Heritage Science

REVIEW

Heritage hydrology: a conceptual framework for understanding water fluxes and storage in built and rock-hewn heritage

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Abstract

Water plays a vital role in the deterioration and conservation of built and rock-hewn heritage and it is generally agreed that climate change is significantly changing the environmental controls on stone decay. We here introduce the framework of heritage hydrology as a holistic way of conceptualising the flows and stores, processes and impacts of water interacting with building materials. We distinguish the basic types of stone-built buildings, ruins and free-standing walls, and rock-hewn sites. Analogous to catchment hydrology, heritage hydrology can be subdivided into water fluxes and water reservoirs, further subdivided into inputs (e.g. wind-driven rain, capillary rise), throughputs (e.g. run-off down façade), storages (moisture content) and outputs (evaporation and runoff). Spatial patterns of moisture are different between buildings and rock-hewn sites, both presenting hydrological complexities. The interaction between mean and short-term precipitation, wind, radiation and resulting evaporation may lead to very different impacts at different heritage sites. We here differentiate between the detail scale, the façade scale and the building or site scale. Patterns at different sites can be very variable on different scales due to the multitude of influencing parameters and it is not clear which scale of moisture variations is actually relevant for decay processes. Temporal patterns are equally scale-dependent and include short-term fluctuations in temperature and rainfall, high-magnitude episodic events such as floods and storms, and longer-term changes as a result of seasonality, interannual variability and secular trends or climate change. Based on the outlined framework we advocate a research agenda for heritage hydrology in the future. This should focus on (1) finding the best combinations of methods to measure and model spatio-temporal patterns in moisture; (2) researching the major factors controlling spatio-temporal patterns in moisture; (3) figuring out which spatio-temporal patterns are most important for driving deterioration and how their respective scales interact.

Keywords: Cultural heritage, Stone decay, Rock moisture

What is heritage hydrology and why does it matter?

Background and definitions

Sustainable management of built heritage requires profound knowledge of how stone buildings and structures respond to their changing environment. Water plays a vital role in the deterioration and conservation of built heritage, but there is as yet no overarching framework for understanding the flows and stores, processes and impacts of water interacting with building materials. We use the term 'built heritage' here to refer to buildings and sites valued for more than their utilitarian value, such as those with historical, aesthetic and communal values. In particular, this paper focuses on three types of heritage i.e. buildings and ruins constructed from natural stone masonry and rock-hewn sites (including rock art and large rock sculptures). However, the issues raised are relevant more broadly to built heritage composed of

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other materials, such as brick masonry, earth and concrete. Heritage hydrology can be seen as encompassing the components of the hydrological cycle involving the interaction of different sources of water (rain, groundwater etc.) with built heritage in terms of runoff, infiltration, evaporation and storage and their impacts on processes of deterioration of heritage building materials [1]. The concept of heritage hydrology can be seen as a subset of urban hydrology or catchment hydrology, and complements heritage climatology which has been described as "…the study of the climate parameters that affect monuments, materials and sites. The parameters used in heritage climatology differ from those typical in meteorology (…) and focus on cycles and combinations of meteorological parameters that relate to material damage" [2, p.2577]. Work on heritage climatology has for example focused on the climatological aspects of humidity and salt weathering as they affect heritage buildings and sites [3, 4]. Large, pan-European projects have used heritage climatology to investigate the impacts of climate change on built heritage (e.g. [4–6]). However, to gain a full picture of the relations between climate and heritage it is necessary to bring in the hydrology, which will pave the way for a future hydroclimatological approach.

In this review, we focus on introducing the framework of heritage hydrology as a holistic way of conceptualising the flows and stores of water involved in deterioration of built and rock-hewn heritage. We review the major challenges facing heritage hydrology and provide an agenda for future research. We have not attempted to review the literature systematically, but rather highlight the key areas of research, main findings and current gaps. In essence, we focus on a key knowledge gap: The spatial and temporal characteristics of water flows/stores in built heritage and the challenges of using currently available techniques to provide information on these characteristics.

Why the conceptual framework is needed/ helpful

The conceptual framework of heritage hydrology is needed in order to provide a holistic understanding of the movement of water in and around built heritage, which in turn will improve hygrothermal modelling and management of deterioration. The focus on water flows is justified by the fundamental importance of moisture and its fluctuations for decay processes. As Sandrolini and Franzoni put it "Moisture is the main cause or concause of decay of ancient building materials" [7, p.1372]. The simple *presence* of water is required for all types of chemical process as well as for the growth of biota. Moisture *fluctuations* are the main cause of crystallisation and hydration of salts and thus, of salt weathering [8], while crossing certain thresholds of water *saturation* enhances the efficiency of frost shattering and also of salt transport into stonework.

In terms of the importance of the *presence* of water to deterioration, McCabe et al. [8] discuss how increased "time-of-wetness" can lead to widespread "greening" by algae colonisation [9, 10]. In turn, the formation of algal biofilms can reduce the permeability of the stone surface, trapping more moisture in the interior. As well as being vital for chemical weathering, the presence of water is a prerequisite for frost weathering and it was found that frost damage increases with water content [11–13]. The frequency and magnitude of moisture *fluctuations* control the efficacy of salt weathering, freeze–thaw weathering, and wetting and drying weathering processes (which can be particularly damaging to building stones containing ample amounts of swelling clays). Thresholds of water *saturation* are fundamental to controlling the rate at which water can enter porous building stones, as well as controlling drying behaviour. All three factors (presence, fluctuations and saturation) are likely to be extensively influenced by climate change. For example, climate change driven increase of winter wetness might result in a greater depth of the wetting front and continued saturation of building block cores [14–16] with knock-on effects of increased chemical alteration within the stone and deeper penetration of salts in blocks [8, 17].

It is generally agreed that climate change is significantly changing the environmental controls on stone decay [14], and that historic buildings are likely to be increasingly vulnerable to adverse climatic impacts, particularly via moisture-induced deterioration [18]. Using a hydrological framework should enhance understanding of this vulnerability by considering the interacting effects on water flows and stores and highlighting the importance of hydrological context. Most current research does not consider built heritage within its hydrological setting [19], which can affect the success of any conservation strategies which focus only on the building itself. There are also challenges linking microscale information about water flows on and in heritage stonework to wider hydroclimatic changes. Climate change predictions can be used to estimate impacts on buildings (e.g. [5, 20]); however, the interaction between changes in mean precipitation, short-term event intensity, wind, radiation and resulting evaporation may lead to very different impacts at heritage sites due to small-scale variation in aspect, shielding, materials etc. Despite recent improvements in resolution, easily available hydroclimatological datasets and most climate change predictions have resolutions much coarser than needed to understand most water-based heritage deterioration processes which occur at cm scale. There is a considerable need for improved downscaling approaches [17] and thus, a consequent and systematic assessment of water fluxes (inputs, outputs) and storages for different settings and positions seems essential to us.

