries. Next to these methods, non-destructive moisture analyses are also frequently used: IR thermography, resistive methods, dielectric methods, microwave instruments [4,14,20,21]. Despite their sustainability, the non-destructive techniques present some disadvantages such as: the semi-quantitative qualitative nature of the results; the relative representativeness of the obtained data (often related only to the surface); the need of calibration with data coming from destructive sampling; and the necessity of an adequate data processing [22–24].

In literature, most of the researches focus on single case studies or on mock up masonries. The analysis of the rising damp phenomena in large zones, such as an entire town in a maritime location, is still limited [25]. A large perspective on rising damp in ancient masonries is crucial for the development of local strategic plans and maintenance policies to ensure the preservation of the built heritage in historical coastal/riverine cities.

Venice is the emblematic case of a historical maritime city affected by rising damp [26]. A large percentage of historical Venetian buildings lives in constant contact with lagoon and canals water. This cause-specific and well-known degradation patterns. Quantitative data regarding moisture content in selected Venetian buildings were collected over time, but an overall assessment of the rising damp phenomena and their consequences at a city level is still missing. Rising damp issues in Venice are quite problematic and difficult to synthetize: water affects different structures, heritage building constructed in different times, various building material, several construction methods, and above all masonries are soaked in very large extensions [27,28].

In this paper, we propose empirical models describing the rising damp process in Venice. Our data are based on literature and grey literature data on quantitative moisture content (MC%) and soluble salt contents (SS%).

The study considers 65 masonries built with full fired bricks and hydraulic lime based mortar joints. Buildings distributions cover the whole city centre. The paper considers data related to a timeframe of 30 years of restoration and research, presenting moistures distribution profiles. An empirical model for the estimation of the general extent of rising damp is proposed. Data mining methodologies are applied with the aim of:

i) highlighting the presence of common trends for the moisture

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distribution in Venice.

ii) understanding the rising damp key factors among the data collected.

iii) proposing a model to understand moisture patterns in Venetian buildings.

The results might be extended for similar analysis in other historical coastal cities.

1.1. Rising damp and Venetian buildings: a literature review

Rising damp phenomena in porous materials have been diffusely studied and described from the point of views of the physics laws, as for example the rise of water within single capillary tubes (Jurin Law), or in more complicated structures [1,7,12,29]. In masonries, the maximum height reached by rising damp and the necessary time to reach the steady state vary according to several factors, such as mortar joint types, the presence of renders, the surrounding environment. According to L'Anson et al., 1986 [7] the maximum height of the moisture front - given by the balance point between the water coming from rising damp and the water evaporated from the wall - is reached in different span of times accordingly the relative humidity (RH). The balance point in rendered walls is at 1.3 m and it is reached in around 8 years with a 80% relative humidity (RH), and in 18 years with a 90% RH environment.

The exceptional flooding in November 1966, with tidal water submerging the 80–90% of the city, raised the interest on rising damp phenomena in Venice. Since then, the Superintendence of Venice, the UNESCO committees, the municipality of Venice, Ca' Foscari University, IUAV University, CORILA (Consortium for coordination of research activities concerning the Venice lagoon system) and several private committees have always had an active role in assessing rising damp and in looking for reliable remediation methods [30–38]. Numerous papers, dossiers, and even well-documented University dissertations have been mainly focused on the relation between moisture and soluble salts contents. According to Italian recommendations (Normal 40/93) [18], usually - in these works - the moisture content was gravimetrically determined on samples collected by drilling the masonries at different heights and depths. Limited complete reports discuss also data by considering the building history and its position on the city fabric (i.e. geographical orientation of the masonry, distance from the canals etc.). Only in few cases, also, the composition of bricks and mortar joints and their porosity were evaluated. The results of these studies highlight the severe condition of the Venetian structures. A moisture content of over 5% has been reported at heights of 2–3 m from the floor level (in brick walls with an average porosity around 20%). Numbers report that the moisture front in Venice reaches in average the height of 1.5–3 m [28,34,39].

Available literature focuses commonly on a single Venetian building, however a first attempt to draw a general empirical model for the rising damp in Venice was discussed in Biscontin et al. [39] (Fig. 1). This work considered and discussed together the moisture and soluble salt data distributions from two representative historical structures: the Bucintoro northern wall in the Arsenal and the Narthex wall in the Saint Mark's Basilica. In the model proposed by Biscontin (Fig. 1) [39] (recalled in 20012 by Hall and Hoff [1]), moisture tends to decrease according to the height and three different moisture areas have been identified. At low height, there is a completely *saturated area*, followed by an *evaporation area* characterized by a rapid decrease of moisture (intermediate area), and, finally, at higher heights, an *area in balance with the environmental humidity*. The *evaporation area* is commonly associated with the maximum soluble salts contents.

Further researches focus on the moisture, relating it to the wall depth of the masonry. It has pointed out a profile that shows a diagonal rising damp curve [1]: a higher MC% is registered in the internal part and a lower MC% on the external. These evidences were found since evaporation occurs on the surfaces. Theoretically, salts with different solubility tend to precipitate at different heights according to their solubility. However, in real cases, the salts' precipitation process is strongly influenced by the salts' mixture and by the environmental conditions. The expected theoretical ion distribution is only partially observed (e.g. nitrates are often observed at higher heights in comparison to chlorides or sulphates) [40].

In relation to the rising damp phenomena, the aggressive environmental conditions of the Venetian lagoon have been exacerbated by the subsidence of the city and by the eustatism of the sea level [41]. Subsidence and eustatism worsen in the middle of the 21st century. and nowadays they contribute to the recurring high tide episodes ("acqua alta") and the consequent flooding of larger areas of the city. In relation to these changes, the development of general models - based on several case studies in Venice – is mandatory for future comparisons with changing scenarios. The aim is expanding the current knowledge on the fragility of the historical buildings and promoting a sustainable conservation policy.

2. Experimental part

2.1. Data collection

In this research, 25 case studies have been collected and analysed. The main characteristics of the buildings detected in each case study are summarised in Table 1, and their location in Venice is presented in Fig. 2. The buildings were selected accordingly the available information on rising damp. Available quantitative data of moisture and salt contents were collected from reports, thesis, papers, and books [32,39,40,42–54]. Only masonries where the rising damp has already reached a balance point, and only masonries manufactured with full bricks and traditional hydraulic lime based mortar joints (without cement), were considered. Buildings, in which methods against rising damp were applied, have been discharged from this study.

In all the selected cases a consistent procedure, based on the recommendation Normal 40/93 [18], was followed for the determination of the moisture content. Gravimetric determination of moisture was carried out on powders samples obtained drilling the masonry on a vertical line at different height and depth. The moisture content percentage is given by (eq. (1)).

$$MC\% = ((Wi - Wd)/Wd) * 100 \tag{1}$$

where Wi = initial weight (g); Wd = dried weight (g).

