SBE21
Sustainable Built Heritage

14-16 April 2021,
Online conference

DRAFT PAPER

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Water absorption characterisation of historic plasters. Comparison of different methodologies in a case study in Tyrol, Austria.

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Abstract. Balancing conservation of historic buildings and improvement of their energy performance is a challenging task that involves multiple factors. Prescriptive standards for interventions of internal insulation in modern materials are not compatible with conservation of historic plasters and thus a more detailed and sympathetic approach must be used. Knowing the hygric behaviour of historic plasters is a prerequisite in the assessment of any intervention of internal insulation. In this paper, four different methods for the quantification of the water absorption coefficient, laboratory and onsite based, are presented and applied to an outstanding case study in Tyrol (AT). The variability observed, between methods but also between the different layers of plasters found onsite and even between measurements, highlighted the need for robust guidelines for the application and interpretation of the results. This study summarises the numerous factors influencing the result of the water absorption measurement and shows a first investigation into one of these aspects (heterogeneity of the wall). Numerical simulation has proven to be an effective tool to use in combination with experimental results in testing the effect of the different parameters affecting the water absorption characterisation of historic plasters.

Keywords – onsite test; laboratory test; case study; water absorption; insulation.

1. Introduction

Exterior walls are responsible for much of historic buildings' character. Since they usually have much higher thermal conductivity than those built nowadays, internal wall insulation is one of the main measures to improve the energy performance of historic buildings. However, application of internal insulation could change considerably the moisture dynamics of the wall and must be assessed carefully. Walls' external finish (whether it is plastered, exposed masonry, or wood) should ensure a continuous layer of protection against wind driven rain to avoid any moisture accumulation. Previous research has looked into the definition of parameters to establish a safe threshold for the application of internal insulation. For instance, German standards define a rain protection coefficient for external renders as a function of their water absorption and diffusion resistance [1]. The water absorption threshold is made even more stringent in the case of internally insulated walls ($Aw < 0.003$ kg/m^2.s$^{0.5}$), far from the performance of traditional lime plasters (see Table 1). This prescriptive approach does not work in the case of historic buildings where the preservation of the historic plaster might become paramount and its substitution with new plasters would not be acceptable. Numerical simulation offers the possibility to assess the feasibility of internal insulation on a case-by-case basis. However, having accurate input data is crucial in obtaining reliable results and thus the characterisation of existing materials becomes essential. This paper discusses the strengths and weaknesses of different testing methods in the water absorption characterisation of historic plasters.

2. Materials and methods

There are several approaches and methodologies for the characterisation of water absorption based on both laboratory and onsite measurements of materials. In this paper, a comparison of four different methods for the determination of hygric behaviour of materials is presented. These methods include some well-known techniques and some innovative approaches, but there are many more that can be found in literature (such as Capillary rise method, Contact sponge method, Mirowski pipe, Franke pipe, X-ray, neutron radiography, or magnetic resonance [3-5]).

2.1. Case study: Silberbergalm

All four different methods were applied to a case study in Tyrol, Austria, in July 2020. Limiting all sampling to a single case study allowed a better comparison between methods, even though numerous layers of different ages and characteristics were found onsite.

The building is an extraordinary example of a “Knappenhütte” (miner hut) dating back to 1378. The building was directly linked to the copper silver mining in the area and served as an entrance to the shafts and lodge for the miners. In the last ten years, after being used as a mountain hut for the farmers during the summer months, it has been neglected. Currently, it is abandoned and in a poor state of conservation. Different recognisable construction phases and numerous layers of plaster provide information about the development of the building. Existing colour settings in the plaster suggest that parts of the rising building fabric still date back to the 16th century. Because of the fragility and the damages on the existing plaster, an extremely sensitive approach was necessary. The application of the measuring methods was accompanied by a relative chronological assessment of the plaster layers in order to make the results obtained comparable.

Figure 1. Pictures of the historic miners' hut in Reith im Alpbachtal, Tyrol, (A. Rieser) and the "Franziszeisische Kataster" of the Habsburg Monarchy from 1855 (marked as “Silberberg”)

2.2. Laboratory measurements

Laboratory tests ensure accurate results but require invasive techniques for the collection of sample material. Especially in the case of historic buildings, the removal of enough sample material to perform the tests is in direct conflict with the preservation of original layers.

