Predicting the microbial exposure risks in urban floods using GIS, building simulation, and microbial models

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Abstract

London is expected to experience more frequent periods of intense rainfall and tidal surges, leading to an increase in the risk of flooding. Damp and flooded dwellings can support microbial growth, including mould, bacteria, and protozoa, as well as persistence of flood-borne microorganisms. The amount of time flooded dwellings remain damp will depend on the duration and height of the flood, the contents of the flood water, the drying conditions, and the building construction, leading to particular properties and property types being prone to lingering damp and human pathogen growth or persistence. The impact of flooding on buildings can be simulated using Heat Air and Moisture (HAM) models of varying complexity in order to understand how water can be absorbed and dry out of the building structure. This paper describes the simulation of the drying of building archetypes representative of the English building stock using the EnergyPlus based tool 'UCL-HAMT' in order to determine the drying rates of different abandoned structures flooded to different heights and during different seasons. The results are mapped out using GIS in order to estimate the spatial risk across London in terms of comparative flood vulnerability, as well as for specific flood events. Areas of South and East London were found to be particularly vulnerable to long-term microbial exposure following major flood events.

1. Introduction

London is one of the most flood-vulnerable major cities in Europe, with risks of tidal flooding from the Thames and fluvial and surface water floods from heavy precipitation. Major tidal floods in 1928 and 1953 caused significant damage to the city, while more recently the summer floods of 2007 saw 1,000 London households flooded following heavy rainfall. It has been estimated that a 1 in 50 year rainfall event would lead to the flooding of 1 in 7 London buildings and damages of tens of billions of pounds [GLA, 2009]. In addition, small, localised floods caused by broken water mains are also a regular occurrence. Climate change is projected to result in rising sea levels and an increased frequency of rain storms, which may lead to a greater frequency of flood events in London.

Flooding can lead to a number of health issues for building occupants. Mould, bacteria, and protozoa can grow or persist on flooded building surfaces, some of which can release harmful bioaerosols into the indoor air [Taylor et al., 2011], leading to potential respiratory problems. Building dampness is one of the key factors associated with the exposure to various microbial hazards. Microbial contaminants on indoor surfaces following flooding may also pose a

health risk to occupants through direct contact, should they touch a surface that is contaminated with a flood borne pathogen. Occupants who choose to leave their flooded properties because of the risks present in damp properties may also experience increased health problems such as mental illnesses [Tapsell and Tunstall, 2008] related to their displacement. The duration of displacement may be prolonged following a flood; the 2007 floods in Hull resulted in over 10% of households remaining in temporary accommodation two years after the event [Hull City Council, 2009]. The reasons for extended displacement can be complex, and include delays in remediation due to insurance issues, busy remediation companies, and the extent of the work required to return the dwelling to a habitable state. However, the amount of time taken to dry different buildings is one of the key issues effecting displacement. Therefore, understanding the duration of damp within buildings under different drying scenarios can help to predict the potential risk to occupants following a flood.

Heat, Air, and Moisture (HAM) models are tools used in building simulation to predict moisture performance, from individual materials, to building envelopes and whole-buildings. HAM models have been used in the past for simulating the impact of flooding on buildings. [Blades et al., 2004; Nicolai and Grunewald, 2006; EU, 2007]. In our previous study, simulations of a the drying behaviour of a number of typical London dwellings indicated that there are differences in the drying rates of different dwelling types following a flood due to the built form and building fabric construction and drying type [Taylor et al, 2012]. One of the key findings of this research was that modern purpose-built flats were more difficult to dry then detached or semi-detached properties, and that buildings with cavity walls insulated with glass fibre, or with an Autoclaved Aerated Concrete (AAC) inner leaf were more difficult to dry that those with solid brick or uninsulated cavity walls with a brick inner leaf.

The types of dwellings and their building fabrics vary throughout London, meaning that the results from our previous research can be applied spatially to determine the drying difficulty of different locations within the research area. Similarly, the depth of flood water during flood events will also vary spatially, meaning that simulations that take into account the depth of a flood event may be applied to models of specific floods in order to predict areas of vulnerability within London. Finally, the city population varies spatially in terms of its socio-demographic profile and population density, and therefore it's vulnerability to health problems following a flood event.

The objective of this paper is to integrate the results of HAM building simulations with GIS-based building stock models and flood models in order to predict the locations within London that are particularly vulnerable to long-term damp following a flood event. Building on previous research, the drying behaviour of different London archetypical buildings will be simulated drying under different conditions and after floods of different heights. The mould model of Clarke et al [Clarke, 1998] is used to predict the risk of mould growth on different surfaces within the flooded buildings and determine the total internal surface area presenting a microbial risk. The simulation results will be used to map both the comparative drying ability of the buildings in different locations by examining the drying time under the same flooding and drying conditions, and the actual drying behaviour after a specific flood event by taking the flood height into account for individual buildings. Finally, areas which may be at high risk due to a high risk of floods, an abundance of slow drying buildings, social vulnerability, and population density are identified. The results of this analysis can be used to identify areas where the city may be particularly vulnerable to the effects of flooding due to the combination of built form, demographics, and flood risk.

2. Methodology

This research required combining a number of different data sources and models including building stock models, HAM simulations, GIS data, and flood models. For more information

on the building stock development, HAM models used, and modelling methodology, readers are advised to refer to Taylor et al [2012].

2.1 Building Simulation

The building stock archetypes used in this study were originally developed by Oikonomou [Oikonomou et al., 2011] and represent 15 of the most commonly occurring built form and dwelling age combinations within their research area (29% of the Greater London Authority household spaces). Some dwellings were not relevant, for example flats above ground level and those with shops underneath, as they would not be directly impacted by flood waters. The English Housing Survey [DCLG, 2008] was used to identify the most common building fabric types in each building archetype; in cases of cavity walls, both insulated and uninsulated walls were considered. Hygrothermal material data for the construction materials in the building envelopes were taken from the WUFI database [IBP, 2007], while information on glass fibre was taken from Hokoi and Kumaran (1993).
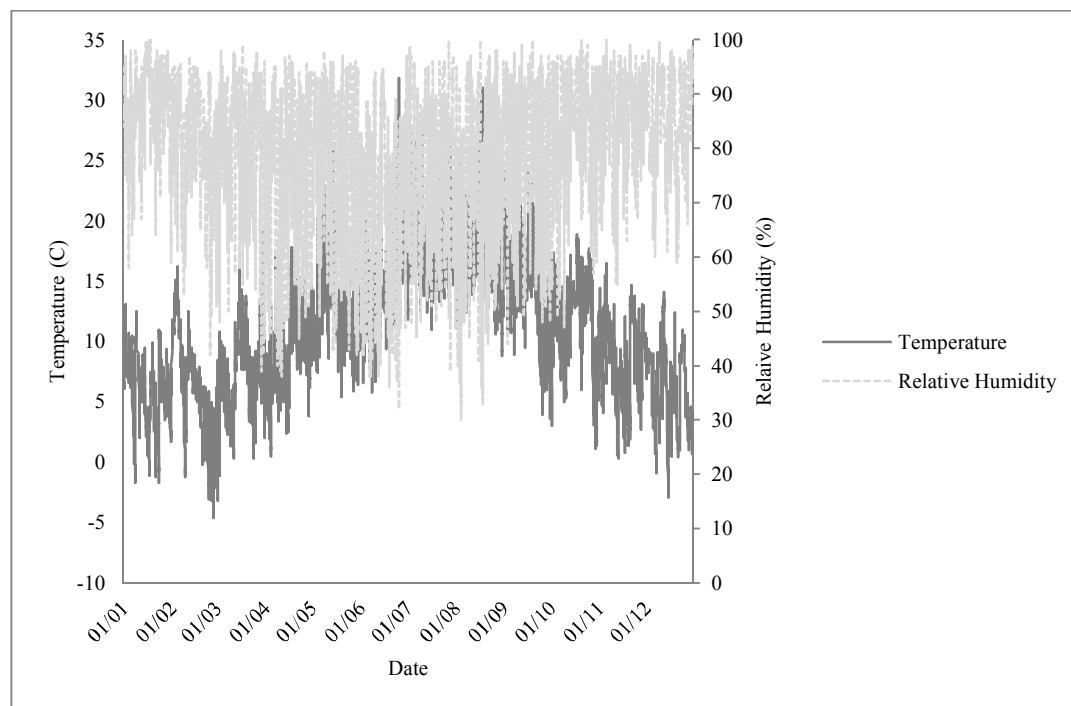
The methodology for simulating the flooding and drying of the archetypes using HAM models has been previously described in Taylor et al [2012]; this paper expands on this initial work by simulating floods at a number of different flood heights. No simulation package was known to be available that would allow both the simulation of water movement into a structure using a pressure head of water, and the whole-building simulation of the internal and external drying of the building. Therefore, two separate HAM models were used to simulate the flooding and drying of the buildings: Delphin 5.6 [Nicolai and Grunewald, 2006] and the EnergyPlus-integrated UCL-HAMT (University College London Heat and Moisture Transfer) [EnergyPlus, 2008]. Delphin was used to simulate the flooding of the wall and floor assemblies, while UCL-HAMT was used to simulate the drying of whole buildings. Two drying scenarios were considered:

