USING MULTI-SENSOR MOISTURE MEASUREMENT IN CONSERVATION THROUGH 'BUILDING PATHOLOGY INDICES' AND 3D DIGITAL DOCUMENTATION

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ABSTRACT

Several non-destructive techniques are commonly used to measure moisture in stone-built heritage, including electrical properties, infrared thermal imaging, microwave measurement and radar. Each technique, as well as the sensors or devices used to implement it, has advantages and limitations. Two factors of significant importance are substances that can influence readings (such as salts) and the uncertainty of depth of penetration. This paper addresses these factors by developing 'indices of consistency' between devices to: a) amplify between devices with similar properties, and b) remove the influence of factors that make the indication of different moisture levels less clear. These indices are a simple algorithm from a class of data processing techniques known as 'data fusion' that combines information from several inputs (devices); the indices are developed from specific combinations which are selected based on the principles and practical experiences with using the devices. These indices have the benefit of synthesising the data collected from several devices into 'challenge-specific' visualisations that streamline interpretation. This principle is employed for data collected from a multi-sensor survey that was undertaken on a stone barrel vault ceiling in Argyle Tower, Edinburgh Castle, which is suspected to have water ingress due in part to its method of construction, exposed location and evidence of salt-related weathering. These indices are then combined with 3D digital documentation to more closely link them with the distinct geometry of this structure and enable a greater level of interpretation.

Keywords:
surveying, data analysis, laser scanning, handheld moisture meters, building pathology

1. INTRODUCTION

Understanding how and where moisture is entering and impacting the fabric of a structure is an important part of building management. This is especially true for the historic environment, in which the nature of construction techniques varies widely and previous adaptations confound attempts to characterise it.

Building pathology is a holistic approach that seeks to understand buildings in relation to their environment, with particular emphasis on defects and remedial action. In this context, it is not strictly essential to characterise absolute moisture contents. By considering the contrast of moisture between surface and depth, as well as the distribution across a façade, a reasonable conjecture can be made about the source of moisture ingress. This evaluation is usually undertaken qualitatively, but can involve more advanced methods, such as data fusion (Kohl et al. 2006). This is a common approach for studying structural elements of historic buildings (Ramos et al. 2015; Mishra, Bhatia and Maity 2019), but is not commonly employed for moisture detection.

Scientific investigations can provide invaluable information on the moisture levels within building materials. Non-destructive tools that use proxies for the moisture content are particularly suited to the historic environment, as they do not require any invasive analysis or loss of material, in line with the ethics of preserving cultural heritage (Pinchin 2008). However, the output from these devices is often in arbitrary units and heavily dependent on the properties of materials present in the structure. Additional factors may also influence their output, due to the measurement method. Gravimetric calibration (using the mass of water present in a sample) is a common technique to relate the output of non-destructive moisture measurement devices to an absolute moisture content (Orr 2019). However, this can add additional time requirements into a project, which may not be feasible for an individual building survey. It also requires that sample(s) of appropriate material are available for testing. Thus, it is not feasible to include in all cases.

Digital documentation is a powerful technique to accurately and precisely produce 3D representations of historic structures (Remondino 2011). This is especially useful in combination with moisture measurement, as their integration enables a deeper understanding of how measured moisture levels relate to the geometry and fabric of a building.

In this paper, we present a simple method for combining moisture measurement data from several devices into indices that can be integrated into a building pathology approach. These indices can incorporate measurements from multiple devices to reduce the influence of their measurement principle due to confounding factors. These indices advance current approaches within building pathology by enabling semi-quantitative comparison between measurement locations with respect to relative levels of moisture.

