Evaluation of Vulnerability to Heavy Precipitation of the Roofs of Historic Chilean Buildings with Wooden Structure. A Methodology to Apply at an Early Stage

A Herrera¹, M A Gálvez²

¹Master candidate. Architecture Department, Universidad Técnica Federico Santa María, Avenida España 1680, 2340000, Valparaíso, Chile.
²Collaborator. Architecture Department, Universidad Técnica Federico Santa María, Avenida España 1680, 2340000, Valparaíso, Chile.

E-mail: miguel.galvez@usm.cl, alejaherrera@gmail.com

Abstract. Deck areas prone to leaking rainwater can be identified at an early stage, even before the filtration process begins to occur. The identification of the factors that determine the degree of roof vulnerability to rainfall and their rainwater drainage system and the elaboration of a diagnostic procedure to be applied is fundamental, above all, for the preventive maintenance of historic buildings. In the absence of Chilean regulations on the sizing of the roof rainwater drainage system, the European standard BS EN 12056-3, the Manual for the Design of Roof Drainage Systems, the Chilean road study procedure manuals and other documents were reviewed, and the principles, concepts, dimensioning parameters, constructive recommendations, etc., were transformed into graphically represented processes to facilitate the evaluation of the safety and vulnerability of the various constructive elements to the filtration of rainwater. The factors that determine the degree of vulnerability of the roof to the filtration of rainwater are given by its conformation, its materiality, its dimensioning and its environment, primarily affecting elements such as the roof, gutters and outlets. The result that the evaluator can expect from the proposed methodology is the identification of the aspects that make both the roof and the rainwater drainage system vulnerable, distributed in space, providing him or her with the basis for designing an intervention plan and preventive actions, and this practice should be implemented for sustainable heritage conservation.

1. Introduction
The roofs of historical buildings deteriorate over time, suffering damage caused by environmental agents, especially rainwater. If this process is not detained, decay spreads and may lead to ruin.

A building cannot be maintained when only attending to other constructive elements, while leaving the roof untouched. According to Portero, Machado and Mazón [1] this enclosure has been considered important since ancient times, due to the fact that given its function, when problems arise it can quickly damage the rest of the building. As argued by Zamora [2], the deterioration and subsequent ruin of older
constructions have started with the roof. The explanation offered by Villalobos [3] is that the roof is the area most affected by the climate and the first source of damage. Therefore, diagnosis and intervention are inescapable despite their high cost.

If maintenance is performed on roofs when there is already severe damage, greater intervention is required to resolve the issue. In the opinion of Cueli and Vega [4], restoration or structural consolidation works generate significant expenses when damage is visible. In this regard, Casas [5] sustains that, according to the International Energy Agency, in Europe nearly 10 billion euros are invested every year to repair moisture damage. This is coherent with what occurs in restoration works, as much damage remains hidden until the outer coating is removed and is therefore not initially considered in the estimates.

Historical buildings in Chile are characterized by the use of wood in their roofs, which are often pitched. This material has been used since pre-Hispanic times, as well as during and after the colonization period.

Zúñiga affirms that the first chroniclers reported that the roofs of 16th-century Mapuche homes were composed of a wooden stick frame and covered in straw and totora [6].

This material was also used in the pre-Hispanic altiplano in northern Chile. Muñoz describes the presence of wooden rafters in the roof, which supported an inclined roof covered in straw and clay [7].

During colonial times, buildings in central Chile also used wood in their roof structures, despite the fact that, according to Aranda, Castro, Lacoste, Pramat and Soto, it was a scarce commodity during the 17th century. It was used in the construction of the roof, rafters and purlin structure [8].

During the second half of the 19th century and at the turn of the 20th century, Pizzi argues that trade with Europe brought with it the balloon frame construction system, which used the wood brought on ships as ballast in the wall and roof structures [9]. Leser describes that the roof framework was supported by a master piece, also wooden, supported by the studs. Chilean port cities changed their image with these types of constructions [10].

Wood continued to be used in the area during German, French, Swiss, Spanish and Chilean colonization. Cerda explains that these immigrants utilized the materials at hand, in this case wood, associated with the culture, identity, heritage and architectural and urban history.