- Comparative drying performance: The drying performance of building archetypes under the same drying conditions and flood height were used to illustrate the difficulty of drying property types. In this case, buildings were modelled as being naturally ventilated buildings with their windows and internal doors open and no central heating following a flood of 0.5m on January 1st.. Abandoned buildings were modelled with all windows and internal doors closed and the heating turned off. A flood height of 0.5m was selected based on the modelled maximum height of a 1 in 20 year tidal flood risk for Hackney, East London

- Actual drying performance: Buildings were simulated as being abandoned, with the windows and external doors closed following a flood on January 1st and July 1st. Buildings were modelled flooded to four different heights (0.1m, 0.5m, 0.7-1.0m, and 2.0m) to examine the relationship between flood height and drying time. The range of flood heights (0.7-1.0m) for the second highest flood was due to the presence of internal doors within the building; as the ceiling height varied in the different dwellings, the flood height had to be shifted to accommodate the 2m high door on internal surfaces, and ensuring that the airflow network remained consistent throughout all the flood heights. Buildings were modelled as being abandoned as it was assumed that the flooded homes would be evacuated or sealed following a major flood.

1
2 To simplify the model, cavities in the external wall and subfloor were modelled in certain
3 assembly types by including a layer of air or insulation in the HAMT assembly. As a
4 consequence, ventilation within these spaces was not modelled, an assumption which may
5 impact drying behaviour, but is representative of a worst-case scenario where air bricks are
6 blocked or not present.
7
8 External conditions were taken from a CIBSE Test Reference Year weather file for London
9 (Figure 1). The flood simulations were started on January 1st, modelling winter floods on
10 North/South oriented buildings only. The simulation timestep was 1 minute. The RH and
11 temperature were output from the surface cell of the interior side of the walls, floors, and
12 ceilings inside the buildings as an hourly average.
13
14 Simulation duration took from 4-12 hours to simulate a single building on a 2.83GHz Intel
15 processor, depending on the building structure and the complexity of the building fabric. In
16 order to increase the speed of simulation, naïve parallelisation was used to run multiple
17 simulations on a single quad-core computer. Additionally, multiple instances were run on the
18 Amazon Elastic Compute Cloud (EC2), as per Hopkins [Hopkins et al., 2011].
19

20
21 **Figure 1. Temperature and RH values for the simulation weather file.**
22
23
24
25 The surface relative humidity and temperature were used to calculate the risk of mould
26 growth using the model developed by Clarke [Clarke, 1998] for *Aspergillus versicolor* and *S.*
27 *chartarum* over time. *Apergillus*, and *Stachybotrys* species of fungi have all been observed in
28 elevated levels in flooded dwellings [Solomon et al., 2006; Dumon et al., 2009], but show
29 different moisture requirements with *S. chartarum* having higher moisture requirements than
30 *A. versicolor* for growth. A Microsoft Excel macro was used to automate the import of the
31 EnergyPlus output files and the total surface area of the building susceptible to mould growth
32 was calculated.
33

4

2.2 Drying Behaviours

The simulation results were used to demonstrate the drying behaviours of the different building archetypes under comparative and actual drying scenarios.

2.2.1 Comparative Drying Behaviour

The comparative drying behaviour of the buildings was taken to be the amount of time (days) required for the buildings to dry to the point where there was no growth risk for *A. versicolor* or *S. chartarum* on any surface inside the dwellings under naturally ventilated scenarios after the 0.5m winter flood. The same flood height and drying scenario was chosen in order to demonstrate the drying abilities of the archetypes under the same conditions.

2.2.2 Actual Drying Behaviour

Those entering properties for the first time following a major flood event will likely be entering an abandoned property where the doors and windows were left closed to prevent intruders during the evacuation of the occupants. Depth-drying curves were developed to predict the instantaneous mould risk inside the property as well as the amount of time a building will remain at risk following a flood event when left abandoned, based on the height-dependent simulation results. These depth-drying curves are based on the depth-damage curves developed for the prediction of financial costs associated with flooding (e.g. [Penning-Rowsell et al., 2005]), and are intended to be applied between the simulated ranges of 0.1m to 2m for different building types and seasons.

In order to describe both the instantaneous risk within a property and the amount of time required for the risk to decrease to zero for *A. versicolor* and *S. chartarum*, a 3D function was fit to the simulation results for the data in the simulated ranges of 0.1m to 2.0m for different building types and seasons. A 3D logistic decline model describes a curve showing the reduction in surface area at risk to mould growth as observed in the simulation results:

$$SA = \frac{a}{1 + exp\left(-(b + c * t + d * h + f * t * h)\right)} + g$$

where SA is the internal surface area at risk of mould growth (m^2), h is flood height (m), t is time (days), and a, b, c, d, f, and g are model parameters. The logistic equation could be re-arranged in order to solve for the amount of time required for the internal surface areas inside the dwellings to reduce to a set value for floods as a function of flood height:
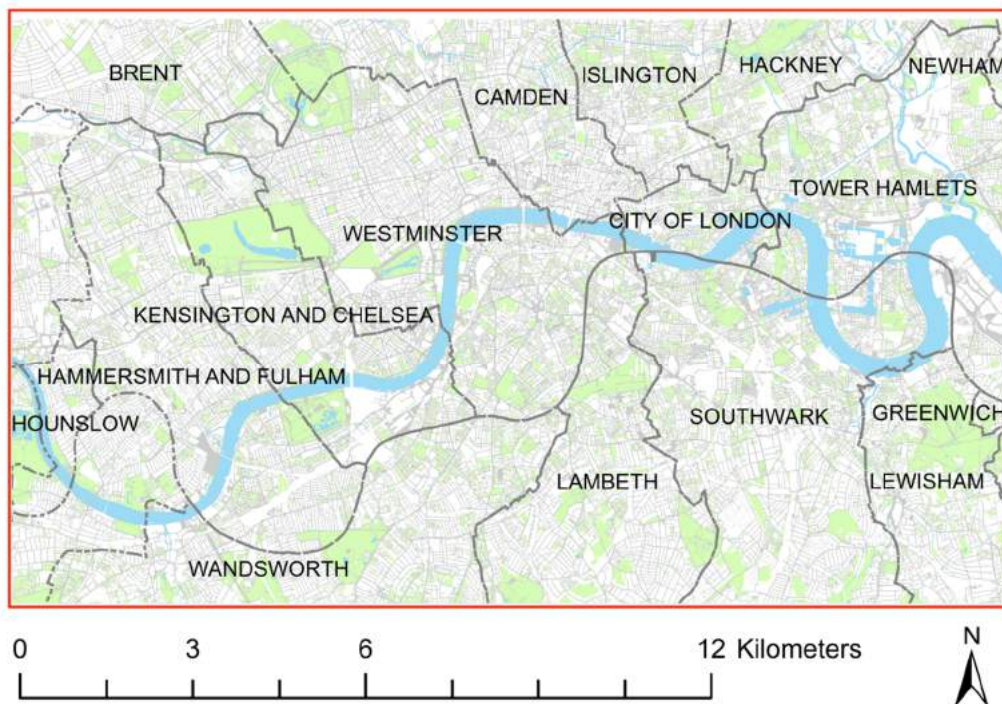
$$t = \frac{\ln\left(\frac{a}{-g} - 1\right) + b + d * h}{c + f * h}$$

This logistic model displays an asymptote which approaches zero over time. In order to force the model to go through SA = 0 when there was no longer a risk of mould growth, the models were fit using a fixed offset (g) set to a nominal value below zero (-10). A major strength of the 3D logistic model is the ability to alter the shape of the decline (concave vs convex decline) by eliminating a model parameter, and making the model applicable to the declines exhibited by both mould species as the buildings dried over time.