2.2.1. Free water uptake

The international standard ISO 15148:2002 [5] describes the procedure for the measurement of capillary absorption coefficient (A_{cap}, kg/m².s$^{0.5}$) and capillary moisture content (w_{cap} kg/m³) in the laboratory and it is primarily targeted at industrial applications. Here, a stricter approach proposed by Dresden University of Technology and described in [2] is adopted. This alternative method is performed in a closed chamber with high relative humidity and the exposed area of the top surface is reduced to minimise evaporation from the sample while avoiding the build-up of air pressure.

As limitations, it is worth highlighting that the number of locations and replicates tested was kept to minimum to limit the removal of material form a historic object. Material handling in the laboratory to produce regular sized samples (Figure 2) is a delicate and time-consuming task. To ensure the accuracy and reproducibility of the measurement, each test was carried out at least twice on every sample.

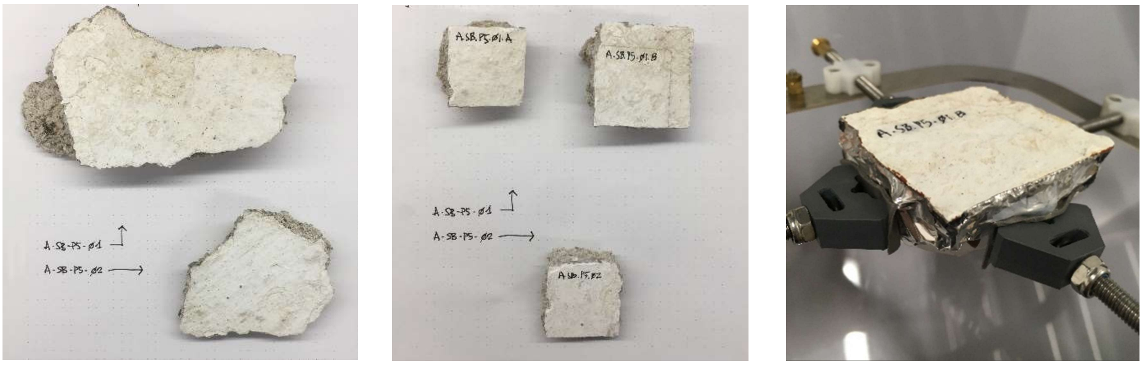

Figure 2. Elaboration of regular samples in the laboratory in preparation for the Free water uptake test

2.2.2. Gravimetric test

The gravimetric test, as described in [6], is used to determine the water content of a certain material. Powdered samples extracted on site are used to calculate the difference between the wet and dry mass of the sample. In this case, the test is used trying to infer the capillary absorption coefficient of the plasters. Samples (Figure 3) were taken immediately after an onsite test had been performed (see section 2.3) and from a dry nearby location. Considering the exposed area of the sample and the duration of the onsite test (that is, for how long the material was exposed to water), an estimation of the capillary absorption coefficient was calculated. Samples needed for this test are much smaller than those needed for the free water uptake test and could represent an alternative method in cases where access to samples is limited. On the other hand, this method presents some limitation as the test is not designed specifically for this purpose. Extraction of sample material with power tools can lead to water evaporation and samples must be transported to the laboratory to be weighed with an analytical scale. To prevent evaporation, samples were collected with a small chisel and a spatula and kept in sealed airtight bags.

2.3. Onsite measurements

Contrary to laboratory tests, on-site measurements can be non-invasive and performed with relatively simple equipment.

2.3.1. Karsten tubes

The use of graduated plastic tubes attached to the wall with mastic allows the onsite measurement of water absorption. The tubes are filled with water and the level is registered at regular intervals. This non-destructive and simple method is described in [3] and has been used in numerous studies with comparative and analytical purposes [2]. For each tested location, at least two tests were carried out, however ensuring a full bonding of the mastic with the plaster was difficult (especially in cases where the plaster had been painted or whitewashed) and in many cases the results had to be discarded due to leaks between the tube and the wall.

