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# An agent based model for risk-based flood incident management

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## Abstract

Effective flood incident management requires successful operation of complex, interacting human and technological systems. A dynamic agent based model of FIM processes has been developed to provide new insights which can be used for policy analysis and other practical applications. The model integrates remotely sensed information on topography, buildings and road networks with empirical survey data to fit characteristics of specific communities. The multi agent simulation has been coupled with a hydrodynamic model to estimate the vulnerability of individuals to flooding under different storm surge conditions, defence breach scenarios, flood warning times and evacuation strategies. A case study in the coastal town of Towyn in the UK has demonstrated the capacity of the model to analyse the risks of flooding to people, support flood emergency planning and appraise the benefits of flood incident management measures.

## Keywords

*Flooding; Risk analysis; Disaster management; Agent based modeling; Evacuation*

# 1 Introduction

As evidenced in many flood events, poor flood incident management (FIM) can result in widespread loss of life and other significant damages. In New Orleans in 2005, although 80 to 90% of the population was evacuated (Wolshon, 2006) there was still very significant loss of life – over 1,100 people lost their lives in the state of Louisiana. In the UK summer floods of 2007, temporary protection could not be deployed due to flooding and congestion of transport links connecting the defence storage depot and the deployment site (Pitt, 2008). Conversely, during the June 2007 floods in Hull, the inability to start up computer systems, and the loss of rainfall radar information did not significantly affect FIM. However, in the same event a severe flood warning was issued late. It is clear that new approaches are required to support flood risk managers to reduce loss of life and damages and explore the wide range of events that can unfold during a flood incident.

This paper describes a simulation approach to estimate the likely exposure of people to flooding during an event and provides a risk-based approach to appraising the benefits of FIM response measures. After this introduction to the challenges of FIM and a brief review of promising methods for FIM simulation, we describe our preferred method, Agent Based Modelling, and its application to a case study in Towyn in the UK.

## *1.1 Flood incident management*

Managing flood events as they occur has potential to reduce the probability of flooding through controlling flood pathways and significantly reduce the damage that is caused by managing losses and influencing the behavior of individuals and organizations. FIM responses are taken (i) in preparation of a flood event, (ii) forecasting and warning during a flood event, (iii) to reduce damages during the event and (iv) to facilitate recovery and minimize the social, health and practical impacts of flooding after an event. A number of FIM responses are listed in

Table 1, this paper focuses on management measures undertaken during the flood, but also considers the benefits in terms of reduction of flood losses from certain interventions preceding a flood event.

Table 1 Flood Incident Management response measures

| FIM response type | FIM policies or interventions |
|---|---|
| *Pre-Event Preparedness Measures* | • Flood plans: Preparation of plans to respond by regional authorities, organisations, communities and individuals<br>• Flood-risk mapping to identify highly vulnerable areas<br>• Education and awareness-raising |
| *Reducing potential flood damages prior to an event* | • Land use planning<br>• Flood-proofing: retrofitting and changing design codes |
| *Forecasting and Warning* | • Flood-forecasting systems: improved sensing, forecasting, and real-time modelling during the event<br>• Warning dissemination systems (including take-up by residents and businesses) |
| *Flood Fighting Actions* | • Demountable/temporary defences deployed before and during the event<br>• Water-level control structures: controllable weirs and sluices<br>• Emergency repair and reinforcing of defences<br>• Emergency diversions: cut-through channels, deliberate breaching of dikes<br>• Temporary floodproofing: Sandbags, cavity blocks etc. |
| *Reduction of flood loses during events* | • Evacuation of flood risk areas<br>• Moving assets to safety |
| *Lessening the impact and facilitating recovery* | • Insurance to share the risk<br>• State aid, compensation<br>• Medical preparedness to reduce health and social impacts |

## 1.2 Challenge of risk analysis for FIM

Flood risk analysis provides a rational basis for the appraisal of policy options, allocation of resources and monitoring performance of substantial government investment in flood management (Hall et al., 2003a). Flood risk is conventionally defined as the product of the probability of flooding and the consequential impact. Economic risk analysis is well established for structural (e.g. embankments) flood management measures (c.f. USACE, 2000; Hall *et al.*, 2003b; Dawson and Hall, 2006; Jonkman *et al.*, 2008). However, less progress has been made with evaluating the effectiveness of FIM measures because they are characterized by complexity:

- Spatial and temporal variations of flood incidents can vary significantly;
- Flood incidents exhibit non-linear behaviour: a small perturbation can cause a large knock-on effect;
- The overall success of a FIM response may not be obvious from studying individual components in isolation;
- FIM involves a series of interactions between individuals and organisations with often conflicting, values and objectives;
- Individuals and organisations with often conflicting, values and objectives;

- Feedbacks within the FIM system lead to dampening of some behaviour and amplification of other;
- The influence of a flood incident usually extends beyond the physical extent of the flood;
- Human systems are reflexive in that they respond and adapt to the conditions to which they are exposed, and;
- The impacts of flooding and the capacity to deliver a successful FIM response is sensitive to prior conditions.

In order to understand how to manage the risk and uncertainties inherent in the whole FIM system it is therefore essential to assess not only the probabilities and consequences of failure from the perspective of individual components, but to consider the wider system performance. Moreover, quantitative information on many elements of the FIM process is sparse, especially with regards to many of the 'softer' systems elements (for example, organisational, resourcing and health and safety issues). However, if FIM measures are to be appraised, and the benefits of FIM at risk management are to be meaningfully compared against the benefits of, for example raising a flood embankment, then these challenges must be addressed.

## *1.3 Simulation of flood incidents*

Fundamental to understanding FIM processes is the means by which risk is communicated, both during a flood event and prior to an event. If people are ignorant of flood risk then they will not account for it at all in their decision making behaviour and respond to flood warnings differently. People become aware of flood incidents through:

- flood warning systems,
- warning and diversion signs deployed near the flooded area,
- use of loud halers and public address systems,
- media reports of flooding,
- communication between members of the public, and,
- emergency responders,

amongst other mechanisms. People’s reaction to becoming informed of a potential flood event varies according to factors such as their previous experience of flooding incidents, experience of receiving ‘false alarms’ and actions taken by government to increase awareness of flood risk.

In order to understand these processes and anticipate likely modes of behavior during a flood, data is generally acquired through surveys. For example, an initial assessment by the Environment Agency on more than 500 flood warnings issued during June and July 2007, reported in the Pitt

Review (Pitt, 2008), showed that around 80 per cent were issued to target (more than two hours before the flood threshold was reached); around 20 per cent were not issued to target (either less than two hours before, or after the threshold was reached) and in about 20 per cent of cases the river concerned did not in the event reach the threshold level. Surveys have shown that for floods in the UK between 1997-2005, between 32% and 69% of people received a warning prior to flooding (Parker et al., 2007a). But after UK floods in Autumn 2000, BMRB (2001a) revealed that 17-23% of people were unable to take action to prepare for flooding, due to age, disability or illness. Whilst a campaign to raise flood awareness nationally in 2001 showed 52% of people were aware they may be at risk of flooding, and that the proportion of those who had taken precautions to prepare for flooding had increased from 5% to 7% (BMRB, 2001b).