The possible procedure discrepancies are related to the height and depth of the sampling, which is strictly dictated by the specific on-site situations, consequently the researchers had to make specific choices case by case.

The soluble salt contents data were reported only in few studies. Their determination has been done according to different procedures, either by conductivity measurements on the collected powders [55], or by Ion Chromatography of few (chlorides and sodium) or more ion species (chlorides, sulphates, nitrates, sodium, calcium, magnesium). The relative low availability of consistent data obliges us to consider soluble salt distribution only in relation to the single case studies.

In some literature studies the location (e.g. over a canal, internal wall, etc.), the orientation of the wall (e.g. northern, southern, etc.), and the exposition to the atmospheric agents were indicated as discriminating factors. In this paper, two major locations (L in Table .1) are considered in relation to the proximity of adjacent the water body: 1 = *nearby canals* (masonries overlooking canals); 2 = *far from canals* (lack of a direct contact with canal water, few meters away from the embankments).

In the literature sources, the sampling height was referred usually to the walking pavement level. To correctly compare data regarding different buildings, in our study the samplings' height has been referred to the height above sea level using the standard local reference of *Punta*

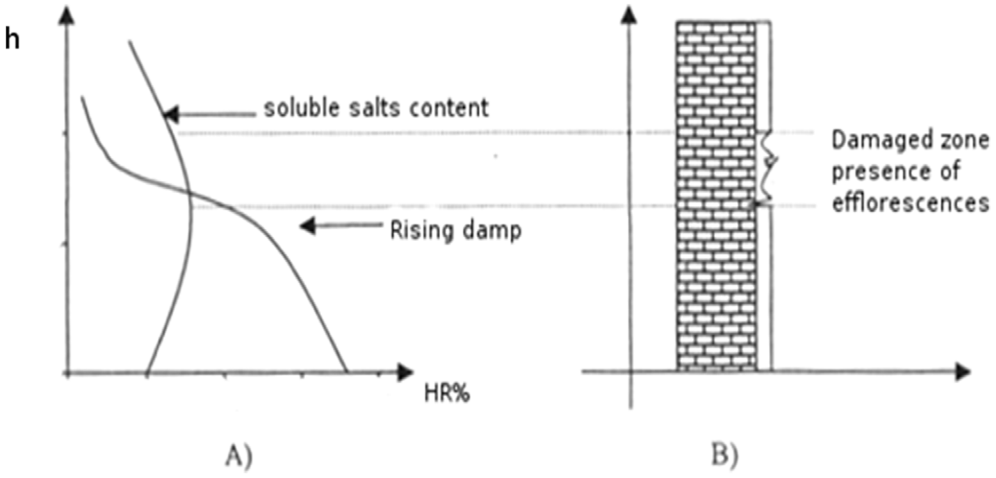

Fig. 1. Empirical model of rising damp phenomenon in Venetian masonries according to Biscontin et al., 1988 [39]. A) Graph reporting the trends of the distribution of moisture content (rising damp) and soluble salt content; B) scheme depicting a section of a masonry affected by rising of salt solutions.

della Dogana (ZMPS), according to the altimetry maps of the Ramses System [41].

When available, information regarding the wall, such as materials, structure, exposure, age, and porosity were reported and considered.

2.2. Investigation of data structure

Using Origin 8.5 software, the moisture and salt content data referred to above sea level ZMPS have been elaborated to obtain contour graphs of the moisture and salt distributions for each masonry [56]. The software employs moisture and/or salt content data, height and depth data as inputs for the elaboration of Triangulation, Linear Interpolation, Drawing of Contour Lines, Connecting and Smoothing procedures. The set of experimental points available for each masonry is usually small (from 3 to 12 entries), therefore a total point increase factor of 15 and a smoothing parameter of 2 has been sufficient to obtain the contour graphs of each site. This allowed an immediate comparison of many sites on a consistent height scale.

A further elaboration has been developed assuming data as a whole, meaning that the collected moisture contents could be considered as measurements not related to a specific site. With this assumption, the dataset was therefore composed of 493 observations (e.g. MC% measurements, 182 of which are referred to masonries nearby water and the remaining 311 are related to masonries far from water). This simplification has been used following the hypothesis that data collected, in similar masonries and in similar environment, might present analogous trend allowing a reliable estimation of statistical models. To create contour graphs with Origin 8.5, a high total point increase factor (700) for the triangulation and a small smoothing parameter (0.01) were chosen to observe the differences and the contribution given by the original data. Two distinct elaborations were obtained by splitting the data which refer to masonries nearby or far from canals (Table 1, column L).

Subsequently, to evaluate the pattern of data among moisture content in relation to the characteristics of the masonries, we have estimates several linear and non-linear models. These statistical models

Table 1
Characteristics of the case studies: L = location within the city (referred to the point of Fig. 2); P = position (1 = nearby water; 2 = far from water); Nr. = number of analysed masonries; H = building altitude above sea level, according to the Ramses altimetry on the ZMPS, expressed in cm [41]; S = soluble salt %; MC% = moisture content %; Notes = other relevant information when available.

Building	L	MC%	S%	P	Nr	H	Notes
Santa Marta, Dorsoduro 2137 [43]	1	x	x	2	2	180	Masonry of the old building, 1883
Santa Marta, Dorsoduro 2137 [43]	1	x	x	2	1	170	Recent masonry (1st half of 20th century)
Santa Marta, Dorsoduro 2196, ex Cotton mill [43]	2	x	x	2	1	170	Built in 1883, covered by cement render till 55 cm
Ca' Foscari Palace, Dorsoduro 3246 [44]	3	x	x	1	3	130	Internal masonry in well heated offices
Venice Arsenal, north masonry of Bucintoro [39]	4	x	x	2	1	170	Internal wall, scarce aeration, no heating
Venice Arsenal, corderie [45]	4	x		2	5	170	Sampling 11/10/1997 20–22 °C; 60–70%HR
Venice arsenal, Tesa 105 [45]	4	x		1	5	170	Only surface samples (0–5 cm depth)
Ex slaughterhouse of San Giobbe [45]	5	x		2	3	130	Built in 1986
Ca' Venier in Castello [43]	6	x	x	2, 1	2	120	
Santa Croce 191 [45]	7	x		1	1	150	
Tolentini IUAV [45]	8	x		1	1	150	
Curch of S. Antonin [46]	9	x	x	1	1	80	Sampling 3-5-2007, after a restoration intervention
Gussoni Grimani della Vida Palace [47]	10	x	x	2, 1	4	110	Sampling 13/12/2001
Ex Royal Palace, Saint Mark's SquareVenezia [48],	11	x	x	1, 2	2	150	
Church of San Zan Degolà [49]	12	x	x	2	4	145	Sampling 26-7-1985 and 24-3-1986
Artigianelli complex [50]	13	x	x	2	2	130	Massari staircase, external wall
Eremite's Monastery [51]	14	x		1	5	110	
Church of S. Elena in Castello [32]	15	x		2	4	150	Only superficial samples (0–5 cm depth)
Church of S. Stefano [32]	16	x		2	6	130	
Palace in Dorsoduro 1113 [32]	17	x		1	1	140	
Church of S. Sebastiano [32]	18	x		1	4	140	
Saint Mark'S Basilica, external wall [43]	19	x	x	1	1	70,	Façade brick walls
Saint Mark'S Basilica, internal wall [43]	19	x	x	2	1	184	Façade brick walls covered by marble panels
Saint Mark'S Basilica, Narthex [52]	19	x		1	3	70	Façade brick walls
Saint Mark'S Basilica, crypt [53]	19	x		1	4	−18	
Basilica S. Maria Assunta in Torcello [54]	–	x	x	2	1		