Hydrological systems of different types of heritage

We focus on structures made of natural stone, whereby we distinguish the following basic types: (1) stone-built buildings, (2) ruins and free-standing walls, and (3) rock-hewn sites which include carved rock art and large rock sculptures. A generalised heritage hydrological system is depicted in Fig. 1. However, as the hydrological settings are fundamentally different between the three mentioned types, more detailed diagrams of their hydrological systems are shown in Fig. 2. Stone-built buildings have an exterior and an interior climate, they are (when properly managed) protected against moisture ingress from underground by foundations and most of them feature various measures to keep water away from the facade (eaves, rain gutters). In addition, other materials are usually used in addition to natural stone, especially mortar joints, renders and plasters, forming a masonry composite (Fig. 2a). Buildings also contain extra material, such as insulation, designed to improve habitability which also affect the hydrology. Ruins and boundary walls (Fig. 2b) also form a masonry composite, although in this situation there is neither an "indoor" climate nor, in most cases, systematic measures to keep water away. One sub-category of freestanding walls with heritage values includes harbour walls and other examples of coastal and freshwater infrastructure whose bases are often submerged in water. A further sub-category is bridges which, like some elements of ruined buildings (such as arches), provide limited shelter from direct rain ingress producing limited "quasi-interior" conditions. The hydrological settings of rock-hewn structures and sites (Fig. 2c and e) are somewhat different as water can ingress from the back and top through fractures or similar water pathways in the solid rock. Thus, the general topographical setting (e.g. distance to flatter areas where precipitation can penetrate) becomes increasingly important, and the character and depth of the "quasi-interior" can be highly variable. In order to broaden the perspective, we include comparison to natural rock faces (Fig. 2d) where topography, aspect and rock structure become the key determinants and no "interior" exists. Rock-hewn structures and sites and natural slopes are clearly elements within broader hillslope and catchment hydrological systems, whereas buildings, ruins and boundary walls are usually components of urban hydrological systems.

Heritage hydrological flows and pathways: current knowledge and challenges

Analogous to catchment hydrology, the system components of heritage hydrology can be subdivided into water fluxes and water reservoirs. Furthermore, all of these storages and fluxes are determined by groups of parameters which are either climatic or depend on material. For example, infiltration of water into masonry is influenced by environmental conditions like rainfall and wind

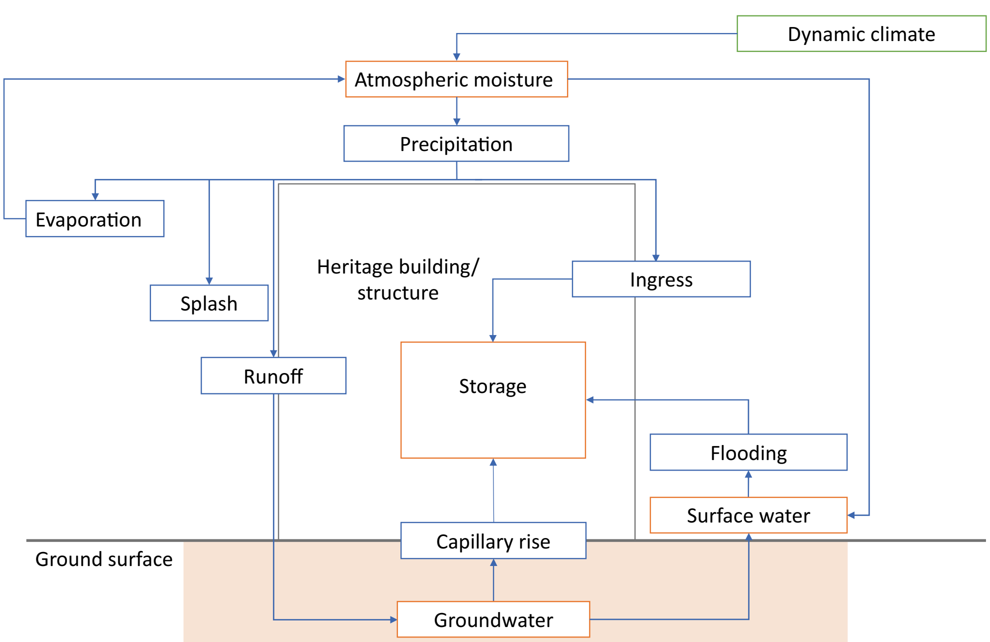

Fig. 1 Conceptual overview of the heritage hydrological system

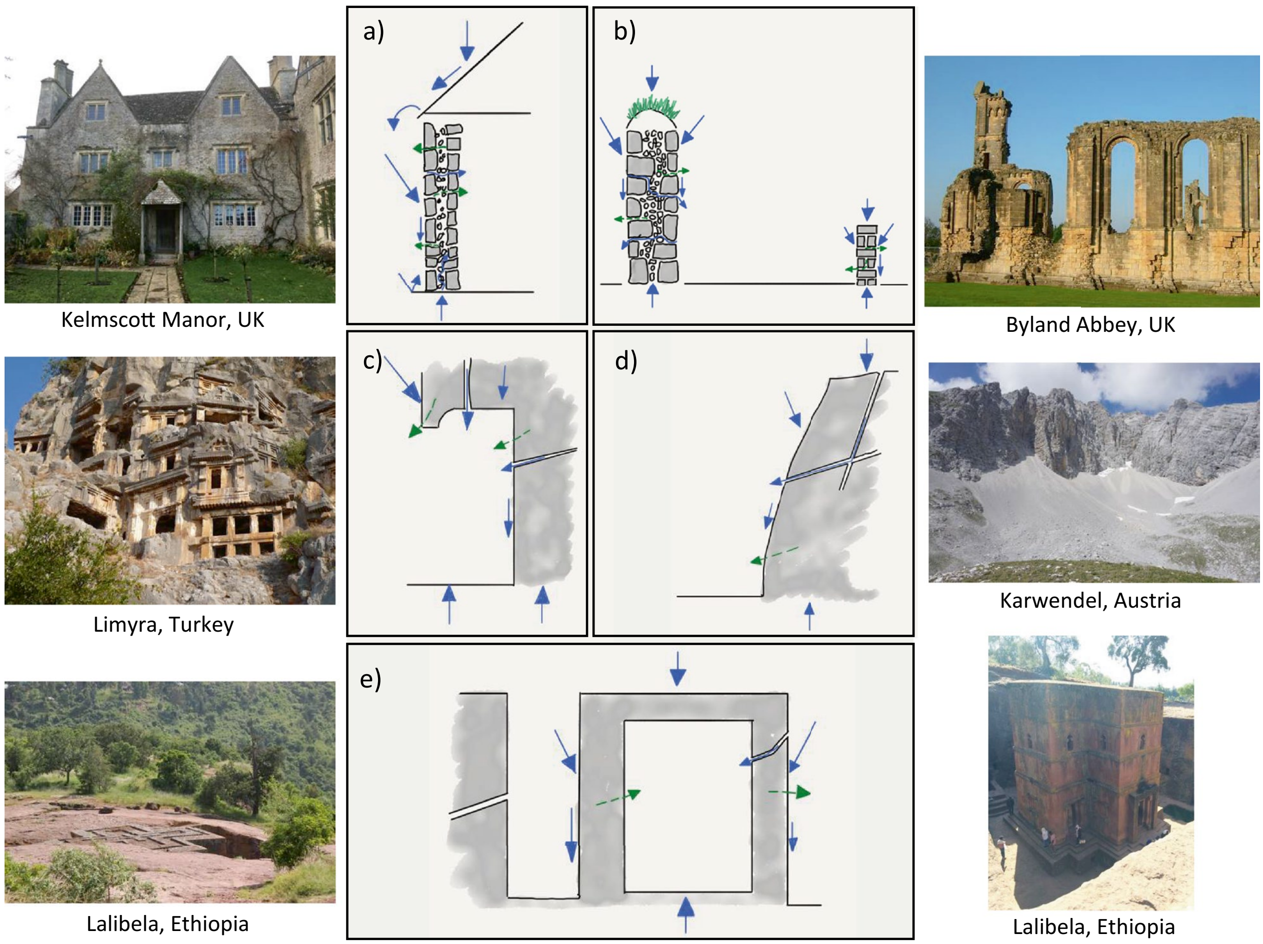

Fig. 2 The heritage hydrological settings covered in this paper: **a** Buildings, **b** ruins and free-standing walls, **c** rock-hewn sites carved into vertical rock slopes, **d** rock-hewn sites carved into horizontal outcrops, **e** natural rock slopes (for comparison). Blue arrows = liquid water, green dashed arrows = water vapour

directions, and also by the permeability and porosity of the different materials making up the masonry.