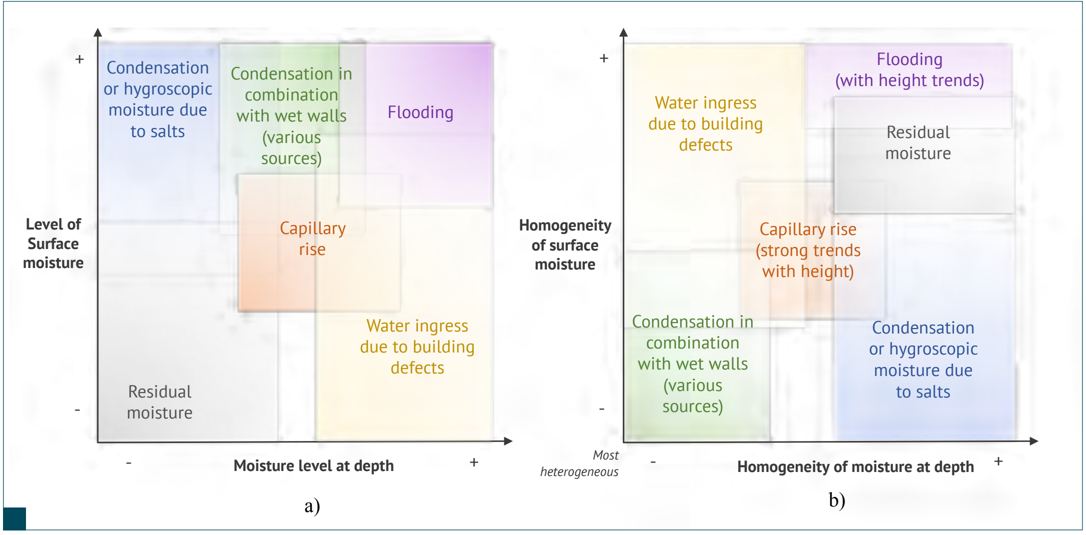


Figure 1:
A two-dimensional visualisation of using comparison between surface moisture and moisture at depth a) and homogeneity of surface moisture and moisture at depth b) to infer potential sources of moisture ingress in buildings. Adapted from Göller (n.d.).

2. BUILDING PATHOLOGY INDICES

A common approach in assessing moisture ingress in building pathology is to compare the relative levels of surface moisture to moisture at depth, and consider how homogeneous (even) the distributions of moisture are across the area of interest. The combination of these two factors can infer potential sources, when considered relative to a suitably 'dry' reference area of measurements. A benefit of this approach is that it is not necessary to make a gravimetric calibration. This comparison of moisture at surface and depth within building pathology is usually undertaken qualitatively (Singh, Yu and Kim, 2010) or semi-quantitatively, with moisture ingress estimated but mapped onto numerical skills broadly relating to 'levels' (Annila, Hellemaa and Pakkala, 2017).

2.1 Visual representation of the building pathology approach

Although typically assessed qualitatively, a two-dimensional x-y plot can be used to visualise the comparison between surface and depth (Figure 1a) and homogeneity (Figure 1b). It is important to note that the boundaries between different types of ingress are subjective and will have significant overlap. Göller (n.d.) has proposed a system of comparison for surface and depth moisture to infer the source causes, although this has also been presented in more qualitative (Stirling 2011) or ranked (Ismail 2019) formats. As the decay mechanisms for certain types of wood are much more defined, these levels are often defined as specific absolute moisture contents (Singh and White 1997), but this is not appropriate for other building materials such as stone. These indices can be supplemented with visual inspection of the distribution of readings or levels to assess if they are dispersed (several areas that are not interconnected) or primarily concentrated into one region. These nuances are not represented by the homogeneity index.