2.3.2. WAM-100B

The last method, described in detail in [4], is in line with the ASTM C1601 procedure and proposes the use of an ad-hoc apparatus to replicate the effect of wind driven rain onsite. The WAM-100B has a much larger sampling area (0.12 m^2) and is equipped with a closed circuit of water that is sprayed on to the surface simulating a rain event. The amount of water absorbed is continuously measured by means of a dedicated scale and logging software. Like in the case of the Karsten tubes, ensuring a good bonding between the apparatus and the wall is key, but can be difficult on uneven surfaces. In this set up however, the test lasts 40 minutes and in some cases the tests must be stopped before their conclusion or the results have to be partially discarded. For the study described here, three tests were performed with very different results. One had to be discarded and a second one showed some leakage so only the data of the first half of the test was used.

Figure 3. From left to right, samples for gravimetric analysis, Karsten tubes and WAM100-B

2.4. Numerical simulation

Lastly, numerical simulation was used to provide some input for the discussion of the results. The software developed by Dresden University of Technology, Delphin 6.0, was chosen. This software counts with a built-in database of material properties. The water absorption coefficient of some of the plasters included in the software are presented in Table 1.

Table 1. Water uptake coefficient (A_W and W_W) of plasters in Delphin 6.0.20 material database

Name	**(En)**	**ID**	**A_W** (kg/m^{2}s^{0,5})	**W_w** (kg/m^{2}h^{0,5})
Kalkputz (historisch)	Lime Plaster (historical)	148	0.127	7.62
Kalkputz	Lime plaster	319	0.05	3.00
Mineralischer Edelputz	Minerally finishing plaster	329	0.002	0.12
Sumpfkalkputz	Pit lime plaster	350	0.3	18.00
Zementputz	Cement plaster	384	0.008333	0.50
Mineralischer Edelputz (leicht)	Mineral fine plaster (light)	475	0.0726018	4.36

3. Results

The first aspect worth observing is the different use of terminology and units found in literature when dealing with water absorption characterisation of building materials. Even the standard 15428 [5] includes a note in the 'Symbols and units' section pointing out that the Water absorption coefficient is defined in seconds (A_W) but that the alternative definition in hours (W_W) is also widely found. To improve readability, both definitions are included in the summary
Table 2 below, but the results discussed in the text are only reported using the main definition of A_W.

As explained in the case study description, the building under study is an old example in poor state of conservation and several layers of plaster from different ages and characteristics were exposed. Of the 5 different sampling locations, four (Pos. 1 to Pos. 4) correspond to the east wall, and one (Pos. 5) to the south wall. Sampling positions 1 and 4, although relatively apart (around 2 m), correspond to the same (identified as the oldest) layer of plaster while sample 2 and 3 were placed on repair layers.

3.1. Free water uptake

Six samples from three different locations were tested in the laboratory. Results presented a great variability and ranged from 0.083 to 0.227 kg/m^{2}s$^{0.5}$. In Delphin database, these values would roughly correspond to a modern mineral fine plaster and pit lime plaster (the worst performing option), respectively (Table 1). In any case, all samples exceeded greatly the upper limit of water absorption recommended in German standards (0.0033 kg/m^{2}s$^{0.5}$).

It is worth noticing the large variability of results also between different specimens of the same area or even same sample. Samples WU/P5/01/ A and B were prepared out of the same wall segment as shown in Figure 2 and yet the results diverge by a factor 2.