To date, three main approaches have been used to quantify the benefits of FIM measures:
(i) *Reduction factors*: FIM measures are represented by adjusting damage functions or the standards of flood protection (e.g. Parker *et al.*, 2007a) using observations from real events, or estimates of the potential to raise protection or reduce damages (c.f. Penning-Rowsell and Green, 2000).
(ii) *Scenario analysis*: A number of pre-determined scenarios are analyzed to explore the effectiveness of FIM measures under a range of internally consistent assumptions (e.g. Evans *et al.*, 2004; Dawson *et al.*, 2009).
(iii) *Interactive techniques*: Methods such as role play (Lonsdale *et al.*, 2008) and desktop exercises such as Exercise Triton (Environment Agency, 2004) provide useful insights into human by gathering experts together to discuss intervention decisions for a given scenario. Evidently, these are both costly to run (in terms of time and resources) and are rarely able to explore more than one scenario.

These methods have undoubtedly provided important insights into understanding FIM. However, they do not fully address the challenges identified previously and so we have developed a simulation approach which addresses a number of the shortcomings of other approaches as it:

- explicitly enables (through dynamic updating in a simulation model) the interactions and feedbacks between floods and human responses to be captured as the flood event evolves;
- can be easily set up to simulate a wide range of flood events, initial conditions and FIM responses, and;
- requires uncertainties about human behaviour and incomplete data (as evident in the survey results described previously) to be made transparent and auditable.

Several modelling techniques, often collectively referred to as social simulation , have successfully been used to represent the behaviour of humans and organisations. A full review is beyond the scope of this paper, Table 2 provides a brief overview of a number of social simulation techniques but interested readers are referred to Gilbert and Troitzsch (2005) and Environment Agency (2006) for more detail. Simonovic and Ahmad (2005) demonstrated the potential for system dynamics to support flood incident management. Here Agent Based Modelling (ABM) was selected as the most suitable to address the challenges of simulating FIM processes because of its capacity to capture interactions and dynamic responses in a spatial environment. Increasingly methods of social simulation are moving towards a common ground, and whilst the model here is predominantly based on ABM, aspects of microsimulation are evident in the identification of agent behaviour rules.

An agent-based model is a computational method for simulating the actions and interactions of autonomous decision-making entities in a network or system, with the aim of assessing their effects on the system as a whole. Individuals and organisations are represented as agents. Each agent individually assesses its situation and makes decisions on the basis of a set of rules. Agents may execute various behaviours appropriate for the system component they represent—for example, producing or consuming. At the simplest level, an agent-based model consists of a system of agents and the relationships between them. Even a simple agent-based model can exhibit complex behaviour patterns because a series of simple interactions between individuals may result in more complex system scale outcomes that could not have been predicted just by aggregating individual agent behaviours.

ABM was developed as a concept in the late 1940s but substantial applications became possible with the emergence of high powered computing. Applications included political science (Axelrod, 1997), management and organisational effectiveness (Samuelson, 2000), and the behaviour of social networks (Sallach and Macal, 200;1Gilbert and Troitzsch, 2005). Human and organizational response to flood risk and flood warnings is strongly related to experience of flooding and flood warnings, and also to a learning process (Parker et al., 2007b), so ABM is well suited to modelling these kinds of system dynamics. ABMs also have a good pedigree in testing the effectiveness of warning dissemination mechanisms and the susceptibility of evacuation routes to overcrowding in fire and terrorist incident simulations (Still, 1993, Galea *et al*., 1996, Wong and Luo, 2005) and situations of 'panic' (Helbing *et al*., 2000, Zarboutis and Marmaras, 2005) making them natural tools for a FIM application.

Table 2 Overview of potential methods for social simulation (more information can be found in Gilbet and Troitzsh, 2005; Environment Agency, 2006)

| **Method** | **Brief overview** | **Agent hierarchy** | **Agent-Agent communication** | **Agent heterogeneity** | **Spatially explicit** | **Feedbacks represented** |
|---|---|---|---|---|---|---|
| *Event and Fault trees* | Event trees use inductive logic. The evolution of a disaster is divided into discrete events, starting from the initiating event (e.g. breach of sea wall). Each event has a finite set of outcomes and form a tree of possible outcomes. Risk is evaluated by analysing the probabilities and consequence of different paths along the tree. Fault trees appear similar, but use deductive logic. The probability of an undesired state of a system is evaluated using boolean logic to combine a series of lower-level events. | ✗ | ✗ | n/a | ✗ | ✗ |
| *Bayesian Networks* | System components are causally connected and these connections can be described in terms of conditional probabilities. The network can be used to determining the probability of particular states or situations (e.g. probability of a successful evacuation). These probabilities can subsequently be used directly in risk-based decision-making. | ✗ | ✗ | n/a | ✗ | ✓ |
| *Microsimulation* | Operates at the level of individual units such as people, households or organisations. Each unit is represented by a set of attributes (e.g. age). A set of rules are then applied to these units leading to simulated changes in state and behaviour. This gives an estimate of the outcomes of applying these rules in terms of both aggregate changes and the distribution of these changes. | ✓ | ✗ | ✓ | Maybe | ✗ |
| *Cellular Automata* | Modelled on a grid of cells, representing individuals or other entities. Each cell has a limited set of states (e.g. 'alive' or 'dead') and at each timestep the state of each cell may change based on its state, nearby cells and uniform model rules. | ✓ | ✓ | ✗ | Y | ✓ |
| *System dynamics* | Used when the macro level dynamics of the system are most important. The system is represented by components (e.g. population) and the differential equations that describe how they change through time (e.g. recognition of danger). This can only be used to understand aggregated behaviour and because there is limited interaction and heterogeneity of agents it is not appropriate when individuals are responsible for determining outcomes. | ✗ | ✗ | ✗ | ✗ | ✓ |
| *Agent Based Models* | Simulates the operations and interactions of multiple agents with macro level system behaviour emerging from these individual interactions. Agent behaviour is determined by rules of interactions with each other and the environment. This method is the focus of this paper and described here in more detail. | ✓ | ✓ | ✓ | ✓ | ✓ |

# 2 An agent based modelling system for FIM

## *2.1 Overview*

Applications of ABM in flooding have focused on estimating loss of life under dambreak scenarios (Hobeika and Jamei, 1985; Johnstone et al. 2005). Furthermore, they have yet to be used within the context of a probabilistic risk analysis. The FIM risk analysis framework is shown in Figure 1. The agent-based model has been developed in the NetLogo ABM development platform. A hydrodynamic model simulates the floodwave was also developed within the ABM platform and interacts directly with the agents and the built environment. Spatial data describing features such as the flood protection structures, property type and its location, the elevation of the floodplain and the transport network are imported into the ABM platform from nationally available datasets. A suite of behaviour rules define how agents and FIM organisations behave. Figure 2 shows a screenshot of the ABM model in the NetLogo interface. A scenario manager, developed in the Python programming language, facilitates batch running of multiple simulations and setting up the model to test different types. These include exploring the impacts of different storm surges, the location of flood defence failure and the FIM responses used such as the amount of warning time given to people. Damage functions describing, for example the relationship between loss of life or some other measure of harm and the properties of the flood, are used to quantify flood risk. A full list of the data used is given in

Table 3.