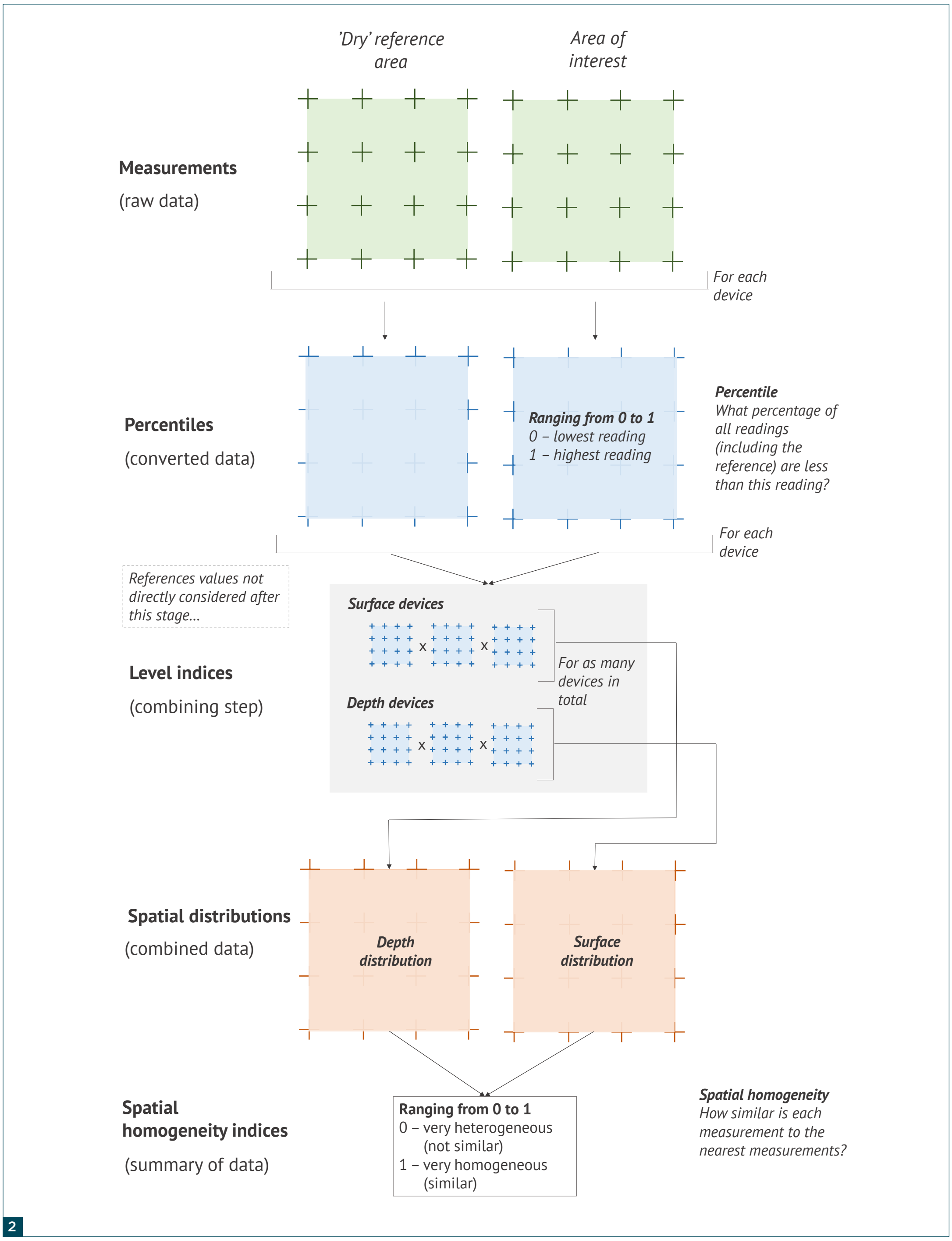


Figure 2:
A visualisation of the calculation procedure for the building pathology indices.

2.2 Calculation procedure

To use the visualisation procedure introduced in Section 2.1 as part of a quantitative evaluation, data fusion can be used (Hall 1997). The indices presented here are mathematical combinations of measurements across conceptual diagrams like those in Figure 1. This enables semi-quantitative comparison between regions of interest. The procedure for determining these indices is summarised in Figure 2. This procedure can be undertaken manually, or automated for ease of repeated use.

2.2.1 Measurement collection

The measurements (typically collected on a grid of points) are taken for the area of interest and a 'dry' reference area. The latter is generally an internal wall, or an area without visible signs of wetness or previous moisture-related deterioration. Measurements can be taken with several devices, which helps to reduce the potential influence of confounding factors due to measurement method.

2.2.2 Conversion to percentiles

The measurements are converted into percentiles: a numeric representation of the percentage of readings each individual reading is greater than. If a reading has a percentile of 90% (0.9 as an equivalent fraction between 0 and 1), its value is greater than 90% of all readings. These percentiles are taken across the area of interest as well as the dry reference. Therefore the percentiles ('relative' readings) of the area of interest increase if they are greater than the reference values, but not if they are similar in magnitude. Converting the measurements to percentiles minimises potential error from unknown types of relationships (e.g. linear, exponential, etc.) between the arbitrary units of moisture measurement devices.

2.2.3 Level indices (spatial distributions)

The level indices represent how much higher moisture levels are relative to the dry reference. They are determined by multiplying the measurements taken with each device on each grid point within each category. The categories are determined by the spatial capture of the device, i.e. whether it is predominantly used to detect moisture at surface or at depth. After the multiplication, the indices are arbitrarily normalised between 0 and 1 for ease of assessment. These can be visualised as two-dimensional distributions of moisture.

2.2.4 Homogeneity indices

The spatial homogeneity indices represent the extent to which adjacent grid points are similar or different in value from one another. It is calculated by finding the average difference between a grid point and each adjacent grid point, and subtracting this from 1. The subtraction is necessary so that a value close to 1 (a higher value) represents a very homogeneous distribution, while a value near to 0 means that a distribution is very heterogeneous.