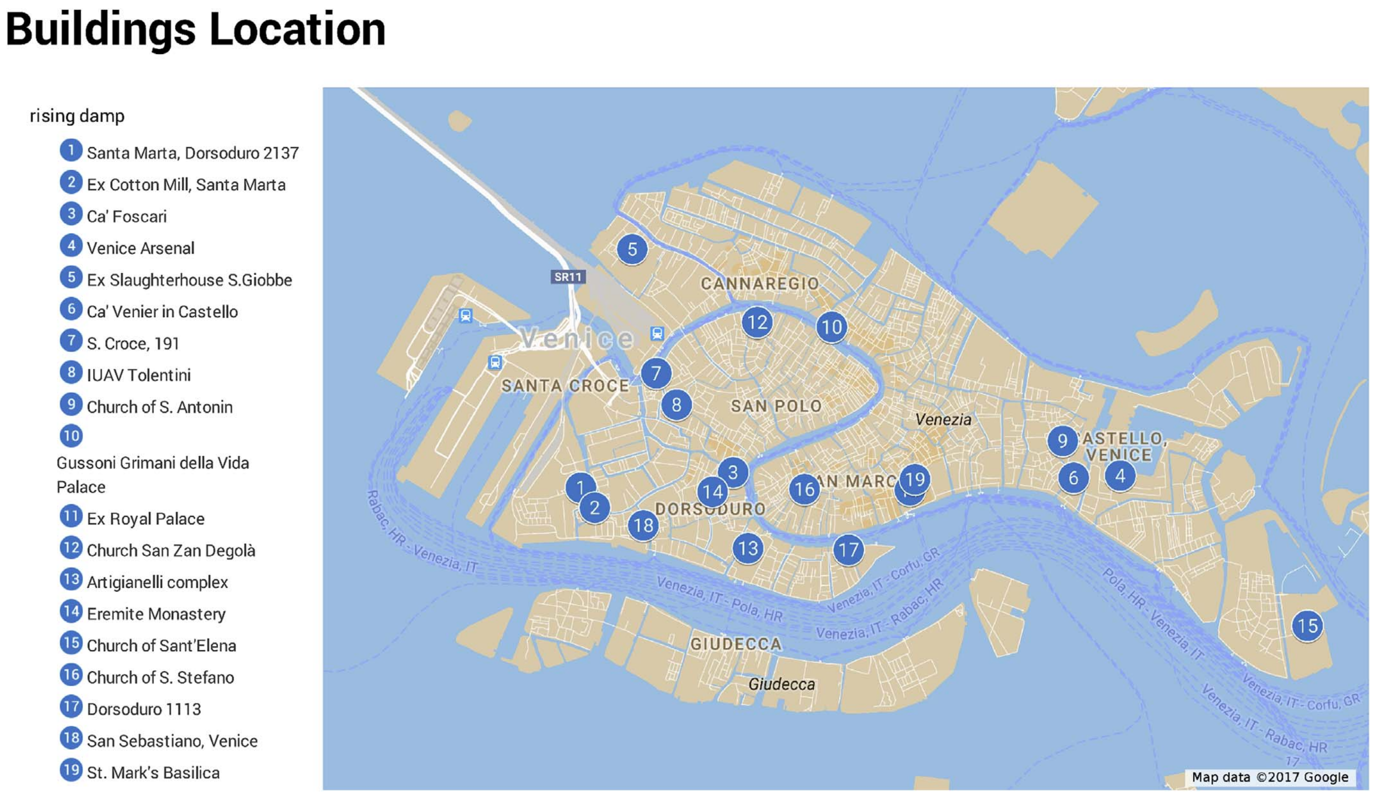

Fig. 2. Location of the investigated buildings within the city of Venice.

are elaborated with the aim of deriving the relations among the value of a continuous target variable Y (or dependent variable) based on the values of several predictor variables Xi, i = 1, …, k (or independent variables). In this work, the moisture content of the masonries is considered as the response variable of the models, whereas predictor variables are the height, the depth and the proximity to the canal. Due data scarcity, this procedure was not applied for the assessment of soluble salt distribution: over 45% of the available literature, in fact, omitted salt content, and/or existing salt content data were measured with inconsistent procedures.

Because of the complexity and the peculiarity of the case study, linear models are usually poor in fitting general trends. Thus, more flexible models are required to achieve a better fitting of the data structure. In this work, we focus on the class of regression tree nonlinear models. Tree-based methods (as regression trees) are, in fact, simple to construct and useful for the interpretation and the prediction of data, as it was proven in many studies [57–61].

Trees are built of leaves and branches: leaves represent specific subset of variable values and branches are the segments of the tree that connect the leave nodes. To estimate the model, leaves are created by recursively splitting the data on the predictor variables. In this way, two child nodes have smaller variability around their average value than the parent node, minimizing the predicting error of the terminal nodes. Terminal nodes of the trees refer to regions of values of the target variable.

As it is computationally infeasible to consider every possible partition of the variable values, greedy approaches are usually used to construct the model. We focus on the approach proposed by Breiman et al. (1984) and Hastie et al. (2001) [57,59] which is nowadays the commonly used method for regression trees estimation.

The estimation of the regression tree was performed using the R statistical software and the “r part” package with standard parameterization [62].

In the regression tree built for the moisture content, each branch connects nodes reporting the mean moisture content and the number of observation in that range. Splitting is estimated based on the optimal partitioning of the predictor variables, e.g. depth, height and location observed for the masonries, till to the final leaves, when further partitioning adds not significant information.

3. Results and discussion

3.1. Typical moisture distribution in Venetian masonries

The contour graphs of moisture content distribution for each masonry indicate the presence of three common trends that we consider influencing the rising damp.

The first type of trend is well represented in three test cases: Ca’ Foscari masonries, Santa Marta ex-Cotton Mill, and Sant’Antonin Church. The moisture distribution in the other masonries can be exemplified by these ones.

The first trend shows a rising damp distribution where moisture decreases with increasing height and decreasing depth, and soluble salts are concentrated in the evaporation zone. This situation is typical of ancient Venetian palaces and buildings located nearby canals, in which the phenomenon is almost stable.