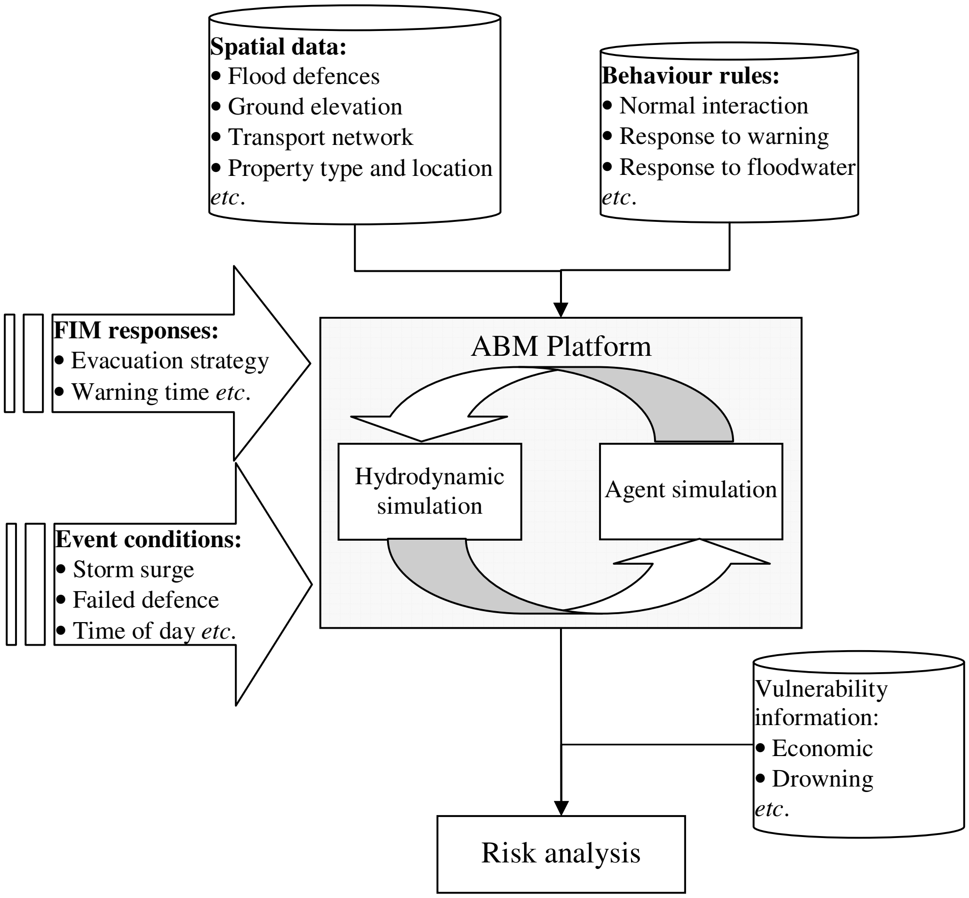
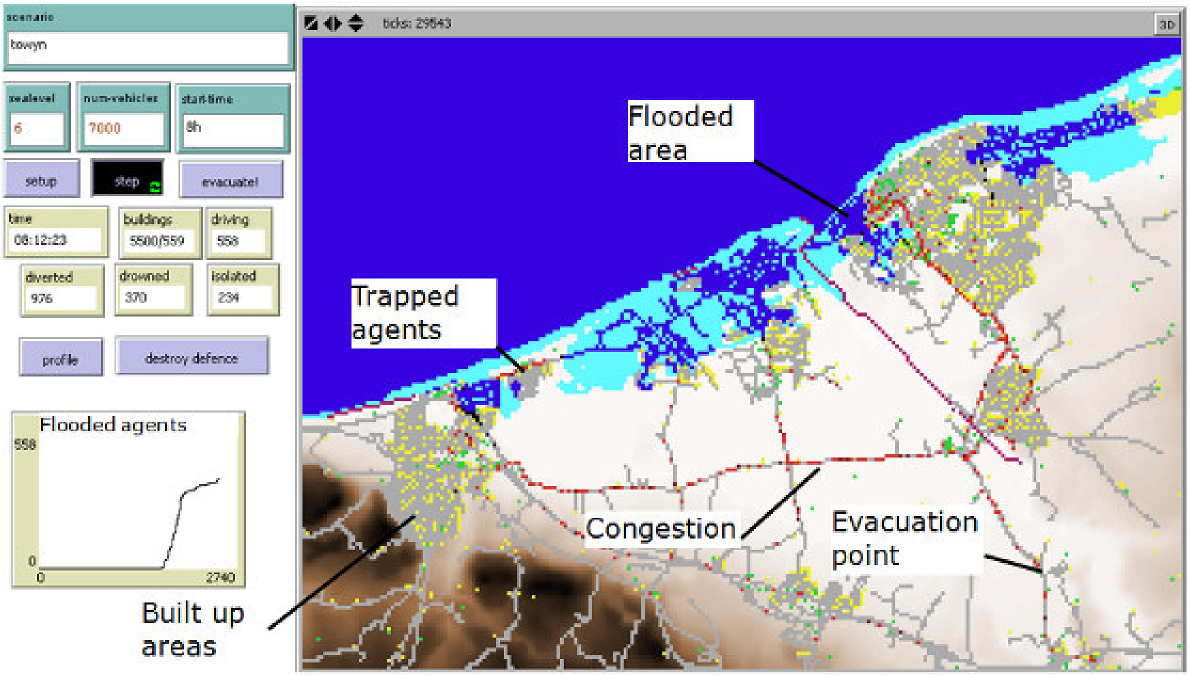


Figure 1 Overview of the risk analysis system for flood incident management

Table 3 Data used to set up the ABM

| Data | Source | Use |
|---|---|---|
| Flood defence location | Environment Agency's National Flood and Coastal Defence Database | Defining flood defence location and breach locations |
| Flood defence fragility | Dawson and Hall (2006) using data from Conwy County Borough Council | Flood defence performance under different storm surge conditions |
| Digital Elevation Map | Interferometric Synthetic Aperture Radar (IfSAR) data and Local Authority manhole surveys from Conwy County Corough Council | Topography |
| Transport network | OS MasterMap | Location, connectivity, capacity |
| Property type | Environment Agency's National Property Database | Type of property: whether residential or the type of non-residential property use |
| Property location | Environment Agency's National Property Database | Eastings and Northings co-ordinates of each property |
| Depth-damage function | Multi-Coloured Manual | Damage functions, conditional on flood depth for each property type |
| Vulnerability function | DEFRA | Conservative estimate of exposure was used here. A more detailed function integrating over depth and velocity could be established. |
| Population profile | UK Census | Number of residents in Towyn. Age profile and employment profile were used to classify transport groups. More detailed studies could use the information on population age and other demographic data to improve the vulnerability assessment. |
| National Travel Survey 2008 | Department for Transport | Travel patterns for different age, employment and genders. |
| Web Interface to Census Interaction Data | The Centre for Interaction Data Estimation and Research | Number of journeys from residence ward to employment ward from census data. |
| 1990 Flood outline | Conwy County Borough Council | Validation of flood spreading model |



scenario towyn

sealevel 6

num-vehicles 7000

start-time 8h

time 08:12:23

buildings 5500/559

driving 558

diverted 976

drowned 370

isolated 234

Figure 2 Screenshot of the agent based model in action. The road network is reported on the raster surface in the model viewer such that every raster cell with a road component on it is shaded. (A video and demonstration version of the model, in the form of a java applet which can be accessed from the author's website: http://www.staff.ncl.ac.uk/richard.dawson/FloodEventABMDemo/FloodEventABMDemo.html accessed January 2011)