An overall index for the area (for both surface and depth distributions) can be calculated by determining the average of the spatial homogeneity indices for the respective grids.

2.2.5 Source identification

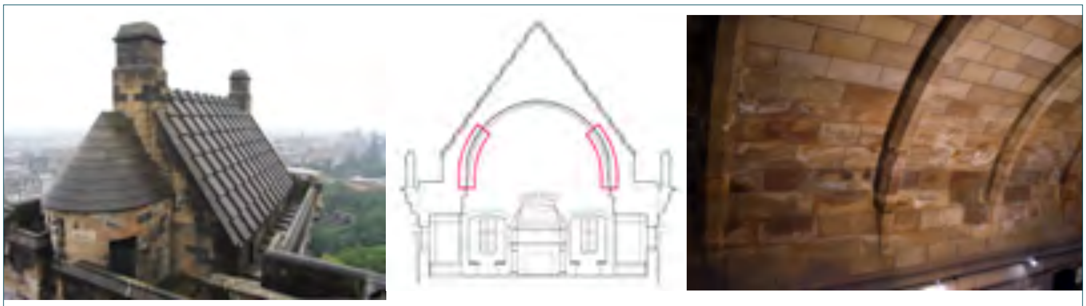
The two types of indices (level and homogeneity) for surface and depth are compared against Figure 1 to determine possible sources of moisture ingress.

2.3 Methods

The details of a case study designed to evaluate this approach are described below.

2.3.1 Case study site: Argyle Tower, Edinburgh Castle

Argyle Tower is a late-19th-century addition to the Portcullis Gate of Edinburgh Castle. The castle's exposed location results in a high exposure to episodes of wind-driven rain (Figure 3a). The tower features a roof formed of interlocked stone 'tiles' on top of a stone barrel vault ceiling interior (Figure 3b). It is unclear from architectural records and drawings what, if anything, is present in this void, nor if there are other architectural elements implemented into the roof structure. The bays near



a) b) c)

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Figure 3:
a) The exterior and context of Argyle Tower, Edinburgh Castle;
b) a cross-section of the construction with the area of interest (location of bays) in red; and
c) an interior view of the deterioration in the bays at the intersection of the vault and the vertical wall.
Image in (a) CC-BY-SA 2.0 Gareth James.

the intersection of the vault and the vertical walls show extensive salt- and moisture-related deterioration (Figure 3c).

Two bays on the north-west aspect were chosen for specific study: Bay A is the central bay, while Bay B is adjacent to the northernmost corner of the tower.

2.4 Moisture measurement

Moisture measurements were taken in two bays of the tower. Measurements were taken on a 10cm grid spacing across an 80cm x 80cm area. Another 80cm x 80cm area was measured at the base of an internal wall to act as the relative 'dry' measurements. Several devices were used to produce the indices (Table 1), each of which has different characteristics such as spatial capture and confounding factors.

Device	Measurement method	Depth(s) of penetration cm	Category	Confounding factors
hf sensor Moisture Measurement System; two models with different calibrations	Microwave	~3, ~30, ~80	Surface, Depth, Depth (respectively)	Metals, voids
Surveymaster Protimeter	Electrical resistance (pin-type)	< 0.2	Surface	Presence of salts
Surveymaster Protimeter	Capacitance	~ 4	Surface	Metals, voids, salts (although minimal)

Table 1:
Moisture measurement devices used in this study.