The data was fit to the curve using the online tool ZunZun [ZunZun.com, 2011], fitting to the lowest sum of squared (SSQ) absolute error. A step-wise regression procedure was followed to eliminate parameters with a large confidence interval. The results were checked against the original data to ensure that the estimate for the drying time (zero- intercept) provided a good estimate of the model results. The parameters for the depth drying curves were calculated for each built form/wall type combination, including both uninsulated and insulated cavity walls in some dwelling types.

2.3 GIS

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 (Figure 2). The extent of the research area was determined by the available building stock and surface height data, and computing power.
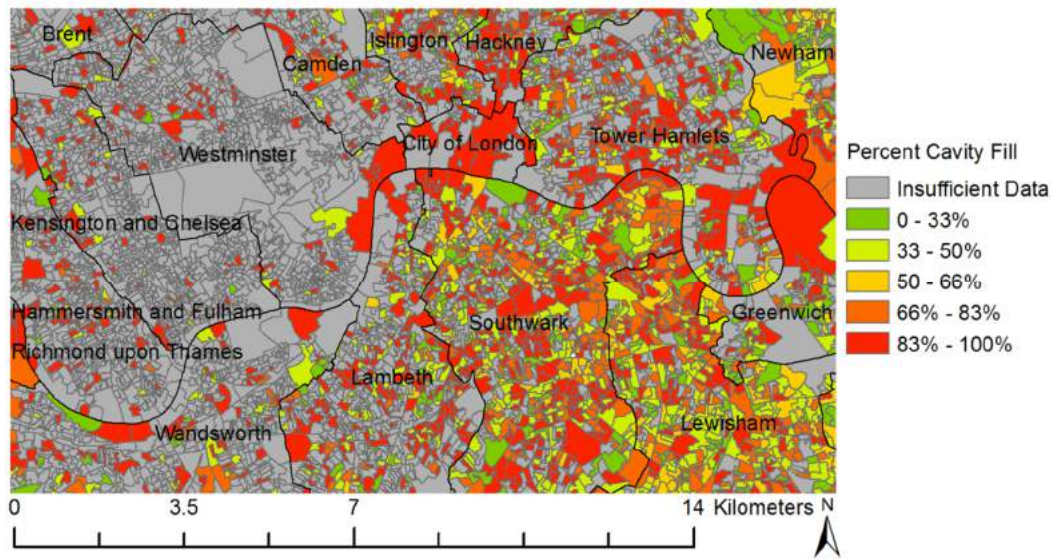

Figure 2. Extent of the research area.

Cities Revealed (CR) [The Geoinformation Group, 2010] and the Ordnance Survey (OS) [Ordnance Survey, 2010] both produce cadastral maps that were used in this research. CR produces a landuse database with building footprints classified as one of 15 building types and 17 age categories, enabling the archetypes proposed above to be mapped to individual properties within the GIS system. The CR geographic dataset is less frequently updated, less widely available, and a less clear provenance than that of the OS Mastermap. For this reason, the OS Mastermap was used as the basis for the cadastral map of the buildings within the research area.

CR building classifications were joined to the OS data through a spatial join, so that the individual OS buildings would be matched with the corresponding CR building information based on the location. The resulting cadastral database was filtered for domestic dwellings by based on the CR land use classifications of different properties.

1   While the EHCS analysis described the frequency of different wall types within building
2   archetypes, the frequency of cavity wall insulation in archetypes with cavity walls is expected
3   to change depending of the locations of the buildings due to regional differences in income
4   and local government programs. The HEED database [HEED, 2009] is a collection of
5   information from energy suppliers, government scheme managers, local landlords, Energy
6   Saving Trust (EST) energy checks, and EST programmes on wall types, cavity wall insulation
7   levels, and building ages. The HEED database was used to gather additional information
8   about the building fabrics of the buildings within the CR database. COA-level data on the
9   percentage of properties with cavity wall insulation was used to determine the probability of a
10 building with cavity walls having insulation within these areas using the ArcGIS spatial
11 overlay tool. The calculated frequency of insulation within a COA was used to adjust the
12 modal wall type of individual buildings within the areas to reflect the local insulation rates.
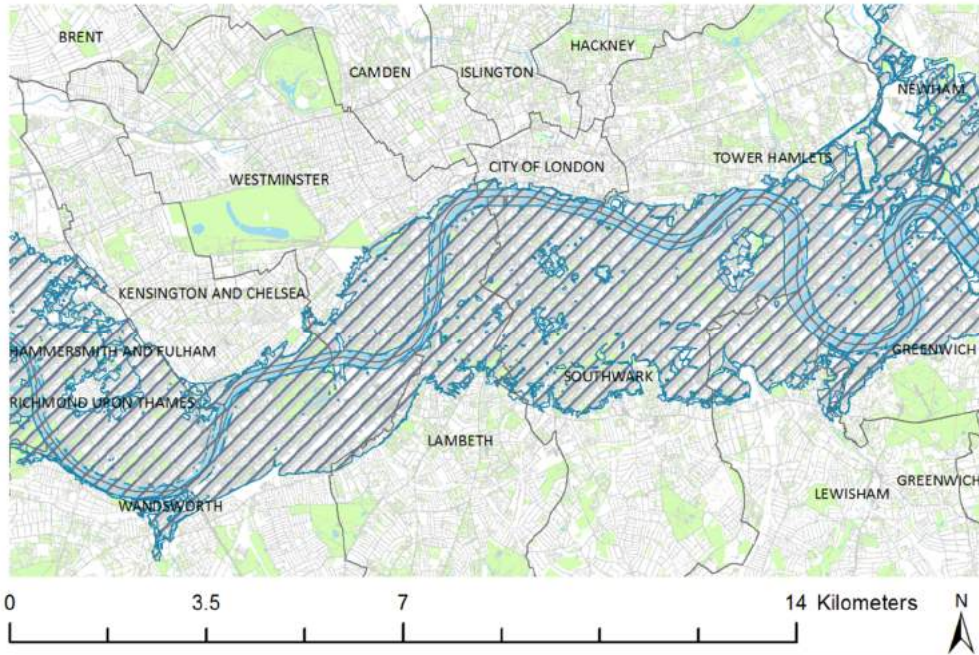13

15 **Figure 3. The frequency of insulation in cavity walls.**
16

17 **2.3.1 Flood Risk Models**

18 A number of flood risk models are available for the UK, which indicate the risk to certain
19 areas of flooding from different water sources. The Environment Agency (EA) produces
20 publically available flood maps for tidal and fluvial floods [EA, 2010], showing the areas at
21 risk for flood events. A flood map with heights for a 1-in-200 year tidal flood event was
22 obtained from the EA for the research area.

1

2
3 **Figure 4. EA 1-in-200 year tidal flood risk map for London.**

4

5

6 In order to determine the flood depth for individual properties, a Digital Terrain Model
7 (DTM) was created developed by filtering a LiDAR -generated Digital Elevation Model
8 (DEM) raster provided by CR to remove buildings and other non-terrain features. To filter
9 buildings from the DEM, the building footprints from the original unfiltered OS Mastermap
10 data were used as a mask; using external data as a mask is an established technique in DEM
11 filtering. A 3m buffer was drawn around the outside of the individual building footprints in
12 order to account for the 2m resolution of the LiDAR data and the area within the buffer
13 clipped from the LiDAR dataset. The DEM was then filtered using a slope-based technique,
14 as per the EA [Priestnall, 2000]. Once the raster had been filtered, the gaps were filled by re-
15 interpolating to a 2m resolution using an Inverse Distance Weighting (IDW) algorithm,
16 leaving a DEM representing the height of the ground without man-made or vegetation
17 features.

18
19 In order to determine the flood heights above ground level, the DTM was subtracted from the
20 flood height raster using raster math. The flood height for individual properties was
21 determined using the ArcGIS Zonal Statistics tool. A buffer was drawn 1m inside the OS
22 Mastermap building shapefiles and the ArcGIS Spatial Analyst Zonal Statistics tool used to
23 determine the mean floodwater height within the buffered area, and the results were appended
24 to the building stock dataset. Buildings that had a flood height below the simulated range of
25 0.1m to 2.0m were approximated to be 0.1m, while those above 2m were assumed to have
26 suffered structural damage, and were not considered in this analysis.

