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Published in: Contributions to building physics : proceedings of the 2nd central European conference on building physics, 9-11 September 2013, Vienna, Austria

Published: 01/01/2013

Document Version
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

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Citation for published version (APA):

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Hygrothermal modelling of flooding events within historic buildings

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ABSTRACT: Flooding events pose a high risk to valuable monumental buildings and their interiors. Due to higher river discharges and sea level rise, flooding events may occur more often in future. Hygrothermal building simulation models can be applied to investigate the impact of a flooding event on the environmental conditions inside a building. The objective of this study is to develop such a model that is able to evaluate the best fitting drying strategy for historic buildings. A model is created based on on-site measurements of the indoor climate conditions in one building that had to cope with flooding in the recent past. The result of this study is a hygrothermal building simulation model that can predict the indoor climate conditions inside a room as a result of a flooding event. Different climate control systems can be integrated in this model to evaluate the most suitable drying strategy to minimize the risk to the building, its interior and its collection. Furthermore, damage functions can be applied to analyse the risk to the collection caused by the flooding event.

1 INTRODUCTION

Preserving historical buildings and their collections for future generations requires an accurate assessment of the impact of climate change on the indoor environment of these buildings. It is expected that, if no preventive or risk reduction measures are taken, climate change can lead to an increase in flood risks due to higher river discharges and sea level rise (IPCC 2007). Previous studies (Cassar 2005, Cassar & Hawkings 2007, Sabbioni et al. 2010) have shown that the increasing frequency of flooding events because of climate change poses a high risk to historical buildings in many areas of Europe. Inside buildings, flooding events can cause enormous damage and may lead to typical failures such as cracks and deformation of walls and floors due to uplifting of foundations or swelling of joists, decreasing strength of building materials and chemical damage to the interior (Drdacky et al. 2006). The collection can be deteriorated by swelling and shrinking of materials, mould growth, corrosion or loss of water-based inks and paints. It is therefore of high importance that adequate drying strategies are applied to decrease the damage potential of a flooding event to the building and its collection.

In the EU project Climate for Culture (Climate for Culture, 2013), the impact of climate change on cultural heritage is assessed. Hygrothermal building simulation models of a large selection of monumental buildings around Europe have been created and validated with on-site measurements. These building simulation models are combined with future outdoor climate scenarios that have been developed by the Max Planck Institute for Meteorology (Jacob 2012). In this way, the future indoor climate conditions inside the buildings can be predicted. Furthermore, damage functions can be applied to analyse the risk to the collection as a result of the environmental conditions in a room.

One of the case studies within the Climate for Culture project is a 17th century castle that frequently has had to cope with flooding events in the basement. These flooding events were caused by high water levels in the surrounding moat because of times of heavy rainfall. Two highly valuable wooden cabinets are located in one of the rooms on the first floor of the castle. Both the cabinets are seriously damaged by cracks in the wood. We want to investigate if this damage could be caused by environmental conditions in the castle as a result of the flooding. Based on this information the impact of future climate change and flooding events on damage to the collection can be predicted. This requires a validated hygrothermal building simulation model and suitable damage functions.

However, flooding events inside buildings are not comprehensively taken into account in the existing
indoor climate simulation models and future outdoor climate scenarios. The objective of this study is therefore to develop a hygrothermal building simulation model that can predict the environmental conditions inside a room as a result of a flooding event. Different climate control systems can be integrated in this model to evaluate the most suitable drying strategy to minimize the risk to the building, its interior and its collection and damage functions can be applied to evaluate the risk of degradation of the buildings and artefacts.

To assess the accuracy of the interior flooding simulation model, the model has to be validated with on-site measurements. However, data from indoor climate measurements during flooding events inside historical buildings caused by extreme weather events are difficult to find. Therefore, in the present study, a case study has been analysed that had to cope with a flooding event caused by a burst water pipe. Accurate measurements of the indoor temperature and relative humidity (RH) for a period of one month before the flooding and several months after the flooding were available for this case study. A hygrothermal building simulation model of the building has been created and validated with the measurements from the period before the flooding. Hereafter, the flooding has been added in the model by the inclusion of a variable moisture source and different drying strategies have been implemented.