## 2.2 *Inundation modelling*

Floodplain flows are described in terms of continuity and momentum equations, discretized over a raster grid of square cells, which allows the model to represent 2-D dynamic flow fields on the floodplain. Flow between two cells is a function of the free surface height difference between those cells (Estrela and Quintas, 1994; Bates and de Roo, 2000):

$$\frac{dh^{i,j}}{dt} = \frac{Q_x^{i-1,j} - Q_x^{i,j} + Q_y^{i,j-1} - Q_y^{i,j}}{\Delta x \Delta y} \tag{1}$$

$$Q_x^{i,j} = \frac{h_{flow}^{5/3}}{n} \left( \frac{h^{i-1,j} - h^{i,j}}{\Delta x} \right)^{1/2} \Delta y \tag{2}$$

where $h^{i,j}$ is the water free surface height at the node $(i,j)$, $\Delta x$ and $\Delta y$ are the cell dimensions, $n$ is the effective grid scale Manning's friction coefficient for the floodplain, and $Q_x$ and $Q_y$ describe the volumetric flow rates between floodplain cells. $Q_y$ is defined analogously to Equation 2. The flow depth, $h_{flow}$, represents the depth through which water can flow between two cells, and is defined as the difference between the highest water free surface in the two cells and the highest bed elevation, as shown in Figure 3. Although this approach is ultimately not as accurate as more sophisticated and computationally expensive codes, it provides sufficient representation of the dynamics of the inundation to enable FIM responses to be tested in this study.

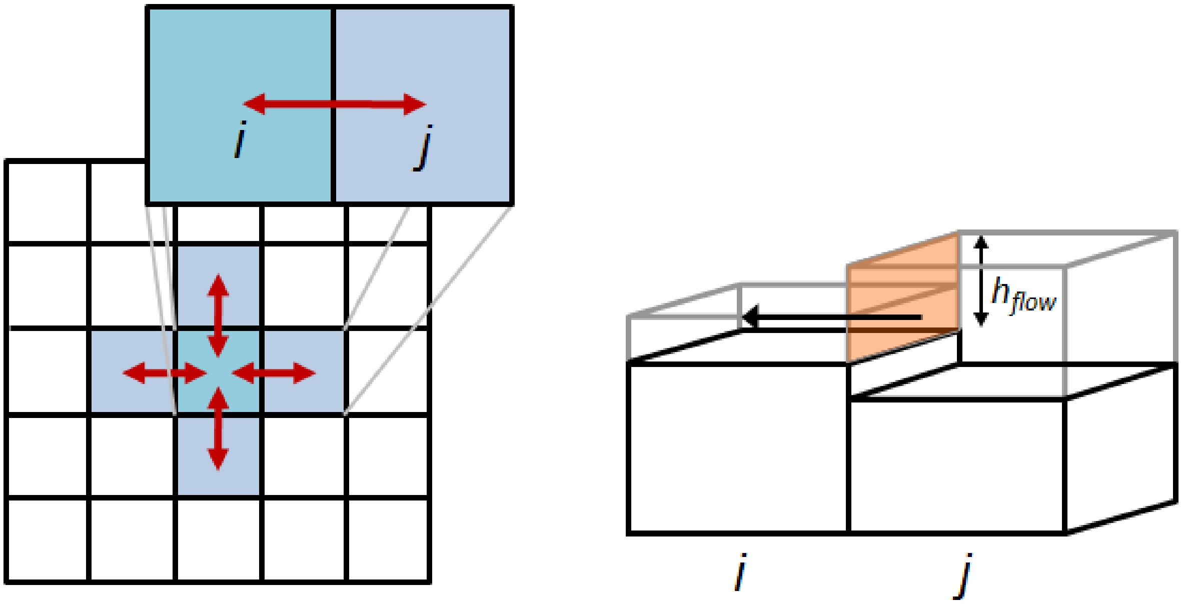


Figure 3 Representation of floodplain flow between raster cells

### 2.3 *Agent behaviour*

The location of people can vary dramatically over the course of the day - for example more people will be in their house during the night, more at work during a weekday etc. However, it is impossible to truly anticipate the location of each individual at any given time - and yet their location at the onset of flooding has significant implications for the management of any given event.

There are two components to determining agent behaviour (i) how the agents behave under normal conditions that determine where the are at the start of a flood event, and, (ii) how agents respond to a flood event, or FIM measures. To address this, each agent is described using a probabilistic finite state machine that describes its possible states, the actions it can take and the transitions between states. The probability of being in a given state (e.g. home or work) has been parameterised using data from the National Travel Survey (ONS and DfT, 2008) which gives:

- Sample diaries of travel patterns for households
- Proportion of journeys at each hour of the day
- Proportion of journeys according to purpose (commuting, business, school, shopping, recreation)
- Proportion of journeys according to gender, household size, age and employment status (full time, part time, self or unemployed)

In addition, the proportion of the population with each of these properties is given in the census (ONS, 2006) whilst the WICID (Stillwell and Duke-Williams, 2003) dataset provides information on the starting census ward (i.e. place of residence) and end census ward (i.e. place of employment) of commuters.

Because the census does not identify individuals against addresses, at the start of each simulation an agent population with the same distribution of age, gender, employment and household size as the census is generated and randomly located within residential properties in the case study domain. According to the demographic properties of the agent, the National Travel Survey is used to generate synthetic daily routines, with WICID data used to identify the proportion of the population commuting between census wards (and into and out of the case study domain if appropriate). To capture variability in the travel survey and uncertainties in behaviour the synthetic daily routines are described in probabilistic terms. To reduce the number of agent types only a limited number of agent classifications were used (Table 4).

Table 4 Classifications used for the determination of agent behaviour

| **Sex** | **Age** | **Employment** | **Household size** |
|---|---|---|---|
| Male<br>Female | 0-16<br>17-69<br>>69 | Full time<br>Part time<br>Self employed<br>Unemployed | 1<br>2<br>>2 |

The travel and census datasets are not reproduced here, but an example of a synthetic daily routine for an agent with demographic properties female agent, aged 17-69, from a household of four and who is employed is shown in Figure 4. In this example, the agent starts the day at 8am with standard deviation of 15 minutes. They then travel, via school to drop their children off, to work with a 0.1 probability of visiting the shops for a while en route and so on. This daily routine can be interrupted when an agent becomes aware of a flood incident, and depending on the time of day they may be in a number of different places. In this case, the agent will choose to evacuate to the nearest shelter with a probability of 0.7, otherwise they try to continue their routine as normal.

