An Agent-Based Model of Flood Risk and Insurance

Jan Dubbelboer[1], Igor Nikolic[2], Katie Jenkins[1*], Jim Hall[1]

[1] Environmental Change Institute (ECI), University of Oxford, UK
[2] Faculty of Technology, Policy and Management, Delft University of Technology, The Netherlands

Abstract

Flood risk emerges from the dynamic interaction between natural hazards and human vulnerability. Methods for the quantification of flood risk are well established, but tend to deal with human and economic vulnerability as being static or changing with an exogenously defined trend. In this paper we present an Agent-Based Model (ABM) developed to simulate the dynamical evolution of flood risk and vulnerability, and facilitate an investigation of insurance mechanism in London. The ABM has been developed to firstly allow an analysis of the vulnerability of homeowners to surface water flooding, which is one of the greatest short-term climate risks in the UK with estimated annual costs of £1.3bn to £2.2bn. These costs have been estimated to increase by 60-220% over the next 50 years due to climate change and urbanisation. Vulnerability is influenced by homeowner's decisions to move house and/or install measures to protect their properties from flooding. In particular, the ABM focuses on the role of flood insurance, simulating the current public-private partnership between the government and insurers in the UK, and the forthcoming re-insurance scheme Flood Re, designed as a roadmap to support the future affordability and availability of flood insurance.

The ABM includes interaction between homeowners, sellers and buyers, an insurer, a local government and a developer. Detailed GIS and qualitative data of the London borough of Camden are used to represent an area at high risk of surface water flooding. The ABM highlights how future development can exacerbate current levels of surface water flood risk in Camden. Investment in flood protection measures are shown to be beneficial for reducing surface water flood risk. The Flood Re scheme is shown to achieve its aim of securing affordable flood insurance premiums, however, is placed under increasing pressure in the future as the risk of surface water flooding continues to increase.

Keywords: Flooding, London, Flood insurance, Flood Re, Agent-based modelling

Introduction

Flooding is the most expensive natural disaster worldwide. Flooding can occur in various forms, such as coastal, river and surface water flooding (sometimes known as 'urban' or 'storm water' flooding). Surface water flooding occurs when an urban area floods during heavy rainfall as a result of a combination of factors, including rainwater not infiltrating the ground and the overflowing of sewers, drainage and small watercourses (European Water Association 2009; Falconer et al. 2009).

---

[*] Corresponding author. Environmental Change Institute (ECI), University of Oxford, OX1 3QY, UK Tel.: +44 (0)1865 275861; fax: +44 (0)1865 275850; e-mail: Katie.jenkins@ouce.ox.ac.uk

Flooding is listed as a major risk on England’s National Risk Register, with properties more likely to be affected by repeated surface water flooding then coastal or river flooding, with estimated annual costs of £1.3bn to £2.2bn (Defra 2011). In England the consequences of surface water flooding were brought to the forefront by the summer floods of 2007. The Pitt Review (Pitt, 2008), which was conducted to provide lessons and recommendations in the aftermath of the 2007 summer floods, highlighted major gaps in the understanding and management of risks from surface water flooding and emphasised the need for urgent and fundamental changes in the way the UK is adapting to the likelihood of more frequent and intense periods of heavy rainfall, particularly given the impact that climate change would have on the probability of similar events in the future.

Findings presented in the UK Climate Projections (UKCP09) show that as a result of climate change the UK weather in the upcoming century will be characterized by more days of extreme precipitation during the winter and summer period (IPCC 2013). These changing precipitation patterns are expected to result in an increase in surface water flood events in the UK (Ramsbottom, Sayers, & Panzeri 2012). Combined with an increasing pattern of urbanisation Defra estimated that damages from surface water flooding could increase by 60-220% over the next 50 years (Adaptation Sub-Committee 2012).

Flood risk emerges from the interplay between biophysical and human factors (Hall et al., 2003b). Biophysical factors determine the frequency, duration and intensity of rainfall, and the runoff that occurs when rain hits the ground. Rainfall may be infiltrated into the ground, but in urban areas with impermeable surfaces will flow on the surface in directions modified by the form of buildings and streets and will accumulate at locations with low topographical elevation. These processes are modified by drains that are designed to convey water away from urban areas on the surface or in pipes (Blanc et al., 2012). The severity of damage that occurs during a surface water flood depends upon the location and value of properties in an urban area and their sensitivity to flood damage. The amount of damage that occurs may be reduced by installing Property-level Protection Measures (PLPMs) that prevent water from entering buildings or reduce the costs of repair, as well as by flood defences and sustainable drainage systems (SUDS) designed to protect entire communities.

Flood insurance helps to ensure that insurance policy-holders do not incur disastrous financial losses during floods. It redistributes losses across the pool of policy-holders and through time. Typically, a householder will pay an annual premium. The cost of repair of flood damage will be reimbursed by the insurance scheme, less some pre-agreed threshold sum (an ‘excess’, or ‘deductible’). Flood insurance arrangements, where they exist at all, differ widely around the world, with varying levels of public and private involvement in the insurance market (Botzen and Van Den Bergh, 2008). In recent years, flood insurance has been provided in the UK via a public-private partnership between the UK government and the insurance industry, known as the Statement of Principles. Private insurers provide flood insurance to both households and small business up to a certain level of risk, while the government commits to investing in flood defences for the higher risk areas. However, with the increase in frequency and extent of flooding there was a need within the UK for a continued, but redefined, public-private partnership. If no action was taken then it raised the issue of affordability and availability of insurance as high flood risk properties could face increasing premiums, potentially to unaffordable levels, or the refusal of cover altogether (Penning-Rowsell, Priest, & Johnson 2014).

In the summer of 2013 the government proposed a new flood insurance scheme, Flood Re, due to be in operation from April 2016. The Flood Re scheme is a non-profit flood reinsurance fund that gives insurers the option to re-insure the highest risk properties. The subsidy for Flood Re is to be claimed from a levy taken from all policyholders and imposed on the insurers according to their market share, with policy-holder premiums fixed dependent on the council tax band of the property insured. The aim of this proposed system is to create a roadmap to future affordability and availability of flood insurance without placing unsustainable costs on wider policy holders and the taxpayer (Defra 2013). Flood Re is proposed as a transitional solution, with an anticipated run time of 25 years, helping to smooth the transition to more risk-based pricing in the future. However, concerns have arisen over the financial sustainability of the scheme given that costs will remain higher than benefits delivered (Defra, 2013, p.30). Secondly, Flood Re is not designed with risk reduction in mind, and it offers no incentives or formal mechanisms to encourage household level flood risk reduction (Surminski & Eldridge 2015). Similarly, implications of the scheme, and potential negative and positive feedbacks, have not been considered in parallel with other flood risk management interventions, including those targeted at surface water flooding.

This gap is the starting point of our investigation. Analysing the outcomes of such insurance reform requires a model that can simulate the dynamics of flooding and the choices made by economic agents. Typically flood risk is calculated using static data on properties at risk and the damage that will occur during a flood (Hall et al., 2003a). However, such an approach does not address the distribution of losses across different householders and the role of insurance in redistributing those losses. Nor does it address the dynamics of householders' locational choices and the ways in which those choices may be modified by flood risk and insurance availability (Dawson et al., 2011). In this paper we address these issues by proposing and demonstrating an agent-based model (ABM) designed to analyse changing flood risk and the role of insurance in this dynamic.

The agent-based model

ABMs have had limited application in the insurance sector to date and to the authors best knowledge no studies exist which are focus explicitly on the issue of surface water flooding. Ulbinaitė and Le Moullec (2010) and Ulbinaitė, Kučinskienė, and Le Moullec (2011) used an ABM to simulate consumer behaviour and insurance choices in general. Brouwers and Bomand (2011) developed an ABM which focused on fluvial flood risk and damage to private property for a case study of the Upper Tisza area in Hungary. The model considers how government, insurer, and property owner agents interact to investigate financial flood risk management policies. In particular, it investigates a baseline scenario where the government compensates property level flood damage and a market scenario where responsibility is shifted to the property owner.

Sobiech (2013) developed an ABM of coastal flooding in North Germany, focussed on simulating and exploring the dynamics of social vulnerability. The ABM was parametrised using survey data and included the perceptual and social context in which decisions are taken, and subjective and objective aspects that may influence self-protective behaviour and vulnerability of individuals. For risk research and management, it highlighted the importance of considering multiple factors within the vulnerability analysis, and the importance of doing so in a dynamic manner.

McNamara and Keeler (2013) highlight how such ABMs could be strengthened by linking behavioural and physical models. They present a study for the US East Coast linking a shoreline dynamics model and ABM of real-estate markets to investigate how people and the market respond to sea-level rise and storminess. The model combines adaptation in the form of coastal defences within both the physical and economic components of the model. Person agents make a cost-benefit based decision on whether to invest in defences, and to what level, as well as valuing property based on various criteria such as expected flood damage and flood insurance costs.