This study describes the validation of the hygrothermal building simulation model and the analysis of the different climate control strategies that were applied. Additionally, the impact of the environmental conditions on the damage potential for a few typical objects of arts was assessed. In future research, the model will be applied to other historic buildings.

2 METHOD

2.1 Case study

The building is a 19th century monumental house located in Western Europe. The building has a unique interior that has not been changed since 1900. The building is currently open to the public from March until October; during the winter the building is closed. A graphical representation of part of the building is shown in Figure 1. The room where the flooding occurred is located on the first floor in the northeast corner of the building.

2.2 On-site measurements

Hourly data were collected of the outdoor temperature and RH at the building site and indoor temperature and RH in the flooded room. The measurement period that is considered in the current study is 1 December 2010 until 31 October 2011. A comparison between the measured outdoor and indoor climate is shown in Figure 2. Before the flooding occurred, the indoor climate in the building was controlled by a conservation heating system. The flooding as a result of a burst in a water pipe started in in the early morning of 31 December. Approximately seven hours later that day, the water was switched off. In the following days, the room contents were salvaged.

In early January, a dehumidifier was installed in the room. Until early April, this dehumidifier was only operated during daytime hours on Monday until Friday from approximately 9a.m. until 6p.m. The measurements show that during this period, daily RH fluctuations over 40% were measured in the room. Hereafter, the humidifier was operated con-
tinuously for about two months. A very slow RH de-
crease was measured, but the humidity ratio consid-
erably increased due to an increasing temperature. In
the beginning of June, measurements of the wall
moisture content suggested that no further drying of
the walls occurred and the dehumidifier was re-
moved. However, in the following weeks the RH in-
creased. Therefore, the conservation heating system
was reinstalled in the beginning of July. Until the
end of the considered measurement period, the hu-
midity ratio inside the room is still higher than the
outdoor humidity ratio. This suggests that the mois-
ture sources in these rooms may not have been com-
pletely removed yet.

2.3 Model

To investigate the impact of the flooding on the in-
door environment and to analyse the drying process-
es, an indoor climate simulation model was created
in HAMBase (De Wit 2006). With HAMBase, the
indoor climate conditions in a multi-zone building
model can be calculated. The model assumes that in
each zone both the air temperature and the vapour
pressure are uniform.

The mass balance in HAMBase consists of four
terms:

\[ G_i + G_s = G_g + G_p \]

where \( G_i \) is the moisture loss [kg/s], \( G_s \) is the
stored moisture [kg/s], \( G_g \) is the vapour production
[kg/s] and \( G_p \) is the humidification or dehumidifica-
tion [kg/s]. Vapour leaves a zone by diffusion and
advection (ventilation air) through the envelope.
Compared to advective losses by air flows, the losses
by diffusion through the construction is negligible.
Moisture is stored in the room air, in furnishing, and
in the zone envelope.

A flooding event can be simulated by modelling a
liquid water source in a zone. The maximum vapour
production rate \( g_{\text{max}} \) [kg/s] is calculated by the mass
of the liquid water together with the evaporation sur-
face area multiplied by the surface coefficient for
vapour transfer \((A\beta)\):

\[ g_{\text{max}} = A\beta(p_{\text{sat}}(T_a) - p_{\text{va}}) \cdot 3600 \]

where \( p_{\text{sat}}(T_a) \) is the saturation pressure [Pa] at the
air temperature \( T_a \) [°C] and \( p_{\text{va}} \) is the vapour pres-
sure of the air [Pa].

The default surface coefficient for mass transfer
(evaporation) in HAMBase is 0.62e-8kg/m²sPa. In
the simulation, it is assumed that the water tempera-
ture is equal to the room temperature.

The hourly energy consumption for latent cooling
\( G_{\text{plant}} \) [Wh] is calculated by:

\[ G_{\text{plant}} = 1000 \times 2500 \times G_{\text{int}} \]

Where \( G_{\text{int}} \) is the vapour production [kg/s]

The current model is a simplified version of one
part of the building where the flooding occurred. The
model consists of four zones: the flooded room, the
adjacent room, the room on the first floor and the at-
tic. The ground floor was modelled as a constant
temperature wall, and the floors and walls between
zones were modelled as internal walls. Internal walls
that are adjacent to rooms that were not included in
the model were considered as adiabatic walls. An
overview of the volumes of the zones is given in Ta-
ble 1.