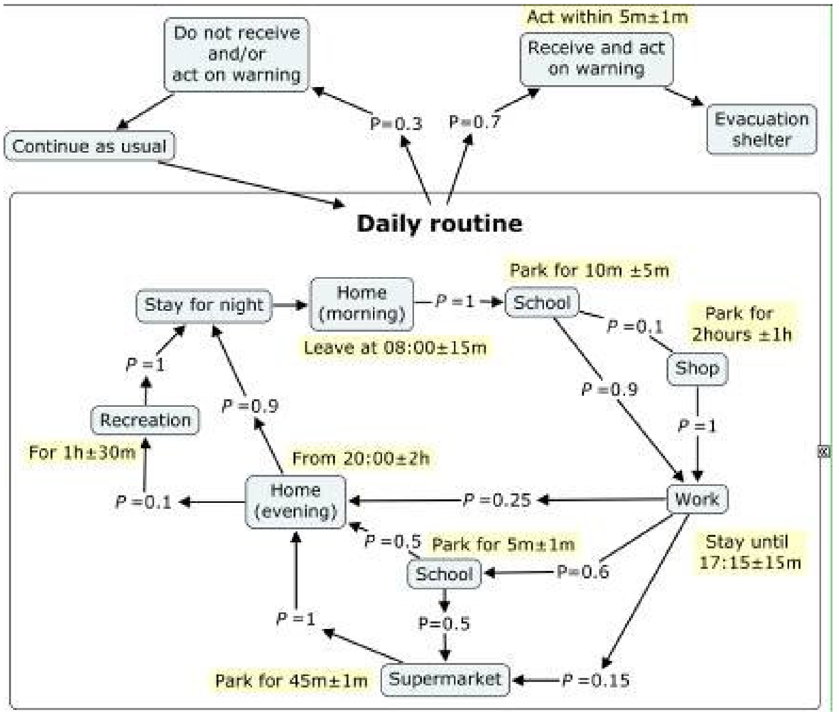


Figure 4 Example of a synthetic daily routine generated from travel survey and census data for a female agent, aged 17-69, from a household of four and who is employed.

To represent the influence of activities not generated by residents in the model domain, agents are generated at major roads entering the model domain. These agent are either employed within the modelling domain, and so appear during working hours only according to the WICID commuting data, or they are transient visitors who either use services (and so make a stop at a non-residential property) or passing straight through.

### 2.4 Traffic simulation

ABMs often use a raster grid through which the agent is able to move. However, in this case there is a tension between the requirements of the hydrodynamic and agent simulation. As the resolution of the DEM is increased, so do the computational demands of the hydrodynamic model. However, to accurately capture agent movement along a roads requires modelling at a resolution finer than road width (in the UK a two-way road can be less than 6m wide, and in the case study below, up to 13 road links were counted as intersecting a 50×50m raster grid cell) to ensure that vehicles are constrained by the location of physical infrastructure. Therefore, we have combined a 50m resolution raster model for the hydrodynamic modelling with a network model for vehicle movement that correctly represents the topological connectivity of the transport network (Figure 5).

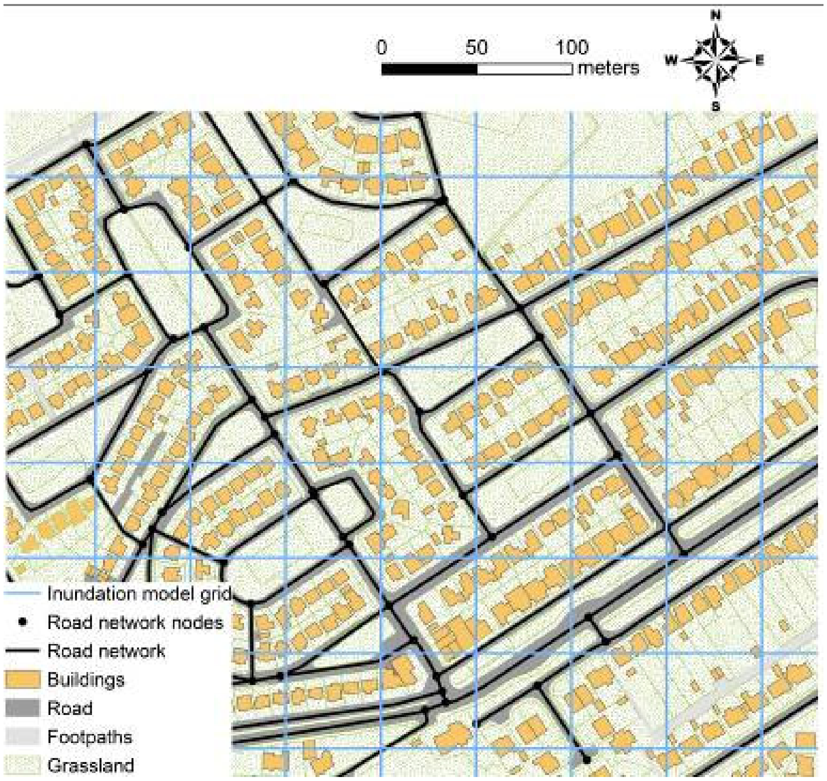


Figure 5 A detail showing the road network, building locations and inundation model raster grid

Each agent moves through the model domain along the network from a start location property to a target property. The choice and time of journey is defined by behaviour rules, as described above. Once an agent has decided to make a journey (e.g. travel to school), it must first choose a building of that type from the properties in the model domain. The National Property Database lists the location and use of each building (e.g. residential, supermarket, shop, school etc.). If detailed information is known then a specific building can be pre-defined, or the agent may be choose the nearest school in preference. However, without complete information the destination school is chosen randomly. Once a destination building is selected the agent identifies an efficient route according to the A* search algorithm (Hart et al. 1968; Dechter and Pearl, 1985). The A* finds the least cost (as a function of both distance and speed) path along the road network from a given initial building to the target building. The agent then 'unparks' itself from the building it occupies and joins the road network at the nearest link. Assuming there is no change in information on its travels, the agent will follow this route. However, if its passage is blocked by floodwater it will re-route itself. Once it arrives at the nearest road section to the destination building, the agent will 'park' and remove itself from the network to allow other traffic to continue to flow. This process is shown in Figure 6(a).

Traffic movement along the road network is simulated using the Nagel and Schreckenberg (N-S) cellular automata pulse model (Nagel and Schreckenberg, 1992; Nagel et al., 1998). Each street section is divided into discrete cells. Typically 7.5m is used which corresponds to typical space occupied by a car in a dense jam (car length plus the distance to the preceding car). Each vehicle is characterized by its current velocity $v$ which can take the values $v$=0,1,2,... ,$v_{\max}$ where $v_{\max}$ corresponds to the speed limit. In the model $v_{max}$ is based on the road classification from the digital mapping dataset MasterMap. $v_{max}$ is 30miles per hour (mph) or just under 50km per hour for most roads, with 60mph and 70mph for single and dual carriageway main roads respectively. In each timestep, vehicles follow the following procedures (shown in Figure 6(b))

a) if their speed is less than the speed limit ($v<v_{max}$) then they increase by one unit ($v=v+1$);
b) subsequently, if their speed becomes greater than the distance, $d$, to the vehicle ahead ($v>d$) of vehicle ahead then the vehicle applies the brakes to reduce the speed to make sure they cover only the distance between themselves and the car in front in the next timestep so $v=\min\{d/t,v\}$;
c) cars do not usually travel at a constant speed, to account for overbreaking and fluctuations in speed the N-S model uses a simple approach to represent this phenomena by assuming that for every vehicle that breaks and has $v>0$ there is a probability $p$ that $v=v-1$.