Filatova et al., (2009, 2011) used an ABM to look at the consequences of a lack of available flood insurance on flood risk and land markets, and built upon this to develop an empirical based ABM of an urban economic system focused on the housing market (Filatova, 2015). This has been applied to a case study of North Carolina, USA, and includes flood risk in the decision making of household buyers, as well as consideration of potential flood damage and insurance premiums. Similarly, an ABM has been developed for a coastal town in New Jersey, USA, the that looks at the effect of sea level rise and alternative flood insurance programs on household locational choices (Chandra-Putra, Zhang, & Andrews 2015). The ABM aims to capture some of the main features of the housing market driven by interactions between buyers and sellers; responses to flooding and alternative flood insurance policies; and implications of different government policies and the provision of flood risk information.

The ABM presented here is novel in its application to a case study of London. Figure 1 provides an overview of the ABM with its key processes and interactions. The model captures the working of a local housing market that is affected by surface water flooding, and represents the characteristics and present situation in the UK, and specifically London. The modelling of the housing market followed the approach used by Chandra-Putra et al. (2015) in that it adopts the experimental economics of a double auction market. However, the double auction market module from Chandra-Putra et al. (*Ibid.*) was re-written to reflect specific characteristics of the study area and to enhance efficiency given the large size of the model. For example, it was re-coded to reflect the UK mortgage system; the specific characteristics of the housing market so that prices reflected the different areas of Camden rather than being related to geographical aspects such as proximity to water and elevation; and the way house prices change in the model based on previous sales was made more efficient given the large number of households. While the code was re-written and parametrised for the case study presented here, the dynamics of how homebuyers place bids and sellers place asking prices, how they bid against each other, buying and selling decisions, and the role of the Bank agent remain similar (highlighted in italics in Figure 1).

The model also includes an elaborate insurance system including the mechanisms underlying the forthcoming Flood Re system, and models the role of the developer and the local government in terms of influencing the built environment, investment in flood risk reduction measures, and the vulnerability of homeowners in this dynamic. The ABM also benefits from the incorporation of a surface water flood event dataset, for present and future climate scenarios, developed by combining probabilistic precipitation projections with detailed surface water flood depth maps (Jenkins et al., 2015). Finally, the presented model is GIS explicit to allow a realistic representation of the built environment and surface water flood risk.

Further details are provided in the sections below aimed at introducing the ABM, its application, and main insights. The construction of the model is done using Netlogo (Wilensky 1999). A copy of the model and further documentation, including full tables of parameters, data values and sources, decision trees, validation of the model and significance testing is available in Dubbelboer (2015), and online at https://www.openabm.org/model/4647/version/1/view. An ODD Protocol describing agents, model variables, the model process and scheduling, design concepts, initialisation and inputs is included in the Appendix.

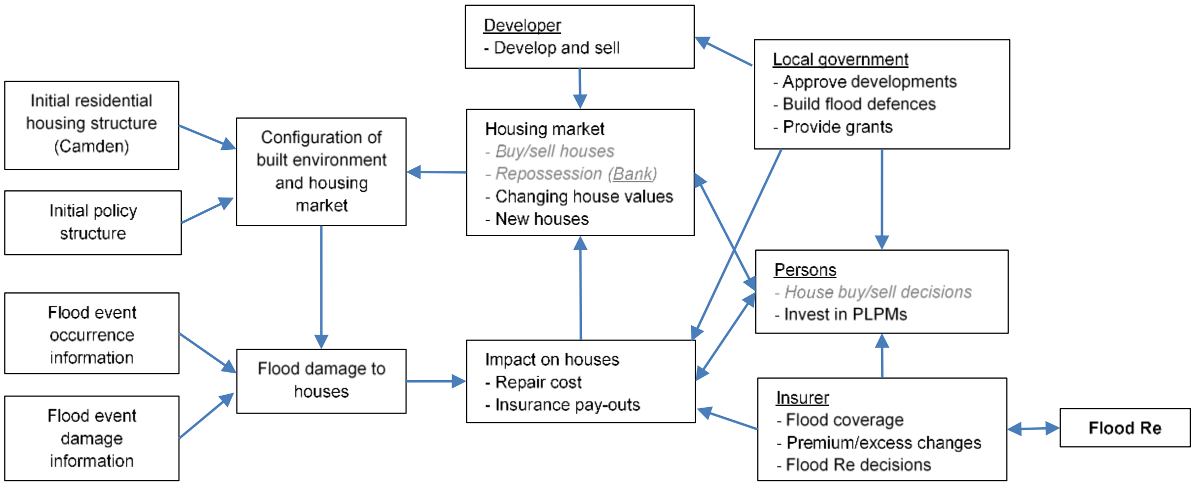

Figure 1: Overview of the model structure

Model environment

ABMs have been considered weak in the past due to limited application of empirical data to parameterise model attributes and validate results. However, these connections are essential if ABMs are to be applied for policy analysis and be seen as robust when exploring future changes in systems e.g. due to climate impacts and adaptation policies (Filatova, 2015). As such, this ABM is parameterised based on a large array of data sources and developed around GIS data to allow a realistic representation of residential buildings and surface water flood risk.

The ABM presented here has been developed for Greater London where the increased population and reduced urban surface permeability due to densifying development mean that London's aging drainage systems are under pressure, and the risk of surface water flooding is particularly acute. Around 680,000 properties are estimated to be at risk with 140,000 Londoners at high risk, and another 230,000 at medium risk (Greater London Authority, 2014). According to the Greater London Authority (GLA), surface water flooding is the most likely cause of a flood event and is probably the greatest short-term climate risk for the greater London area (Greater London Authority 2009, 2011a).

In this paper the ABM is applied to a case study of the London Borough of Camden. This encompasses an area of 21.8km^2 and a population of approximately 228,400 people (Greater London Authority, 2015a). Surface water flooding poses a large risk to Camden due to the nature of summer thunderstorms and the topography of the area, with a historic precedent for such events (Drain London, 2011). The area is not at risk of flooding from the River Thames or any other open rivers.

The study used GIS data from the London Datastore (Greater London Authority 2015b), residential building data from Landmap (2014) and derived data from the UK Buildings Residential Building Class Dataset[1], and detailed surface water flood depth maps generated by the GLA Drain London Project (Greater London Authority 2015a). In figure 2 the interface of the model can be seen in which the GIS data provides the boundary of the Borough of Camden; locations of residential houses; major parks and designated development areas. This sets up an initial modelling environment with 95,561 houses of 4 different types; detached, semi-detached, terraced and flats. The ABM includes six different agents: people, houses[2], an insurer, a bank, a developer and a local government, each with their own behaviour (summarised in Table 1 and outlined below).

Figure 2: Interface representation of the study area of Camden and its location within Greater London (inset). The map of Camden also highlights the location of residential buildings (shading reflects different property types: red=flats; orange=terraced, green=detached; and yellow = semi-detached), large areas of green space (shaded green), and opportunity areas designated for future large scale development (shaded blue).

Modelled agents

Each unit of time, or "tick" in the model represents a year. Within this year all agents perform tasks based on the information that is provided to them as outlined below and summarised in Table 1.

---

[1] The GeoInformation group data ® copyright by The GeoInformation® Group, 2014 Licence No. 3786.

[2] We model houses as separate agents as they need to be able to behave independently from each other and the person agent. They respond to what is happening in the model even if they are not owned, such as being hit by a flood. A single patch can contain multiple houses, and a single building footprint multiple dwellings (e.g. a block of flats).

Persons

Each person can be classified as a homeowner, buyer or seller and performs tasks depending on the class they are. Homeowners start by renewing their annual flood insurance. For this they ask the insurer agent to calculate their flood insurance premium and flood insurance excess. All homeowners are required to have flood insurance in the model. This reflects the current situation in the UK where home insurance (which incorporates flood insurance) is a pre-requisite for obtaining a mortgage, resulting in a high flood insurance penetration rate of 95% (Lamond et al., 2014). As such, in the model homeowners will always accept the quotes they get from the insurer and the insurer cannot deny providing someone flood insurance.

After insuring their house, a homeowner can decide to sell the house. A homeowner has three different motives for deciding to sell their house in the model. Firstly, if their annual fees are higher than the income they can spend on the house for three consecutive years the house is foreclosed and sold to the Bank. Secondly, if they can make a suitable profit on their house homeowners would look to sell. The homeowner will check if the house value is at least 10% higher than the value paid following the assumption of Chandra-Putra et al. (2015). If this is the case, people who can make a profit will sell for this reason. Thirdly, a percentage of homeowners may decide to sell regardless of profit if they wish to move to a different location. The percentage of movers for these reasons is set at 2.7% of homeowners annually, estimated based on information for Camden from the ONS (2014) and London Datastore (2015b).

If a homeowner decides not to sell her house she will then decide whether to invest in PLPMs to make the house more flood resistant and resilient. Anxiety and insecurity about floods is assumed to play the most important role in the decision to invest in PLPMs. As such, in the model it is assumed that 34% of people affected by flooding will invest in PLPMs after the event (Harries 2012), and based on availability of government grants, while 1% of people invest proactively in PLPMs (based on expert opinion and analysis of data from Defra (2008)).

