

# THE SIMULATION OF THE POST FLOOD DRYING OF DWELLINGS IN LONDON

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## Abstract

Climate projections indicate that the UK will experience more frequent extreme precipitation events and a rise in sea levels, with the greatest relative sea level rise occurring in the South-East of England. As a result, flooding is expected to occur more frequently in London. Flood simulation modelling has previously been done to predict the impact on the built environment for a variety of scenarios for London. However, such models have not taken into account the detailed hygric behaviour of the building stock under flooding and drying conditions which can vary significantly between property types, and can lead to prolonged damp and health problems. To address this problem, a building stock model of central London has been developed in a Geographic Information System (GIS), with information on the age, structure, and height of each dwelling and assumptions about built form based on historical building standards and surveys. This paper describes a novel methodology for the development of a building stock model with the necessary information to carry out hygrothermal simulations of the penetration of water into the building envelopes of flooded homes and the subsequent drying under different environmental scenarios. It discusses how the risk of damp in flooded homes can be modelled using hygrothermal methods and supplemented with mould models. By combining the multidisciplinary components of GIS, building simulation, and microbiological modelling, a holistic picture of the potential health implications of flooding at a population level across different temporal and spatial scales can be developed.

**Keywords:** *Climate Change, Flood, GIS, building stock, Hygrothermal, mould*

## 1. Introduction

The world is currently experiencing a change in climate, which is predicted to bring changes in climate variability and extreme events, such as more frequent heat waves, less frequent cold spells, and a greater intensity of rainfall events. The impacts of climate change on the UK have been studied in the UKCPO9 climate change scenarios [1], and are predicted to lead to more frequent intense rain storms, which can cause surface and fluvial flooding. Surface flooding due to heavy rains occurs frequently in London; recently 320 London properties were flooded in the Autumn of 2000, and over 1,100 London households were flooded in the summer of 2007 [2], indicating that flooding is a problem even with current rainfall patterns. A combination of rising sea levels, sinking land, and large changes in winds and storms also means that the South East is predicted to experience the largest sea surface rise in the UK, and an increased frequency of tidal surges. This would lead to an increase in the risk of tidal flooding in London and the Thames Estuary. An increase in flood frequency and severity will test the resilience of the building stock and local communities to water damage and contamination.

Following a flood, improperly dried buildings can remain damp for long periods of time. This is significant as dampness in building materials in homes is consistently associated with respiratory illnesses, such as asthma, wheeze, cough, respiratory infections, and upper respiratory tract infections [3]. While most literature has focused on mould growth, bacteria [4-6], protozoa [7, 8], and viruses [9, 10] have also been found on damp surfaces or in elevated levels in the indoor air of damp houses.

Microbes such as mould and bacteria can release spores or fragments, and toxins into the indoor air, which may impact the health of occupants. During flooding, building surfaces can become contaminated with pathogens from the floodwater. The survival of pathogens on surfaces can also show a dependence on water availability and temperature [11], meaning the ability of a material or envelope design to dry quickly can impact the contamination levels.

Different building materials and envelope designs will react differently to moisture in both liquid and vapour form. Understanding how the building stock will respond to changes in the climate and extreme events can help predict how the long-term health of the population may be impacted under different scenarios. The objective of the study presented in this paper is to examine how existing building stock information developed for energy studies can be used to develop building archetypes suitable for use alongside building physics and microbial models to inform the flood vulnerability of existing buildings to damp and post-flood microbial persistence. This paper presents a novel methodology of combining building stock data and hygrothermal inputs in order to simulate the flooding of London. Future work on building simulation and the application of microbial models to the building archetypes and stock model will be discussed.