27

28 **2.3.2 Mapping Drying Data**

29
30 By simulating dwellings drying after the same flood height, and under the same drying
31 conditions, information of the comparative difficulty to dry of dwellings was obtained, while
32 height related drying information for abandoned dwellings allowed for the actual drying
33 behaviour to be modelled. The comparative drying behaviour of different buildings was

mapped to demonstrate the variation in vulnerability of locations within the research area regardless of flood event and depth, while the actual drying behaviour took into account the flood depth as calculated by the flood risk model.

2.3.2.1 Comparative Drying Behaviour

The comparative drying behaviour was taken to be the length of time following the flood required for the modelled built form/wall type combinations to dry under the same naturally ventilated conditions to the point where there was no mould growth risk inside the dwellings, with the assumption that all visible mould would be removed before the occupants move back in. The drying results were joined to the geodatabase of individual buildings with the CR built form and HEED cavity wall insulation data. The mode drying time was then calculated for each COA in the research area using the ArcGIS Overlay-Spatial join tool, resulting in an estimate of the comparative drying times of the most common building archetypes within the COAs. Maps were created for the comparative drying times of the different contaminating species modelled, and used to identify locations where the building types would be vulnerable to long-term damp following flooding. In cases where the built form/wall type combinations did not dry using natural ventilation within the year-long simulation period, the individual buildings were classified as being > 1 year.

2.3.2.2 Actual Drying Rates

The parameters of the depth-drying curves were joined to the building stock geodatabase, and the flood depths used to calculate the duration of contaminant risk for *A. versicolor* and *S. chartarum* for both summer and winter floods. The mean risk duration for the COAs was calculated using the ArcGIS Overlay-Spatial join tool, and the results mapped.

2.3.3 Mapping Populations Demographics and Vulnerability

Mapping has also been used to show the vulnerability of resident populations to floods based on socioeconomic data and using research into past flooding events. The Social Flood Vulnerability Index [Tapsell, 2002] assesses the vulnerability of populations to adverse health effects based on three social characteristics and four financial-deprivation indicators. To know which populations are at risk from floods for socioeconomic reasons informs the development of processes to predict regions vulnerable to flooding in London. The UK Census [ONS, 2001] provides aggregate statistics on the demographics and socio-economics of the UK within specific geographic areas. This data is used extensively to determine population characteristics within a region, and can be used to describe a flood-affected population.

To map the vulnerability of Londoners to a flood event, 2001 Census data was acquired from the Census Dissemination Unit for the four financial indicators (Unemployment, Overcrowding, Non-car ownership, and Non-home ownership) and three social indicators (Long-term sick, Single parents, and the Elderly (over 75)) over a COA. The resultant SFVI was mapped using ArcGIS to the census output area level.

In addition to the SFVI, Census data was obtained for the number of individuals living in households and the number of households within the COAs. The average actual drying time predicted for each COA for *A. versicolor* and *S. chartarum* for the EA 1-in-200 year tidal flood event was multiplied by the average number of individuals per dwelling within the COA in order to estimate the number of person-years residents would be exposed to damp

indoor spaces (should they choose to stay), or displaced (should they leave their damp homes).

3. Results

3.1 Simulations

3.1.1 Comparative Drying Behaviour

Comparative drying times were calculated as being the amount of time taken for the microbial risk inside buildings drying in winter under natural ventilation conditions to decrease to zero on all internal surface areas. The drying time for each building archetype with their modal wall type was calculated for each microbial species modelled (Table 1).

Table 1. Drying time (days) of archetypes using natural ventilation following a 0.5m winter flood.

Building	Wall	*A. versicolor*	*S. chartarum*
H01	Solid Brick Wall & Suspended Wooden Floor	201	180
	Uninsulated Brick/Brick Cavity	180	161
H02	Insulated Brick/Brick Cavity	234	222
	Uninsulated Brick/Brick Cavity	162	142
H03	Insulated Brick/Brick Cavity	219	208
	Uninsulated Brick/AAC Cavity	> 365	234
H04	Insulated Brick/AAC Cavity	> 366	272
H05	Solid Brick Wall & Suspended Wooden Floor	213	186
	Uninsulated Brick/Brick Cavity	191	163
H06	Insulated Brick/Brick Cavity	261	233
	Uninsulated Brick/AAC Cavity	> 365	234
H07	Insulated Brick/AAC Cavity	> 366	272
H08	Solid Brick Wall & Suspended Wooden Floor	216	198
	Uninsulated Brick/Brick Cavity	172	150
H09	Insulated Brick/Brick Cavity	218	201
	Uninsulated Brick/AAC Cavity	> 365	162
H10	Insulated Brick/AAC Cavity	> 366	271
	Uninsulated Brick/AAC Cavity	> 367	271
H11	Insulated Brick/AAC Cavity	> 368	321
H12	Solid Brick Wall	233	216
	Uninsulated Brick/Brick Cavity	180	161
H14	Insulated Brick/Brick Cavity	234	222
	Uninsulated Brick/Brick Cavity	218	198
H15	Insulated Brick/Brick Cavity	272	246

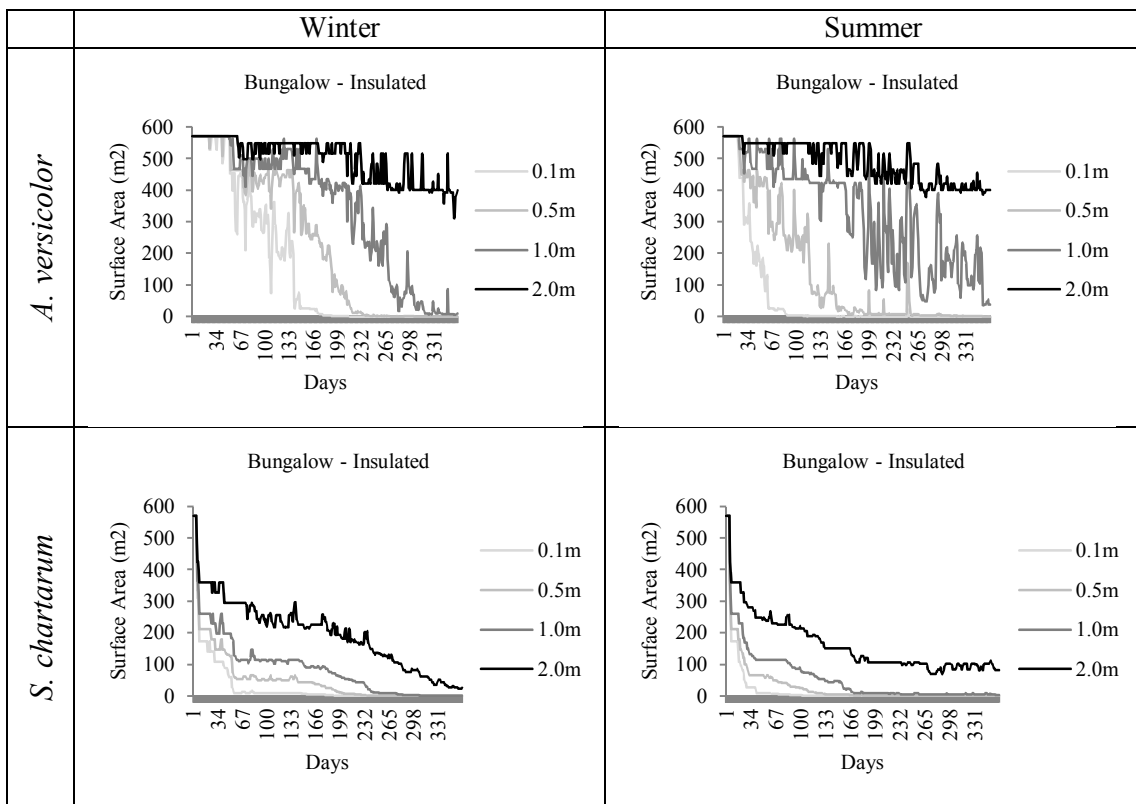### 3.1.2 Actual Drying Behaviour

1   As expected, dwellings that were flooded to a greater depth took a longer time to dry than the
2   shallower flood events. The reduced drying rate caused by a lack of ventilation, and the
3   increased amount of water inside buildings caused by high flood levels meant that many
4   buildings showed a risk for microbial growth for the entire year-long simulation period. Due
5   to the moisture requirements of the different species, *A. versicolor* remained a risk inside
6   buildings for longer than *S. chartarum*.
7
8   Figure 5 shows the impact of flood height on drying behaviour of a bungalow (Archetype
9   H09), as well as the differences in the drying rate for abandoned buildings following winter
10 and a summer flood. Winter floods were found to generally dry slower than summer floods.
11 Exceptions were observed for buildings that had a wall type that was particularly slow to dry,
12 such as insulated AAC walls, where the drying period ran into the winter, extending the
13 amount of time required for the structure to dry.
14
15