If a homeowner does decide to sell her house she becomes a home seller and will put her house on the market. When a home seller has found a suitable homebuyer she will not simply leave the market but instead can re-join the market as a homebuyer. Additionally, external homebuyers can also enter the market. The total number of homebuyers was based on projected population trends for Camden to 2041, which also accounts for national and international migration (Greater London Authority 2015c). In this way people can stay within or join the modelled market, which puts pressure on the housing market as is the present case in England (Inman 2014).

Homebuyers search for a house to buy every year. Similar to assumptions made by Chandra-Putra et al. (2015) it is assumed that a homebuyer’s search is driven primarily by the most expensive house they can afford to buy. It is also assumed that they will prefer new build developments, and search for a specific house type prioritised as detached, semi-detached, terraced and flat. Homebuyers may also consider flood risk in their purchase decision. In England and Wales this information is obtainable online in the form of detailed flood risk maps maintained by the Environment Agency, and estate agents are required to communicate to buyers any recent flooding incidents. Based on survey data it is assumed in the model that 57% of homebuyers would investigate the flood risk of a property they considered buying (Home Check, 2012). However, the implications of this are not clear, particularly for London where due to the unprecedented demand for housing evidence suggests that flood risk has limited if any lasting effect on the saleability and value of property. Given these uncertainties, it is assumed that homebuyers look back at the flood history of a house for the past three years, with more recent events having a larger effect on their behaviour (Lamond et al., 2009). Homebuyers that consider flood risk will not buy a property if it has flooded in that year. Where a house was flooded in the previous year only 50% of risk adverse homebuyers will consider buying it. For flooding 2 years ago this percentage drops to 25%.

Insurer

The main task of the insurer is to provide every agent owning a house (person agents, the bank or the developer) with flood insurance. In the ABM we assume that an insurer has detailed information that provides an estimate of surface water flood risk (see *flood risk modelling* below). Based on that risk estimate the insurance premium and excess can be calculated for each household. In this analysis we only model the technical side of flood insurance and not the commercial side (i.e. competition between insurers which might modify the offered premium). As we are focussing on surface water flooding we limit the insurer's attention to the surface water flood history of a house and the estimated surface water flood risk.

The insurer first sets the flood insurance excess for all houses. The assumption is made that the flood insurance excess amount is non-negotiable and will initially be equal to £200 per household per year. Houses hit during a surface water flood event will see their insurance excesses increase by 1/3rd, to a maximum of £2500, as normally the excess would not be more than that as homeowners would not be able to get a mortgage (House of Commons Environment, Food and Rural Affairs Committee, 2013).

The surface water flood risk estimates are summed across all affected houses in the model representing the insurers expected annual loss. The insurer deducts from this the total value of excesses paid and the total base flood insurance premium paid by all households in the model, assumed to be £50 per house per year. The remaining loss that has to be covered is spread across the households at risk of surface water flooding, by increasing their flood insurance premium proportionally to the flood risk they are in. In this way people owning a house in surface water flood risk will receive a higher flood insurance premium. Insurance premiums are calculated at each time step and will reflect the dynamic nature of surface water flood risk in the model. For example, due to changes in the built environment and investment in PLPMs and SUDS which can alter the level of flood damage and risk to properties.

Insurers typically pass on risks above a set threshold by purchasing reinsurance on the global market. In this case study the Flood Re scheme represents a government designed reinsurance entity. When switched on in the ABM the insurer has the option to re-insure eligible properties (built pre-2009) into Flood Re. The insurer will have to pay to re-insure a household into Flood Re with a fixed premium per policy capped dependent on the property value (approximated according to the local property council tax rate ranging from £210 to £540 in the study area) (Defra, 2013). In this way the total compensation the insurer pays following a flood will be lower when the Flood Re option is selected, as they are no longer required to compensate the highest risk houses.

In the model there are no constraints on the available assets of the Insurer or the Flood Re Scheme, with both able to go into debt. This is captured in this way as throughout the Flood Re consultations concerns have arisen over the financial sustainability of Flood Re given that costs will remain higher than benefits delivered (Defra, 2013, p.30). As such, potential costs and the economic implications of the scheme can be investigated for different scenarios.

Developer

The main task of the developer is to build new housing projects and to sell the houses it builds. After the housing market is run within a tick of the model, the developer will look at the demand for housing and available properties on the market and build houses to meet the unmet demand. A simplification in the model is that house development is done on a house-by-house basis and not based on projects in which multiple houses are built at the same time.

Other ABMs have focused specifically on developer decision making. For example, in terms of the mix, timing and intensity of developments based on the developer's characteristics, available site characteristics, market conditions, and the regulatory environment (e.g. Parker et al., 2015 and Magliocca et al., 2014). In this study the main driver for a developer building properties is profit. For every house the developer wants to build they will try to find the optimal location. This is defined as available land with the highest economic value of surrounding houses. Given the specific application of the ABM to London and Camden the developers decision making is limited as the locational choices and intensity of developments is based on the GIS maps of planned opportunity areas (figure 2) and data on development targets set by the national and local government. Within the opportunity areas the developer is free to build as many houses as optimal per year, with a maximum limit on total houses (Camden Council 2015). Outside of the development areas the developer is limited by a maximum number of houses it can build per year (150-200) reflecting the planned housing trajectory of Camden (Camden Council 2013).

Once the developer has chosen a location to build a house they assess if it is profitable. If the estimated market value of the house is at least 20% higher than the build cost they will create a development proposal for approval by the local government. If the government approves the development proposal (see *Local Government* below) the developer will start building the house. The building of a house is assumed to take one year, after which the developer puts the house on sale for the estimated market value. Land value, the type of house to build, and the house price once completed are calculated based on the characteristics and values of the surrounding houses. When it comes to flood risk one important assumptions made here is that the building of new houses does not influence the flood risk of houses surrounding the development. Based on reports for London it is initially assumed that 50% of all new build houses will be built with flood defences in the form of SUDS (Defra 2011).

Local government

The main task of the local government in the model is to protect people living in the Borough against floods. The local government aims to reduce flood risk through investment in PLPMs (implemented by homeowners and linked to government funded grants) and surface water flood reduction projects in the form of SUDS. Based on available literature it is initially assumed that these measures will reduce household flood damage by 75% (Thurston et al. 2008) and 35% (Defra 2011) respectively. The amount of assets the local government can spend on SUDS and PLPM grants every year is equal to the annual subsidy they receive from the national government and a small percentage of their income from selling land to the developer and collecting property taxes from home owners. Initially it is assumed that up to 80% of this budget can be spent annually on SUDS and 20% for PLPM grants. Based on past funding for flood repair and renewal grants in the UK it is assumed that each person can receive up to £5000 to invest in PLPMs (Defra 2014).

Every year the local government will proactively search for SUDS projects to invest in. Every project consists of a minimum of 100 houses that are in close proximity to each other. The projects are selected based on the flood risk of houses and the benefit-cost ratio that the local government would achieve for each project. From the 10 projects the local government will try to build as many as it can within its available budget, starting with the projects with the highest benefit-cost ratio. The second task of the local government is the evaluation of development proposals. Just as development proposals are made on a house-by-house basis, the proposals are evaluated in the same way. Although regulation on approving development proposals states that local governments should consider flood risk, figures indicate that in 75% of cases flood risk is not looked at (Wynn 2005). As such, a development proposal will be approved by the local government in 75% of all cases. In remaining cases the development proposal will be approved if the flood risk of the development is lower than the governments acceptable maximum flood risk. If this is not the case the development proposal can still be approved based on the profitability of the land sale to the local government. This reasoning reflects the current pressure local governments are put under by central government to develop more houses within their borough (Camden Council 2013; Greater London Authority 2011b), and highlights trade-offs which must be made when addressing flood risk and housing shortages.

Bank

The task of the bank is to foreclose on houses if the owner was not able to afford their house fees for three consecutive years, following the approach of Chandra-Putra et al. (2015). After foreclosing on a house the bank puts the house up for sale at its current value.

Table 1 summarizes the main agent behaviours included in the model.