## **2. Theory**

### **2.1 Hygrothermal and Mould Models**

Heat, Air, and Moisture (HAM) computer models simulate the transport of heat, air and moisture within building assemblies. HAM models vary widely in their complexity, from simple steady-state models that do not take account of changing external and internal conditions, to complex whole building simulation models that calculate air and heat flow throughout the building and take into account transient heat, air, and moisture levels (eg. EnergyPlus)[12]. The family of HAM models of relevance to the current work operate by dividing wall assemblies into 1, 2, or 3D cells, and using numerical techniques to calculate the flow of heat, and liquid and vapour phase water from cell to cell. By taking into account the hygrothermal properties of the materials in the assembly, and the internal and external environmental conditions, such HAM models can calculate the moisture content and temperature at various positions throughout the assembly, which can then be used to predict the risk of microbial growth.

HAM models are widely used to assess the hygrothermal performance of buildings, and have been extensively validated and such tools have been used for simulating the drying of flooded buildings. For example, the modelling of the drying of a wooden church after a flood [13], and the simulations of the forced drying of historic wall constructions [14] have been done using EnergyPlus and WUFI, respectively. Delphin has been used to simulate walls of buildings in Dresden following the flooding of the River Elbe in 2002 [15]. HAM simulations offer a quicker and cheaper method of examining the absorption and drying of flooded buildings as compared to the alternative of physically constructing walls and buildings, flooding them, and then measuring the rate of drying [16-18].

As noted, mould growth is a serious problem in damp and flooded buildings. Relative humidity, temperature, nutrient availability, and colonising species are all important factors in mould growth on building surfaces. A number of models have been developed in order to predict the risk of mould growth in buildings, and are used alongside HAM models [19-22]. These models can be used to help predict the risk of mould growth in damp houses, but may have difficulty modelling the survival of viable spores when conditions dry. Further work is required to adapt these to the mould and bacteria species that are specifically found in flooded buildings.

### **2.2 Building Stock Models**

Any potential building stock model for flood recovery will be complex due to the variations in the physical form of dwellings and the wide range of internal and external climates that can occur. In the UK, the housing stock has been constructed over a long period of time, with a wide range of materials and building techniques used, meaning that a range of assumptions are required in the development of a model. Many of these assumptions are already in use - building stock models are widely used for

energy consumption estimation and energy policy development in the UK - and these models can be adapted for hygrothermal simulation.

Building stock models can be classified as bottom-up or top-down models. Bottom-up building stock models are built from a hierarchy of disaggregated components, which are then combined according to estimates of their individual impacts. Bottom up models based on building physics tend to consider dwelling archetypes, which are considered to be representative of the dwellings within a building stock. Building physics calculations are then used to estimate, for example, the energy consumption based on utilisation scenarios. There are a wide number of different bottom-up building stock models for the UK, which range from 2 to 1,000 building archetypes [23]. Top-down models are built from aggregated data, for example fitting historical energy consumption data, and so do not have the level of constructional detail or historical flood recovery data required for this study.

Of the existing building stock models in the UK, most bottom-up models divide the building stock into age-use groups, and define building archetypes to represent these building types. Buildings of different ages have different built forms, and can use different building materials. In studies of energy consumption, this is reflected, for example, in the differing heat transfer characteristics (U-values) for walls of different ages [24], which are based on assumptions about materials and material thicknesses. The structure of the building is used to infer the area of external walls and the internal layout of buildings, in order to calculate heat loss. Consequently, building stock information available for analysis tends to be divided into age brackets and building types that have similar layouts, and wall and floor constructions. Many of the assumptions made about building envelope design and construction are based on surveys, such as the English Housing Condition Survey (EHCS) [25] and knowledge of historical building trends [26]. The EHCS is a survey of the condition and energy efficiency of housing in England and describes the building fabric characteristics of surveyed buildings. Allen and Pinney [27] describe standard dwelling dimensions, construction, and occupancy schedules for building simulation modelling, while the Standard Assessment Protocol (SAP) for energy performance rating of buildings [24] and the Building Research Institute's BREDEM model [28] also lists a number of building envelope assumptions used in building stock modelling.