Ca’ Foscari Palace [42] represents a typical Venetian Gothic palace with basement made by Istria stone, full brick masonries rendered with *cocciopesto* (traditional Italian render with feeble hydraulic properties, obtained by mixing finely crushed bricks or tiles with water and lime) and *marmorino* (typical Venetian plaster obtained adding powdered marble to a lime base) [43,44]. Both for indoor and outdoor application, *cocciopesto* have been widely used in Venice as a storage layer for salts thanks to its pore structure, breathability, and its fair salt and moisture resistance. While *coccopesto* is mainly used as base for the application of other plasters, *marmorino* is mainly a decorative plaster used for imitating marble slabs. *Marmorino* is characterized by a reduced porosity, high water vapor permeability and reduced formation of salt efflorescences. The application and use of *cocciopesto* and *marmorino* slightly affects the moisture and salts distribution within the

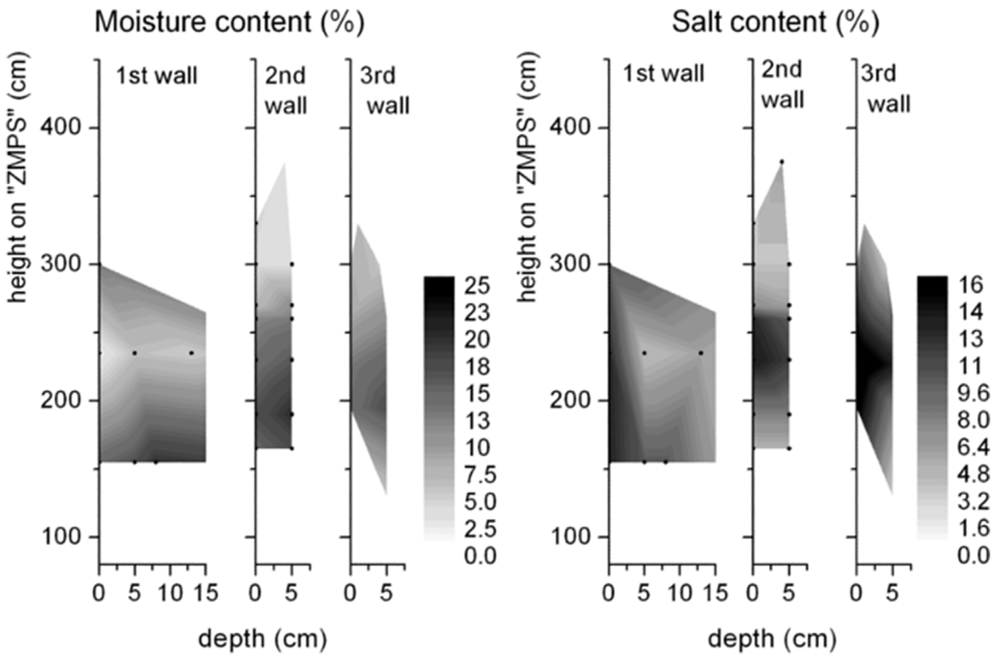

Fig. 3. A) moisture and B) soluble salt distributions on three examined walls in Ca' Foscari Palace, the sampled points are indicated with black dots.

masonry in comparison to unrendered walls (less than cement systems with lower permeability) [44].

Two walls are in direct contact with the Canal Grande. Samples of three internal walls were collected in 1982 [43] and in 2001 [44]. Fig. 3 highlights that in Ca' Foscari the moisture content MC% decreases at increasing heights, in particular over + 200 cm on ZMPS. In the first wall, a slight increase of MC% at + 300 cm might be due to the hygroscopic retention of water, as it corresponds also to a higher value of salt content. High salt contents can be found around + 230 cm to + 250 cm, where the evaporation zone and the crystallization level take place. The distribution follows the empirical trends proposed by G. Biscontin (1988) [39], with slight variations due to salt accumulation, partially due to the render presence or to local cracks.

This trend is the same in Saint Mark's Basilica, the Tolentini ex-Monastery (IUAV), the Eremite's Monastery, Ca' Venier, the external masonries of Gussoni della Vida Palace and of the ex-Royal Palace.

The second trend is found studying the masonries of the Santa Marta ex-Cotton Mill, the S. Giobbe ex-Slaughterhouse (UNIVE), the Arsenal Corderie, the internal masonries of Gussoni Palace. The ex-Cotton Mill is a large factory of the 19th century. It is located in one of the highest parts of the city (+170 cm), with the east facade built with red full bricks and non rendered masonries facing the canal. The samples collected in the ex-Cotton Mill [43] show lower moisture content values coupled with lower salt contents in the internal wall (Fig. 4A). At the same time, a decreasing in moisture content with increasing heights and a decreasing of MC% on the surfaces was detected on a masonry nearby a canal (Fig. 4B). The evaporation zone, where moisture rapidly decreases and higher salt contents were measured, ranged from + 250 cm to + 300 cm. By comparing the ex-Cotton Mill distributions with the ones collected in Ca'Foscari, it is possible to notice that, at similar heights, slightly lower moisture contents are present in the ex-Cotton Mill. On the contrary, the salt contents are higher in Ca' Foscari, probably due to the building's age and the consequent "storage effect".

The last trend is represented by the moisture distribution of the Sant'Antonin Martire Church [45,46].

Traditional foundation date of the church is around the early 7th century. The church was rebuilt starting from 1668, it was restored in 1968 with partial replacement of damaged bricks with new ones ("*cuci-scuci*" intervention), 1993, 2001–2003 [46]. Before 1993, the masonries, made of local bricks with a thickness ranging from 30 to 50 cm, were seriously affected by rising damp till 2.00 m above the ground level and the floors were damaged by flooding during high tides (height on ZMPS + 80 cm). The moisture content of Sant'Antonin Church is low and remains quite constant at increasing heights, while it raises quickly at increasing depths (Fig. 5): this is probably due to a high evaporation rate and drying of the external parts. The soluble salts are mainly deposited in the + 180 cm - + 230 cm range and in the external parts, where evaporation occurs. This last trend was found also in Gussoni Palace, Tesa 105 and Bucintoro Wing of the Arsenal, Artigianelli Complex, S. Zan Degolà church.

Commonly, Venice moisture values seem to depend more on the heights and on the distances from canals than on the masonry ages, which mainly influences the salt contents. In turn, a higher salt content might cause hygroscopic moisture phenomena and enhance the moisture content also at higher heights.

The comparison between internal and external masonries is symptomatic of what happens nearby or few meters far from canals (since 3–4 m): moisture content is high in masonries facing straight to canals, but it decreases in internal buildings.

The increase of moisture contents with increasing depth is not always clearly visible, and it is strongly influenced by the masonry structure, by the presence of hygroscopic salt deposits, non-documented *cuci-scuci* interventions of the lower parts of the masonry, and by surrounding environmental conditions. *Cuci-scuci* is a restoration intervention and takes place with the removal of damaged stone or brick elements with new dry ones, with possible modification of the moisture and salts distribution within the wall.