The ultimate sources of moisture in built structures are precipitation, soil- or groundwater, and to a lesser extent, capillary condensation from humid air. In some settings (e.g. harbour walls) moisture also routinely comes from open water, and a wide range of built heritage sites are also exposed to episodic moisture ingress from surface flooding (Figs. 1 and 2). Table 1 summarises the major fluxes and storages including their spatial coverage and, for fluxes, the magnitude and frequency characteristics (i.e. do they occur continuously, or frequently in low amounts and/or rarely in large amounts). Water from all these sources may enter the structure by capillary uptake or through macro fractures and design faults, and is distributed in the stonework by the same mechanisms. Storage of moisture may occur, usually in patches near the surface but to a greater extent deeper inside the structure (Smith et al. [14] call this 'deep-seated wetness'). The main pathway of water output is by evaporation while splash effects and runoff reaching the ground are restricted to periods of heavy precipitation. In limited situations, where there is extensive biological cover on walls, uptake by plants and transpiration may also contribute to water outputs. The fragmentary knowledge of the outlined system components of heritage hydrology is, to a large extent, due to difficulties of measurement. This applies above all to the storage component (which is the moisture stored over short or longer timescales in the stonework), but also to the hydrological fluxes involved.

Fluxes

Inputs: Wind-driven rain (WDR), capillary rise and condensation

As most building walls are more or less vertical, normal rainfall falls only on roofs, wall tops or ledges. For

Table 1 Major flows and storages considered within heritage hydrology, their characteristics and major effects

Category	Name	Magnitude and frequency	Spatial cover	Major effects
Inputs	Wind-driven rain (WDR)	High magnitude, low frequency (but variable)	General (certain directions favoured)	Water ingress to porous materials, runoff generation
	Capillary rise	Continuous, with high magnitude, low frequency events	Lower parts of structures	Water ingress to porous materials, deep-seated wetness generation
	Capillary condensation	Continuous	General	Material moisture equilibrium (" baseline")
	Surface floodwater	High magnitude, low frequency	Lower parts of structures	Water ingress to porous materials, deep-seated wetness generation
Throughputs	Runoff (down facade)	Low magnitude, low frequency	Patchy	Supports biofilms and chemical transformation on building surfaces
	Ingress (capillary)	Low magnitude, low frequency (corresponds to WDR)	General (certain directions favoured)	From WDR and capillary rise
	Ingress (cracks)	High magnitude, low frequency	Patchy	Higher velocity flow through cracks and design faults, gravity influenced
Storages	Surface wetness		Patchy	Influenced by factors controlling 'time of wetness', affects biofilms/chemical reactions
	Deep-seated wetness		General	Influencing indoor climate, mould etc
Outputs	Splash	Low magnitude, low frequency	Patchy	Driving rain may be splashed away from less porous or saturated surfaces
	Runoff (to ground)	Low magnitude, low frequency	Patchy	Usually controlled by 'water goods' (drainpipes etc.) in managed buildings
	Evaporation	Continuous	General	Encourages internal water movements and transport of soluble salts

water supply to vertical structures above the fringe of capillary rise, wind-driven rain (WDR) is the most important moisture source, is also responsible for the soiling of façades, and can be associated with mould growth inside the building [21]. WDR can be defined as "rain that is given a horizontal velocity component by the wind [...] that is driven against the windward facade of buildings" [22]. Droplets can impact surfaces at different impact speeds and angles, and the outcomes may be spreading, splashing or rebound. Droplets may coalesce and form a water film and run down the façade, eventually being absorbed in the material or leaking into the structure at joints and cracks [23].

WDR loads on building or rock-hewn façades are influenced by a wide range of parameters at different scales, of which normal rainfall, wind speed and wind direction are the cardinal ones. However, building geometry and size, position on the building façade, environment topography, turbulence intensity and even raindrop-size distribution have considerable impact on WDR load [23, 24]. There are four methods of estimating WDR exposure (Table 2), of which wind-tunnel experiments are not treated here in detail due to the special equipment required. Of the other three, all have their advantages and disadvantages. (a) *Experimental measurements* are generally time-consuming and prone to errors. Different sizes and shapes (circular, triangular) of vertical gauges have been used. Ref. [25]

Table 2 Methods of assessing WDR exposure and their advantages and disadvantages

Method	Advantages	Disadvantages	Key references
Wind tunnel measurement	Controllable experimental design	Specialized, expensive equipment	[32]
On-site measurement	Accommodates all geometries and topographies, realistic exposures	Large error margins are possible, time-consuming	[25, 33]
Semi-empirical equations	Ease of use, applicable to all sites where appropriate data is available	Estimates WDR exposure	[22, 26, 34, 35]
Numerical methods	Accounts for all parameters	Computationally demanding, specialized tools needed	[23, 30, 31, 36]

found that adhesion water which can evaporate from the surface of the collectors is a significant source of error. (b) *Semi-empirical formulas* are based on experimental observations showing that wind vector and vertical rainfall are the most important control factors of WDR, thus allowing a regional-scale assessment of WDR loads from climate data (e.g. [26]). At the building scale, these parameters are supplemented by proportionality factors which are dependent upon the position at the building [22, 27]. Abuku et al. [21] and others observed that the highest values are found at the top edges of buildings due to the higher wind speed and accelerated wind flow around the corners, while areas near the base of large buildings often receive no WDR at all. Catch ratios for natural rock outcrops are widely unknown (to the knowledge of the authors). Semi-empirical models may deviate from field measurements by up to 88%, and the outcome of individual semi-empirical models may differ by up to 300% [28]. (c) *Numerical simulations* are mostly based on computational fluid dynamics (CFD) (e.g. [29–31]). As CFD simulations provide impact velocities and angles for each droplet size at any location, they can deliver detailed spatial and temporal information on WDR even on complex geometries [23]; however, the required computer power and technical experience are high.

Wind-driven rain at cultural heritage sites is a complex and multiscale phenomenon. Bridging the scales from regional approaches to the scale of districts to individual buildings and to small-scale droplet impact (and vice versa), is still a major challenge [23]. While field experiments and CFD simulations focus almost exclusively on building structures, very little is known about WDR distribution at rock-hewn sites and natural rock outcrops. At these near-natural sites, as well as in the context of greening cities, the link between WDR and vegetation of different size (lichens, creepers, trees) needs to be further explored.

Capillary rise is the second prominent source of moisture inputs. There are several framework conditions that determine if damp can rise in the masonry. On the large scale, water supply is determined by climate, controlling the water saturation of the soil surrounding the foundations. Furthermore, groundwater level is paramount. Apart from these large-scale factors, the detailed situation at the building site influences the potential for capillary rise. This includes drainage around the foundations as well as the shielding and evaporating role of vegetation. Finally, water ingress into the stonework is determined by material properties and by protective measures like hydrophobic treatments and consolidation. The issues of capillary rise of moisture and of its removal from the building structure were reviewed by Franzoni [37, 38]. Coping with capillary rise is an urgent problem in heritage conservation, as the techniques of damp removal are not always successful and data about their effectiveness in the field are limited [38].

Sorption of water vapour at the surface and along the inner surfaces of pores is also an important process of water input. It mainly occurs when the rock or stonework is cool and moist air can condensate. The particularly critical time of year for this process in the mid latitudes is spring. It is a well-known mistake in moisture management to ventilate churches and other historic buildings at this time, as the condensation of moisture on the cool walls can severely damage frescoes, for example. However, absorption and capillary transport in the liquid phase is quantitatively much more effective [39]. Thus, desorption and drying is the more important process in the vapour phase, which is accordingly treated in 2.1.3 (Outputs).