The required meteorological data file in HAM-
Base consists of the outdoor air temperature, outdoor
RH, direct solar radiation, diffuse solar radiation and
cloud cover. Outdoor temperature and RH data were
measured at the building site. Solar radiation and
cloud cover data were obtained from a nearby
weather station.

Table 1. Model volumes.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flooded room</td>
<td>49m³</td>
</tr>
<tr>
<td>Adjacent room 2nd floor</td>
<td>67m³</td>
</tr>
<tr>
<td>Room 1st floor</td>
<td>161m³</td>
</tr>
<tr>
<td>Attic</td>
<td>64m³</td>
</tr>
</tbody>
</table>

2.4 Validation

First, the HAMBase model was validated for the pe-
riod before the flooding occurred, from 1 December
2010 until 30 December 2010. The set points for the
conservation heating, internal heat loads and ventila-
tion rate are given in Table 2. All values were kept
constant during the entire validation period. In the
prediction of moisture transport, the ventilation rate
is of high importance. However, because no meas-
urement data of the ventilation rate were available,
the rate was estimated based on the output of the
HAMBase model.

A comparison between the simulated indoor cli-
mate conditions and the on-site is shown in Figure 3.
Because RH fluctuations are maintained low by the
conservation heating system, the simulated RH is
within the accuracy of the measured RH most of the
time. However, the simulation model predicts a
slightly lower indoor temperature and humidity ratio
than the measurements. This could be caused by a
slightly varying heat load and vapour production
within the room.

Table 2. Set points December.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{\text{min}}</td>
<td>5°C</td>
</tr>
<tr>
<td>T_{\text{max}}</td>
<td>22°C</td>
</tr>
<tr>
<td>RH_{\text{min}}</td>
<td>58%</td>
</tr>
<tr>
<td>RH_{\text{max}}</td>
<td>61%</td>
</tr>
<tr>
<td>Internal heat load</td>
<td>100W</td>
</tr>
<tr>
<td>Ventilation rate</td>
<td>0.1h⁻¹</td>
</tr>
</tbody>
</table>
3 RESULTS

3.1 Impact analysis

A prediction of the vapour concentration in the air as a result of the flooding was calculated in HAMBase. The on-site measurements were used as minimum and maximum set points for temperature and RH and an infinite capacity for heating, cooling and (de)humidification was applied. Figure 4 shows the required hourly energy use for heating, cooling, latent heating, and latent cooling. Table 3 and Table 4 contain the released and absorbed amount of vapour per period as well as the heating and cooling demand. In the analysis, six periods are distinguished: the period before the flooding (1 – 30 December), the day of the flooding (31 December), the first drying period (January – early April), the second drying period (early April – early June), the third drying period (early June – early July) and the fourth drying period (early July – 31 October). It can be seen that the required cooling demand is very low in each period. Because no cooling system was present in the building, this shows that the temperature prediction of the HAMBase model adequately complies with the real situation. Use of the dehumidifier increases the indoor temperature because energy is added by the compressor and by the latent heat from the condensation process. It can be seen that in the first drying period, high concentrations of vapour were removed during daytime hours. At the same time, the dehumidifier supplied heat. After daytime hours, the vapour concentration in the air quickly increased and the indoor temperature dropped. During the second drying period, when the room was continuously de-

![Figure 3. Validation of hygrothermal building simulation model from 1 December until 30 December.](image)

![Figure 4. Upper graph: required hourly energy demand for heating (+) and cooling (-). Lower graph: required hourly energy demand for latent heating (+) and cooling (-).](image)