3.2. *Towards a unified model for moisture and salt distribution in Venice*

The observations of the moisture distribution are typically related to specific cases. More general trends might be individuated analyzing the case studies as a whole. Some simplifications and basic assumptions are necessary: i) the use of a consistent height measurement value (ZMPS reference); ii) the independence of observations, e.g. each value is considered as an independent observation not directed referred to the specific masonry; iii) the distinction of values referred to masonries nearby and far from canals.

The third assumption derives from the observation that the distance from the canals can drastically influence the moisture distribution. A

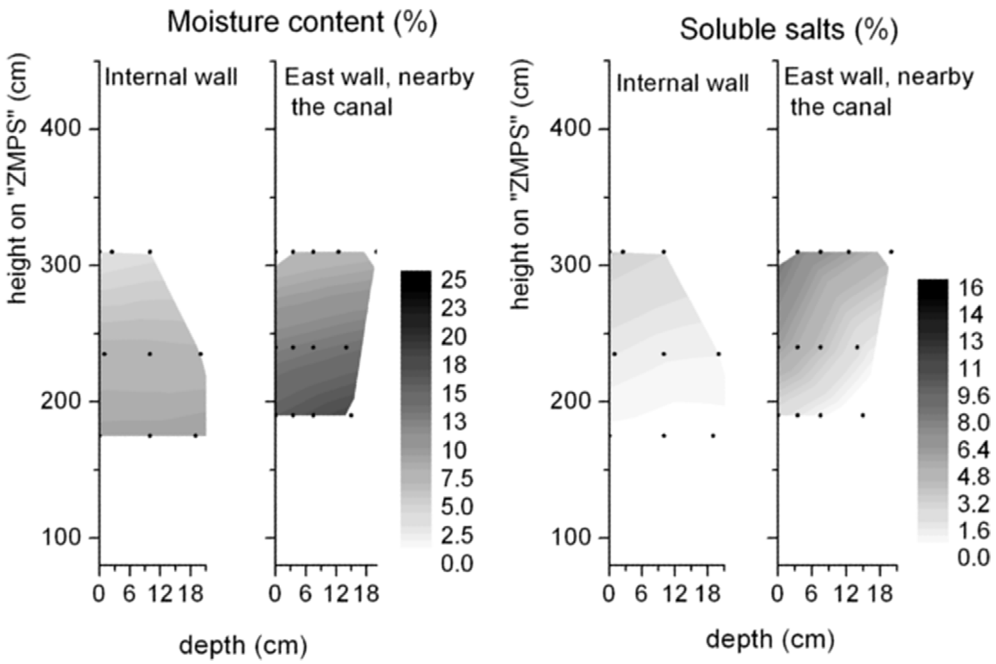

Fig. 4. A) moisture and B) soluble salt distributions on two walls of the Ex Cotton Mill in Santa Marta.

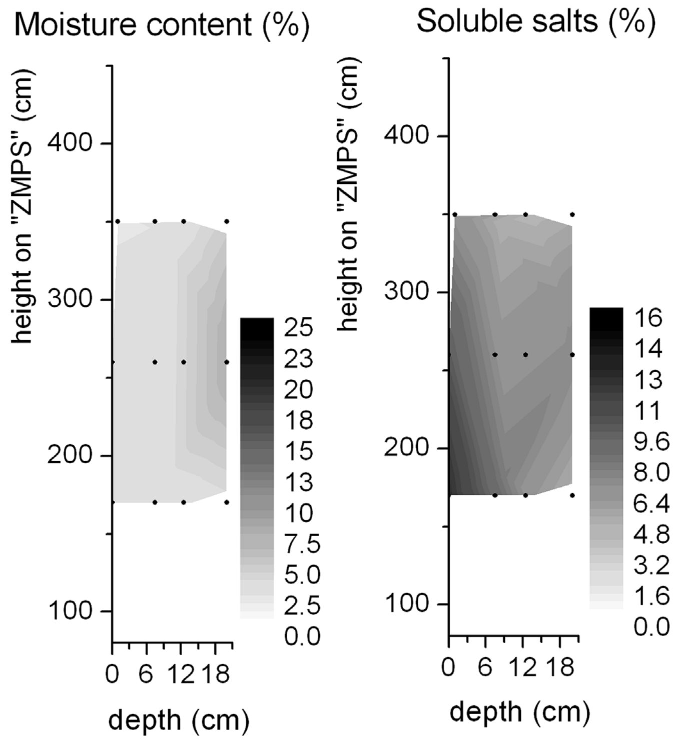

Fig. 5. A) moisture and B) soluble salt distributions on two walls of the Church of S. Antonino Martire.

statistical *t*-test, to verify the hypothesis that the mean value of the MC% of masonries nearby canals is greater than the one of the masonries far from canals, has been conducted. The result proved that the distance from water was statistically significant on the moisture content amount with a p-value equal to 0.004529.

Once the rising damp balance point is reached, other differences, such as masonry ages, palace locations, and restoration interventions, did not seriously affect the distributions.

To empirically highlight some informative patterns in the data, the MC% values related to masonries located nearby water and far from water have been plotted versus heights and depths value to obtain two general distributions. The graphs of Fig. 6 show the position of each sampling point within masonries nearby (Fig. 6A) and far from water (Fig. 6B). For the ex-Royal Palace, Gussoni Palace and Saint Mark's Basilica data regarding masonries in contact and far from water were both available. The contour plot representations of the MC% distributions nearby and far from water are presented in Fig. 7A and B.

Numerous data from different sites can be observed between +100 cm and +400 cm in height and 0–20 cm in depth. Heights lower than +110 cm and depths higher than 25 cm were observed exclusively for the Crypt in Saint Mark's Basilica and the Gussoni Grimani della Vida Palace.

The obtained distributions are not homogeneous. Higher moisture contents were observed around +120 cm–250 cm in the nearby water distribution (Fig. 7A), even if high moisture contents were detected also at higher heights (e.g. the Palace in Dorsoduro 1113 and in the Saint Mark's Basilica). The MC% is high, with values over 13% also in the same range of far from canals distribution (Fig. 7B), however, it rapidly decreases at increasing heights.