While energy models are concerned with the thermal performance of the building envelope, hygrothermal simulations are interested in the *combined* thermal and hygric performance of the buildings. Building stock models for hygrothermal simulations require many of the same inputs as energy simulations. Age-structure archetypes can be used to estimate the wall constructions for internal and external walls, and the surface area of the floors and walls exposed to flooding and drying scenarios. The age of the dwelling can also be used to infer the air change rates, which can be used to model the internal drying of unventilated spaces buildings. However, hygrothermal simulations require additional information about the materials within the envelope that are not contained in the harmonised standard hygrothermal design values used for energy simulations [29]. Parameters such as porosity and detailed water absorption and desorption functions up to material saturation are important for HAM simulations. Harmonised design values for the hygrothermal properties of building materials in energy studies has previously been determined by statistically analysing existing material data [30].

Geospatial databases have been developed in previous studies for energy simulation data at levels ranging from the individual building to administrative area. Geographic Information Systems (GIS) enable the storing of building information in a spatial database, the mapping and dissemination of the building stock data, and can act as a platform for energy simulations. Energy simulation algorithms require a large amount of input data, which is costly and time consuming to collect via house by house surveys, so GIS can also be used to infer building characteristics using remotely sensed data such as aerial imagery. A range of different sources of geographic data are available that contain building stock data relevant to hygrothermal simulations. These databases can be used to develop a bottom-up building stock model with information that can be used to model the flooding and drying of geographic areas.

### 3. Methodology

The research area for the present study was selected to be an area of London extending from Richmond in the west to Greenwich in the east – an area covered by approximately 250,000 homes,

and at risk of flooding. The main GIS database used was Ordnance Survey Mastermap [31], a continuously updated cadastral map, that has a Topographic Layer with individual building footprints and crude land use information. As it is the most recently updated topographic map available, the building footprints were used as a basis for the model. OS Address Point data was used to determine the number of dwellings in each residential building [32] based on matching Topographic Identifiers (TOID). Cities Revealed [33] produces a landuse database with building footprints classified as one of 15 building types and 17 age categories. The building classification can be used to fit suitable building archetypes to individual properties within the GIS system. The Cities Revealed building classifications were joined to the OS Mastermap data through a spatial join (Figure 1).

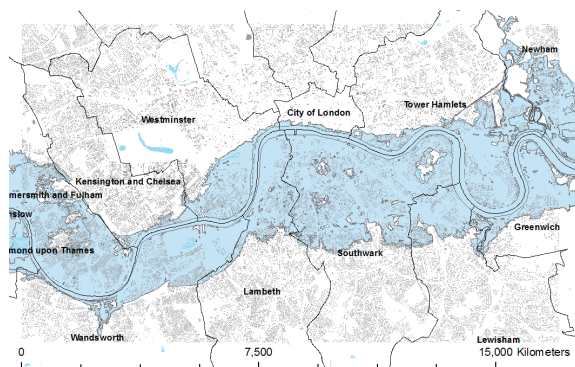


**Figure 1.** *Ordnance Survey Mastermap with Cities Revealed building age characteristics*

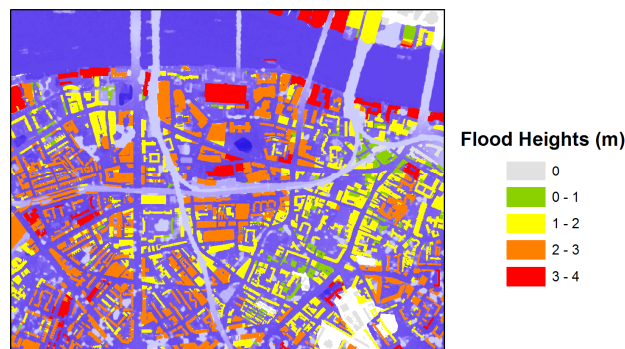
Building height information is required to determine the depth of any flood water. Total height was derived for individual properties from a LiDAR (Light Detection and Ranging) -generated Digital Surface Model (DSM) raster provided by Cities Revealed. The ground level heights of the dwellings were determined by filtering the DSM to create a Digital Terrain Model (DTM).