16 **Figure 5. An example of the drying behaviour of archetype H9 (bungalow) following floods of**
17 **four different heights for summer and winter floods.**
18
19 The parameters and model fits for the depth drying curves for each building for *A. versicolor*
20 contamination risk following a winter flood can be seen in Table 2. The fit of the model is
21 indicated by the R^2 and RMSE of the model fit, and the confidence intervals of the parameter
22 estimates. The models were found to offer a strong estimate of the variation of the drying
23 rates of buildings flooded to different heights.
24
25 **Table 2. Parameters for a depth-drying curve for *A. versicolor* growth risk following a winter**
26 **flood.**

Dwelling	Wall	a	b	c	d	f	g	r-square	RMSE
H01	Pre19299Solid	573	3.3	-0.03	6.32	-	-10	0.955	49.7
H02	Uninsulated	461	3.24	-0.0302	4.53	-	-10	0.941	47.2
	Insulated	465	3.14	-0.029	4.39	-	-10	0.938	48.4

11

H03	Uninsulated	493	1.73	-0.0239	0.0379	0.00726	-10	0.91	45.8
	Insulated	493	1.73	-0.0239	0.0379	0.00726	-10	0.91	40.8
H04	Uninsulated AAC	271	2.93	-0.00678	2.62	-	-10	0.794	9.9
	Insulated AAC	271	2.93	-0.00678	2.62	-	-10	0.794	9.9
H05	Pre19299Solid	461	3.42	-0.032	7.08	-	-10	0.948	42.2
H06	Uninsulated	234	6.24	-0.0272	3.61	-	-10	0.833	28.6
	Insulated	234	6.24	-0.0272	3.61	-	-10	0.833	29.6
H07	Uninsulated AAC	271	2.93	-0.00678	2.62	-	-10	0.794	9.9
	Insulated AAC	271	2.93	-0.00678	2.62	-	-10	0.794	9.9
H08	Pre19299Solid	633	0.435	-0.0217	5.45	-	-10	0.941	64.6
H09	Uninsulated	520	2.91	-0.0369	5.69	-	-10	0.958	48.3
	Insulated	528	3.16	-0.0335	4.45	0.000716	-10	0.961	44.9
H10	Uninsulated AAC	483	2.93	-0.019	4.56	-	-10	0.879	51.7
	Insulated AAC	483	2.93	-0.019	4.56	-	-10	0.879	51.7
H11	Uninsulated	296	1.42	-0.00893	1.94	-	-10	0.863	27
	Insulated	296	1.42	-0.00893	1.94	-	-10	0.863	27
H12	9InchSolidBrick	281	1.76	-0.0239	5.94	-0.00541	-10	0.957	24.5
H14	Uninsulated	465	3.14	-0.029	4.39	-	-10	0.938	48.4
	Insulated	493	1.73	-0.0239	0.0379	0.00726	-10	0.91	45.8
H15	Uninsulated	296	1.42	-0.00893	1.94	-	-10	0.863	27
	Insulated	296	1.42	-0.00893	1.94	-	-10	0.863	27

3.2 GIS

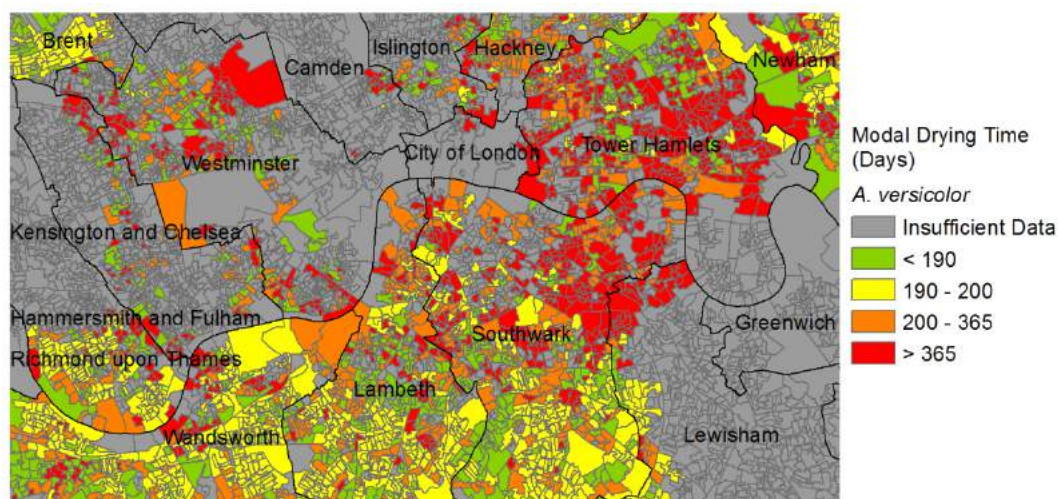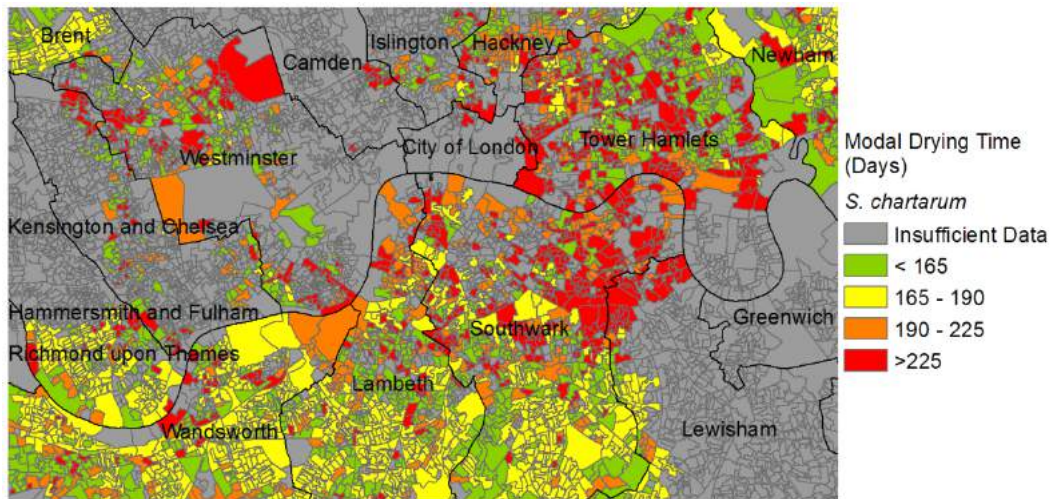### 3.2.1 Comparative Drying Behaviour

The areal mode of the drying times of the building archetypes within London for the different contaminants modelled can be seen in Figure 6 and Figure 7.

Figure 6. Comparative vulnerability of the London building stock to prolonged *A. versicolor* risk following flooding.

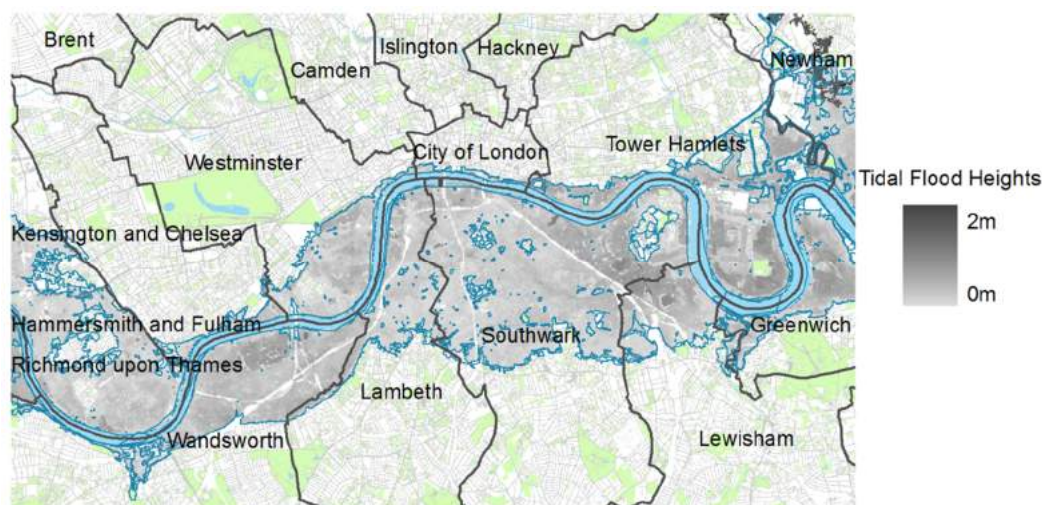Figure 7. Comparative vulnerability of the London building stock to prolonged *S. chartarum* risk following flooding.