Throughputs: runoff down façade, ingress by capillarity and permeability

We differentiate between "runoff down façade" which infiltrates later at another part of the building structure or evaporates, and "runoff to the ground" which belongs to outputs (see Sect. 2.3) even if the formation mechanism is the same. While ample investigations on WDR and capillary rise have been carried out, less research has been done on the response of the building walls and the water fluxes after the impact of raindrops. WDR reaching the surface of a structure can enter the pore structure or run off from the surface. As a first approximation, this process is equivalent to the generation of Hortonian overland flow in catchment hydrology: If the rain load surpasses the capillary absorption capacity, the surplus water runs off. However, on built heritage runoff generation is a much more complex process including splashing or bouncing of raindrops, spreading of water, film forming and evaporation. The situation may be further complicated by water-repellent coatings, plasters, or weathering rinds. Blocken et al. [22] present a detailed review of rain water runoff from building facades which highlights that, as the highest catch ratios are found at the upper parts of a building, runoff usually starts there. Due to flow accumulation, the highest runoff per unit area is usually found some meters below the upper edge of the building. Surface structures and protrusions present important modifications for runoff. While ideally, protrusions can cause the water to drop down, water ponded at horizontal ledges can enter cracks and cause localized moisture problems [22]. Runoff at rock-hewn sites or at natural rockwalls is highly influenced by (micro-) topography and has rarely been addressed systematically.

Capillarity defines unsaturated water flow, while permeability describes saturated water flow for which a pressure gradient is required [40]. Capillary flow is the most common water transport mechanism in buildings and free-standing walls (as complete saturation does rarely occur here due to arid microclimate) while permeability is more common close to groundwater and in rock-hewn structures. Capillarity is the absorption of water against gravity per square root of the unit time by a given cross-sectional area, and is determined by porosity and pore radius. As long as the moisture content at the wetted surface is below the capillary moisture content, the absorption flux is equal to the supplied flux (e.g. WDR), on condition that the supply flux is sufficiently small, which is generally the case for WDR and a relatively dry wall [22, p.353]. Capillarity of building stones is the most important determining factor for the level of capillary rise [41] which is one of the main factors in deterioration.

Many studies of capillary absorption and permeability of heritage stones have been performed, both in the lab and on site. Permeability is determined by means of permeameters in the laboratory, either using triaxial tests or under constant head conditions [42]. Capillary water absorption can be determined by the weight gain of rock samples with one surface in contact with water [39]. Benavente et al. [40] and de Boever et al. [43] demonstrated that capillarity correlates with permeability of building stones and that permeability can, thus, be calculated from capillary suction experiments. However, material properties of weathered stones may differ considerably from freshly quarried stones (which are mostly used for controlled laboratory tests) e.g. in terms of disintegration, surface crusts and treatments. While the absolute amount of water absorption generally increases with weathering, water penetration depth is often higher in the fresh than in the weathered stone [44]. The water absorption kinetics was faster in the weathered samples, and the amount of water absorbed increased with the number of weathering cycles. Vandevoorde et al. [45] compared in situ applicable measuring techniques for analysis of the water adsorption by stone, namely the contact-sponge method, Karsten tubes and Mirowski pipes and assessed them against standardized capillary rise tests in the laboratory.

One of the most prominent challenges surrounding capillarity and permeability is to transfer the results obtained from intact rock samples under controlled conditions in the lab to "real-world" masonry, in which single stones may derive from different periods of construction or might have been replaced by repair works. Furthermore, inhomogeneities and cracks are rarely addressed in field studies. Experiments on the ingress of moisture though cracks have mainly been carried out in cementitious materials. The consensus view is that cracks facilitate rapid ingress of moisture. However, ingress depends on crack orientation: water ingress parallel to a coalesced crack is facilitated, while lateral distribution remains relatively constant, and isolated micro cracks may even inhibit water sorption [46]. The ingress of water in cracked concrete specimens has been visualized via electric resistivity tomography (ERT) (e.g. [47, 48]) while [49] investigated crack-moisture interaction in a numerical model. Nevertheless, given the extremely diverse possible properties of cracks (direction, continuity, opening width, crack branching, tortuosity), there is still ample need for research. Very few studies have dealt with the role of cracks for water penetration in natural stone or in rockwalls.

Outputs—evaporation and runoff

Water can leave the structure through evaporation, splash and runoff to the ground. Strictly speaking, the latter two processes are not outputs in the narrower sense as the water in question does not come out of the structure, as it does not enter it in the first place. Abuku et al. [21] measured WDR impact with high speed cameras and found that drops can either splash or bounce depending on diameter, impact speed and impact angle. Some of these droplets can eventually reach the ground. Currently, state-of-the-art hygrothermal models do not take runoff into account [22]. Runoff to the ground is rather improbable on vertical building facades, as WDR input is of low intensity in most cases and the stonework is usually not saturated. This restricts runoff events to exceptional rainstorms. Thus, evaporation is the most important process of water output and, as Hall and Hoff [50, p.239] put it '…it is the evaporation of water at building surfaces that drives the flow of moisture through building structures.' Evaporation from building material surfaces has proved very difficult to monitor directly, and usually calculations of potential evaporation or PE (i.e. evaporation from an open water surface) are used. Hall and Hamilton [51] report on the development of a patch evaporimeter which could be used to measure PE at points across building surfaces, while [52] introduce a field-based method using sandstone cores.

The moisture content of natural stone is in static and dynamic equilibrium with atmospheric humidity. Water output from stonework works almost exclusively via the vapour phase. The equilibrium line between the ambient air humidity and the water content of a porous material such as rock or building stone is called the moisture sorption isotherm. The shape of the isotherm varies with the pore radius distribution of the sample. Most isotherms drop quite steeply between 95% and approx. 80% air humidity, which means that a slight drop in air humidity sets the drying process in motion. Due to the high surface area of porous stone, the drying rate of the materials can be higher than the evaporation rate of a free water surface [53]. Surface sealing by misplaced treatments or by crust formation can inhibit the drying out of the stone and cause prolongation of periods of dampness under the surface [54, 55].

Several gaps in knowledge remain about water fluxes within heritage hydrology settings, as some are easier to measure than others, and the measurement or estimation methods vary. In particular, it remains challenging to measure outputs by evaporation. There is still a need for comparable datasets on fluxes (inputs, throughputs and outputs) in different settings.

Stores

Moisture content or dampness is a measure of water stored in masonries. In most cases, high levels of dampness are considered negative because moisture increases heat conductance, transports damaging salts and promotes the growth of mould and other biota. We make a distinction between more mobile short term stores (hours to weeks) which are often surficial and longer term stores (months to years). The latter were termed 'deep-seated wetting' [14]. Accordingly, damage to the stonework might ensue from small-scale fluctuations, as well as from the time of wetness [56] which could become increasingly important within thick heritage walls in many areas as a result of climate change.

As pointed out in the previous sections, dampness may derive from wind-driven rain, capillary rise or episodic flood events (predominately in the liquid phase) and is reduced by evaporation (mainly in the gaseous phase). Thus, stone moisture is determined by the ratio between these two fluxes which are controlled by capillarity and water vapour diffusivity, respectively. As evaporation occurs more or less continuously from the inner and the outer surfaces of a building wall, mean dampness is usually highest in the core of a wall and decreases towards the evaporating surfaces. During rainfall, moisture in exposed surfaces increases rapidly and the water is distributed within the stonework by capillary transport. Prolonged periods of rainfall can cause the wetting front in building stone to penetrate 25 cm or deeper [57]. This means that moisture levels at or near a weather-exposed surface fluctuate strongly while they are more constant in the interior [58, 59]. The equilibrium level of this deep-seated moisture is likely to change slowly in a changing climate because of shifts in the mentioned ratio between capillary uptake and evaporation. Particularly in the north of Europe, winter precipitation is expected to increase which would increase the time in which build heritage sites remain wet ("deep-seated wetness") with impact on stone deterioration [14]. Deeper, continuous wetness is likely to allow deep-seated salt penetration. A current major challenge is to provide meaningful measurements of moisture levels and their fluctuations in built heritage.