The N-S model has been shown to represent macro-level traffic phenomena such as spontaneous jams and the relationship between traffic flow rates and density. The schematic in Figure 6 shows a 1D simulation. At junctions, flow is more complex. Some rules can be established automatically from the road network data, for example, the direction of road links, give way to vehicles from the right at roundabouts, the location of one way roads. However, information on traffic light signals was not available. Moreover, to represent signals represents a level of granularity higher than other aspects of the modelling system. Therefore, at junctions with unknown priorities, to avoid a situation where two vehicles occupy the same part of the road network, vehicle positions are updated in a random order, rather than in parallel.

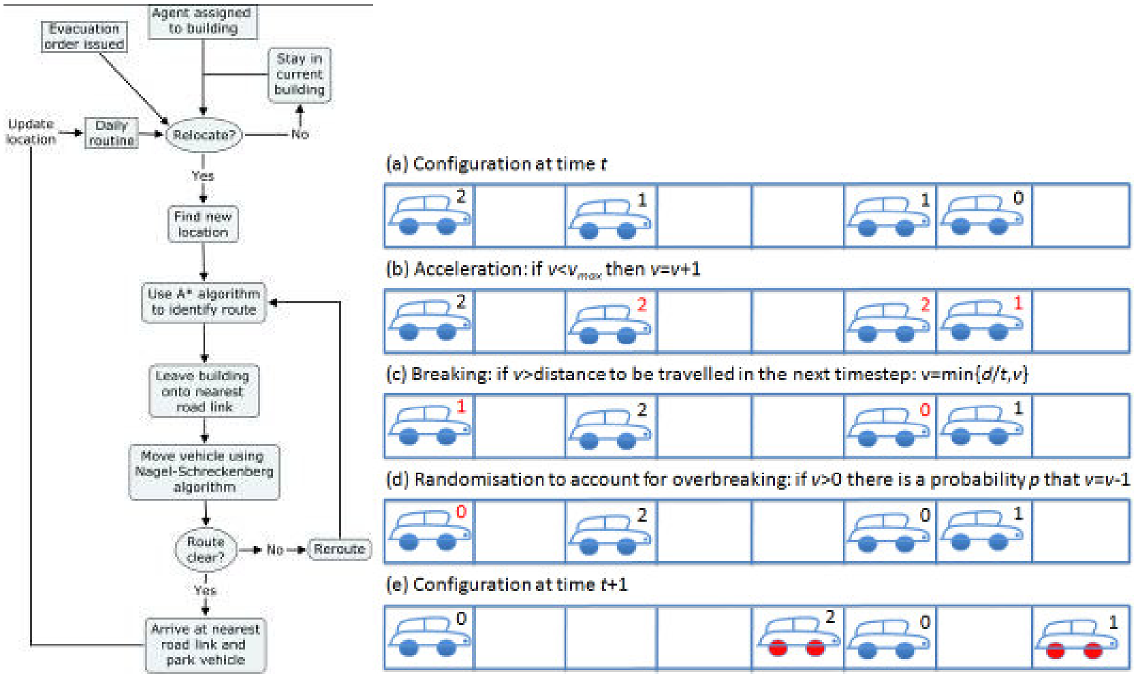


Figure 6 (a) Overview of the transport model steps (b) Schematic of the calculation steps of the Nagel-Schreckenberg cellular automata traffic model

## *2.5 Vulnerability*

Although flood fatalities can occur through a number of mechanisms such as physical trauma, heart attack or electrocution, drowning accounts for two thirds of fatalities (Jonkman and Kelman 2005). Research has established that the relationship between the probability of death or serious injury as a result of exposure to flooding (c.f. Abt, 1989; Karvonen et al., 2000; Lind et al., 2004; Jonkman and Penning-Rowsell, 2008) is dominated by (i) the depth of floodwater, and, (ii) the velocity of the floodwater, although the rate of water level rise can also be important. However, other factors such as the age, fitness, height and weight of the individual can be important in determining their vulnerability. A full review of the data and methods is provided by DEFRA and Environment Agency (2003) and Jonkman et al. (2008) . Rather than seeking to predict mortality, which can be subject to random factors as well as those considered previously, here we report agents exposed to a depth of floodwater of 25cm or greater which, under relatively fast flowing (2.5m/s or greater) conditions is the threshold for the most vulnerable people (DEFRA and Environment Agency, 2003). This provides a conservative estimate of those individuals placed in harm's way as a result of floodwater rather than an estimate of mortality.

## 3 Flood risk analysis

Flood risk, $r$, is calculated as a function of the probability of an event, $\rho$, and the consequences (usually economic damages, but any damage function can be used) of that event, $d$, for a set of input conditions, defined by the vector $\mathbf{x}:=\{x_1, x_2,\ldots,x_n\}$, where each variable $x_i$, represents a particular property (*e.g.* fragility of flood defences) of the flood system:

$$r = \int \rho(\mathbf{x})d(\mathbf{x})d\mathbf{x} \tag{3}$$

This calculation has been successfully applied to estimate economic damages associated with the risk of flood defence failure both nationally (Hall et al., 2003) and at the case study site in Towyn (Dawson and Hall, 2006). The variables in **x** represent those associated with the reliability of flood defences, the location and type of property in the floodplain, the hydrodynamic boundary conditions and their frequency.

The inclusion of FIM policies essentially acts as a modifier to either the consequences of flooding (*e.g.* where FIM action leads to reduced damages because a flood warning has been successfully announced, received, understood and acted upon) or probability of flooding (*e.g.* where FIM action leads to reduced failure probability of a defence because a flood warning has been successfully announced, received, understood and acted upon by shoring defences or putting up temporary barriers). These can be represented by additional variables in the vector **x** used to describe the system, and may include factors such as the number of people subscribed to the Automatic Warning System, and the proportion of those who receive the message. The benefits of FIM policies in terms of risk reduction, $B_{FIM}$, can be calculated as:

$$B_{FIM} = \int \rho(\mathbf{x}')d(\mathbf{x}')\mathrm{d}\mathbf{x} - \int \rho(\mathbf{x})d(\mathbf{x})\mathrm{d}\mathbf{x} \tag{4}$$

where **x**' is the state of the system with no FIM policy, and $\mathbf{x}_{FIM}$ is the state for a single or portfolio of FIM policies. The output from the ABM can quantify the impacts with a FIM policy in place, $d(\mathbf{x}_{FIM})$, or without, $d(x_i)$, in terms of the number of people exposed to flooding or damages avoided.

The failure of each flood defence contributes leads to different spatial hazard patterns. The total risk to people, expressed in terms of expected number of agents exposed to 25cm depth of flooding, $R_A$, is calculated using:

$$R_A = \sum_{i=1}^{N} \int f(H_s, W)P(B_i|H_s, W)A(W_{FP} > 0.25)dH_s dW \tag{5}$$

where there are $N$ flood defences; $f(Hs,W)$ is the joint probability density function describing the loading space of significant wave height, $H_s$, and water level, $W$; $P(B|H_s,W)$ is the fragility function describing the probability of a breach in defence *i* occurring as a result of the joint loading conditions; $A(W_{FP}>0.25\text{m})$ is the number of agents exposed to floodplain water depths, $W_{FP}$ above the threshold of 25cm.