Agent	Main Behaviours
Person	Decide to buy or sell properties Required to renew flood insurance annually Pay household fees Decide whether to invest in PLPMs (assumed that 1% of homeowners invest proactively per year, while 34% invest reactively following a flood) May consider flood risk when considering to purchase a new property
Insurer	Estimates household surface water flood risk for every property in model (where in place they account for PLPMs and SUDs in these estimates) Sets insurance premiums and excess levels for every property in model Provides all households with flood insurance Decide whether it is cost effective to place high risk properties into Flood Re Provide compensation, minus the excess, to properties following a flood event
Local Government	Invest up to 80% of their local flood defence budget (or more in the year of a flood event) in SUDS projects which protect houses at highest risk of flooding and provide a cost-benefit ratio of 1:5 or greater Invest up to 20% of their local flood defence budget to provide £5000 grants to households investing in PLPMs Evaluate and approve/reject property development plans based on their financial benefits and flood risk Sell land to developers for approved property developments
Developer	If demand for new properties outstrips available properties on the market propose to build new properties to meet demand Identify optimal land to maximise profits from developments, within allocated development areas and the local governments planned development trajectory Submit development proposal to be approved by the local government Build new houses (initially assumed that 50% of all houses built will have SUDS) and sell on the market

Bank	Reposes houses if the owners are unable to afford household fees for three consecutive years Sell houses on market

Table 1: Summary table of main agent behaviours

Flood damage data

Surface water flood risk maps have been generated for Greater London for 1 in 30, 1 in 100, and 1 in 200 year return period rainfall events as part of the Drain London project (Greater London Authority 2015a). These maps reflect present day climate, topographic data and information on the surface water drainage system at a fine resolution (5x5m). The data represent the modelled effect of a uniform rainfall event across all of Greater London. In practice, rain storms are spatially heterogeneous, and so the flood outlines have been rescaled to reflect a wide range of more realistic spatial patterns of rainfall, using hourly rainfall data from a spatial version of the UKCP09 Weather Generator (WG) (Kilsby, Jones, Harpham, Glenis, & Burton 2011). The WG is also used to produce synthetic time series data of spatial rainfall events on an annual basis for a baseline period (1961–1990), the 2030s (2020-2040), and 2050s (2040-2060) under high emission scenarios (equivalent to the IPCC SRES B1 and A1FI scenarios). For each time period 100 runs are provided reflecting different vectors of change factors used in the WG to explore the effect of climate model uncertainty (Jenkins et al., 2015).

Data on the residential properties in Camden which would be affected by surface water flooding, and the subsequent economic damages, are calculated based on the Drain London flood depth maps. By overlaying the spatial flood maps onto the residential building data properties at risk of surface water flooding, and the flood depth, were identified. Economic damages to residential buildings were estimated using flood depth-damage functions for short (<12hr) duration floods (Penning-Rowsell et al. 2010). This provides an estimate of damages to residential building fabric and contents based on building type and age. As such, when a surface water flood event of given severity is projected to occur the residential properties affected and corresponding flood damages are readily known.

Initial houses in the model are also assigned a surface water flood history. The length of the flood history is dependent on the build year of the property, and reflects a random time slice from the baseline flood event time series. The household damage for given return periods do not change under the future climate scenarios (just the frequency of events of this magnitude). To illustrate the effect of climate change the change in probability of surface water flood events of a given magnitude are estimated and accounted for in the probability damage curves and subsequent estimates of risk.

Flood risk modelling

Based on the economic damage to houses for given flood events, every house in the model has a level of flood risk assigned to it. This flood risk is recalculated every year to reflect the dynamic changes in the model including investment in flood protection measures and the creation of new houses. The flood risk of every house is calculated based on the formula in Bevan and Hall (2014, p.17). In any given year (*t*), the risk ($r_{i,t}$) is given by:

$$r_{i,t} = \int_0^\infty D(x_t) f(x_t) dx_t \tag{1}$$

where, $D(x_t)$ is a damage function with x changing overtime, $f(x_t)$ is the flood probability distribution.

To create a damage-probability graph for each house using the formula above, assumptions are made given only three flood return periods (1 in 30, 1 in 100, and 1 in 200) are available. Namely, it is assumed that the function is linear between the three known points. As the damage probability function will never have a probability of zero the function is forced to meet the axis by assuming that the damage with zero probability is the maximum damage that can be done to a house. There are many factors which would influence this at a household level, and given a lack of data this is currently assumed to be 20% of the building value. The slope of the function is assumed to extend horizontally until it crosses the x axis (damage). A maximum limit is put on this assuming that it is highly unlikely that a house will be hit by a flood more than once every 2 years (i.e. 50% probability). Household flood risk is then calculated as the area under the line.

Experimental Setup

The ABM has been developed to investigate surface water flood risk in London and assess the interplay between different adaptation options; how risk reduction could be achieved by homeowners and the local government; and the role of flood insurance and the forthcoming Flood Re scheme. In order to test and validate the ABM an initial assessment was made of the potential role of PLPMs and SUDS, and Flood Re for managing surface water flood risk. The ABM interface was designed to allow these options to be ‘switched on and off’ and tested individually and in combination to explore potential negative and positive feedbacks which could occur when adaptation options and insurance mechanisms are considered in parallel. The model was run using flood event time series data for the baseline (1961–1990) and the 2030s and 2050s high emission climate change scenarios, run at a yearly time-step for 100 simulations of the 30-year time series data so as to sample stochastic variability in the flood event series.

As ABM can be chaotic with results varying between runs it is recommended to explore the variability in outputs by performing many repetitions (van Dam, Nikolic, & Lukszo 2012). The 300 repetitions that are performed here for every experiment provide a more accurate representation of the behaviours in the model, as well as representing uncertainty in the climate scenarios. Given the model size, complexity, and multiple simulations required the ABM was run on a state-of-the-art high-performance computer facility. The data analysis was carried out using the free and open source program R. Output metrics were collected annually, including number of houses in flood risk; flood risk level; flood damage; flood insurance premium cost; number of houses re-insured in FloodRe; number of persons that invest in PLPMs every year; and the number of houses for which flood defences were built.

Results

Flood protection measures

The ABM allows an investigation of how different agents could contribute to surface water flood risk reduction. Looking at the percentage of houses in the model protected by different flood protection measures gives an indication of the level of investment made in PLPMs by agents, both proactive and reactive, and investment in SUDS made by the local government and the developer. Figure 3 highlights that for PLPMs most investments are made proactively rather than reactively over time. This is because reactive investments only occur following a flood event and the government budget for grants in any year is limited. The developer steadily invests in flood defences over the years whilst developing houses. The largest percentage of houses protected by flood protection measures are covered by investments by the local government, although the range in results varies the most (represented by the green dots). In the first 10 years the local government mostly invests in flood defences in the same way over all runs. However, after this point a large range can be seen reflecting how the local government reacts to flood events of different magnitude and frequency in the runs, and their decisions to invest more or less of their budget in SUDS projects.

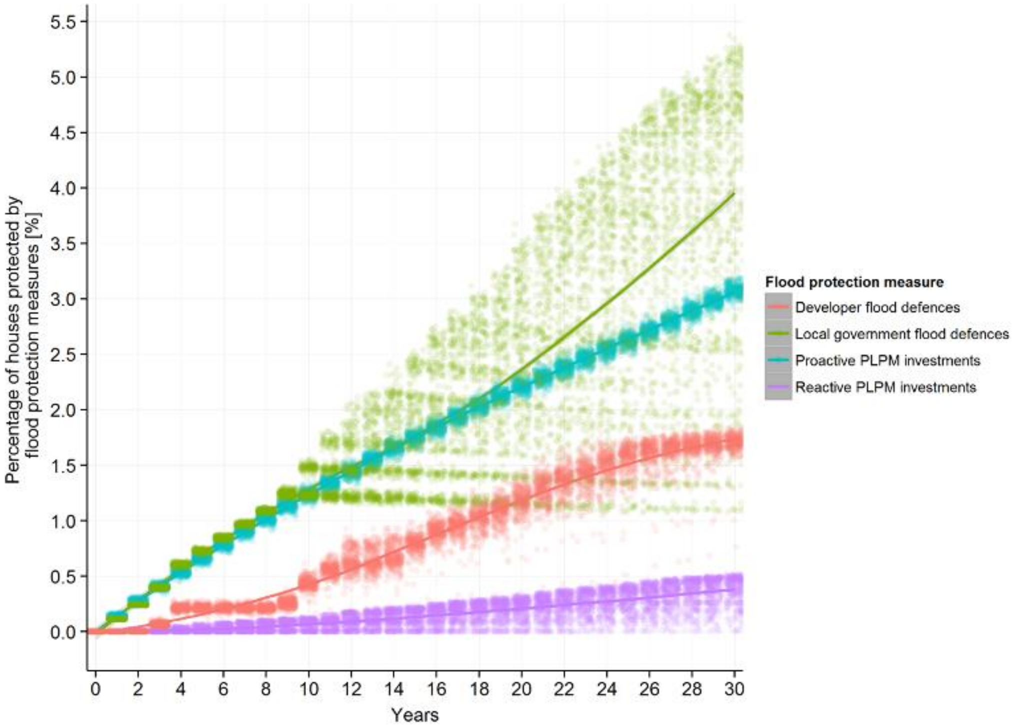

Figure 3: The percentage of houses protected by flood protection measures over time. The lines represent results averaged across each of the 300 model repetitions (dots).