Additional relevant spatial building data is required to match archetypes to building footprint data. The HEED database [34] is a collection of information from energy suppliers, government scheme managers, local landlords, Energy Saving Trust (EST) energy checks, and EST programmes on wall types, cavity wall insulation levels, and building ages. This information is valuable because it provides information on the frequency of insulation in aggregated areas down to census output area detail, or around 125 households. In the present study, the HEED data on insulation and wall type was used to supplement the topographic data.

While the focus of this paper is on building characteristics, many other factors are vital to hydrothermal flood modelling. The depth and duration of the flood, the water temperature and salt concentrations, and the drying conditions, such as external weather and internal conditions will impact building behaviour. Understanding the impact of a flood on the building stock requires information on the geographic extent and height of any floods. The Environment Agency's (EA) flood risk map [35] shows areas with risks of 1 in 100 years for river flooding, 1 in 200 years for sea flooding, and a 1 in 1000 years for extreme sea or river flood events (Figure 2). In this study, the EA flood risk map was used to determine the height above ground that individual properties would be flooded under different scenarios by comparing the flood heights to the Digital Terrain Model (DTM) (Figure 3).



**Figure 2.** Environment Agency tidal and fluvial flood map of the research area.



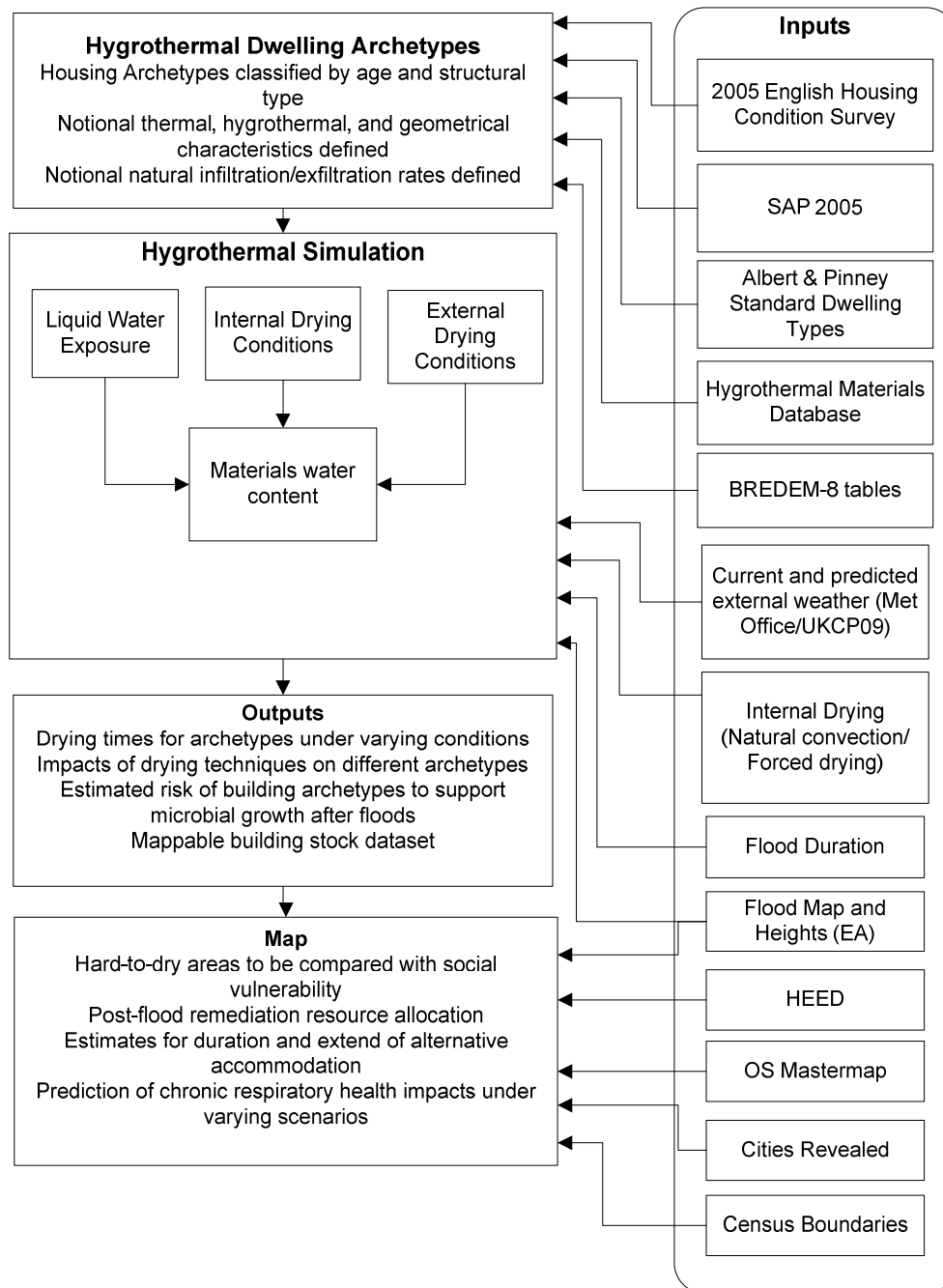
**Figure 3.** Flood heights assigned to individual properties in the flood zone for a 1 in 1000 year event.