Measuring moisture in stonework

Despite the central importance of stone moisture for heritage conservation, "the core problem in the evaluation of the mitigation measures against rising damp is how to measure materials moisture" [37, p.133]. Even though a wide range of measurement techniques is available, there is no one ideal technique that combines non-destructiveness, reliability, repeatability and applicability at field sites. Table 3 gives an overview of the available techniques and their advantages and disadvantages. Reviews of moisture measurement techniques in porous media were presented e.g. by [50, 58, 60].

The gravimetric technique is a direct measure of water content and is thus, often used as reference method. It uses stone fragments that are chipped of or collected in the field, and are oven-dried in the laboratory to determine the water content. The fundamental problem of this technique is the destructiveness, the lack of repeatability and in most cases, the limited amount of samples. These disadvantages can be partially compensated by the use of pieces of stonework or drill powders placed inside sealed drill holes [7].

All other methods are indirect and use chemical, physical or electrical parameters of the stone that change with water content (such as electrical resistance, capacitance, IR emissivity, microwave attenuation etc.).

Measuring Borehole Humidity is based on the equilibrium between stone moisture and water vapour concentration in the surrounding air. Successful application is limited to unsaturated conditions, e.g. indoor or arid environments [67] as the relative humidity at the evaporation front quickly reaches 100% [52]. Due to the unfavourable hysteresis behaviour, humidity is stuck at 100% for most of the time when measuring in humid outdoor conditions.

The electrical resistance of porous samples changes with water content by several orders of magnitude [55, 58, 68]. Problems occur due to the salinity of the pore water which is generally unknown. As salts are usually present in urban settings and sites with capillary rise, resistivities can change by orders of magnitudes. For conversion to gravimetric moisture contents, calibration curves for different materials have to be derived in the lab, and the geometry of the sensor configuration needs to be taken into account [58, 68]. 2D-resistivity (Earth Resistivity Tomography, ERT) is an extension of conductance measurements. The use of numerous (up to 50 and more) electrodes together with a control unit

Table 3 Overview of a selection of moisture measurement techniques used for rock, stone and other porous building materials (for a more comprehensive list see [60, 61])

Technique	Principle	Invasiveness	Strengths	Weaknesses	References
Gravimetric	Oven-drying of samples	High (chipping off or drillhole)	Reference method	Low temporal resolution	[7]
Borehole humidity	Equilibrium between air humidity and rock moisture	Moderate (drillhole needed)	Monitoring possible, good calibration via sorption isotherms	Not suitable for high saturation, values are stuck at 100% for long periods	[60]
Infrared thermography	Modification of temperature by attenuation and evaporative cooling	None	Quick spatial overview at high resolution	Only qualitative surface information; reflectivity at different angles	[62]
Electrical resistivity	Electrical current flow between two (or four) electrodes	Moderate (drillholes needed)	Simple, relatively cheap, strong response to water content	Strongly affected by pore water salinity; individual calibration required	[58]
2D/3D-electrical resistivity (ERT)	Combining automatically switched measurements to a 2D or 3D section	High with drilled electrodes; none when adhesive electrodes are used	Producing clear and instructive sectional views		[55]
Microwaves	Attenuation or reflectance of microwaves (1–10 GHz)	None when surface sensors are used	Unaffected by pore water salinity	Calibration required, limited depth information, susceptible to surface roughness	[63]
Ground-penetrating radar	Attenuation of electromagnetic waves (10–1000 MHz)	None	Measurement along profile lines or 2D arrays	Affected by coupling conditions at uneven surfaces	[64, 65]
Time-domain reflectometry		Moderate (drillholes needed)	Less error sources than electrical resistivity, only slightly influenced by salts	Physically difficult to install, edge effects along sensor rods	[66]

allows to calculate the 2D- or 3D-distribution of electrical resistivity. The results can visualize water absorption and desorption of stonework [55], the level of capillary rise [69] and the salinity of groundwater [70].

Infrared thermography (IR) can be used for moisture detection as wet surfaces are usually cooler due to evaporation. In a study by Grinzato et al. [71] capillary rise was evaluated under laboratory conditions; the authors observed temperature differences of up to 7 K between dry and wet brick. Thus, cold temperature anomalies are normally used to detect moisture, while warm thermal anomalies relate to potentially unstable structural conditions (cracks, cavities, blistering) rather than to dampness [72]. Making use of these anomalies, IRT is frequently used for mapping moisture distribution on building facades [73, 74]. Most investigation only make use of relative temperature differences; emissivity and reflectivity of the building materials are important issues [75] if quantitative assessments are to be carried out. Complex surface topography poses numerous pitfalls for interpretation when reflecting colder or warmer surfaces (Sass et al., in prep.).

Microwave measurements of moisture are based on the difference between the relative permittivity of water and most geological materials in the microwave frequency range (between approx. 1 and 300 GHz). Available handheld devices work from the surface by producing an electromagnetic wave and measuring the proportion of energy that is reflected. Commercial or self-developed handheld sensors (e.g. [63, 76]) work in a frequency range around 1–10 GHz. In this frequency range, it is assumed that the influence of salt content can be neglected [77]. Handheld microwave sensors are very good for quick surveys of spatial moisture distribution [63, 76]. Varying surface roughness, particularly on near-natural surfaces, can influence the results. In most applications, merely semi-quantitative, unitless moisture indices are measured as "calibration is cumbersome and tedious" [77], even if some linear calibration curves between water content and microwave reflectance have been established [63, 76, 78, 79].

Similar to microwave and TDR sensors, ground-penetrating radar (GPR) uses electromagnetic waves (at buildings: approx. 200 MHz–1 GHz) to investigate the dielectric properties of the wet stonework. Both propagation velocity and reflectivity of the EM pulse are determined by dielectric permittivity (or contrast in permittivity, resp.) which depends on water content [66]. Using full-waveform analysis, the thickness of the saturated layer in weathered rock could be accurately determined [65]. Such quantitative estimations usually work well in the laboratory, while on-site measurements are mostly limited to qualitative estimations [66]. Application is restricted to comparatively smooth surfaces.

The principle of time domain reflectometry (TDR) is based on the propagation velocity of an electromagnetic wave along a probe. EM propagation velocity is a function of permittivity, which is high in wet media due to the high electric polarizability of water [66]. Soil moisture measurement is the main application of TDR [80]; however, the method has also been applied to solid media like concrete and clay brick [81], limestone [82] and fractured rock [83]. In solid rock, TDR probes are technically difficult to install and susceptible to water movement along the rods [58], which is why they are often firmly embedded in building material [84]. Backfill material used to facilitate installation in fractured media always affect the measurements [83]. In all building materials, empirical calibration using the gravimetric method is advisable [66, 81].

In summary, a range of techniques is available which have to be chosen with care to match the respective task. While most methods can easily detect spatiotemporal differences in dampness, quantitative statements require complex calibration. This is particularly valid for nondestructive testing (e.g. [73]), especially when dealing with historic building structures where collecting calibration data this is not always possible in practice [62]. Further techniques are under development or used in single studies (e.g. ultrasonic, fibre optics, x-ray tomography) but have not acquired usability in the sense of a standard tool.