Figure 4 shows how these investments act to reduce flood damage to houses in the model. In contrast to figure 3 the greatest economic benefits result from developer investment. This reflects the fact that developers build a lot of new properties in areas of high flood risk in the model, where flood damages would be relatively high and so defences have a large benefit. The percentage of houses protected by local government flood defences and proactive investments in PLPMs are similar (figure 3), and the reduction in flood damages also remains similar (figure 4). This is even though flood defences are assumed to reduce flood damage by 35% (Defra 2011) compared to PLPMs which are assumed to reduce damage by 75% (Thurston et al. 2008). This reflects the rationale of the local government to build flood defence projects in the highest risk areas where economic benefits are greatest, compared to people who will invest in PLPMs in a less rational manner reflecting anxiety and emotions (Harries 2012). This is illustrated in figure 5 which shows modelled flood risk maps for Camden at the start of a single model run, and the spatial pattern of investment in flood protection measures.

Government investments focus on the areas in the study area that have the highest flood risk, while investments in PLPMs appear to be more random.

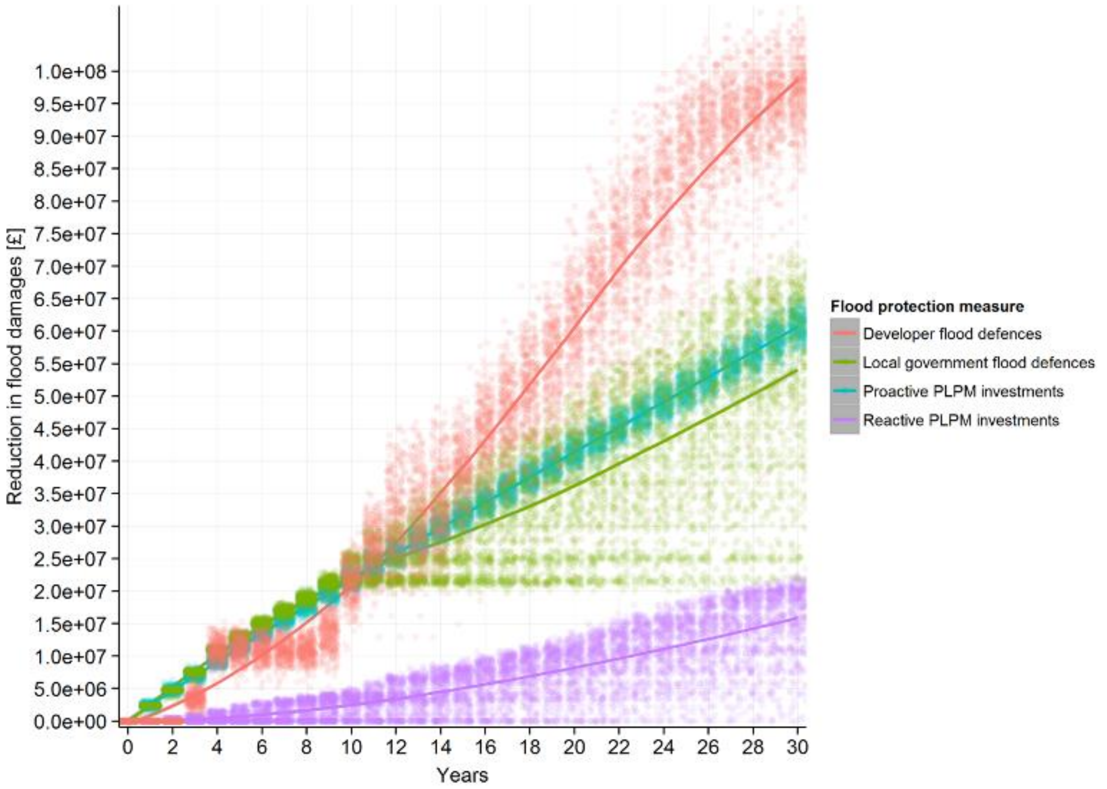

Figure 4: Effect of flood protection measures on the reduction of flood damages

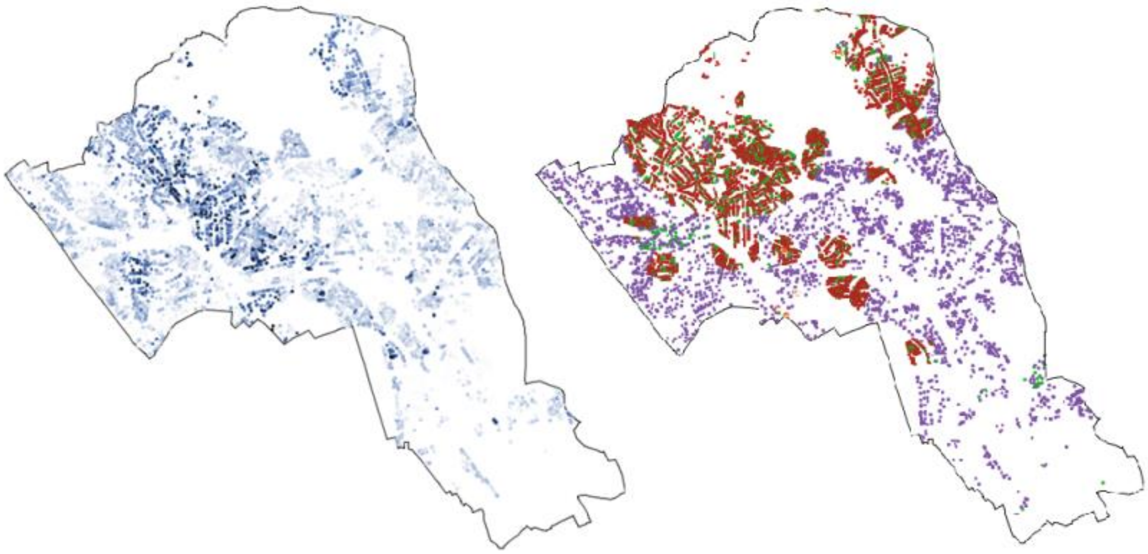

Figure 5: The left image shows flood risk in Camden at the start of a single model run (darker blue indicates higher flood risk). The right image shows the spatial pattern of

investment in flood protection (red reflects investments in flood defences by the local government; purple shows PLPM investments; and green reflects properties that have both).

Figure 6 highlights the positive effect that flood protection measures have on the level of flood risk houses are in, disaggregated by existing houses and newly developed houses (in the first 4 years no developer houses are built). New houses see benefits from flood protection measures straight away as from the start the developer builds a lot in high risk areas where the highest profits can be reached. This is particularly important given that new properties built post-2009 will not be eligible for the forthcoming Flood Re scheme, and as such will not be guaranteed affordable flood insurance if they are at high risk. For initial houses in the model the effect of flood defences on flood risk increases gradually over time as investment increases. However, in both cases the overall trend in flood risk still increases with and without flood protection measures. This reflects the cumulative effects of flood events, the continued development of properties in areas of flood risk, and the annual inflation related increase in flood damages used to calculate flood risk in this version of the ABM.

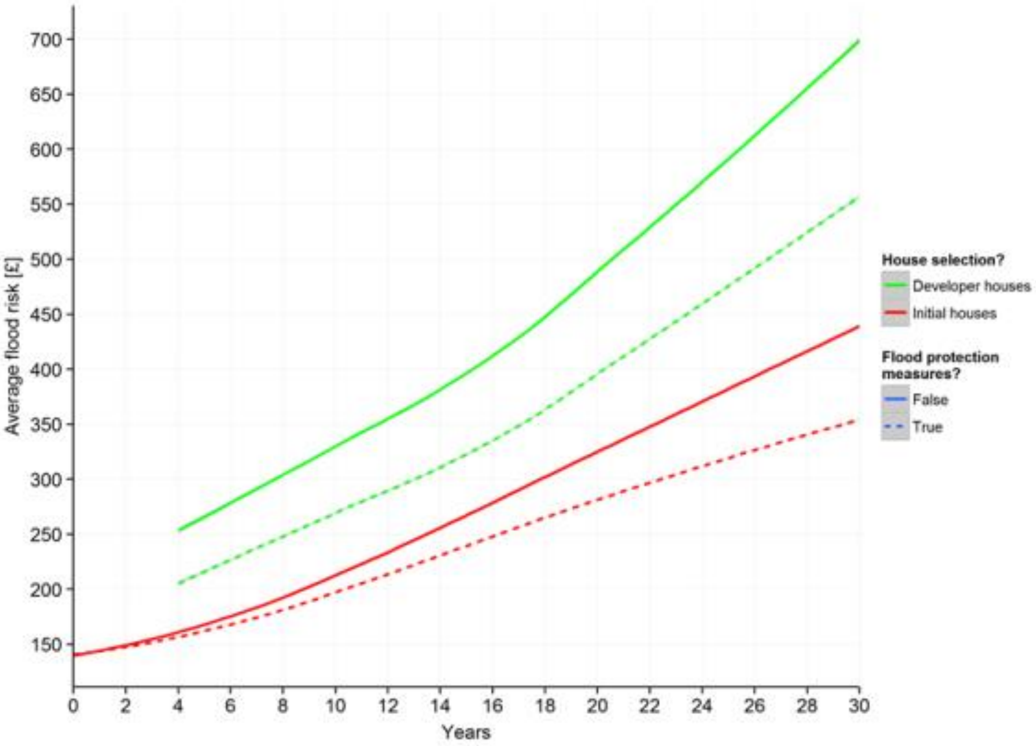

Figure 6: Effect of flood protection measures on the average flood risk over time

Flood insurance schemes

The second area of investigation focuses on the specific role of the Flood Re scheme. Given the way in which Flood Re is designed to work we test its ability to cover high flood risk houses and make insurance more affordable. Figure 7 shows the annual trend in the percentage of all houses in flood risk which would be re-insured by Flood Re. Initially only about 5% of houses in flood risk are re-insured by Flood Re. However, with increasing flood risk (e.g. figure 6) and the associated increase in flood insurance premiums (figure 8) the trend quickly increases over the first ten years. The percentage of houses in flood risk re-insured into Flood

Re then remains relatively constant, declining from around 90% to 75%. This decline reflects the continuing development of houses, often in areas of high flood risk, which contribute to the overall flood risk of the study area but are not eligible for the Flood Re scheme.