To better evaluate these trends, we have estimated several linear and non-linear models including multivariate linear regressions (with interactions) and polynomial regressions (with different degrees of the polynomial). The response variable MC% have been modeled in function of the predictor variables H (height in cm), D (depth in cm), and L (distance from water). Different models have been compared. In this paper, we present the main results for a significant subset of the obtained models. F-tests have been calculated to detect the model with the highest support ratio for the observed data. This draws the following model:

$$MC\% = \alpha + \beta_1 D + \beta_2 H + \beta_3 D{*}H(L\ \text{nearby}) \tag{2}$$

When the model is compared to the one including the main effects only (e.g. the effects of D, H, L without considering their interactions), it has F-value equals to $F_{1,488} = 28.316$ (p-value ≈ 0). While, when it is compared to the complete model with all the interaction terms (e.g. by considering D*H, D*L, H*L, D*H*L terms) it shows an F-value equals to $F_{3,485} = 1.816$ (p-value = .14). Estimated coefficients for the selected parameters, their relative standard errors, and p-values are reported in Table 2. Tests of significance indicate that all the parameters of the model are strongly significant (p-values close to 0). Explaining the

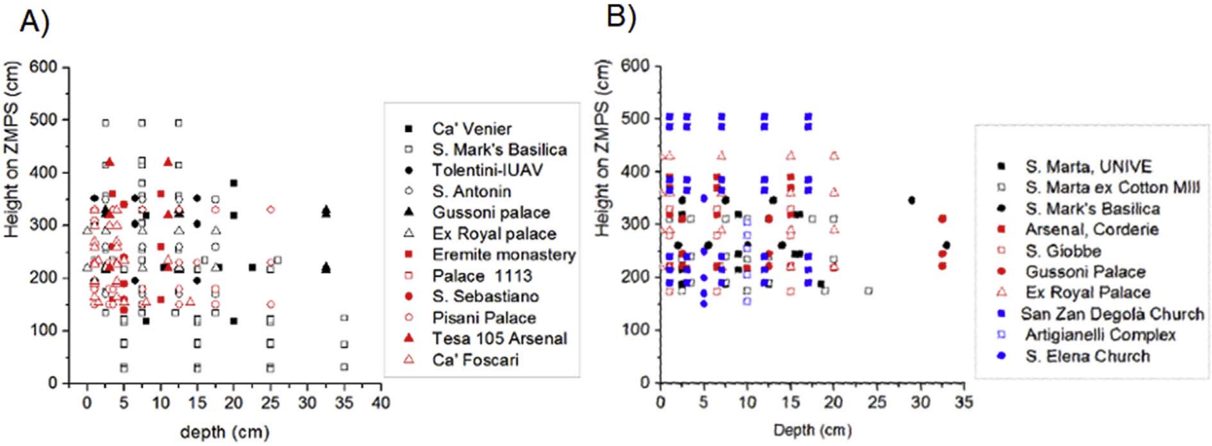

Fig. 6. Sample point position in masonries located nearby water (A) and far from water (B).

response of the model, the estimated value of β_3 indicates that the location can be considered as a significant variable, nevertheless, its contribution is small. This result supports our previous achievements.

The Adjusted-R^2 statistic value for the model in eq. (2) is 0.2459, and the residual standard error is 6.682. This indicates the poor goodness of fit of the model, considering the non-homogeneous data, as previously empirically observed. Residual diagnostics were used to investigate the model assumptions and the model fit. The Q–Q plot in the left panel of Fig. 8 (Fig. 8A) represents the residuals of the selected model computed with all the observations. This indicates: the presence of outliers in the left tail of the distribution, the departure from the assumptions, and the goodness of fit. The plot of the residuals against the fitted values (Fig. 8B) shows a pattern: the relationship may be non-linear and the model will need to be modified accordingly. Several transformations of the data have been tested, without improving the results.

Despite the weak goodness of fit, the model shows a general trend in line with what is observed for single masonries. Fig. 9A and B displays the calculated 3D curve of the model and the calculated contour plot, showing that lower MC% is found at higher heights. MC% decreases with depth for lower heights (up to around +250 cm) and increases with depth at higher heights (above 250–300 cm). This highlights different behaviors “over” and “under” the evaporation zone. Under the evaporation zone, the water wets the masonry coming both from the under-laying soil, from side canals and by direct contact with the surface during high tides flooding. Over the evaporation zone, water rises from underneath bricks within the wall and evaporates on the surfaces.

Table 2
Estimated, standard errors, t-values and p-values for the parameters included in the model.

Coefficients	Estimate	Std. error	t-value	p-value
α	24.35	1.37	17.760	< 2e-16
β_1	−0.40	0.09	−4.138	4.13e-05
β_2	0.05	0.005	−10.898	< 2e-16
β_3	0.002	0.0004	5.410	9.87e-08

3.3. Regression tree model

The high significance of the estimated parameter values combined with the lack of fitting suggested that the previous class of models was quite adequate to derive global patterns. To overcome these problems, we derived non-parametric non-liner models in the class of regression trees.

We have estimated a regression tree model with the aim of deriving global patterns of relations among MC% and the characteristics of the observed masonries. Classical linear and non-linear regressions were not adequate to consider the available data. The achieved model is reported in Fig. 10.

The estimated variable importance in deriving the regression tree for each predictor variable was: H = 72%, D = 23% and L = 5%. This

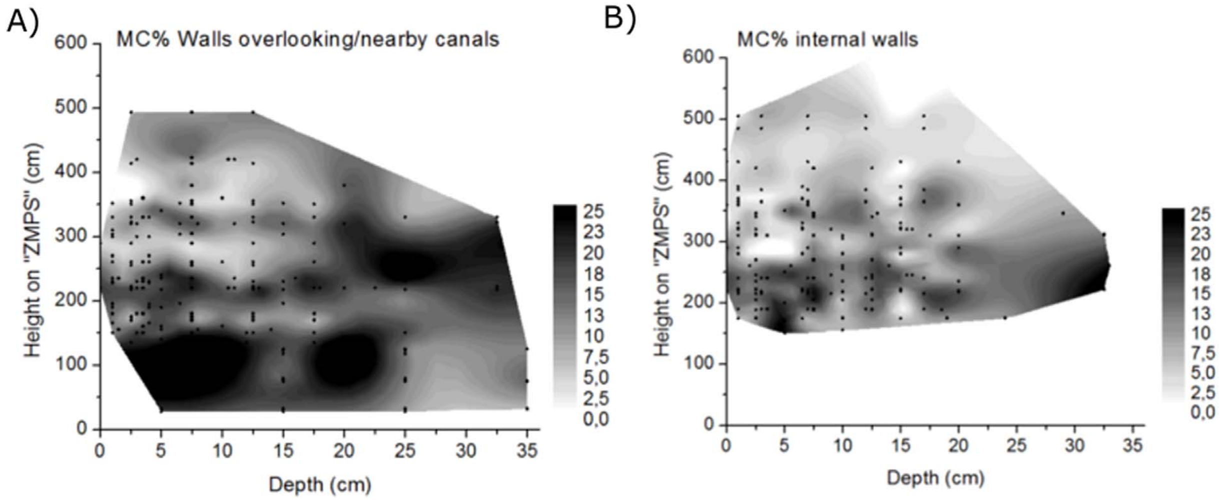

Fig. 7. Moisture content MC% distribution of masonries located nearby water (A) and far from water (B). Below +100 cm, there is a high contribution of MC% measured within the Crypt in Saint Mark's Basilica, which is surrounded by an underground canal and maintained dry with pumps.