Table 2: summary of results of laboratory and onsite measurements

Sample ID	**Method**	**Test**	**Position**	**Δt** (s)	**Δm** (kg)	**Area** (m^2)	**Aw** ($kg/m^2s^{0.5}$)	**Ww** ($kg/m^2h^{0.5}$)
WU/P1/01	Laboratory	Water uptake	1	1711.5	0.03119	0.005225	**0.144**	8.66
WU/P1/02	Laboratory	Water uptake	1	813.5	0.00926	0.001561	**0.208**	12.48
WU/P2/01	Laboratory	Water uptake	2	2417.0	0.06106	0.005477	**0.227**	13.61
WU/P5/02	Laboratory	Water uptake	5	756.5	0.00406	0.001685	**0.088**	5.26
WU/P5/01B	Laboratory	Water uptake	5	449.0	0.01045	0.002928	**0.168**	10.10
WU/P5/01A	Laboratory	Water uptake	5	2611.0	0.00723	0.001700	**0.083**	4.99
GT/P4/01	Laboratory	Gravimetric	4	2454.0	0.00205	0.000900	**0.046**	2.76
KT/P1/01	Onsite	Karsten tube	1	75.0	0.00450	0.000511	**1.017**	61.05
KT/P1/02	Onsite	Karsten tube	1	480.0	0.00450	0.000511	**0.402**	24.13
KT/P1/03	Onsite	Karsten tube	1	1320.0	0.00450	0.000511	**0.243**	14.55
KT/P2/01	Onsite	Karsten tube	2	1620.0	0.00450	0.000511	**0.219**	13.14
KT/P3/01	Onsite	Karsten tube	3	870.0	0.00450	0.000511	**0.299**	17.92
KT/P3/02	Onsite	Karsten tube	3	150.0	0.00450	0.000511	**0.719**	43.17
KT/P3/03	Onsite	Karsten tube	3	2700.0	0.00550	0.000511	**0.207**	12.44
KT/P4/01	Onsite	Karsten tube	4	270.0	0.00470	0.000511	**0.560**	33.60
KT/P4/02	Onsite	Karsten tube	4	300.0	0.00500	0.000511	**0.565**	33.91
WAM/P4	Onsite	WAM 100-B	4	2427.2	0.70600	0.120000	**0.119**	7.17
WAM/P5	Onsite	WAM 100-B	5	316.1	0.60800	0.110000	**0.233**	13.97

The ISO standard 15148:2002 [5] foresees three different types of outcomes when it comes to the resulting graphs of mass increase per area as a function of time (squared): (1) a straight line, (2) a straight line with a sudden decrease in slope, or (3) a curve of some form. The results obtained in the laboratory all lie within the second type, as illustrated in Figure 4. In those cases, the water uptake coefficient is calculated using only the values before the change in the slope. Despite the high difference between samples in terms of duration and mass increase, it is worth noticing that all samples presented a very strong correlation between $\Delta m/m^2$ and $\sqrt{t}$ (see R^2 value in Figure 4). That is, the curve of water absorption against time (squared) followed a straight line during the first phase of the measurements.

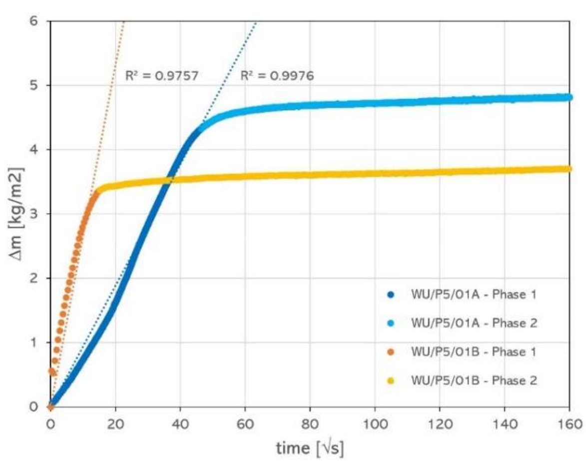

Figure 4. Free water uptake results (kg/m^2 against $\sqrt{s}$) of two specimens of the same wall sample

3.2. Gravimetric test

The samples for gravimetric measurements were taken from position 4 of the east wall, in correspondence with the first test carried out with the WAM-100B apparatus. Thus, it was expected a certain degree of agreement between both sets of data. However, the A_W calculated with the gravimetric test was 0,046 kg/m^{2}s$^{0.5}$, around a third of the result obtained with the other apparatus. As explained above, the plaster in positions 1 and 4 was very similar, so a certain agreement was also expected between the results of the gravimetric test and the WU/P1 and KT/P1 samples. These tests also resulted in much higher values of A_W than those calculated with the gravimetric approach. It is worth highlighting that because of the way the sample material is collected, calculating the exact area was problematic and, especially considering the small size of the samples, these errors could have led to inaccurate results.

3.3. Karsten tube

Up to nine successful tests were performed with the Karsten tubes in four different locations. The results ranged from 0,207 to 1,017 kg/m^{2}s^{0,5}. The lowest values are comparable with those obtained with the free water uptake tests, whereas the highest end of the results is only comparable to materials like Cellulose insulation (0.563 kg/m^{2}s$^{0.5}$), or even Calcium Silicate (1.115 kg/m^{2}s$^{0.5}$), a material used in construction for its capillary transport properties. As described before, faulty tests were discarded and the results presented here correspond only to those tests were no leak was observed.