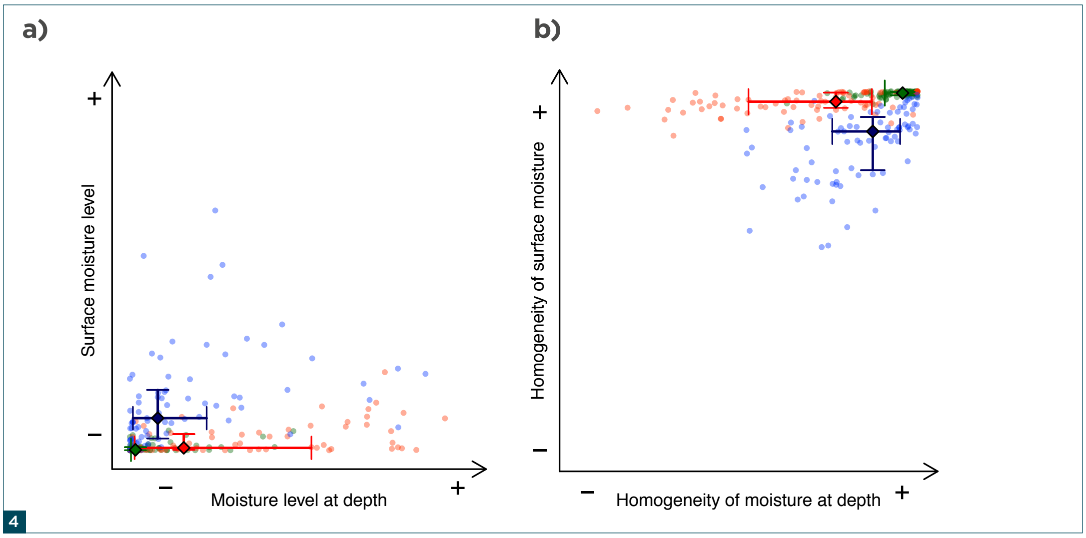

Figure 4:
The level a) and homogeneity b) indices for the bays plotted onto the framework presented in Figure 1: Bay A (red), Bay B (blue), and the reference measurement grid (green). Smaller circles represent individual grid points, while the large squares are the median (the index value which is greater than half of those within the grid) that are presented with the inter-quartile range as whiskers (a range in which 50% of the data centred around the median lie).

2.5 Digital documentation

Argyle Tower was recorded using Terrestrial Laser Scanning as part of Historic Environment Scotland's Rae Project, an ongoing commitment to digitally document all of the organisation's properties in care. The wider 3D dataset for this survey incorporates the entirety of Edinburgh Castle, including interior and exterior spaces. The capture and processing methodology is broadly outlined in *Short Guide 13: Applied Digital Documentation in the Historic Environment* (Historic Environment Scotland 2018). The registration methodology used targets and point-cloud-based feature alignment. In addition, a traverse survey methodology linked the Argyle Tower data to the wider control network of the Castle dataset. The 3D point cloud dataset generated by the laser scanning was then used to create a high-resolution 3D model using CapturingReality's RealityCapture software. For visualisation, the 2D plotted moisture data was subsequently projected onto the subject areas using 3D modelling software Autodesk 3DS Max.

2.6 Results

2.6.1 Evaluation of the indices

Figure 4 shows the level and homogeneity indices on a two-dimensional plot within the building pathology index framework presented in Figure 1. The comparison of these two indices allows for sources of moisture to be inferred.

The median surface level index for Bay A is negligibly greater than the dry reference index (Figure 4a). In contrast, Bay B has a higher median level of surface moisture. Both have higher levels of moisture at depth, but that for Bay B is more significant. Significant spread of individual grid points is apparent. Although several grid points in both bays are clustered around the median reference level index, others are significantly greater than the median values, indicating a wide spread of indices. Bay A primarily has greater depth level indices, while the extreme grid points in Bay B exhibit greater spread in both levels of surface moisture and moisture at depth.

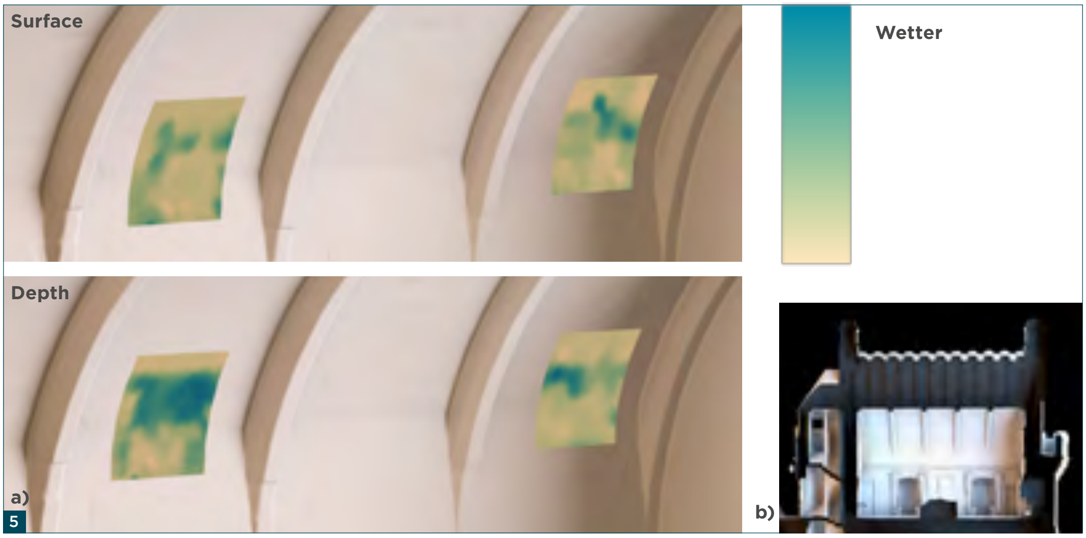

Figure 5:
a) Surface and depth level indices for Bay A (left) and Bay B (right);
b) A 3D cross-section of Argyle Tower, in which the box indicates the measurement locations.