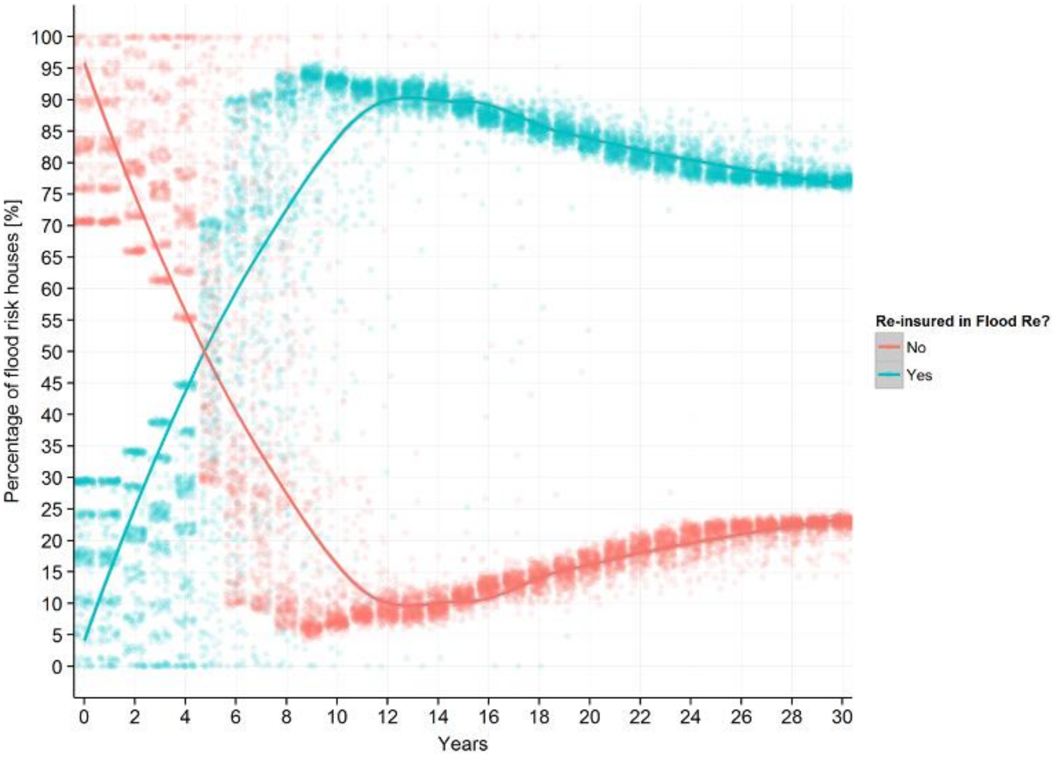

Figure 7: Percentage of flood risk houses re-insured in Flood Re over time

Figure 8 shows the main effect of the Flood Re scheme when it is combined with existing flood insurance. Flood Re is shown to lower the flood insurance premiums of high risk properties significantly. Where initially the average insurance premium increased from an average of £75 to £400 in 30 years, Flood Re more than halves this to an average of around £170 after 30 years. The upward trend seen here also comes from new houses being built by the developer in areas at risk of surface water flooding, which are not eligible for the Flood Re scheme. This supports the main aim of Flood Re to lower flood insurance premiums and suggests the model is capturing the main function of the scheme correctly.

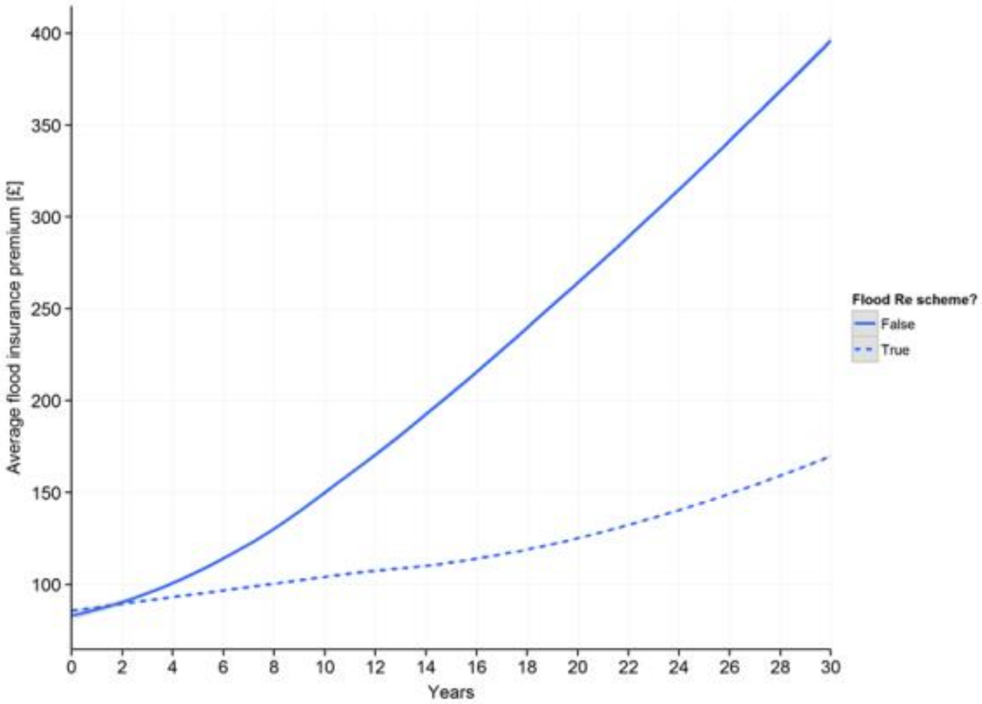

Figure 8: Effect of Flood Re on the average flood insurance premium over time

Finally, we explore the interactions between Flood Re and investment in flood protection measures. While Flood Re does not directly incentivise investment in PLPMs or SUDS figure 9 highlights a positive feedback. Fewer properties are re-insured into Flood Re when such flood risk reduction measures are in place. This is as PLPMs and/or SUDS are accounted for when estimating the potential damage to properties affected by flooding, and consequently lowers the insurer’s estimate of flood risk of protected properties and in some cases the need to place the property into Flood Re. In these simulations a combination of SUDS and PLPMs are shown to be most beneficial in terms of reducing the number of properties which are placed into Flood Re. This highlights the importance of investing in surface water risk management if the viability of flood insurance is to be maintained in the future.

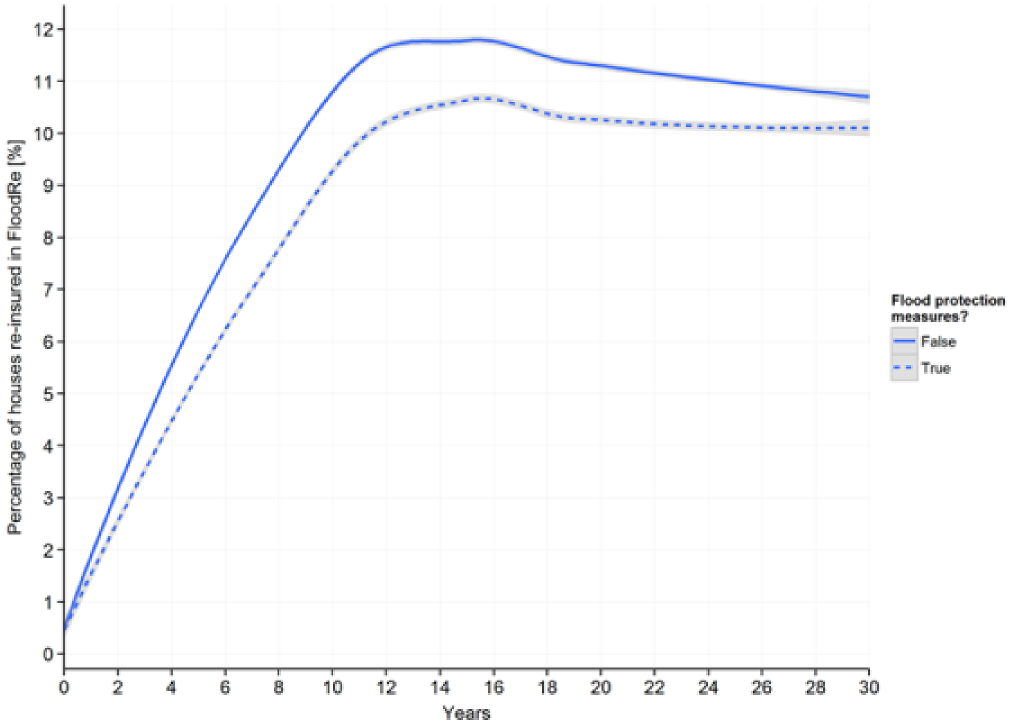

Figure 9: The effect of flood protection measures on the percentage of houses re-insured into Flood Re over time