Variability between tests, even those positioned close to each other on the same layer, is noticeable. In position 1, results ranged from 0.243 to 1.017 kg/m^{2}s^{0,5} with a duration of 1320 and 75 seconds respectively, and in position 3 from 0.207 to 0.719 kg/m^{2}s^{0,5} with durations of 2700 and 150 seconds.

In some cases, and because of the high speed the water was absorbed, the test lasted less than 15 min and the procedure recommended in the standard could not be followed. Instead, the A_W values were calculated using the first and last measurement recorded. In any case, the regression lines resulted from the calculations showed a very good fit in all tests proving a good linearity of the results. All calculations were made assuming as exposed area the inner diameter of the tube. No correction due to possible imperfections in the application of the mastic between the tube and the wall was applied.

3.4. WAM100-B

Lastly, the tests carried out with the WAM-100B apparatus obtained an A_W value of 0.119 and 0.233 kg/m^{2}s^{0,5} in positions 4 and 5, respectively. The test in position 5 had to be stopped halfway through the experiment and only the first half of the data could be used. Thus, the accuracy of the result might be affected by a defective installation of the apparatus. On the other hand, the test in position 4 did not show any sign of leakage and the results present a very strong linearity, indicating a successful installation of the device.

The results obtained for WAM/P4 (0.119 kg/m^{2}s^{0,5}) are very close to those reported in Delphin's material database for historic plasters (0,127 kg/m^{2}s^{0,5}). However, results obtained with the free water uptake test and Karsten tubes for the same locations are considerably higher (positions 1 and 4 are considered equivalent for the sake of comparison of results).

4. Discussion

The discrepancies in the results obtained with different methods and apparatus have been previously investigated. For instance, Vandevoorde et al. [3] investigated the effect of porosity on different methods and concluded that the use of Karsten tubes was best suited to porous materials, whereas methods like the Contact Sponge were better suited to measure the initial uptake of less porous materials. Geyer et al. [7], on the other hand, have proposed a set of conversion functions based on empirical data that would correlate the onsite method results to the laboratory measurement values. This approach however still needs extensive testing to prove its validity for different materials. The results obtained in our research, for instance, would not align with those functions.

The variability between values obtained with the same method and within the same areas can be explained as a result of historic plasters' heterogeneity or as a consequence of the implementation. Original plasters found in old buildings have been exposed rain, sun, and wind for decades if not longer. The decaying process will never be completely homogeneous as it is affected by many factors (level of exposure, composition and thickness of the different layers, type of aggregates and nature of the binder, wear and tear, etc.) and thus it is crucial to define experimental methods that minimise the uncertainty in the result. In Table 3, a summary of the variables affecting the result is presented. Along with the different variables, a qualitative estimation of the impact that each variable could have on the different methods is included. The gravimetric test is not included in the table as the method still needs further development for its implementation.

Table 3. Variables affecting the reliability of different methods of water absorption characterisation

Variable	**Related to**	**Impact on results**			**Ref**
		WU	KT	WAM	
Sampling area and shape	*Heterogeneity, defects, distribution*	medium	high	low	4,7
Starting conditions	*Water content*	low	high	high	2
Environmental conditions	*Temperature and Relative humidity*	low	high	high	3,7
Wall stratigraphy	*Saturation time, homogeneity results*	low	high	medium	-
Intrusiveness	*Access to samples, replicates*	high	low	medium	5,6,7
Applicability	*Installation, duration, errors*	low	medium	high	2,3,7

The table should be expanded in the future to include other experimental methods and quantify the impact of each variable. Here, a first look into one of the identified variables is presented. The evaluation of different methods should consider that heterogeneity of the walls could influence the water uptake results as each layer would have a different behaviour. This is especially important in the case of onsite measurements where the actual composition of the wall cannot be seen. To explore this issue a series of free water uptake tests have been simulated using different configurations of wall stratigraphy.

The left graph in Figure 5 shows the simulation results for four different build-ups: from just 3 cm of historic lime plaster, to a full wall stratigraphy with 3 cm of plaster, 10 cm of mortar, and 40 cm of stone. The zoomed area in bottom right corner of the graph clearly shows that the first phase of the water uptake does not change independently of the wall type. In all four configurations the water uptake follows the same trend and ends at the same point. It can also be noticed that one phase occurs after each other, as one layer saturates after each other. This becomes evident looking at the simulation with 3 cm plaster, 10 cm mortar and 40 cm sandstone, where three distinct phases can be detected, following perfectly what described in ISO 15148:2002 as Type B.