The use of wood is predominant in the structure of historic Chilean buildings, particularly in the roof structure, which uses trusses or rafters to create pitched roof planes, as suggested by Beinhauer [11].

The objective of this paper is to address this issue through the proposal of a methodology for the early detection of areas prone to the rainwater filtration, in order to be applied in historic Chilean buildings, before rain damage is visible, and even before filtrations occur.

Other diagnosis methods are based on the detection of flaws and are not meant to be applied at an early stage. Visual methods are employed based on the expert's experience and knowledge, who must heighten his or her sense of observation and review historical and current documentation. There are also destructive and non-destructive methods that use certain devices. [12] They recognize a prior stage in which the historical, environmental, geometric, and material documentation is collected [13] and the building is inspected. Subsequently, an analysis phase compares the documentation to in situ observations, and a diagnosis hypothesis is posited and tested with respect to the determination of pathologies [14]. Therefore, these are not preventive methodologies.

In Chile, precipitation behavior is varied, so in order to assess roof vulnerability, it is important to have information about the geographical distribution of high-intensity rainfall and establish criteria, because as argued by Ávila and Marín [15], extreme events with very high-intensity but low-frequency precipitation may provoke disasters.

Based on a probabilistically estimated extreme precipitation mapping proposal by the present author, the BS EN 12056-3:2000 design and roof drainage calculation standard [16] and the bibliography, vulnerability indicators are identified in relation to slanted wood-structure roofs. Based on these indicators, a methodology is proposed in order to determine, at an early stage, the degree of roof vulnerability to filtrations.
2. Proposed Methodology

The proposed methodology consists of three stages as shown in Table 1.

Table 1. Stages of methodology.

| Stages of the methodology | Stage 1 of the methodology |
|----------------------------|----------------------------|
| Stage 1                    | Obtaining information from written documents, legal, press and other documents |
| Stage 2                    | Obtaining information from graphic documents, maps, photographs and other documents |
| Stage 3                    | Obtaining building information in situ |

Vulnerability analysis

| Stages of the methodology | Stage 2 of the methodology |
|----------------------------|----------------------------|
| Stage 2.1                  | Generate updated roof plan |
| Stage 2.2                  | Use plans in technical sheets |

The information contained in the forms found in figures 1 and 2 is collected during an on-site visit.

Figure 1. Technical data sheet 1.
2.1. Stage 3: Information Analysis
The methodology proposes questions that the evaluator will answer based on the data collected in the previous stages to learn more about the building. These questions are deduced from the vulnerability factors that have been detected as influential upon roof vulnerability in historic Chilean buildings to the threat of intense precipitations.

This stage is described in greater detail below, explaining and justifying the vulnerability factors used and the scoring system applied to ultimately determine roof vulnerability.

3. Vulnerability Assessment

3.1. Vulnerability Factors
The factors that determine the vulnerability of wood-structure roofs in historical buildings to intense precipitations are three-fold:

- Intrinsic factors: These refer to the roof's inherent qualities that make it vulnerable to threats. Three criteria have been distinguished: morphology, material and structural, and conservation status, each of which have their own indicators.
- Contextual factors: These correspond to external features that affect the roof, such as the surrounding vegetation and winds.
- Management factors, related to actions performed to avoid rainwater filtrations, such as roof maintenance.