## 4 Case study: Towyn

The case study site is centred on Towyn in North Wales (Figure 7). Parts of the town are built on areas of coastal lowland that were reclaimed during the eighteenth century. Approximately ten square kilometres and 2,800 properties were inundated in 1990 when 467 m of seawall (marked defence F in Figure 7) was breached (Roe, 1993). Around 6,000 people were evacuated and placed temporarily in nearby schools and community centres after being rescued by emergency services and the RNLI (Jones, 1990). The flooding lasted several days and a large proportion of the houses, many of which were bungalows, were flooded to a depth of 2m by water contaminated by sewage (Riley and Meadows, 1995). Repairs to the whole housing stock damaged were estimated to cost between £22.4million and £100.8million (Tooley, 1992). Fortunately, there were no casualties as an immediate result of the flooding although 50 people were thought to have died prematurely as a result of the flood (Welsh Consumer Council, 1992).

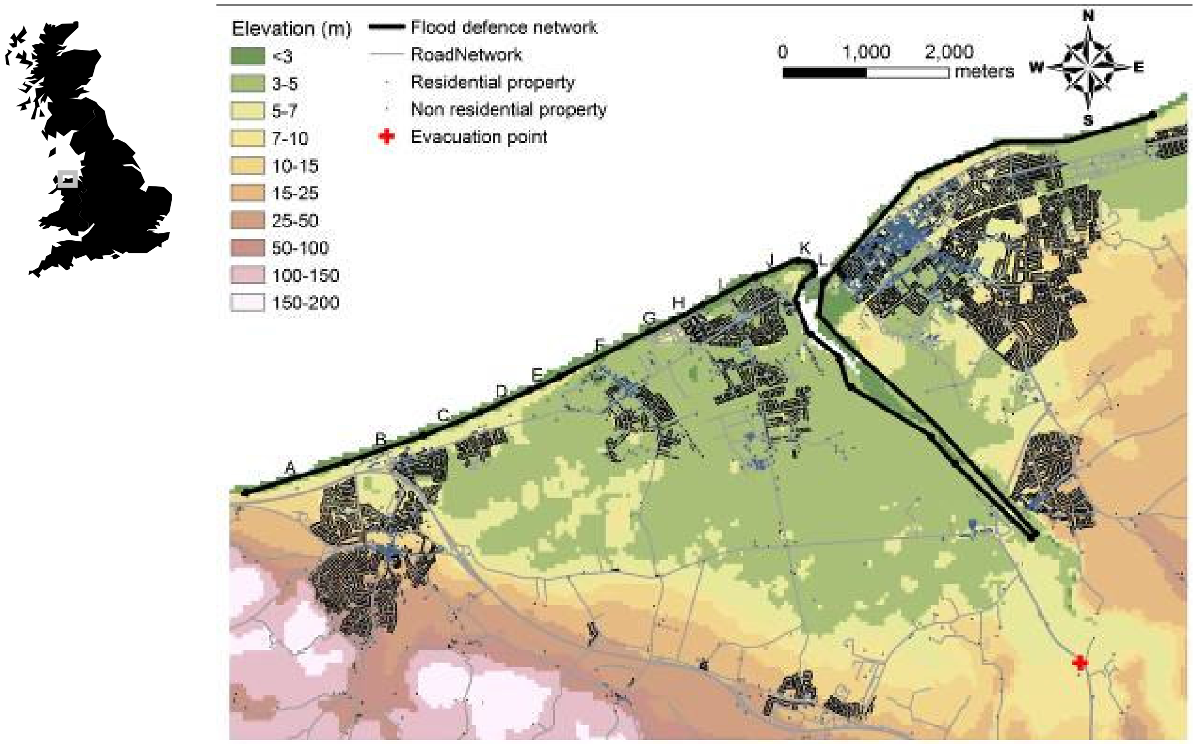


Figure 7 Map of Towyn showing its location in Wales, the flood defence network, topography, the location of residential and non-residential properties, the road network, the 1990 flood outline and the location of an evacuation shelter that has been included for the purposes of this modelling study.

The 1990 flood event provides validation data for the inundation model. This type of model was first applied to Towyn by Bates et al. (2005) and the same good fit achieved between observation and model output is also attained in the NetLogo implementation. The agent based model was set up as described above for 9,201 agents representing the population in the model domain. Data used in this case study is nationally available, and provided in standard formats, so scripts were developed to automate the process of importing data into NetLogo and facilitate transferability to future case study sites.

Whilst there are aggregate records of the impact of the flood (e.g. number of houses flooded) there is insufficient information on the behaviour and responses of individuals and organisations during the event itself to parameterise the agent behaviour rules. In many instances roles and responsibilities have also changed, for example the Environment Agency, who are now the principal flood risk management operating authority in England and Wales, were only formed in 1996. Moreover, much has changed in Towyn in the 20 years since the flood and whilst changes in demography and the built environment are recorded, the response of individuals and organisations today would be influenced by the 1990 event. The purpose of this case study is therefore not to simulate the 1990 event exactly but to demonstrate the utility and potential of an agent based model to be used in a risk analysis to support flood incident management by exploring the vulnerability of the region to different types of flood events and compare the effectiveness of different flood event management strategies.

In total, 6394 simulations were run to produce the results reported. Each simulation represents 3.25 hours of event time, with four simulations taking around 7.5 minutes to run in parallel on a 2.67GHz quad core processor. In each case the simulation begins at 7:15am and runs until 10:30am, whilst the flood event starts at 8am. Except for the additional simulations reported in Table 5 and Figure 12, the flood results from the failure of a defence caused by a storm surge which raises mean sea level to 6m above Ordnance Datum. This was deliberately chosen to be higher than the 1990 flood (~4.7m) to ensure substantial flooding for each defence failure (sensitivity to water level is shown in Figure 12). In each simulation, the time and location at which agents are exposed to water depths of greater than 25cm is recorded, as is the speed and total number of vehicles using each road. The model is run to simulate a number of defences breaching, different flood warning times and alternative evacuation shelter locations.

Figure 8 shows the location, whether driving or parked at some location, of the average number of agents exposed to 25cm water depth from 2173 simulations of defence F failing with no flood warning. Of particular note is that many of the agents that are parked have been caught around schools and in commercial/industrial locations, which might be expected at this time in the morning during the school run and start of the working day.