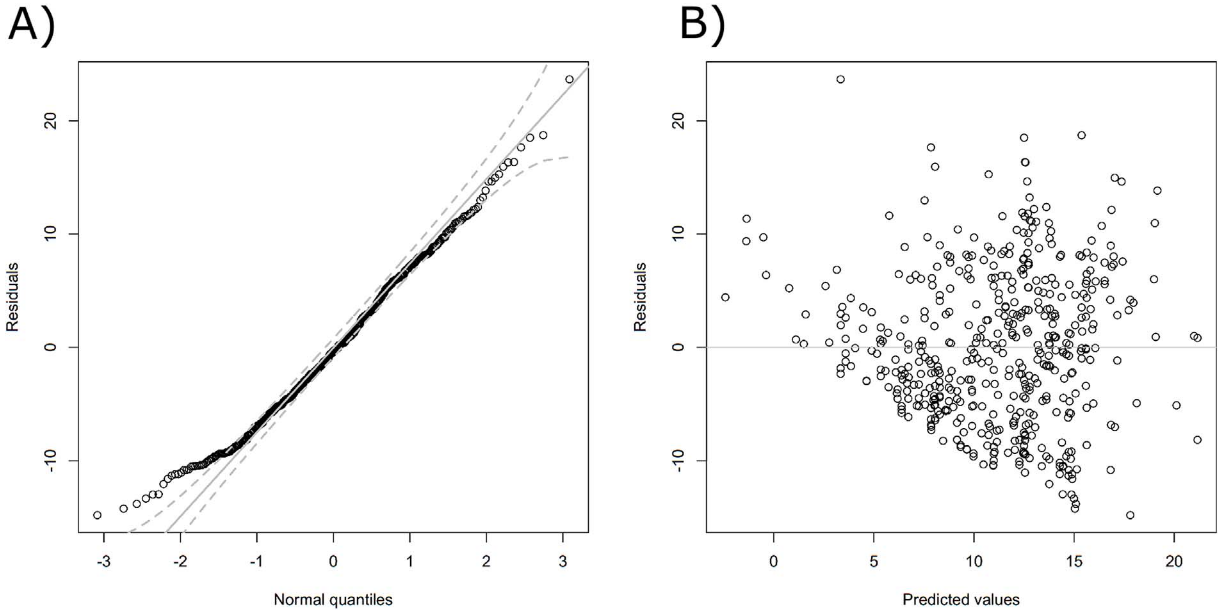

Fig. 8. Residual diagnostics of the estimated model.

implies that the estimated tree was constructed considering only H = height and D = depth values.

At the tree's root, the mean value of MC% - calculated on the 493 observation-is equal to 11.

The height value of 248 cm represents the first threshold in the data splitting: below this value, the mean of MC% is 15%, whereas for higher values of height the mean value of MC% is 8%, corresponding to the evaporation zone. Over this height (left branches of the tree) the partition depends mainly on the depth values, with higher moisture contents for depths over 19 cm.

Under 248 cm, splitting branches are still due to the height parameter (e.g. node at 168 cm) and only in a second step to the depth values. Higher moisture contents are observed under 145 cm and on the external parts (depth values smaller than 9 cm). Moisture contents around 13% can be found between 168 cm and 248 cm in heights.

The estimated regression tree has the main advantage to allow the visualization of data and to highlight which parameter, height or depth, can significantly affect the MC% values. This tree highlights that the height is the most important parameter, while the depth has a second role and it is, probably, more influenced by other factors, such as age of the buildings materials, exposure, ventilation, location of the water bodies (exactly underneath or on the side of the basement), etc.

Consequently, the tree could be used as an assessing map that gives expected MC% values in the Venetian masonries at a certain depth and height.

4. Discussion

The presence of brick masonries built with similar construction techniques, the presence of permanent water bodies with a given sea level, and the fact that the masonries have been exposed to rising damp of salt water for long times, make Venice as a unique case study with regards to rising damp.

In particular, the diffuse use of traditional full bricks with

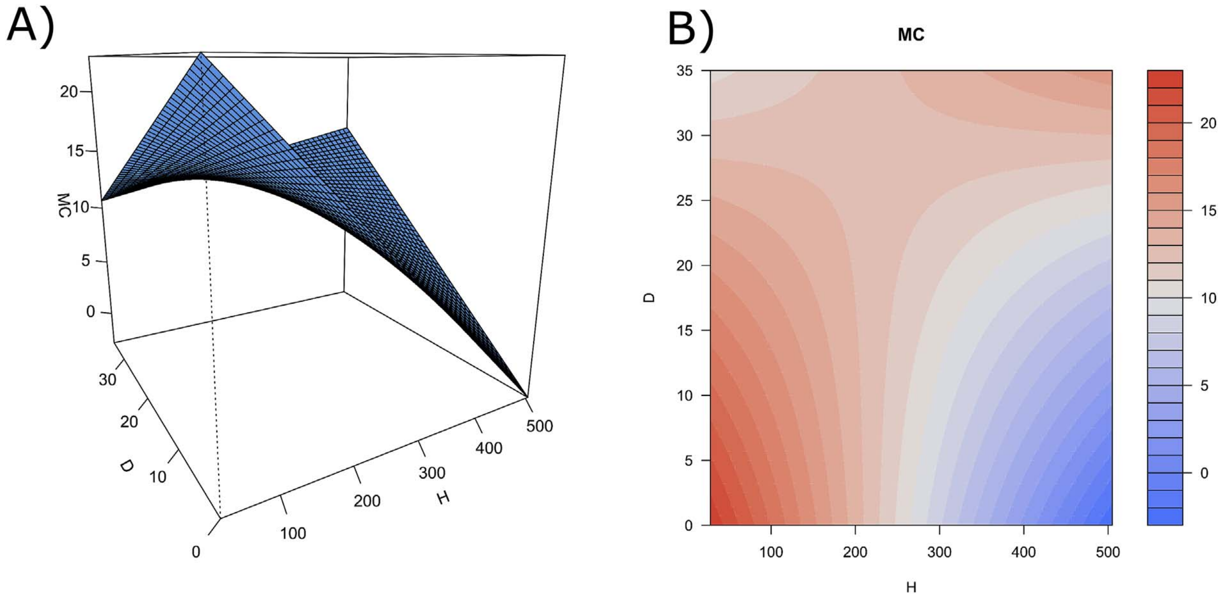

Fig. 9. 3D perspective plot (A) and contour plot (B) of the estimated model.