These maps suggest a higher proportion of hard-to-dry properties in the East of the study area. Southwark and Tower Hamlets appear to be particularly vulnerable because of their large number of relatively slow drying properties. There was insufficient data to calculate many of the areas in the study, due to a lack of coverage of the CR data and because the archetypes modelled did not contain all of the London building stock. However, the results give an indication of the drying performance of buildings across many areas of the city.
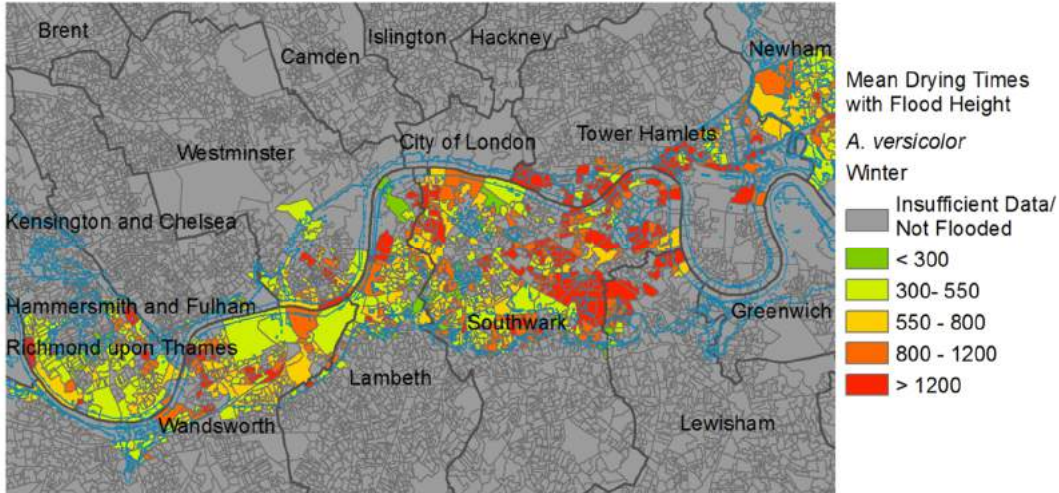
3.2.2 Actual Drying Behaviour

The raster indicating the calculated depth of the flood event based on the differences between the predicted flood heights provided by the EA and the calculated DTM can be seen in Figure 8. The average depth was found to be 0.8m, with parts of Southwark close to the Thames particularly vulnerable to deep flooding based on this scenario. The east of the research area alongside the Thames was found to be vulnerable to particularly deep flooding based on this scenario.
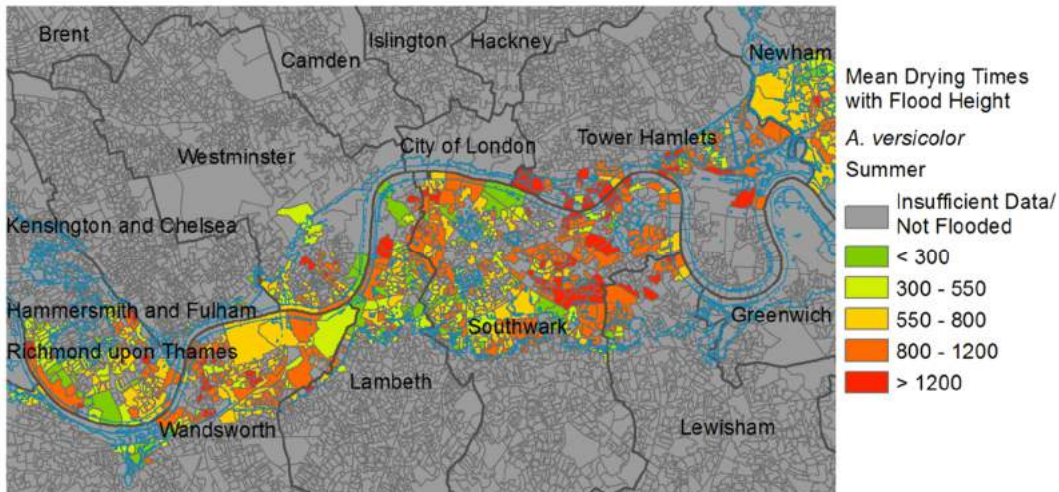

Figure 8. The depths of a 1-in-200 year tidal flood event in London.

Calculating the mean drying times of all known buildings within the COAs in London allowed for the estimation of how the variation in flood heights may impact on the drying
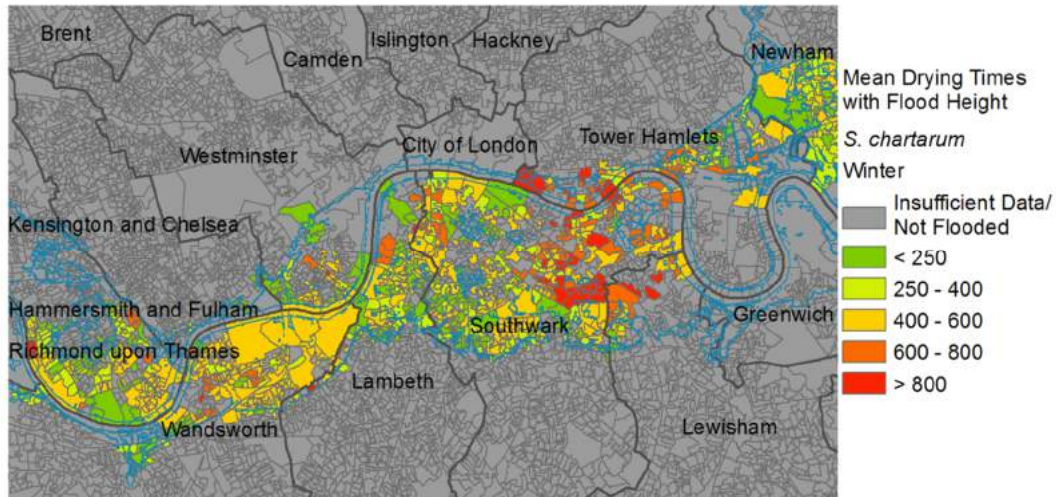
1 rates of properties based on their location. The application of the depth-drying curves to the
2 tidal flood risk scenario for the mould contaminants following winter and summer floods can
3 be seen in Figure 9, Figure 10, Figure 11, and Figure 12. As with the comparative drying
4 results, Southwark was found to be particularly vulnerable to long-term damp, and by taking
5 into account flood depth, the problem was emphasised.
6

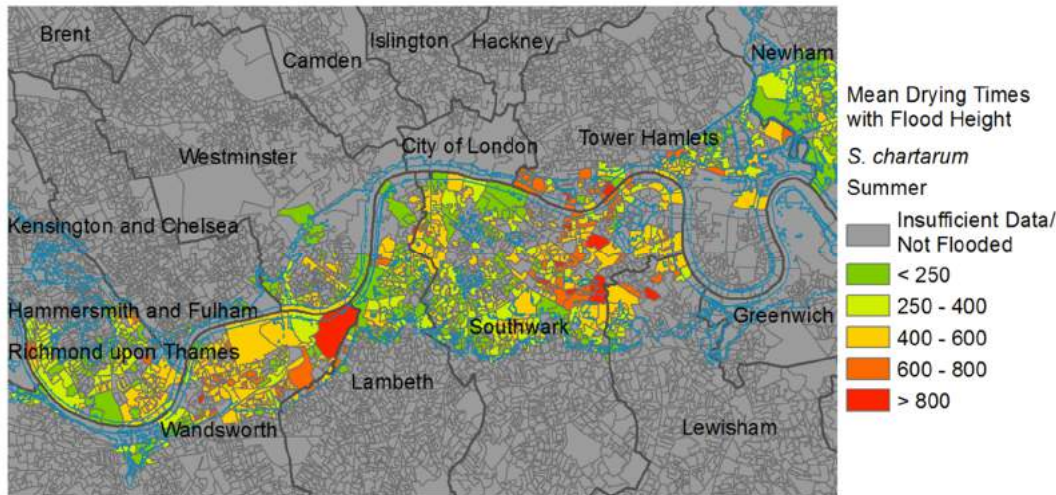7
8 **Figure 9. Average duration of risk (days) of contamination for *A. versicolor* following a winter**
flood. 9

10
11 **Figure 10. Average duration of risk (days) of contamination for *A. versicolor* following a summer**
12 **flood.**

Figure 11. Average duration of risk (days) of contamination for *S. chartarum* following a winter flood.