Different flood durations and heights will be simulated in hygrothermal models for walls and floors in 2D (WUFI, Delphin) and for whole-buildings (EnergyPlus) for each building archetype under different environmental conditions. These models will simulate the movement of water into the building envelope, and the subsequent drying of the building under a range of internal and current and future external weather conditions. 2D models will be used to compare simulated data against previous laboratory and field measurements of flooded walls and floors, while whole-building simulation will enable the prediction of water vapour movement throughout the building zones causing damp in areas that were not physically contacted by flood water. EnergyPlus will also be used to calculate ventilation rates within the buildings under different scenarios (e.g. windows open, dehumidifier), as well as within any wall cavities, in order to help determine the most effective means of drying. The temperature and relative humidity at surfaces within the envelope where microbial growth can occur and impact indoor air, such as the interior surface and inside the cavity, will be determined.

#### 4. Results

Presented here is the novel methodology that has been developed in the first phase of the work (**Error! Reference source not found.**). The proposed model outlines the necessary inputs required to develop and implement a hygrothermal flood simulation model. Later phases will implement the methodology, and the outputs from the integrated simulations will be presented in future papers. Microbiological models are not detailed in this methodology, but will be combined with the model outputs at a later stage.

There are many uncertainties associated with such complex simulations and work is necessary to understand how the assumptions made about the built form and material parameters impact the model. For example, the hygrothermal material properties are assumed to be homogenous, while in reality materials can vary significantly. Consequently, further work is required to understand how variations in the input parameters in Figure 4 can impact drying characteristics. A sensitivity analysis in the next phase will help to identify the impact of such uncertainties.



**Figure 4.** Schematic of the hygrothermal flood modelling process

## 5. Conclusion

Building archetypes can inform the hygrothermal simulation engine in order to understand the drying of the building stock under a range of different flooding scenarios and drying scenarios. As the model is composed of notional building types which are intended to represent average buildings within each archetype, the model will not be able to calculate the actual hygrothermal performance of *individual* buildings. However, the great value of the work is that the building stock model can be used in order to determine the relative risk of post-flood damp at small and intermediate areas.

Application of biohygrothermal models can then help identify how long buildings will be at risk of mould growth following a flood based on the material substrates and the temperature and relative humidity values output by the HAM simulation. Adapting these models to show persistence, or decline of mould, and bacterial behaviour will further enhance the power of the model.

The objective of this phase of the work was to develop a novel methodology for performing hygrothermal simulations of flooding scenarios for the London building stock. The outputs from this research will inform the drying times of different buildings and localities, and their potential for lingering damp and contamination, which can be used alongside analyses of social vulnerability to flooding of the population. The results will be of great interest to flood remediation organisations, health agencies, insurance organisations, and social housing providers.

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