Discussion and Conclusions

The paper presents an ABM developed to model the dynamics of surface water flooding, changing surface water flood risk, and how adaptation and insurance decisions could affect future surface water flood risk in that dynamic. While the focus of this paper is a case study of Camden the ABM is applicable to the broader situation in Greater London and could be extended to other areas in the UK or specific situations in other countries (dependent on availability of relevant data and computational resources). The analysis is novel due to its dynamic nature and as different combinations of surface water flood risk management options can be modelled, to include structural adaptation options, insurance, and the specific case of Flood Re.

Filatova (2015) highlight the need to move from conceptual modelling experiments to simulating real life situations through the use of available data. Both KISS (Keep It Simple Stupid) and KIDS (Keep It Descriptive Stupid) models have benefits and disadvantages. In this study we follow the KIDS approach to help facilitate real life policy testing. One downside of this approach is that ABMs inevitability become more complex and can forego comprehensibility and transparency. The systematic approach to recording assumptions and extensive verification efforts (e.g. see documentation available at https://www.openabm.org/model/4647/version/1/view) work to limit the problems of transparency. Additionally, the physical limits to agent behaviour provided by the detailed GIS data and flood maps further strengthen the realism of the model.

The paper demonstrates how the ABM captures essential features of the flood insurance scheme and flood protection investments. While it has not been possible to validate the model in terms of the Flood Re system (it is due to begin in April 2016) the overall patterns of behaviour shown by the ABM are in line with the available literature, real world data for London and Camden, and expert opinions. In the creation of the model different experts were consulted to provide expert knowledge, opinions, and feedback to help parameterise and validate the model, and the process has been strengthened by ongoing stakeholder input and interaction.

A second limitation, as with all ABMs, is that the results must be carefully interpreted given the underlying assumptions which are necessary given the model complexity. Nevertheless, the ability of the framework to incorporate different agents with their own behaviours; flexibility for testing different conditions and behavioural rules; flexibility to test and evaluate different policies and options; and the ability to visualise and quantify this in a spatial and dynamic manner, highlights the potential benefits of such an approach to support and inform decision making with regard to surface water flood risk and management strategies. The user interface has been developed in such a way that allows different policies, combinations of policies, agent behaviours, mechanisms of the Flood Re scheme, and research questions to be easily explored.

In particular, the model is timely in its contribution to the assessment of the existing public-private partnership and the Flood Re scheme, which have until now received insufficient attention due to lack of data or analysis. Based on the future scenarios of climate change and surface water flood events, analysis has been undertaken to explore the implications of future climate change on the proposed Flood Re scheme. The results have been of interest to stakeholders, and reported in the recent Prudential Regulatory Authority (2015) report on the impact of climate change on the UK Insurance sector. Applications also include an integrated assessment of surface water flood risk and management strategies under future climate change, which focuses on the interplay between different adaptation options; how risk reduction could be achieved by homeowners and government; and the role of flood insurance and the new flood insurance pool, Flood Re, in the context of climate change (Jenkins et al., 2016). Thirdly, the model has been used to assess the role of the current insurance partnership for incentivising resilience under future climate change, challenges faced, and how the inclusion of other agents, such as local developers, could enhance the risk reduction potential and future resilience of the Flood Re scheme. This includes an assessment of the role of different agents and how they could adapt their behaviour to address future risks (Jenkins et al., 2015). Lastly, an area of ongoing research is focused on testing the mechanisms of the Flood Re scheme and different transition options back to risk based pricing.

Overall the ABM has highlighted how socio-economic development can exacerbate current levels of surface water flood risk in Camden, with an increase in the average risk to properties in the model. Our analysis of different response mechanisms and interventions indicates that the implementation of SUDS and PLPMs are beneficial for reducing surface water flood risk. However, even with SUDS and PLPMs in place the average surface water flood risk continued to increase over time. Given the potential implications of climate change this illustrates the danger of further trade-offs between future development plans and flood risk management and need for further investigation in this area.

The model also highlighted that Flood Re would achieve its aim of securing affordable flood insurance premiums. However, Flood Re has no additional benefits in terms of overall risk reduction. This reflects concerns that the new scheme is missing an opportunity to contribute to risk reduction, which is important to its own resilience under future climate change. As such, the ABM is well suited to investigate how extensions and modifications to the proposed Flood Re scheme could better facilitate risk reduction.

The above issues and questions are all highly relevant aspects for the ongoing regulatory and political approval process for Flood Re, which have until now received insufficient attention due to lack of data or analysis. The development of the ABM addresses this gap and future findings are expected to provide important input to the current discussion about the design and operation of Flood Re, particularly with regards to incentivizing flood risk reduction measures.

Acknowledgements

This paper has benefited from research undertaken as part of the ENHANCE Project (Enhancing risk management partnerships for catastrophic natural hazards in Europe), funded under the Seventh Framework Programme of the European Union under grant agreement No 308438.

The authors are grateful for expert opinion and input to the model design provided by Dr Swenja Surminski and Dr Florence Crick of the Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science. We are also very grateful to Prof. Clinton J. Andrews and Mr Handi Chandra-Putra who kindly shared their ABM code, allowing us to develop and expand our model in a timely manner.

To gather large arrays of data from the agent based model two cluster computer systems were used. Initially the High Performance Computing (HPC) system at the Technical University of Delft was used. At a later stage the University of Oxford Advanced Research Computing (ARC) facility was used http://dx.doi.org/10.5281/zenodo.22558.

References

ADAPTATION SUB-COMMITTEE. (2012). *Climate Change - Is the UK preparing for flooding and water scarcity?* London: Committee on Climate Change.

BEVAN, K., & HALL, J. (Eds.). (2014). *Applied Uncertainty Analysis for Flood Risk Management*. London: Imperial College Press.

BLANC, J., HALL, J. W., ROCHE, N., DAWSON, R. J., CESSES, Y., BURTON, A. & KILSBY, C. G. (2012). Enhanced efficiency of pluvial flood risk estimation in urban areas using spatial–temporal rainfall simulations. *Journal of Flood Risk Management, 5*, 143-152.

BOTZEN, W. J. W. & VAN DEN BERGH, J. C. J. M. (2008). Insurance Against Climate Change and Flooding in the Netherlands: Present, Future, and Comparison with Other Countries. *Risk Analysis, 28*, 413-426.

BROUWERS, L., & BOMAN, M. (2011). A computational agent model of flood management strategies. In H. A. do Prado, A. J. B. Luiz, & H. C. Filho (Eds.), *Computational Methods for Agricultural Research: Advances and Applications* (pp. 296–307). Hershey, PA, USA: IGI Global.

CAMDEN COUNCIL. (2013). Camden's housing strategy 2011-2016. http://www.camden.gov.uk/ccm/cms-service/download/asset?asset_id=2683563. Archived at: http://www.webcitation.org/6ZYDShmt4.

CAMDEN COUNCIL. (2015). Opportunity Areas. http://www.camden.gov.uk/ccm/content/business/starting-and-growing-your-business/about-camdens-economy/opportunity-areas-.en. Archived at: http://www.webcitation.org/6ZYD6sRkd.

CHANDRA-PUTRA, H., ZHANG, H., & ANDREWS, C. (2015). Modeling Real Estate Market Responses to Climate Change in the Coastal Zone. *Journal of Artificial Societies and Social Simulation, 18*(2).

DAWSON, R. J., BALL, T., WERRITTY, J., WERRITTY, A., HALL, J. W. & ROCHE, N. (2011). Assessing the effectiveness of non-structural flood management measures in the Thames Estuary under conditions of socio-economic and environmental change. *Global Environmental Change, 21*, 628-646.

DEFRA. (2008). *Consultation on policy options for promoting property-level flood protection and resilience.* London: Defra.

DEFRA. (2011). *Commencement of the Flood and Water Management Act 2010, Schedule 3 for Sustainable Drainage: Impact Assessment*. London: Defra.

DEFRA. (2013). *Securing the future availability and affordability of home insurance in areas of flood risk*. London: Defra.