The homogeneity indices (Figure 4b) for both bays are less than those for the reference grid, meaning they are more heterogeneous (less even). Bay A exhibits much more heterogeneity in the depth measurements with regards to the median and extreme values. In contrast, Bay B has more significant heterogeneity in the median and extreme indices for both surface moisture and moisture at depth, but this is less extreme than the spread of Bay A.

2.6.2 Spatial distribution

The distribution of level indices (determined from the device readings summarised in Table 1) for the bays are presented in Figure 5. The distributions have been superimposed onto a 3D model, to better understand how the measurement grid fits into the context of the complex roof construction.

In both bays, a significant decrease in the distribution of level indices is apparent in a band in the upper region. This band is possibly related to a change in wall structure, which represents the point at which the vault separates from the vertical and a cavity is introduced.

The surface of Bay A is characterised by areas of higher indices that are not interconnected. In contrast, the level indices at depth are primarily in one region, just beneath the upper band of lower indices. The surface of Bay B has fewer areas of higher level indices, but they are again disparate and not interconnected. Similarly, the depth indices are only higher in a single area, although a few other groups of moderate indices are present at depth as well.

3. DISCUSSION

A summary of the spatial distributions and median level and homogeneity indices enables potential moisture sources to be inferred (Table 2).

Despite its utility, limitations of the methods must be considered. First, certain ingress pathways are heavily dependent on weather events and environmental conditions. It is difficult to attribute moisture ingress to a building defect if the previous weather (and exposure) is unknown. As well, a suitable 'dry' reference area must be identifiable, to contextualise the readings in the area(s) of interest.

More broadly, the challenge of establishing the accuracy and utility of the indices is dependent on several factors. Principally, it should be assessed in a wide variety of suspected types of moisture ingress. As well, their function and ability to characterise types of ingress may differ depending on the mode of construction and materials used, as well as the information available and discernible about the structure and its use. It is likely that the distribution of values within the level and homogeneity indices will vary depending on these factors, making it difficult to assign prescriptive ranges of values for types of ingress. Future work could explore more advanced fusion algorithms, especially those which incorporate supervised and unsupervised learning techniques.

Table 2:
Summary of moisture levels in the bays.
Low: Less than 0.25; moderate: 0.25 to 0.50, high: greater than 0.75.

Bay	**Surface level index** *Median*	**Depth level index** *Median*	**Surface homogeneity index** *Median*	**Depth homogeneity index** *Median*	**Spatial features**	**Potential source(s)**
A	Low	Low to moderate	High	Moderate to high	*Surface:* non-interconnected areas; *Depth:* one main region	Residual moisture, water ingress due to building defect(s)
B	Low	Moderate	Moderate	Moderate	*Surface and Depth:* few non-interconnected areas	Residual moisture, condensation or hygroscopic moisture due to salts

4. CONCLUSION

This paper has presented a way of semi-quantifying a building pathology approach to assess moisture sources. The procedure of utility of these was demonstrated with a case study of a complex historic building in a Scottish context. Integrating moisture measurement techniques with 3D digital documentation contextualised the analysis within the complex barrel vault ceiling structure of the building, enabling a greater understanding of the issues. It also allows for results to be presented in a way that is more effectively communicated to a wide range of audiences, in contrast to colour plots presented out of context.

Future work will investigate whether the method can be extended to a wider range of moisture ingress pathways, and streamline the procedure for more efficient integration with moisture surveying and practice. This will require evaluation of a wider range of materials and scenarios, which can be studied both within laboratory and in situ contexts. Data fusion algorithms beyond those evaluated herein may provide further opportunities for advancing methods of building pathology.

The protocol enables a more accurate and in-depth understanding of moisture ingress pathways between areas of interest within the same structure. This is an integral part of building conservation as part of efficient and effective management of the historic built environment.

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