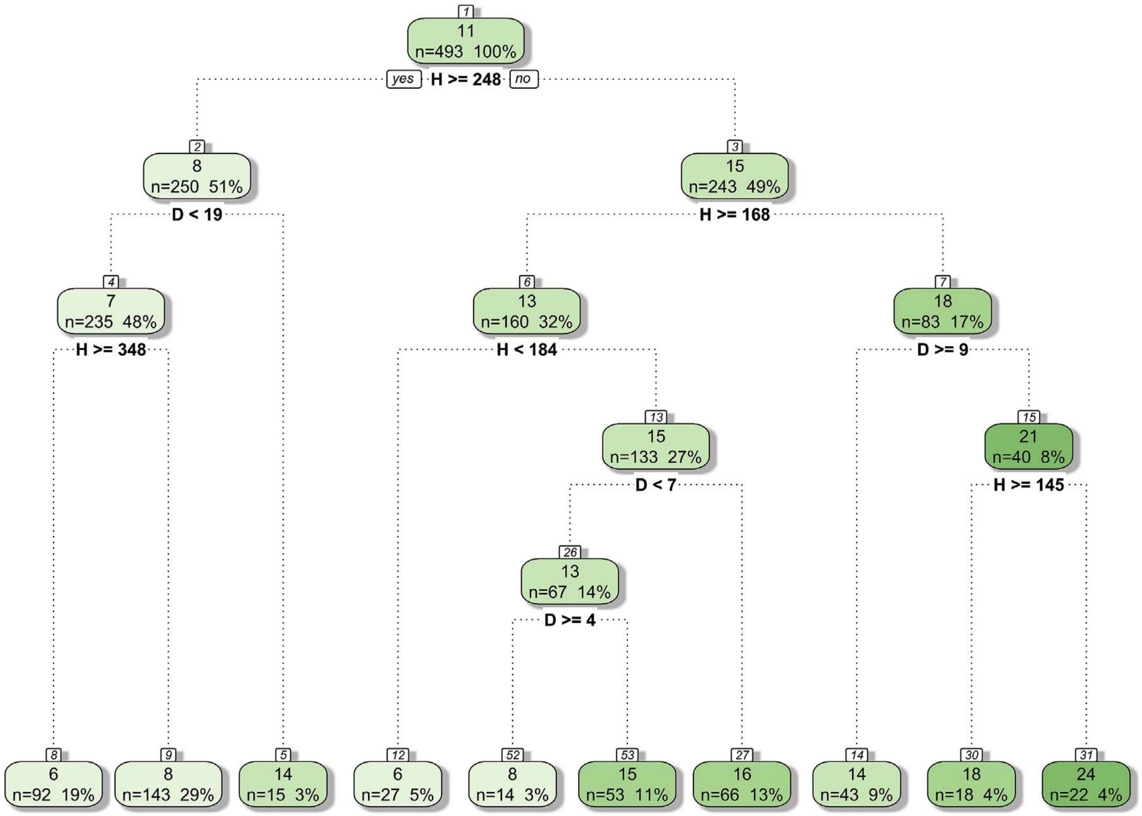

Fig. 10. Regression Tree of moisture content data in Venice. The graph indicates the MC% average calculate for each node. H = height; D = depth; n = nr of observation; percentage of the observation on the total observations; right direction = no; left direction = yes.

comparable porosity [40,44,52], of lime based mortars, and of renders permeable to water assure that the considered Venetian masonries have a similar behavior to rising damp. The presence of render layers influences the moisture distribution in comparison to non-rendered brick walls. However, when permeable breathable lime renders are used, the equilibrium between capillary water absorption and moisture evaporation is established at similar heights.

The presence of permeable systems, in contact with a stable water body (the lagoon) for long times (the considered buildings date back to the 19th century, at least), implies that a steady state is reached.

The development of several different models based on MC% in relation to heights, depth and to single masonry or multiple masonries, arise the following considerations:

- The distributions are influenced by known factors, e.g. specific structure and decay, that should be evaluated case-by-case. In the case of Saint Mark's Basilica, the data collected within the crypt and in an internal wall, covered by non-permeable marble panels, showed moisture distributions different from the other walls [52,53]. In the case of the crypt, the use of ZMPS as common altimetry level allows to use the data in the models' development. The crypt's data draw the typical behavior of a completely soaked masonries located under the water level and provide additional information to the model. The data of the masonry covered by marble panels (soaked with water till 4 m) were discharged, since they constitute a non-homogenous system in comparison with the other masonries. For the same reason, data collected from masonries restored with methods against rising damp need to be considered separately.
- The distributions are influenced by different unpredictable or non-documented factors, such as the specific masonry structure and decay phenomena (e.g. non-documented maintenance intervention with partial replacement of bricks), by the presence of salt deposits, by specific location (e.g. ventilation and exposure to atmospheric agents). These lead to a non-homogeneous distribution of the data when considered as a whole. Collecting a high number of experimental observation, from different masonries and location, could help in reducing the contribution due to specific cases when developing general models.
- The data considered as independent observations of the same system were used to develop linear models. However the results highlight that MC% data do not follow a linear model, even considering interaction effects. On the data collected from multiple building assets the physical laws and models reported in literature, which regards small samples, single masonries or single buildings studied under controlled conditions [1,4,7,9,10], do not apply straightforward. The data show complex structure, that need to be investigated with a non-linear approach such as the regression tree.

The results confirm the inverse relationship between MC% and height. Masonries are soaked with water till 150–200 cm over ZMPS, an evaporation zone range from 200 cm to 300 cm over ZMPS, in this area salts deposits are often present, lower MC% values are observed above.

The relationship between depth and MC% is different below and above the evaporation zone, with higher MC% on the surfaces of the lowest parts of the masonries and lower MC% on the surfaces of the highest parts. Thus, the results are not linked to the position of the building within the city but are related to its altitude and with its location considering the distance to the nearby water.

Up to now, the literature considered the lower part of the buildings uniformly soaked with lagoon water, that can be considered as a stable water body. The different trend of MC% in depth - above and under the evaporation zone - suggests that buildings having water bodies directly on their sides or basements are more affected by rising damp. Water –- from side canals and during high tides flooding - penetrates the surface and spread within the masonry, then rising damp take place within the wall. This occurs mainly for buildings located nearby canals and for the lowest parts of the city. In buildings located far from water, the soil is more uniformly wet, and suction occurs mainly on the vertical axis. Above the ground level, evaporation phenomena occur on the surfaces counteracting the suction of water due to rising damp.

5. Conclusions

The comparison of moisture contents of different Venetian buildings has been used for highlighting common trends in masonries affected by rising damp. The analysis and the development of several different models, based on MC%, collected from existing literature and covering a period of 25 years, led to the following results:

- The distributions are influenced by unpredictable and non-documented factors such as the specific masonry structure and decay phenomena.
- An inverse relationship between MC% and height was found, with wet masonries till 150–200 cm over ZMPS, an evaporation zone from 200 cm to 300 cm over ZMPS, lower MC% values above.
- Considering in-depth MC% distribution, higher MC% was observed on the surfaces, while lower MC% values were observed below and above the evaporation zone, respectively.
- The results are related to the buildings altitude on the lagoon level and to the buildings distance from water.

The opportunity to enlarge the data set, with further data possibly from the same buildings, would increase the knowledge regarding rising damp in Venice. The proposed models are the starting point for a tool that can check the effectiveness of future structural intervention against rising damp. The model could be useful to assess the validity of safeguarding measures, such as the maintenance embankments, the raising-up of the external pavements, the use of pumps, the waterproofing foundation's' insulation and the other flood control measures.

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