DEFRA. (2014). Flooding recovery: households and businesses applying for the Repair and Renew Grant Scheme. https://www.gov.uk/government/publications/flooding-recovery-households-and-businesses-applying-for-the-repair-and-renew-grant-scheme. Archived at: http://www.webcitation.org/6ZYEU6IbB.

DRAIN LONDON. (2011). Surface Water Management Plan: London Borough of Camden: Camden Council.

DUBBELBOER, J. (2015). Structuring flood insurance in the UK: An assessment of the London market using Agent Based Modelling. Delft University of Technology.

EUROPEAN WATER ASSOCIATION. (2009). *EWA Expert Meeting on Pluvial Flooding in Europe*. Brussels: EWA.

FALCONER, R. H., COBBY, D., SMYTH, P., ASTLE, G., DENT, J., & GOLDING, B. (2009). Pluvial flooding: new approaches in flood warning, mapping and risk management. *Journal of Flood Risk Management, 2*(3), 198-208.

FILATOVA, T., PARKER, D., & VAN DER VEEN, A. (2009). Agent-Based Urban Land Markets: Agent's Pricing Behavior, Land Prices and Urban Land Use Change. *Journal of Artificial Societies and Social Simulation, 12*(1).

FILATOVA, T., PARKER, D., & VAN DER VEEN, A. (2011). The Implications of Skewed Risk Perception for a Dutch Coastal Land Market: Insights from an Agent-Based Computational Economics Model. *Agricultural and Resource Economics Review, 40*(3), 405-423.

FILATOVA, T. (2015). Empirical agent-based land market: Integrating adaptive economic behavior in urban land-use models*. Computers, Environment and Urban Systems, 54*, 397-413.

GREATER LONDON AUTHORITY. (2009). *London Regional Flood Risk Appraisal*. London: GLA.

GREATER LONDON AUTHORITY. (2011a). *The London Climate Change Adaptation Strategy*. London: GLA.

GREATER LONDON AUTHORITY. (2011b). *The London Plan: Spatial Development Strategy for Greater London*. London: GLA.

GREATER LONDON AUTHORITY. (2014). Flood risks in London: Summary of findings. London: GLA.

GREATER LONDON AUTHORITY. (2015a). Drain London. http://www.london.gov.uk/drain-london. Archived at http://www.webcitation.org/6YIlgF36K.

GREATER LONDON AUTHORITY. (2015b). Ward profiles and atlas. http://data.london.gov.uk/dataset/ward-profiles-and-atlas. Archived at: http://www.webcitation.org/6Ze2kH8rz.

GREATER LONDON AUTHORITY. (2015c). 2015 round population projections. http://data.london.gov.uk/dataset/2015-round-population-projections. Archived at: http://www.webcitation.org/6hYBbc46S.

HALL, J. W., DAWSON, R. J., SAYERS, P. B., ROSU, C., CHATTERTON, J. B. & DEAKIN, R. (2003a). A methodology for national-scale flood risk assessment. *Water & Maritime Engineering, 156*, 235-247.

HALL, J. W., MEADOWCROFT, I. C., SAYERS, P. B. & BRAMLEY, M. E. (2003b). Integrated flood risk management in England and Wales. *Natural Hazards Review, 4*, 126-135.

HARRIES, T. (2012). The anticipated emotional consequences of adaptive behaviour - impacts on the take-up of household flood-protection measures. *Environment and Planning A, 44*(3), 649-668.

HOME CHECK. (2012). National surveys reveal highly concerning results regarding flooding and flood risk. http://www.homecheck.co.uk/Article.do?articleId= 15755.

HOUSE OF COMMONS ENVIRONMENT, FOOD AND RURAL AFFAIRS COMMITTEE. (2013). Managing Flood Risk. Third Report of Session 2013–14. Volume I. London: The Stationery Office.

INMAN, P. (2014). Mark Carney: rising house prices pose biggest risk to recovery. http://www.theguardian.com/business/2014/may/18/mark-carney-house-prices-risk-economy-bank-of-england. Archived at: http://www.webcitation.org/6ZYBNuPnc.

IPCC (Ed.) (2013). *Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Vol. 1). Cambridge: Cambridge University Press.

JENKINS, K., HALL, J., SURMINSKI, S., & CRICK, F. (2015). London Case Study: Flood risk and climate change implications for MSPs. ENHANCE deliverable 7.3: University of Oxford

JENKINS, K., SURMINSKI, S., HALL, J., & CRICK, F. (2016). *Assessing surface water flood risk and management strategies under future climate change: an agent-based model approach.* Centre for Climate Change Economics and Policy Working Paper No.252; Grantham Research Institute on Climate Change and the Environment Working Paper No.223.

KILSBY, C., JONES, P., HARPHAM, C., GLENIS, V., & BURTON, A. (2011). *Spatial Urban weather Generator for Future Climates*. ARCADIA Task 3 Report.

LAMOND, J., PROVERBS, D., & HAMMOND, F. (2009). Flooding and Property Values. In S. Brown (Ed.), *Findings in Built and Rural Environments (FiBRE)*. London: Royal Institution of Chartered Surveyors.

LAMOND, J., & PENNING-ROWSELL, E. (2014). The robustness of flood insurance regimes given changing risk resulting from climate change. *Climate Risk Management, 2(1-10).*

LANDMAP. (2014). Building Class. http://learningzone.rspsoc.org.uk/index.php/Datasets/Building_Class/Download-Building-Class. Archived at: http://www.webcitation.org/6Ze3ANv4E.

MAGLIOCCA, N.R., BROWN. D.G., McCONNELL, V.D., NASSAUER, J.I., WESTBROOK., S.E. (2014). Effects of alternative developer decision-making models on the production of ecological subdivision designs: experimental results from an agent-based model. *Environment and Planning B: Planning and Design*, *41(907-927).*

MCNAMARA, D.E., KEELER, A. (2013). A coupled physical and economic model of the response of coastal real estate to climate risk. *Nature Climate Change, 3*(559-562).

ONS. (2014). 2011 Census: Internal and international migration for the United Kingdom in the year prior to the 2011 Census. Office for National Statistics: London. Archived at: http://www.webcitation.org/6hYb2MBBK.

PARKER, D.C., SUN, S., FILATOVA, T., MAGLIOCCA, N., HUANG, Q., BROWN, D.G., RIOLO, R. (2012). *The implications of alternative developer decision-making strategies on land-use and land-cover in an agent-based land market model.* International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany.

PENNING-ROWSELL, E., PRIEST, S., & JOHNSON, C. (2014). The evolution of UK flood insurance: incremental change over six decades. *International Journal of Water Resources Development, 30*(4).

PENNING-ROWSELL, E., VIAVATTENE, C., PARDOE, J., CHATTERTON, J., PARKER, D., & MORRIS, J. (2010). *The Benefits of Flood and Coastal Risk Management: A Handbook of Assessment Techniques*. London: Flood Hazard Research Centre.

PITT, M. (2008). Learning Lessons from the 2007 Floods, The Pitt Review. London: Cabinet Office.

PRUDENTIAL REGULATION AUTHORITY. (2015) The impact of climate change on the UK Insurance sector. Prudential Regulation Authority: London.

RAMSBOTTOM, D., SAYERS, P., & PANZERI, M. (2012). *Climate Change Risk Assessment for the Floods and Coastal Erosion Sector. UK Climate Change Risk Assessment*. London: Defra.

SHELTER. (2014). Repossession and Eviction Hotspots: September 2014. London: Shelter.

SOBIECH, C. (2013). Agent-Based Simulation of Vulnerability Dynamics: A case study of the German North Sea Coast. Berlin: Springer-Verlag Berlin Heidelberg.

SURMINSKI, S., & ELDRIDGE, J. (2015). Flood insurance in England – an assessment of the current and newly proposed insurance scheme in the context of rising flood risk. *Journal of Flood Risk Management*. DOI: 10.1111/jfr3.12127.

THURSTON, N., FINLINSON, B., BREAKSPEAR, R., WILLIAMS, N., SHAW, J., & CHATTERTON, J. (2008). *Developing the evidence base for flood resilience*. London: Defra.

ULBINAITĖ, A., KUČINSKIENĖ, M., & LE MOULLEC, Y. (2011). Conceptualising and Simulating Insurance Consumer Behaviour: an Agent-Based-Model Approach. *International Journal of Modeling and Optimization, 1*(3), 250-257.

ULBINAITĖ, A., & LE MOULLEC, Y. (2010). Towards an ABM-based framework for investigating consumer behaviour in the insurance industry. *ekonomika, 89*(2), 95-110.

VAN DAM, K. H., NIKOLIC, I., & LUKSZO, Z. (Eds.). (2012). *Agent-based modelling of socio-technical systems*. Netherlands: Springer.

WILENSKY, U. (1999). NetLogo Software. *Available at http://ccl.northwestern.edu/netlogo/ Last Accessed June 2015*.

WYNN, P. (2005). Development control and flood risk: Analysis of local planning authority and developer approaches to PPG25. *Planning, Practice & Research, 20*(3), 241-261.