3.1.1. Intrinsic factors: Morphology Criteria
Related to the roof’s geometric design and rainwater evacuation system.

- Roof plane pitch: The roof plane must meet the minimum recommended pitch according to the roofing material. As the slope increases, so does the flow rate, contributing to the evacuation of rainwater from the roof. This is vital, especially in the case of permeable materials.
- Location of gutters: May be along the perimeter or inside the building’s roof. While these are hydraulically similar, perimeter gutters may overflow safely outside the building, while interior gutters that overflow generate filtrations.
• Gutter straightness: If the gutters have an angle of over 10°, their flow capacity is reduced, which may be solved by placing a box-receiver in the angle.
• Roof components: Elements that perforate the roof covering, such as chimneys, hatches, ducts, etc.. They generate joints in the roof that may filter if not adequately sealed and when located very close to the vertical faces.
• The flow capacity of the gutters: This is based on its section, which must be suitable for transporting the flow of rainwater received. The calculation proposed in the BS EN 12056-3:2000 standard is applied [16].
• Gutter slope: The maximum recommended slope is 1%, since the flow capacity may be up to 55% higher than a leveled gutter. Higher slopes lead to higher flow rates, and the resulting turbulence raises the risk of local overflow. If there is no slope or the slope is inverted, the difference in level between the two extremes drives the flow during rainfall, but afterwards, some water may remain stagnant until it evaporates, leading to material decay.
• Capacity of outlets: If the potential output flow is lower than that carried by the gutter, its capacity to discharge the associated design rainfall flow must be confirmed. The calculation proposed in the BS EN 12056-3:2000 standard is applied [16].
• Existence of a parapet: The point of contact between the wall and the roof represents a barrier for fast water flow, therefore the water-tightness of the joint must be guaranteed.
• Existence and access to expansion joints: Access to the building’s expansion joints is necessary in order to maintain their seals and conserve their water-tightness.

3.1.2. Intrinsic Factors: Material and Structural Criteria
• These are conditioned by the inherent qualities of the roof materials, the rainwater evacuation system and the structure.
• Roof covering permeability: Degree of water-tightness provided by the roof material.
• Structural deformations: Any deformation that may be found in the roof which could affect its integrity and lead to filtration.
• Durability: Maintenance of the physical and chemical qualities of the roof covering, gutter and outlet materials, without alteration during their useful life and maintaining their functionality [17].
• Installation quality of the roof covering, gutter and outlet materials: The evaluator must verify that the materials have been properly installed so as to not affected their functionality.
• Roof covering continuity: Analysis of any joints and couplings between the roof material units.

3.1.3. Intrinsic Factors: Conservation Status Criteria.
• Conservation status of the roof covering, gutter, outlet elements: The evaluation approach must be focused on anticipating the occurrence of filtrations.

3.1.4. Contextual Factors. Exposure Criteria.
• The existence of deciduous trees means that the leaves can fall into the gutters or outlets, with the possibility of obstructing these or reducing their capacity.
• Wind: The evaluation must consider the predominant winds at the building site and the effect of environmental elements.

3.1.5. Management Factors. Maintenance Plan Criteria.
• Roof maintenance: The existence and application of a maintenance plan and action protocol in the event of high-intensity rainfall.
Table 2 below summarizes the vulnerability factor indicators to be evaluated for each criterion.
Table 2. Vulnerability indicators.

| VULNERABILITY FACTORS | VULNERABILITY CRITERIA | VULNERABILITY INDICATOR |
|------------------------|------------------------|------------------------|
| INTRINSIC FACTORS      | MORPHOLOGY CRITERIA    | a) Roof plane pitch    |
|                        |                        | b) Location of gutter  |
|                        |                        | c) Gutter straightness |
|                        |                        | d) Roof components    |
|                        |                        | e) The flow capacity of the gutter |
|                        |                        | f) Gutter slope       |
|                        |                        | g) Capacity of outlets |
|                        |                        | h) Existence of a parapet |
|                        |                        | i) Existence and access to expansion joints |
| MATERIAL AND STRUCTURAL CRITERIA | a) Roof covering permeability |
|                                      | b) Structural deformations |
|                                      | c) Durability |
|                                      | d1) Installation quality of the roof covering materials |
|                                      | d2) Installation quality of the gutter materials |
|                                      | d3) Installation quality of the outlet materials |
|                                      | e) Roof covering continuity. Vertical |
|                                      | f) Roof covering continuity. Horizontal |
| CONSERVATION STATUS CRITERIA | a1) Roof covering |
|                                      | a2) Roof valley, hip |
|                                      | a3) Gutter |
|                                      | a4) Outlet |
| CONTEXTUAL FACTORS | EXPOSURE CRITERIA | a) Existence of deciduous trees |
|                      |                      | b) Wind |
| MANAGEMENT FACTORS | MAINTENANCE PLAN CRITERIA | a) Roof maintenance |

3.2. Procedure.
The methodology is applied by responding to questions related to each indicator, yielding a traffic light color that indicates the level of vulnerability. This must be analyzed for each gutter, from its highest point to its outlet towards a downspout. Each gutter must be associated with an area of the roof and an outlet. This outlet shall be shared for all gutters that empty into it. The set of elements related to each gutter shall be called a “section.”