This clear distinction between the phases can only occur if the layers are perfectly homogeneous and bonded to each other. In reality, especially in historic buildings, layers are much more heterogeneous and might present some cracks (or smaller fissures more difficult to detect) that could influence the water uptake measurement. If a crack is present in the outer layer, it is likely that the water will be transported further into the wall before the plaster has reached its saturation. Eventually, what the results of a water uptake test would show in that case is an averaged value of both materials being saturated simultaneously. This issue should be further investigated to understand its effect on the final A_W value.

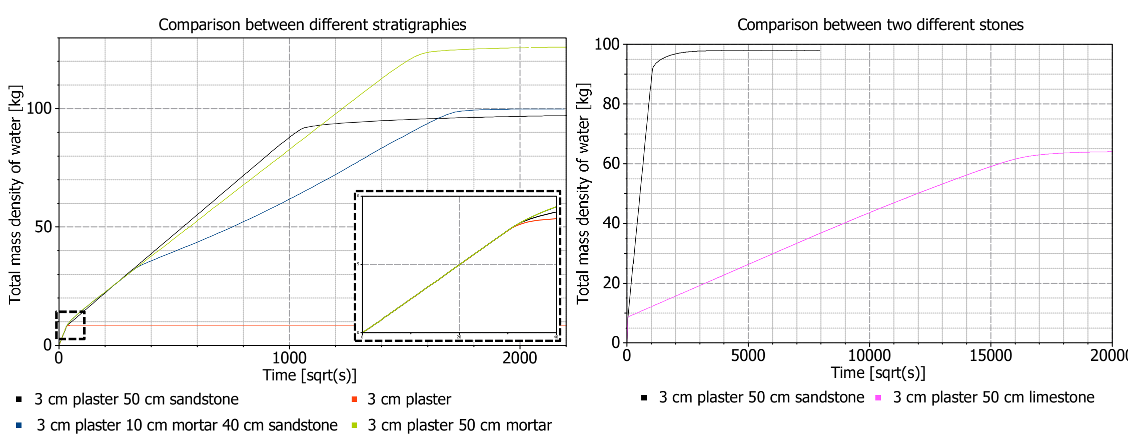

Figure 5. Simulation results for total mass density of liquid water (kg) versus time (√s)

On the right-hand side of Figure 4, the curves of two simulated walls with identical build-up but different stones are presented. Sandstone and limestone show different slopes, as expected from the different water absorption coefficient of both materials (0.0644513 $kg/m^2s^{0.5}$ and 0.00367 $kg/m^2s^{0.5}$ respectively). In the case of limestone, saturation is an extremely long process. This might explain the second slope observed in some of the samples measured in the laboratory. In Figure 4, it can be seen how the curve after the saturation on the plaster is not completely flat (as would happen in the case of monolithic samples) and continues to gain mass over time.

Therefore, and according to the results obtained with the simulations, if the calculation of the water absorption coefficient takes place before the external layer is completely saturated (approximately 20 min in this case), on site measurements can be a reliable method as they are not influenced by the remaining layers of the wall.

5. Conclusions

All results of water absorption achieved in this study exceeded largely the upper threshold proposed in the German standards. Even more so if looking at the new and more stringent limits proposed by Zirkelbach, D & Künzel, H.M. [1]. These results could immediately discourage anyone from pursuing any intervention of internal insulation. However, previous studies have shown [8] that the final performance of a wall depends to a great extent of the local climatic conditions and thus a detailed analysis might uncover potential opportunities for the improvement of the thermal performance of historic walls even in the case of poorly performing plasters. Simulation will thus play a crucial role in the assessment and with that characterisation of pre-existing materials.

At the moment, there is not enough evidence on how the results obtained with different methods can be related. Also, there are several parameters affecting the results and there is a lack of clear guidance on the choice and application of the method. Simulation has proven to be a very useful tool in testing the effect of the different parameters. A sensitivity analysis that combines numerical and experimental data would allow an exploration and quantification of the impact of each parameter separately.

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Acknowledgments

The authors are grateful for the financial support from the European Regional Development Fund under the Interreg Alpine Space programme to the Project ATLAS (ID: ASP644).