<table>
<thead>
<tr>
<th>Period</th>
<th>Drying strategy</th>
<th>Released vapour [kg]</th>
<th>Absorbed vapour [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – 30 Dec (30 days)</td>
<td>Conservation heating</td>
<td>10.8</td>
<td>9.33</td>
</tr>
<tr>
<td>31 Dec (1 day)</td>
<td>No dehumidification</td>
<td>3.90</td>
<td>0.230</td>
</tr>
<tr>
<td>January – April (94 days)</td>
<td>Dehumidification during daytime hours</td>
<td>181</td>
<td>142</td>
</tr>
<tr>
<td>April – June (63 days)</td>
<td>Continuous dehumidification</td>
<td>110</td>
<td>11.7</td>
</tr>
<tr>
<td>June – July (32 days)</td>
<td>No dehumidification</td>
<td>29.7</td>
<td>11.5</td>
</tr>
<tr>
<td>July – October (115 days)</td>
<td>Conservation heating</td>
<td>136</td>
<td>53.3</td>
</tr>
</tbody>
</table>
Table 4. Required heating and cooling demand per period, predicted by HAMBase.

<table>
<thead>
<tr>
<th>Period</th>
<th>Drying strategy</th>
<th>Heating demand [kWh]</th>
<th>Cooling demand [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – 30 Dec</td>
<td>Conservation heating</td>
<td>520</td>
<td>0.00</td>
</tr>
<tr>
<td>31 Dec</td>
<td>No dehumidification</td>
<td>2.63</td>
<td>1.45</td>
</tr>
<tr>
<td>January – April</td>
<td>Dehumidification during daytime hours</td>
<td>547</td>
<td>31.1</td>
</tr>
<tr>
<td>April – June</td>
<td>Continuous dehumidification</td>
<td>1283</td>
<td>0.321</td>
</tr>
<tr>
<td>June – July</td>
<td>No dehumidification</td>
<td>44.3</td>
<td>74.1</td>
</tr>
<tr>
<td>July – October</td>
<td>Conservation heating</td>
<td>1085</td>
<td>16.7</td>
</tr>
</tbody>
</table>

3.2 First drying strategy: Intermittent dehumidification

In early January, low amounts of vapour were removed from the air during the daytime mostly due to an increased ventilation rate. The absorbed vapour concentration considerably increased after the humidifier was installed. Set points for the internal heat loads, vapour source, maximum RH, dehumidification capacity and ventilation rate for the entire first drying period are given in Table 5. The dehumidifier that was placed in the room in early January had an extraction rate of 30l/day (=1.3kg/h) and a maximum power consumption of 1500W. Based on the derived amounts of released and absorbed vapour, profiles for released and absorbed vapour were defined for weekdays and weekends and implemented in the simulation model. Comparisons between the measurements and the simulated indoor climate conditions are given from 30 December – 6 January and 14–21 February in Figure 5 - 6. In the first week, dehumidification was very irregular; therefore, the simulation does not comply with the measurements during weekdays. In February, the simulated RH is regularly within ±5% from the measurements. On 14 and 16 February, the RH rises earlier in the measurements than in the simulation, probably because the dehumidifier was switched off before 4p.m.

Table 5. Set points for internal heat load, vapour source, maximum RH, dehumidification capacity and ventilation rate from 31 December – early April.

<table>
<thead>
<tr>
<th></th>
<th>During daytime hours (Monday – Friday from 9a.m. until 4p.m.)</th>
<th>Outside daytime hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal heat load (Q_{in})</td>
<td>Early January: 100W Hereafter: 1000W</td>
<td>100W</td>
</tr>
<tr>
<td>Vapour source (G_{in})</td>
<td>-</td>
<td>0.02-2kg/h</td>
</tr>
<tr>
<td>RH(_{\text{max}})</td>
<td>50%</td>
<td>-</td>
</tr>
<tr>
<td>Maximum dehumidification capacity</td>
<td>Early January: 0.5kg/h Hereafter: 1.3kg/h</td>
<td>-</td>
</tr>
<tr>
<td>Ventilation rate (v)</td>
<td>0.2h(^{-1})</td>
<td>0.2h(^{-1})</td>
</tr>
</tbody>
</table>

3.3 Second drying strategy: Continuous dehumidification

In the second drying period, starting early April, the dehumidifier was working continuously. A gradual reduction of the internal vapour production from approximately 0.18kg/h to 0.14kg/h was predicted. Set points for the internal heat loads, vapour source, maximum RH, dehumidification capacity and ventilation rate for this period are given in Table 6. Because the measured RH very slowly decreased from about 90% to 45% in three months, it seems that the dehumidifier was not operating at full capacity. However, the dehumidifier did cause a significant increase of the indoor temperature. This was taken...
into account in the simulation model by a constant internal heat load of 1000W. Figure 7 shows that the simulated temperature within ±2°C from the measurements, the simulated RH is within ±5% from the measurements and the humidity ratio is within ±2g/kg from the measurements.