The level of vulnerability associated with each traffic light color is seen in Table 3.
Table 3. Traffic light indicators and vulnerability level.

| Traffic light indicators | Vulnerability level |
|--------------------------|---------------------|
| Green                    | Low                 |
| Yellow                   | Medium              |
| Orange                   | High                |
| Red                      | Critical            |

The factors, criteria and indicators form a decision tree that orders these as branches (See table 2). Each part of this tree is assigned a weight in order to calculate an overall score. The methodology used to calculate the weights was the Analytical Hierarchy Process proposed by Saaty, for pairwise comparison that admits intermediate and inverse situations [18]. The scale used is seen in the example in Figure 4.

This methodology considers the participation of experts who compared different factors, criteria and indicators, separately, to produce the results by indicator provided in Table 4.

Table 4. Weights of the vulnerability level.

| Indicators                  | Vulnerability level |
|-----------------------------|---------------------|
| Gutter capacity             | 0.1667              |
| Combined outlet capacity    | 0.1667              |
| Roof maintenance            | 0.3333              |
| Other indicators            | 0.0159              |

Once the partial result is obtained by section and by indicator, the evaluator must add up the building’s total score. To do this in each indicator, the percentage obtained for the sections analyzed and obtained for each traffic light must be recorded.

Then all of the indicators are added up by traffic light. This will identify the percentage of the building’s roof corresponding to each level of vulnerability.

4. Application

The proposed methodology was applied to the second-floor roof of the Rioja Palace in Viña del Mar, as shown in the layout in Figure 3.
Figure 3. Roof plan of Rioja palace. Source: Author based on P-AR-02-01 Lámina 2 Revisión 1”. Author: Josefina Atria.

Figures 4 provide image of the building under review.
Figure 4. Rioja Palace roof. (a) Downspout 06-01 corner. (b) Section 06-01-01. (c and d) Roof covering 06. (e) Outlet BALL 06-01. (f) Section 06-01-02.

The data recorded in forms 1 and 2 are indicated in figures 5 and 6.

**Figure 5.** Form 1 Section 06-01-01.
Although the methodology was applied to all sections of the second-floor roof of the Rioja Palace, many of the indicator results were repeated. Of the twenty-four indicators, twenty have the same result in all sections of the roof and four vary according to the section to which they belong.

Table 5 shows the results that are the same for all sections analyzed, and Table 6 provides a summary of the variable results corresponding to four indicators.
Table 5. Equal results for all sections.

| VULNERABILITY FACTORS | VULNERABILITY CRITERIA | VULNERABILITY INDICATOR | TRAFFIC LIGHT |
|-----------------------|------------------------|------------------------|---------------|
|                       | MORPHOLOGY CRITERIA    | a) Roof plane pitch    |               |
|                       |                       | b) Location of gutter  |               |
|                       |                       | c) Gutter straightness | Variable      |
|                       |                       | d) Roof components     | Variable      |
|                       |                       | e) The flow capacity of the gutter | |
|                       |                       | f) Gutter slope        |               |
|                       |                       | g) Capacity of outlets | Variable      |
|                       |                       | h) Existence of a parapet |               |
|                       |                       | i) Existence and access to expansion joints | |
|                       | MATERIAL AND STRUCTURAL CRITERIA | a) Roof covering permeability | |
|                       |                       | b) Structural deformations |               |
|                       |                       | c) Durability          |               |
|                       |                       | d1) Installation quality of the roof covering materials | |
|                       |                       | d2) Installation quality of the gutter materials | |
|                       |                       | d3) Installation quality of the outlet materials | |
|                       |                       | e) Roof covering continuity. Vertical | |
|                       |                       | f) Roof covering continuity. Horizontal | |
|                       | CONSERVATION STATUS CRITERIA | a) Roof covering | |
|                       |                       | a2) Roof valley, hip   |               |
|                       |                       | a3) Gutter             |               |
|                       |                       | a4) Outlet             |               |
|                       | CONTEXTUAL FACTORS    | a) Existence of deciduous trees | Variable |
|                       | EXPOSURE CRITERIA     | b) Wind                |               |
|                       | MANAGEMENT FACTORS    | a) Roof maintenance    |               |