Spatial patterns of moisture

Moisture distribution varies widely between different heritage sites. At each site, fluxes and stores are governed by the individual geographical and topographical settings, the materials used, meso- and micro climate, and the respective site management. This means that every structure is unique, even if certain similarities can be identified. Patterns of moisture are different between buildings and rock-hewn sites, both presenting hydrological complexities. Intact buildings have pronounced indoor and outdoor climates and may involve complex combinations of geomaterials, e.g. mortars, plasters and plinths. Sculpted facades at natural rock outcrops are fundamentally different (and equally complex) as they are even more closely interconnected with their environment—with flows potentially coming in from behind and to the sides as well as via rainfall and groundwater rise.

We here differentiate between the detail or micro scale (= single building elements like stone blocks, ledges, or pillars, or similar elements of decimetre- to metre-size at carved rock sites); the façade scale (= e.g. side of a building, single wall, or rock wall in which e.g. tombs were carved, at the size of metres to tens of metres); and the building or site scale (= e.g. an entire building or structure including different orientations, an archaeological site in its entirety, or a rock massif in nature, at the scale of tens to hundreds of metres). Spatial patterns of moisture can be investigated by means of all techniques that deliver data over a certain area or volume, or that can be quickly applied in survey lines or in a grid. In practice these are IRT, GPR, 2D/3D-resistivity and all kinds of handheld moisture meters, particularly conductance, capacity and MW sensors.

Figure 3 shows an example of moisture variations at different spatial scales at a test wall site at the University of Bayreuth campus: (a) patchy patterns of small-scale differences within single blocks, often being wetter at the base of the block; (b) different moisture at different elevation above ground, i.e. signs of capillary rise at both west-facing walls; (c) differences between different faces of the same structure, e.g. drier east face and wetter west face at the "rock" structure; (d) differences between different structures; e.g. the unshielded "rock" structure is wetter on average, and the "house" is wettest at the north side, although the two structures are only 3 m apart from each other.

a. Detail scale (= micro scale)

It has repeatedly been found that moisture distribution can vary on a very small scale. Valek et al. [62] investigated artificial sandstone walls of 1.0 × 1.5 m size using handheld moisture meters (capacitance, microwave) and found very patchy patterns, differing from between adjacent stone blocks. Despite the irregular patterns, higher dampness towards the base was found. Similar patchiness was found at a boundary wall built of natural stone [85] and at test sites of granite and sandstone separated by mortar joints [63]. McCabe et al. [86] pointed out that iron coatings and biota crusts cause considerable block-scale heterogeneity, in most cases with heightened moisture levels underneath impermeable coatings. The same was found for artificial moisture barrier coatings by means of numerical simulations [87]. Ahmad [88] presented a conceptual diagram showing the impact of architectural detailing on heritage hydrology using the example of a small turret on the façade, and distinguishing rain stores, spillways, drainways, exclusion zones and upflows. Heterogeneity on the decimetre scale can also be found at natural rock outcrops due to the complex combination of water percolation, condensation and capillary rise.

b. Façade scale (= rockwall scale)

Barbosa et al. [74] suggested to map moisture distribution using IRT and to classify damp areas according to the origin of moisture: Air moisture (correlating to capillary condensation), percolation moisture (rainwater infiltration), upward moisture (capillary rise), accidental moisture (pipe leakages etc.) and building moisture (inherited deep-seated storage). At their study site, a public school building in Brazil, they identified percolation moisture at upper façade and upward moisture at its base (Fig. 4). Valero et al. [73] investigated a parish church by means of electrical conductance and IRT and found wet parts in the middle of pillar front while the base was dry; this pattern they assigned to rainwater and runoff water

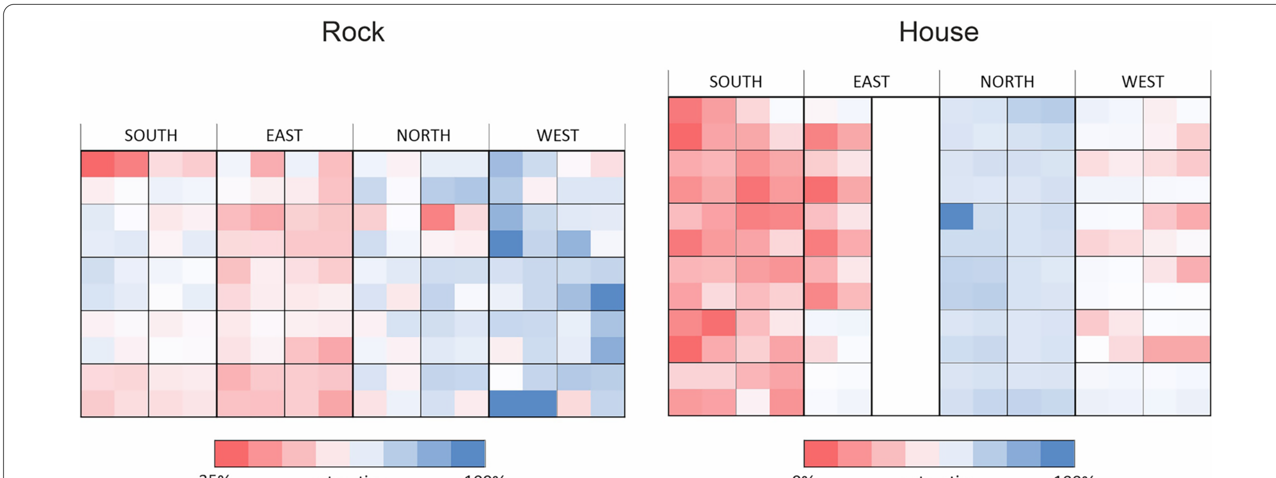

Fig. 3 Relative differences in dampness derived from handheld microwave sensor (hf-sensor P1M, penetration 2–3 cm) at a test wall site at campus Bayreuth. Left side: cube-shaped structure without roof and with sand filling (simulating natural rock), right side: hollow, roofed structure on a concrete foundation, simulating a building. Material: Franconian sandstone ("Trebgaster Sandstein"); size of each block is 30 × 30 × 30 cm

Fig. 4 Moisture distribution at a public school façade in Juiz de Fora, Brazil derived from IRT images. The colours denote different origins of water (see text): upward moisture (blue); accidental moisture (green); percolation moisture (red); building moisture (magenta) (Taken from [74], Fig. 6])

penetration. These results illustrate that individual, broadly comparable sites can show very different origins and spatial patterns of moisture. At natural rock sites other patterns emerge. Based on IRT surveys at rock cave sites in Georgia [72], higher dampness was found distributed over the rock outcrop along water runoff pathways and systems of open cracks, while at the monastery of Petra (Jordan), wetter areas were caused by seepage water at the base of the site.

c. Building scale (=mountain scale)

Investigations of moisture distribution on the scale of entire buildings or sites are carried out by practitioners e.g. for building management purposes, but are comparatively rare in research focused studies. Studies on WDR distribution based on CFD modelling (e.g. [31]) should be mentioned here, although they mostly deal with the amount of impacting rain rather than with the resulting water content of the stonework. Solla et al. [89] investigated a granite arch bridge in Spain using IRT and GPR and located one wetter vault caused by local conditions. Cardarelli et al. [70] presented data on an ERT survey of a Roman building in Ostia Antica and located the main moisture problem through capillary rise. Sass [76] investigated sandstone rock towers in Saxony (Germany) using microwave sensors and ERT, and found wetter conditions at north faces shielded from radiation, however, smaller-scale patterns often masked the exposure differences. This problem is a significant fundamental challenge for any large-scale investigation as moisture is much more variable on the small scale (compared e.g. to temperatures).

The superposition of moisture on different scales is visualised in Fig. 5. The multitude of influencing parameters on different scales leads to a complex distribution of moisture. It is not possible to give a general answer as to which dimension of moisture distribution is relevant for management and protection.