Table 6. Set points for internal heat load, vapour source, maximum RH, dehumidification capacity and ventilation rate from April – early June.

<table>
<thead>
<tr>
<th>Internal heat loads (Q_{int})</th>
<th>1000W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour production (G_{int})</td>
<td>(April) 0.18kg/h</td>
</tr>
<tr>
<td></td>
<td>(May – June) 0.14kg/h</td>
</tr>
<tr>
<td>RH_{max}</td>
<td>50%</td>
</tr>
<tr>
<td>Maximum dehum. capacity</td>
<td>0.13kg/h</td>
</tr>
<tr>
<td>Ventilation rate</td>
<td>0.2h⁻¹</td>
</tr>
</tbody>
</table>

Figure 7. HAMBase validation from 11 until 18 April.

3.4 Third drying strategy: Removal of dehumidification system

In the third drying period, starting early June, the dehumidifier was switched off. Set points for the internal heat loads, vapour source, maximum RH, dehumidification capacity and ventilation rate for this period are given in Table 9. An average released vapour amount of 0.02kg/h was predicted based on the measurements. A comparison between the simulated and measured indoor climate conditions for June is shown in Figure 8. Both the simulation model and the measurements show a gradual RH increase from early June and a decrease of the indoor temperature. The simulated humidity ratio adequately corresponds to the measured humidity ratio. However, as the indoor temperature is slightly overestimated by the simulation model from the middle of June, the simulated RH is approximately 3-6% below the measured RH.

Table 7. Set points for internal heat load, vapour source, maximum RH, dehumidification capacity and ventilation rate from early June – early June.

<table>
<thead>
<tr>
<th>Internal heat loads (Q_{int})</th>
<th>0W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour production (G_{int})</td>
<td>0.02kg/h</td>
</tr>
<tr>
<td>RH_{max}</td>
<td>-</td>
</tr>
<tr>
<td>Maximum dehum. capacity</td>
<td>-</td>
</tr>
<tr>
<td>Ventilation rate</td>
<td>0.2h⁻¹</td>
</tr>
</tbody>
</table>

Figure 8. HAMBase validation from 20 until 27 June.

3.5 Fourth drying strategy: Conservation heating activated

In the fourth drying period, starting early July, the conservation heating system was switched on again. Set points for the internal heat loads, vapour source, maximum RH, dehumidification capacity and ventilation rate for this period are given in Table 10. The hourly vapour production in the HAMBase model corresponded to the average released vapour amount in the third drying period. The temperature threshold was maintained at 22°C. From the middle of October, RH had been reduced to 63%. The comparison between the simulation model and the measurements (Fig. 9) show that the simulation model from September slightly overestimates the indoor humidity ratio. This could indicate that the internal vapour production in the room was steadily reducing.

Table 8. Set points for internal heat load, vapour source, maximum RH, dehumidification capacity and ventilation rate from early July – 31 October.

<table>
<thead>
<tr>
<th>Internal heat loads (Q_{int})</th>
<th>0W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour production (G_{int})</td>
<td>0.03kg/h</td>
</tr>
<tr>
<td>RH_{max}</td>
<td>63%</td>
</tr>
<tr>
<td>Maximum dehum. capacity</td>
<td>-</td>
</tr>
<tr>
<td>Ventilation rate</td>
<td>0.2h⁻¹</td>
</tr>
<tr>
<td>T_{min} for conservation heating</td>
<td>5°C</td>
</tr>
<tr>
<td>T_{max} for conservation heating</td>
<td>22°C</td>
</tr>
</tbody>
</table>
3.6 Damage risk assessment for collections