Table 6. Summary localized results.

| FACTORS          | CRITERIA               | INDICATOR VARIABLE | Number of gutters per traffic light |
|------------------|------------------------|--------------------|-----------------------------------|
| INTRINSIC FACTORS| MORPHOLOGY CRITERIA    | c) Gutter straightness | 31  0  0  9                        |
|                  |                        | d) Roof components  | 21  10  0  9                       |
|                  |                        | g) Capacity of outlets | 8  32  0  0                        |
| CONTEXTUAL FACTORS| EXPOSURE CRITERIA     | a) Existence of deciduous trees | 28  0  0  12                     |

Table 7 shows the results for the entire building. For each indicator, it shows the percentage of sections obtained for each color. Therefore, each percentage is recorded as a decimal.
Table 7. Roof results.

| VULNERABILITY CRITERIA | VULNERABILITY INDICATOR | Number of sections per traffic light |
|------------------------|-------------------------|------------------------------------|
| **MORPHOLOGY CRITERIA** |                        |                                    |
| a) Roof plane pitch    | 1                       | 0 0 0 0                            |
| b) Location of gutter  | 0                       | 0 0 1                               |
| c) Gutter straightness  | 0.775                   | 0 0 0 0.225                         |
| d) Roof components     | 0.525 0.25              | 0 0 0 0.225                         |
| e) The flow capacity of the gutter | 1 | 0 0 0 |
| f) Gutter slope        | 0                       | 0 0 1                               |
| g) Capacity of outlets  | 0.2 0.8                 | 0 0 0                               |
| h) Existence of a parapet | 1                      | 0 0 0                               |
| i) Existence and access to expansion joints | 1 | 0 0 0 |
| **MATERIAL AND STRUCTURAL CRITERIA** |                        |                                    |
| a) Roof covering permeability | 1 | 0 0 0 |
| b) Structural deformations | 1 | 0 0 0 |
| c) Durability          | 0                       | 1 0 0                               |
| d1) Installation quality of the roof covering materials | 1 | 0 0 0 |
| d2) Installation quality of the gutter materials | 0 | 0 1 0 |
| d3) Installation quality of the outlet materials | 1 | 0 0 0 |
| e) Roof covering continuity. Vertical | 1 | 0 0 0 |
| f) Roof covering continuity. Horizontal | 0 | 1 0 0 |
| **CONSERVATION STATUS CRITERIA** |                        |                                    |
| a1) Roof covering      | 0                       | 1 0 0                               |
| a2) Roof valley, hip   | 0                       | 1 0 0                               |
| a3) Gutter             | 0                       | 0 1 0                               |
| a4) Outlet             | 1                       | 0 0 0                               |
| **EXPOSURE CRITERIA**  |                        |                                    |
| a) Existence of deciduous trees | 0.7 | 0 0 0 0.3 |
| b) Wind                | 0                       | 1 0 0                               |
| **MAINTENANCE PLAN CRITERIA** |                        |                                    |
| a) Roof covering       | 0                       | 0 1 0                               |

The weighted results according to the importance of each indicator are shown in Table 8.

Table 8. Weighted results.