Figure 12. Average duration of risk (days) of contamination for *S. chartarum* following a summer flood.

3.2.3 Human Impact

The social vulnerability to flooding analysis identified the more vulnerable populations that live within London based on socio-economic data. The results of the SFVI analysis, generated using the procedures explained in Tapsell et al (2002) can be seen in Figure 12. The social vulnerability of Londoners to flooding increased towards the East of the research area, and was particularly high in the London boroughs of Newham, and close to the river in Southwark.
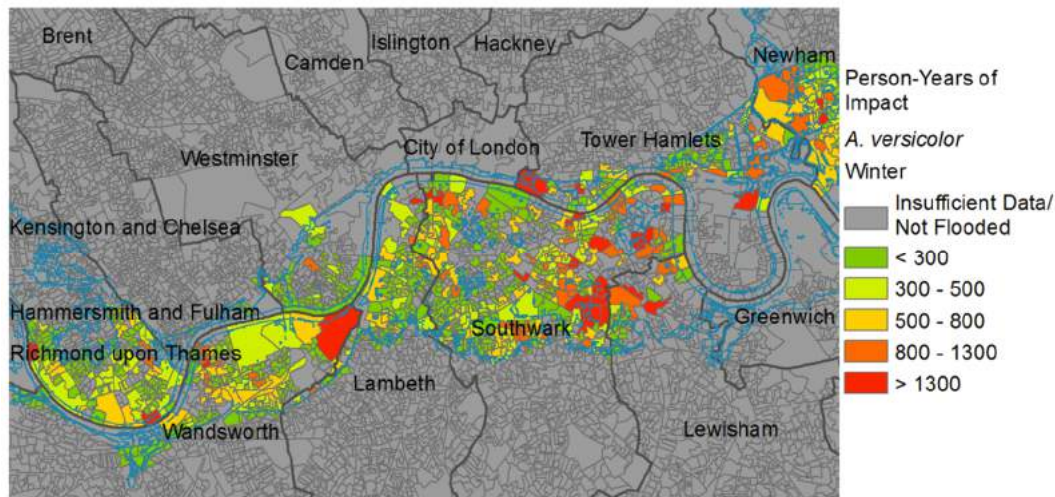
15

1
2 **Figure 13. Social vulnerability of populations in London to flooding based on the SFVI.**
3
4 Combining GIS Census data and flood maps indicated that a large of population of Londoners
5 would be affected by the 1-in-200 year tidal flood scenario. The number of domestic
6 buildings flooded, the estimated population affected, and the number of person-months that
7 the population would be impacted due to the drying behaviours of the buildings for each
8 Local Authority can be seen in Table 3. Southwark and Hammersmith and Fulham are likely
9 to experience the highest coverage of floodwater for the 1-in-200 year tidal flood, the greatest
10 number of flooded dwellings, and total flooded population. The largest impact in terms of
11 person-months was observed in the Borough of Southwark. An example of the calculated
12 person-years affected by the flood event can be seen in Figure 14.
13
14 **Table 3. Impact of a 1-in-200 year tidal flood event. Person-years are representative only, and are**
15 **extrapolated from buildings of known archetype only. Where there were no known archetypes**
16 **within a borough no person-years are reported.**

| | | Domestic Buildings Flooded | | Total Person-Years | | | |
| | | | | *A. versicolor* | *A. versicolor* | *S. chartarum* | *S. chartarum* |
Local Authority	Estimated Population Flooded	Total	Of which are known & modelled	Winter Flood	Summer Flood	Winter Flood	Summer Flood
City of London	18	17	0	-	-	-	-
Greenwich	5095	2506	0	-	-	-	-
Hammersmith and Fulham	40877	19465	4555	11947	51055	61421	42435
Kensington and Chelsea	1991	1082	32	84	2853	3073	1140
Lambeth	8831	4205	834	3523	17761	16776	9398
Lewisham	8332	3576	172	1116	23199	20532	12566
Newham	7477	3155	1648	6533	12507	13638	6782
Richmond upon Thames	160	80	0	-	-	-	-
Southwark	41645	18759	3477	19181	103484	95333	53318
Tower Hamlets	13440	6046	580	3744	39025	36555	17019
Wandsworth	15706	7841	3236	11187	27106	31587	19575
Westminster	5875	3363	166	611	12371	11981	5485
Total	149446	70095	14700	57925	289362	290895	167718

17

16

1
2 **Figure 14. Impact of the tidal 1-in-200 year flood event in terms of the potential displacement or**
3 **exposure to poor indoor conditions in person-years for *A. versicolor* following a winter flood.**
4

4. Discussion

6
7 By applying the building simulation results to the geospatial building stock data, areas of
8 London which are particularly vulnerable to flooding due to their combination of building
9 archetypes, flood risk, and sociodemographic profile have been identified.
10

4.1 Comparative Dwelling Drying Behaviour

12
13 By comparing the drying time of buildings flooded to the same height and drying under the
14 same conditions, it was possible to demonstrate the drying performance of locations in
15 London based on the most commonly occurring building types within these areas. The mould
16 species analysed showed a greater potential for long-term contamination in flooded dwellings
17 in the East of the research area, alongside the Thames. The London Borough of Southwark
18 was found to be particularly vulnerable to long-term mould growth following flooding.
19
20 This information can help identify locations vulnerable to a flood event, without modelling a
21 specific flooding scenario, and is relevant to insurance organisations, remediation
22 organisations, and government officials responsible for disaster response. While the maps are
23 for specific microbial species following a flood, the drying behaviours mapped can be
24 generalised to inform to potential for contamination of a range of moisture-dependent flood-
25 borne contaminants.
26

4.2 Dwelling Drying Behaviour for Specific Flood Events

28
29 The predictions of vulnerable locations within the research area using depth-drying curves
30 and the 1-in-200 year tidal flooding scenario provided predictions consistent with the
31 comparative drying rate observations, with the East of the research area around the Thames
32 identified as being particularly vulnerable to mould contamination. The developed curves can
33 be applied to other flood depth models in the future for other specific flooding scenarios,
34 provided there is sufficient coverage of building stock data with known archetypes.
35
36 The depth drying curves developed from the simulation data are best-estimates based on the
37 simulation results, and are not absolute values. These curves can be applied to estimate the

drying duration for periods up to one year, and in some cases can be used to extrapolate the drying time for longer periods when simulation results show some degree of decline in contamination levels within the simulation period The need to extrapolate certain simulations (for example modern purpose-built flats with brick/AAC walls flooded to 2m) means that there is a greater uncertainty associated with these fitted curves.

The curves are only valid for heights above 0.1m and below 2.0m. Attempts to fit curves through 0 for unflooded properties produced unstable models, and so were not incorporated. For all properties flooded above 0m, the assumption is that the floor would be made wet, meaning that the total surface area of the flooded building would not differ significantly from the 0.1m flood height (excluding only the surface area of the walls), meaning that this likely offers a good estimate of the drying times of smaller floods.

The depth-damage curves modelled based on the simulation data are applicable to the scenarios used in the building simulation - namely, a 24 hour flood with freshwater. In mapping the response of the building stock to a specific flood event, a large-scale tidal flood has been used to determine the water depth. The 1-in-200 year tidal flood was used rather than any of the freshwater flooding scenarios, as it allowed for the demonstration of the drying ability across a wide range of the London building stock due to the large extent of the flood. Since tidal floods will contain salts, it is likely that drying will take longer than the simulation results suggest. None the less, the maps produced provide an indication of the comparative drying abilities of the different COAs following a flood. For floods over 24 hours in length, more water may be absorbed into the building fabric. For many of the modelled cases (Solid 9" Brick Walls, Brick Cavity Walls, Concrete), the walls reach capillary saturation within 24 hours and no further water is absorbed, meaning the additional duration of the flood will not impact on the drying time. For walls containing AAC, the longer duration will allow more water to move into the material. This will result in the already slow-drying AAC and insulated AAC walls, taking even longer to dry since there is a greater amount of water to remove from the fabric. Consequently, longer flood durations will result in the already at-risk areas becoming more at risk while the low-risk areas will remain the same.