Objects stored in the room were removed immediately after the flooding event and successfully conserved. The wet floorboards were lifted and stacked on spacer bars so that the floorboards and exposed joists could begin to dry. After several weeks, mould growth was observed on the walls and stacked floorboards in the room. A prediction of the damage risk for objects of art in a room based on the indoor temperature and relative humidity was generated with the specific climate risk assessment method (Martens 2012). This method predicts the microclimate that an object experiences, which is defined by the indoor temperature, indoor RH, and the response time of the object. The method assesses the potential of four different risk types (mould growth, chemical degradation, mechanical degradation of the base material, and mechanical degradation of the pictorial layer) on four well defined objects of art (paper, panel paintings, wooden furniture and wooden statues) and is based on literature (Sedlbauer 2001, Michalski 2002, Mecklenburg et al. 1998, Bratasz et al. 2008). The lifetime multiplier (LM) assesses chemical degradation; the number of time spans that an object remains usable in comparison to a condition of 20°C and 50%RH. Mechanical degradation of the base material of panel paintings, furniture or a sculpture may occur when the entire object responds to a slow change of RH over time. The dimensionally changes of the object may be hindered by the construction of the object and lead to damage like cracks. Damage to the pictorial layer of panel paintings may occur when RH variations last longer than the response time of the panel. The moisture content within the panel changes and the object will swell or shrink. As the response of the gesso layer to RH variations is very fast, the mismatch in the response of gesso and the unrestrained wood support can lead to fracturing of the pictorial layer.

Figure 10 shows the output of the specific climate risk assessment method for the flooded room. A white colour in these figures represents a low risk for the specific object, light grey complies with a moderate risk and dark grey represents a high risk. An ‘x’ in a box indicates that the damage function is not available for the specific object. A considerable risk on mould growth was predicted in the room. It is expected that immediately after the flooding event, germination may occur. The specific climate risk assessment model for biological degradation indicates that mould growth may be visible from around 15 January. Besides that, a high risk on chemical degradation of all four types of objects is predicted as well as a moderate risk on mechanical degradation.

4 CONCLUSION

This study investigated the environmental conditions inside a historical building after a flooding event as a result of a burst water pipe. A prediction of the internal vapour production as a result of the flooding and the amount of vapour in the air that was removed by the dehumidifier was generated by comparing a free floating simulation model with the measured indoor climate conditions. During the first drying period (from January until April), a large part of the moisture in the room was removed by the dehumidifier. However, high RH fluctuations were measured in the room because the dehumidification system was only functioning during daytime hours. When the dehumidifier was switched off in the afternoon, the vapour concentration in the air rapidly increased. In the second drying period (continuous dehumidification from April until June), the capacity of the dehumidification system was relatively small. Consequently, the internal vapour production slowly reduced and the maximum RH threshold was achieved after several weeks. The heat release of the dehumidifier also caused a considerably temperature increase. Removing the dehumidifier in June caused
a steady increase of the released vapour into the air, which indicated that the walls and floor were still drying. After about one month, the conservation heating system was switched on. A constant internal vapour production of 0.03kg/h was added in the simulation model to comply with the measurements from July until November. The conservation heating system was able to bring the RH to an acceptable level from October and the internal vapour production was gradually reduced.

It was shown that HAMBase was able to generate an adequate prediction of the indoor temperature, RH and humidity ratio. Assuming constant profiles for weekdays and weekends did not include irregular internal heat sources due to persons or changes in the set points of the dehumidifier. Besides that, the ventilation rate was difficult to predict because no data were available. Therefore, it may be possible that different solutions exist to include the flooding event in the simulation model.

The specific risk assessment method was applied to assess the damage potential of the flooding to objects of art and a hygrothermal building simulation model was created to investigate the effect of the different drying strategies. The specific climate risk assessment method predicted considerable fungal growth in flooded room from the middle of January, which corresponds with the visible damage in the room. The flooding event also caused a high risk on chemical degradation and moderate risk on mechanical degradation of several typical objects of art.

Application of the created hygrothermal building simulation model to simulate flooding events in other historic buildings will be subject of future research.

5 ACKNOWLEDGEMENTS

This work was supported by European Commission funding through the EU Climate for Culture project 226973 within FP7-ENV-2008-1. The authors would like to acknowledge the National Trust for assistance with case study data.

6 REFERENCES