Temporal patterns (including changes induced by climate change)

Moisture fluxes and stores within heritage walls vary over time, in response to short-term (diurnal) fluctuations in temperature, relative humidity and rainfall, high magnitude episodic events such as floods and storms, and longer-term changes in environmental conditions as a result of seasonality, interannual variability and secular trends or climate change. It appears that there are fewer published studies looking at these temporal fluctuations than studies which focus on spatial patterns (as reviewed in Sect. 2.4). It is not yet clear whether the different types of heritage site portrayed in Fig. 2 exhibit different temporal moisture patterns and behaviours. Most work, as reviewed below, focuses on relatively simple walls and buildings. The use of realistically complex test buildings, such as the brick VLIET building constructed at K U Leuven in 1996, allows monitoring of hygrothermal behaviour over a range of timescales.

a. Short-term (minutes to days) fluctuations

Relatively few studies have been carried out of how heritage stonework responds to changes in environmental conditions over timescales of minutes to days. Some very careful observations have been carried out under controlled laboratory conditions. For example, Franzen and Mirwald [39] performed a lab-based experimental study based on gravimetric measurements to illustrate the dynamic behaviour of sorption and desorption on Baumberg Sandstone under naturally dynamic RH conditions. Taking measurements of humidity and sample mass every 10 min over a 2 month period they found a ‘breathing’ response of the stones as uptake and loss of water vapour accompanied changes in humidity. More recently, Chabas et al. [90] report on the use of a new environmental chamber (CIME2) which is able to simulate the response of stone (again, based on gravimetry) to different types of wet deposition (rain, drizzle and mist)

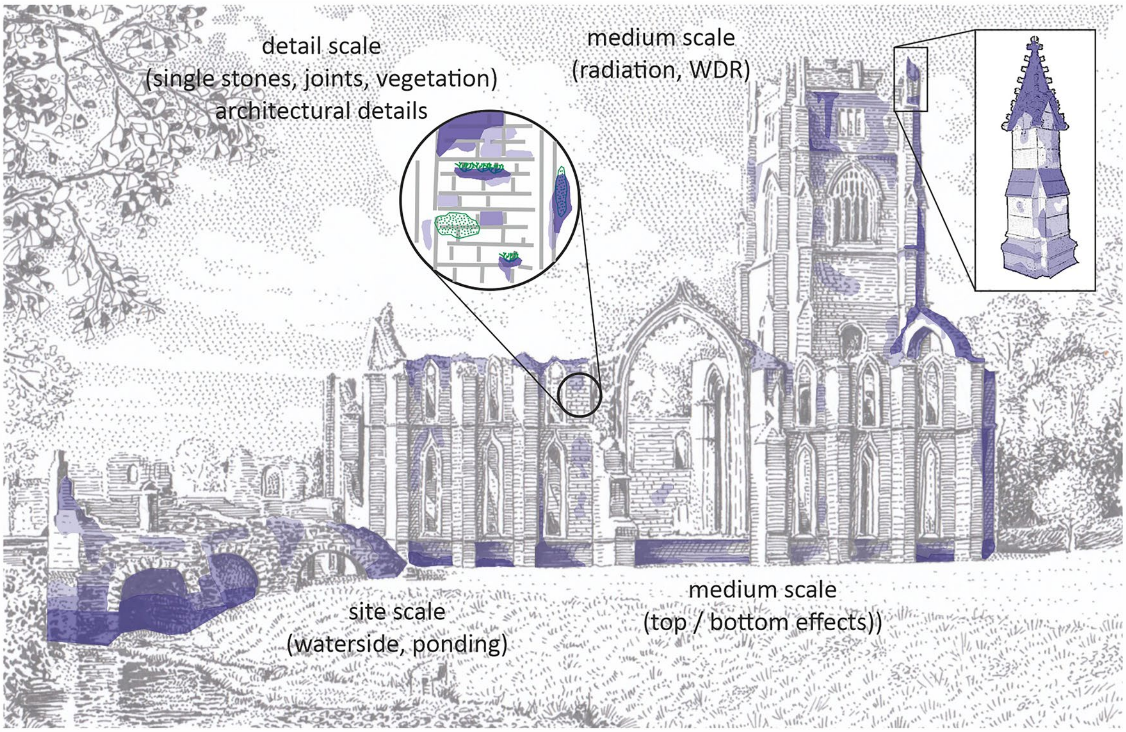

Fig. 5 Hypothetical distribution of moisture patterns at a ruined site. Large-scale patterns (e.g. position at waterside), medium-scale patterns (capillary rise, exposition to WDR and radiation) and small-scale patterns (building stones, micro-topography, biota) combine to produce a complex distribution. Background image: Fountains Abbey by Trevor Yorke

under more realistic conditions than most previous laboratory simulations.

Published site-based studies of heritage hydrology over minutes to days usually involve repeat surveys using some of the techniques listed in Table 3 and often aim to investigate the response of stonework to rain events. Studies using test blocks or test walls are more common than those based on real buildings. For example, McAllister et al. [59] looked at temperature and moisture dynamics in sandstone blocks in Belfast exposed to rainfall. Peakmoor Sandstone blocks were exposed in a frame with one vertical face (20×10 cm) exposed, and resistivity sensors used to measure moisture conditions at different depths inside the stone. Figure 6 illustrates the response of sensors in the block facing NE at depths from 50 to 5 mm to a series of rainfall events.

Similar data was collected by Orr et al. [63] but at a larger scale, and using different measurement techniques. They simulated a driving rain event using a pressurised spray on a granite test wall and used non-invasive microwave equipment and high resolution GPR to map and monitor the wetting and drying. Measurements were taken every few hours on granite blocks and also on horizontal and vertical mortar joints providing a record of the moisture dynamics of different materials at different depths.

b. Response to seasonal and longer-term changes

Studies focusing on seasonal and longer term moisture dynamics tend to be based on monitoring and modelling of real walls and buildings. For example, D'Ayala and Aktas [18] investigated the response of two brick-built heritage buildings to changing atmospheric conditions (RH and WDR) in flood-prone Tewkesbury, UK, using a network of temperature and relative humidity sensors embedded at different depths inside the walls. The two buildings showed different dynamics—one responded almost instantaneously to changing atmospheric RH, while the other showed a lagged response. More recently [91], used a combination of sensors, CFD modelling and IRT to produce a 12 month picture of moisture dynamics across a 400 year old church in Valencia, Spain. Data from the sensors and infra red thermography provide complementary information which is used to validate the CFD simulations.

Modelling based on the Sharp Front theory has proved to be particularly useful in investigating seasonal moisture dynamics. For example, HYDRUS modelling was