| VULNERABILITY CRITERIA | VULNERABILITY INDICATOR | Weighted score associated with each traffic light |
|------------------------|-------------------------|--------------------------------------------------|
| **MORPHOLOGY CRITERIA** |                        |                                                  |
| a) Roof plane pitch    | 0.0159                  | 0 0 0                                             |
| b) Location of gutter  | 0                       | 0 0 0.0159                                        |
| c) Gutter straightness  | 0.0123225 0.00035775    | 0 0 0.0159                                        |
| d) Roof components     | 0.0083475 0.00039755    | 0 0 0.00035775                                    |
| e) The flow capacity of the gutter | 0.1667 | 0 0 0 |
| f) Gutter slope        | 0                       | 0 0 0.0159                                        |
| g) Capacity of outlets  | 0.03334 0.13336         | 0 0 0.0159                                        |
| h) Existence of a parapet | 0.0159                | 0 0 0                                             |
| i) Existence and access to expansion joints | 0.0159 | 0 0 0 |
| **MATERIAL AND STRUCTURAL CRITERIA** |                        |                                                  |
| a1) Roof covering      | 0.0159                  | 0 0 0                                             |
| a2) Structural deformations | 0.0159          | 0 0 0                                             |
| c) Durability          | 0                       | 0 0 0.0159                                        |
| d1) Installation quality of the roof covering materials | 0.0159 | 0 0 0 |
| d2) Installation quality of the gutter materials | 0 | 0 0.0159 |
| d3) Installation quality of the outlet materials | 0.0159 | 0 0 0 |
| e) Roof covering continuity. Vertical | 0.0159 | 0 0 0 |
| f) Roof covering continuity. Horizontal | 0 | 0 0.0159 |
| **CONSERVATION STATUS CRITERIA** |                        |                                                  |
| a1) Roof covering      | 0                       | 0 0.0159                                          |
| a2) Roof valley, hip   | 0                       | 0.0159 0 0                                        |
| a3) Gutter             | 0                       | 0 0.0159                                          |
| a4) Outlet             | 0.0159                  | 0 0 0                                             |
| **EXPOSURE CRITERIA**  |                        |                                                  |
| a) Existence of deciduous trees | 0.01113 | 0 0 0.00477 |
| b) Wind                | 0                       | 0 0.0159                                          |
| **MAINTENANCE PLAN CRITERIA** |                        |                                                  |
| a) Roof covering       | 0                       | 0 0.3333                                           |
| **TOTAL ROOF**         | 0.37494 0.216835 0.3651 0.043725 |                                                  |
37.5% of the roofs studied present low vulnerability, 21.7% have medium vulnerability, 36.5% have high vulnerability and 4.3% present critical vulnerability.

5. Conclusions

The roof capacity is determined by the dimensions of its rainwater evacuation system, which shall meet the requirements for protecting the building from filtrations, due to rain intensity, roof covering material absorption and a roof collection area. However, even when these requirements are met in theory, there are factors that may reduce the admissible flow of the rainwater evacuation system. These factors could increase the roof's degree of vulnerability. Therefore, it is fundamental to analyze a triad of factors: design capacity – rain intensity – vulnerability factors.

When performing a prior filtration diagnosis, the cost is lower than when there is already damage, as it is not necessary to perform any tests to determine the extent of damage. It will also reduce future maintenance costs.

When evaluating vulnerability prior to filtration and its effect on the roof structure, the latter has no participation. It only influences performance when damage has been suffered that affects the roof's water-tightness.

Because water often follows hidden routes, the origin of moisture is not evident, therefore the identification of damage under the roof will not necessarily provide any evidence as original site of filtration. When diagnoses are focused on damage, it is not possible to specify the location of all filtration spots.

The application of this methodology also helps detect problems in roof projects and is therefore suitable to be applied during their review.

While the results of this methodology correspond to the percentage of the building’s roof associated with each level of vulnerability, it is equally important to consider the localized result, which reveals the areas prone to filtration although a generalized application may offer a favorable result. In order to recognize the spatial distribution of the different levels of roof vulnerability associated with the building's twenty-four indicators, an appropriate outcome could be a vulnerability map which easily points out the most vulnerable areas so as to perform corrective actions.

In the case of the Rioja Palace, the most vulnerable elements are the gutters located inside the building, 90° angles that modify water flow, no incline at the lowest extremes which causes the accumulation of sediment and vegetation growth, nearly 2% inclines that produce turbulence and a high probability of being clogged by leaves from nearby trees, all of which are high vulnerability indicators. This is in addition to the owner's failure to clean and maintain the roof. The early detection of these conditions and the effects produced on the gutters may allow for low-cost corrective actions to guarantee that the roof will continue to fulfill its role of protecting the building from environmental agents and to prolong the useful life of the roof.

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