The depth drying curves also assume that the ground floor is at the same height as the surrounding terrain, meaning that basements and subfloors are not considered. It is difficult to estimate the ground floor level of buildings relative to surrounding terrain without conducting individual surveys of buildings within the research area, however, an EHCS analysis included in the EA Contaminated Land Exposure Assessment (CLEA) model suggests that the rate of basements within properties modelled in this study is low (0 - 7.8% depending on archetype) [EA, 2005]. As building stock models improve, it may be possible to refine the model further to account for basements.

The likelihood of a flood event occurring which matches the extent and depth predicted by the risk models is low, as flood models predict areas at risk, but that may not necessarily experience flooding. However, as flood risk models can identify vulnerable properties within a location, depth-drying curves can be used to identify vulnerable properties similar to how depth-damage curves can be used to predict the cost of damage to a specific property, given a flood event. The curves may also be applied retrospectively to predict the instantaneous risk inside properties which have been abandoned following a flood event, to provide information to occupants and remediation staff entering these properties for the first time after a flood. It is important to note that the simulations that form the basis for the comparative drying times and the actual drying curves are based on models which do not consider the impact of salts, flood duration, and variation in built form on the drying behaviour, meaning that these results are illustrative rather than definitive.

4.3 Social Vulnerability and Dwelling Drying Performance

The results of the SFVI indicate that the most vulnerable populations live in Southwark, Newham, and in the North West of the research area in Brent and Westminster. The SFVI has been developed to determine the relative vulnerability of populations to health problems following a flood event. There are a number of different potential health consequences following flooding, including exposure to microorganisms and mental health issues caused by the trauma of a flood event and potential displacement from homes [Taylor et al., 2011]. By identifying areas where both populations are vulnerable to flooding and buildings are susceptible to long-term damp and microbial contamination, it is possible to predict locations that may have a substantially increased health risk to the resident population. This is particularly relevant when considering health issues caused by long-term exposure to contaminants in the indoor environment or the length of time that an inhabitant is displaced from their property, which will both be related to the drying behaviour of their dwelling.

Previous research has indicated that the slowest-drying building archetypes were post-war and modern purpose-built flats, which may be the types of properties occupied by more socially vulnerable individuals [Taylor et al, 2012]. The type of property that an individual occupies may be a factor in their vulnerability to long-term health problems following a flood event, and deserves further research.

The SFVI applied was developed following research into different flood events across the UK, and so is likely to offer reasonable insights into the behaviour of the London population. However, the London population may differ from the research population for many of the metrics used to calculate the SFVI index - for example, non-car owners will be more prevalent in London than in other areas of the UK. The differences in the population statistics and behaviour may mean that the models estimate a higher vulnerability across the research area than may actually exist.

4.4 Highly Vulnerable Areas

Areas where the actual drying time and the exposed population was high resulted in high person-years of exposure to damp dwellings or long-term displacement. The hardest affected borough is Southwark, with Hammersmith and Fulham and Lambeth both showing high numbers of person-years of impact following the 1-in-200 year flood event. Person-years provides a simple indication of the level of exposure to either displacement or damp indoor conditions, and further analysis by epidemiologists may help to better understand the health consequences across the research area. The person-years calculated may also help plan the disaster response by providing an indication of the numbers and duration of alternative accommodation necessary to prevent inhabitants remaining in unfit homes.

There were a number of locations where the vulnerability of the local building stock coincided with locations that were at flood risk and where the population was vulnerable. Wards such as Livesey, Rotherhithe, and South Bermondsey were vulnerable for multiple reasons, and so should be given priority during long-term flood response planning. This may include taking additional measures to ensure that the local population is provided with alternative accommodation rapidly, and that mental health services are made available rapidly to those affected by a flood event. Highly vulnerable properties include those built and administered by local authorities as low-income housing. The information produced by this research will enable local authorities to better plan the recovery and remediation of council-owned flats in order to prevent major health problems among residents.

4.5 Limitations of Research

Both the comparative drying predictions and the depth drying curves make assumptions about the built form and wall type within the properties, which may not provide a precise estimate of the contaminant load and drying time within specific properties in relation to variations in building geometry and fabric. The built forms for the different age groups have been modelled so as to offer the drying behaviour of the worst-case scenario wall types - for example it has been observed that solid-closed cell (e.g. polyurethane) insulated cavity walls dry faster than glass fibre-insulated walls [Escarameia et al., 2007]. There was no data made available to this research on the rates of different types of insulation in cavity walls in the UK, and so by using the results for glass fibre rather than solid insulation, the model is able to account for one of the worst performing insulation types possible in flooded dwellings.

There were limits to the amount of building stock data available across the research area, and the areal information was estimated only from the numbers of known building types within the areal units. The amount of data available was also limited by the presence of unmodelled built form/age combinations and buildings that had not been identified in the CR database. Rather than make further assumptions about the characteristics of these properties, these were ignored in the spatial mapping of the vulnerability of areas of London. Further research can develop drying data for different buildings; meanwhile improvement of building stock models can help to reduce the numbers of unknown properties.

Building archetypes are meant to represent 'typical' buildings within a building stock, and as such are not representative of any individual property within the stock. The ecological fallacy is a misinterpretation of statistical data arising from the assumption that individual members of a population have the average characteristics of the population as a whole. The values presented in the areal units represent the drying time and vulnerability levels to flooding of all the buildings within this area, and it would be an ecological fallacy to conclude that these values apply to any individual unit within the area. The value of any individual property would be better estimated using the drying curves derived from the simulations.

By using the modal wall built forms and wall types within the COAs to estimate the comparative drying time, the results provide an indication of the majority built form, age, and wall type combination within the area. This ignores the variation of the building stock within the areal units, which is unlikely to be consistently of the same type, but is not vulnerable to skewing from properties that take an extended period to dry. The average dwelling time was calculated when mapping the actual drying time using the depth-damage curves. The number of known and modelled properties within a COA will influence the uncertainty of the estimate of the drying times for both modal and average calculations, and can be improved on as building stock information becomes more complete. The modelled information on the drying characteristics of different dwellings can also be improved by developing models for different building archetypes, archetypes with minority wall types, and those drying under different scenarios; however, the amount of time required to perform a simulation was prohibitively large, meaning it was unrealistic to simulate curves for all possible combinations of building, age, building envelope, and drying scenario within the limits of this research.

In mapping, the Modifiable Areal Unit Problem (MAUP) occurs when point-based phenomena is aggregated into areas. The areal values are heavily influenced by the 'modifiable' boundaries of the areas which can, in the UK for example, be reported in terms of COAs, Postcode Areas, Medium Level Census Output Areas, Local Authorities, Boroughs, and so on. By adjusting the boundaries, the areal value can change, and the interpretation of the map can change. By calculating areal statistics based on individual properties within areal units, the MAUP needs to be recognised. COAs were used as boundaries since they are the smallest units available with census and HEED data and because of the very local variations

in building stock and flood depths. Using larger areal units may change the conclusions of the study, as the differences between areas may average out.

Despite the assumptions and limitations of the research, the results present a most useful prediction of the vulnerability of the London domestic building stock to flooding, and when combined with other flood-risk factors a useful picture of the potential chronic problems following a flood event can be obtained.

5. Conclusions

Application of the simulation results to the GIS-based building stock data has revealed areas of London where the building stock will be particularly prone to long-term contamination risk following flooding. Many of these areas at risk of prolonged contamination also lie in areas at risk of flooding, where the population may be more dense or vulnerable, or where there may be the potential for elevated contamination in the water. In particular, the London Borough of Southwark is predicted to be at particular risk following a large flood event due to the combination of building types, flood risk and depth, social vulnerability, and population density. Understanding these vulnerable locations can help to plan the response of the health authorities, emergency services, remediation organisations, and local authorities to a flood event. While the immediate response to flooding will depend on those hit hardest at the time of the flood, the long-term response should consider the vulnerability of the population and the buildings they inhabit in order to best manage the allocation of health resources, the remediation of properties, and the provision of temporary accommodation for victims.

7. Acknowledgements

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