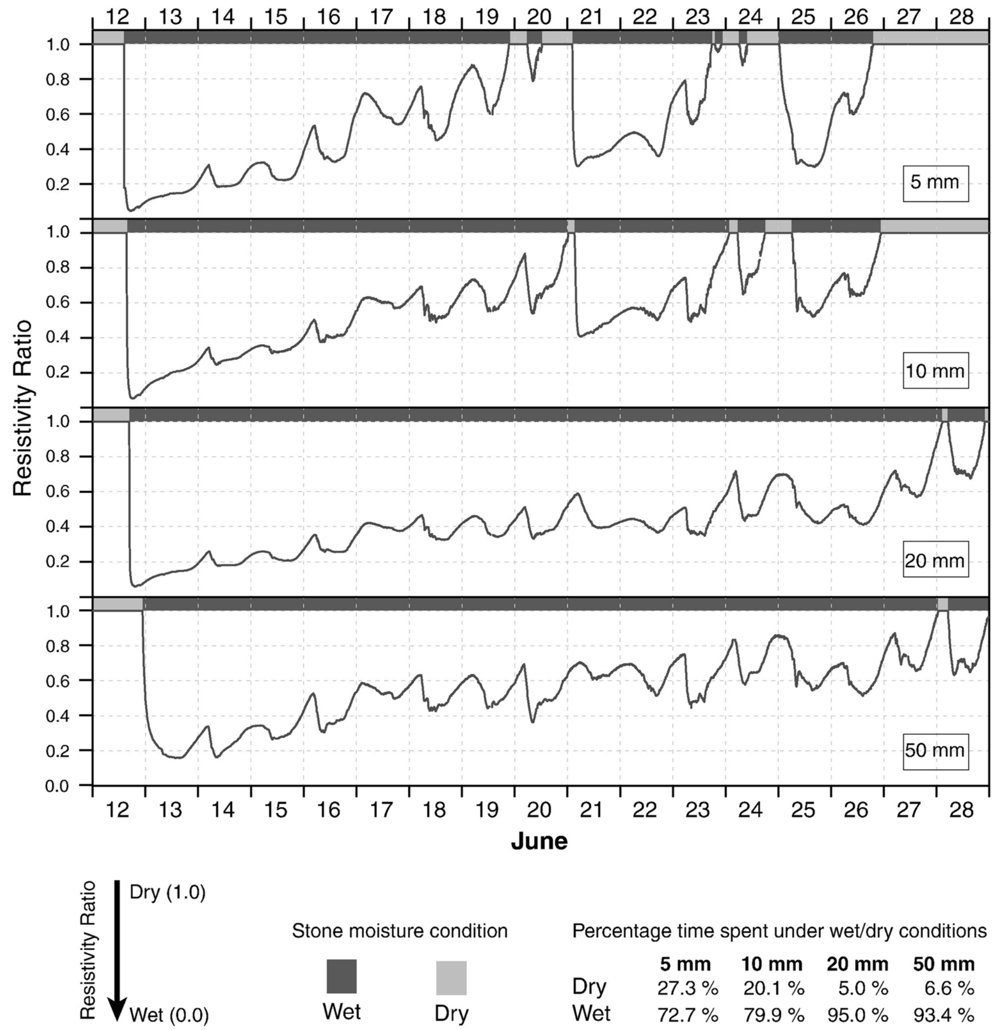

Fig. 6 Response of a Peakmoor sandstone block to a rainfall event as reflected in resistivity ratio data from resistivity sensors located at different depths within the block. Low resistivity ratio values signify wetter conditions (Reproduced from Fig. 11 in [59])

used to investigate the dynamics of capillary rise in stone walls as a response to seasonal and climate change-induced changes in evaporation [92]. They found that higher potential evaporation leads to lower capillary rise heights, higher rates of water flow and more rapid response to seasonal shifts in potential evaporation. Partial validation of the model results came from data from Mediterranean and northern European walls (Egypt and Oxford, respectively). D'Agostino [93] did a similar modelling study focused on the crypt of Lecce Cathedral in Italy to investigate seasonality in capillary rise. Both studies reveal a large amount of water flux through capillary rise, which is likely to have significant consequences for the deterioration of building materials. Vogel et al. [94] build on this Sharp Front modelling approach, using the Richards equation to investigate the dynamics of capillary rise in a sandstone church in the Czech Republic. They carried out monitoring of moisture on site over a 2 year period to parameterize and validate the model. The study found that, over the long term in this church, second stage evaporation (controlled by material properties) is more important than stage one evaporation (controlled by environmental conditions). Combined modelling and monitoring studies using multiple techniques to capture inputs, throughputs and outputs are now feasible and likely to generate useful results.

While most monitoring and modelling-based studies usually only investigate the dynamics of moisture over 1 or 2 years, longer-term changes are of great interest. For example, it is highly likely that during the last few hundreds of years, the hydrology of heritage sites has varied as a result of, for example, changes in climate such as the Little Ice Age. Over tens to hundreds of years the wall characteristics are also likely to have changed, both as a result of deterioration and as a response to repairs and conservation efforts. However, there are no instrumental records of moisture within walls that we are aware of over such long timescales. It may be possible to extract some information from historical imagery (which might, for example, depict changes in heights of capillary rise and surface runoff patterns). Looking towards the future, numerical modelling provides a good set of tools to investigate the likely impacts of climate change over decadal and century scales on moisture dynamics within heritage walls and sites. For heritage buildings, research on future hydrological behaviour needs to consider the operational context and practical issues such as the need for energy retrofit interventions designed to reduce their carbon footprint and help contribute to net zero goals. Such interventions may enhance the risks of moisture problems [16].

Heritage hydrology: conclusions and future research agenda

The review and synthesis presented in this paper raise six key points about the state of research on moisture regimes and dynamics on heritage buildings and sites, from which we develop a research agenda for heritage hydrology in the future. Point one is that three characteristics of moisture regimes are important to deterioration, i.e. presence, fluctuations and saturation thresholds. Second, there is a wide range of different heritage hydrological settings (illustrated in Fig. 2) ranging from masonry building walls to natural rock slopes, and as yet no clear understanding of the commonalities vs specificities of these different settings. Third, the different components of the heritage hydrological system depicted in Table 1 have been studied in greater or lesser detail so far, depending on their importance and ease of measurement. Fourth, while there is now a wide array of techniques available to measure and monitor moisture regimes in lab and field settings, work still needs to be done to understand how comparable different measurement approaches are. The fifth point is that, especially at the small scale, there are now many measurements of the spatial patterning of moisture, but lack of clarity about the causes of these patterns. Finally, while there has been less research focusing on the temporal dynamics of moisture on heritage walls and sites (and studies have mainly concentrated on short term behaviour), studies combining measurement and modelling have proved particularly useful. There are several remaining open questions and gaps in knowledge. For example, it is not clear which spatial and temporal scales of moisture variability (detail vs. site scale, diurnal vs annual) are most relevant for decay processes. At present, there is a lack of research carried out at whole building or site scales over multi-annual timescales which are vital for managing moisture problems. Future development and upscaling of the use of tools such as the sustainable legacy indicator tool (LegIT) could be helpful here [95, 96].

A research agenda for the future for heritage hydrology should focus on addressing three broad questions:

1. What are the best combinations of methods available to measure and model spatio-temporal patterns in moisture on built and rock-hewn heritage and compare them between sites?
2. What are the major factors controlling observed spatio-temporal patterns in moisture on built and rock-hewn heritage?
3. Which spatio-temporal patterns in moisture are most important for driving deterioration of built and rock-hewn heritage and how do their respective scales interact?

This research agenda requires a coordinated approach, linking different research teams and methodologies. It should be based on data collected through rigorous laboratory experiments, detailed studies of test walls, and instrumented sections of walls at heritage sites. It should deploy numerical modelling techniques to build on the data collected and explore the causes and consequences of moisture regimes which provide fundamental links between climate and the deterioration of built and rock-hewn heritage.

Acknowledgements

We thank Blen Taye Gemeda for permission to use two of her images of Bete Giorgis, Lalibela, Ethiopia in Fig. 2.

Author contributions

This review paper is based on a joint idea of HV and OS and was written in equal parts by both authors. This applies to conceptualization, resources, visualization and writing of all parts. OS, HV: conceptualization, resources, visualization writing—50%. All authors read and approved the final manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL, funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 491183248. Funded by the Open Access Publishing Fund of the University of Bayreuth. No further funding was needed for preparing the paper. University of Bayreuth Centre of International Excellence "Alexander von Humboldt" awarded a short term grant to HV which facilitated this joint undertaking.

Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study, except of those used for the exemplary Fig. 3. These datasets are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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Received: 7 March 2022 Accepted: 13 April 2022
Published online: 23 May 2022

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