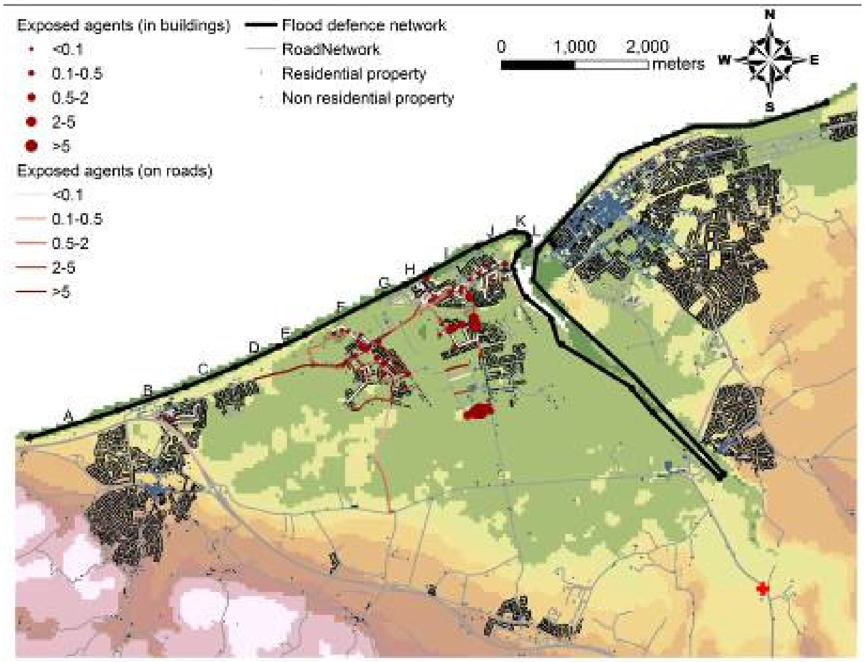


Figure 8 The location on the road network (when an agent is on a road link the entire link has been highlighted) or in a building (denoted by circles), and number of agents exposed to water depths of greater than 25cm from 2173 simulations of storm surge 6m and failure of flood defence F.

Figure 9 both quantifies the benefits of providing a flood warning, and also gives an indication of some of the uncertainties in the model as a result of its design described above. These are (i) the probabilistic description of agent behaviour, (ii) random assignment of agents to buildings, and (iii) the random sequencing of agent movement. Here, the number of agents exposed to water depth greater than 25cm are 21 (with a standard deviation of 4.5) and 219 (with a standard deviation of 14.2) for the 'with a flood warning' and 'without a flood warning' cases respectively. In this example, flood warning provides a tenfold reduction in the exposure of the population. The increased variance for simulations with no flood warning is a result of more vehicles being in the flood risk area at the time the flood starts, which means there is greater potential for the sensitivity of the number of agents exposed to floodwater to the initial conditions and model sequencing to mediate the simulation result.

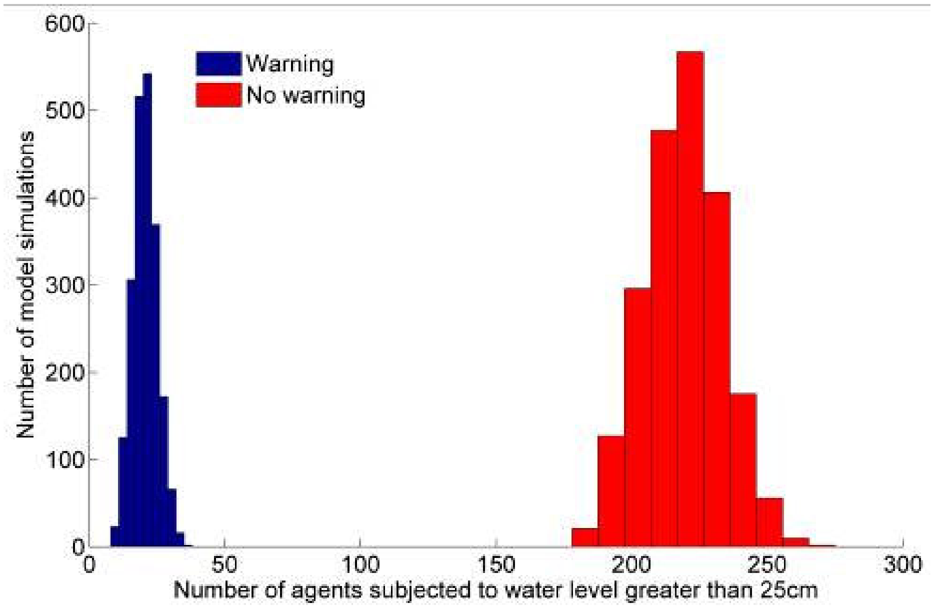


Figure 9 Histogram of number of agents exposed to 25cm depth water for a sample of 4346 simulations where for half of these, a flood warning is given (and acted on immediately) approximately an hour before the defence breaches and where for the other half, no warning is given at all. In each simulation only defence F is assumed to have failed.

Additional uncertainties arise from other parameters, such as the percentage of individuals who receive and act on a flood warning. Although there is evidence to aid in the parameterization of these values, as described in Section 1.3 this can still be uncertain. Figure 10 demonstrates how uncertainty in this can influence the outcome of a flood incident. As fewer agents receive a warning the mean number of agents exposed to floodwater increases. Moreover, the variance also increases. This highlights the importance in providing timely and good quality flood warning information, and ensuring people know how to act effectively when they receive it.

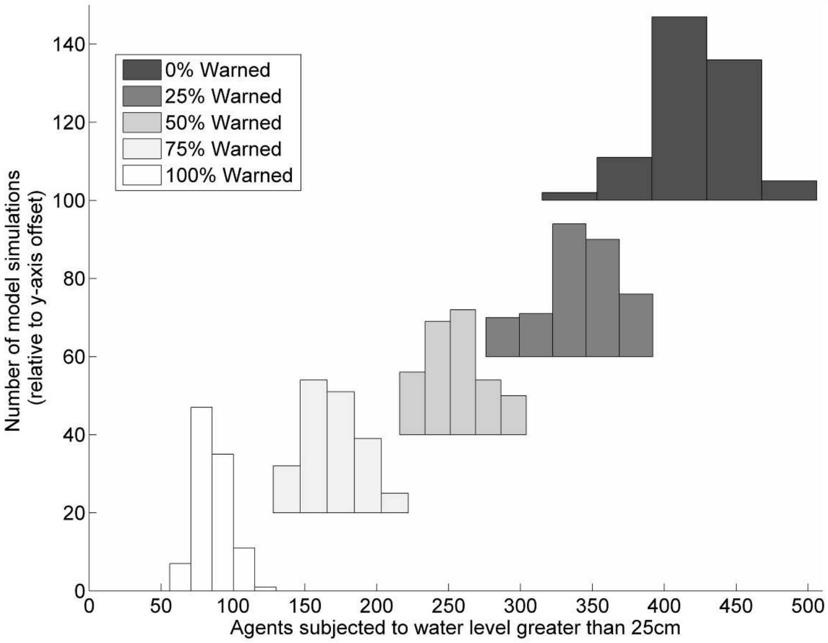


Figure 10 Histograms of the number of agents exposed to 25cm depth water according to the proportion of the population who receive a timely warning and are able to act upon it.

Figure 11 uses the flood warning simulations from Figure 9 to show where in the model domain roads are more prone to congestion, measured in terms of vehicles per hour, during a flood event evacuation. Agents are assumed to all evacuate to a hypothetical evacuation shelter in the Southeast of Towyn. Whilst, there is a general increase in road traffic activity on a number of roads because vehicles that would have been 'parked' at work or elsewhere evacuate. As might be expected, congestion is most likely to be observed in the roads leading to the evacuation point and in locations of high residential and commercial density. However, it is clear that in this hypothetical scenario any emergency response from outside Towyn may have their ingress to the town hindered by evacuating agents. Testing different locations for evacuation centres and other facilities relevant to flood incident management (e.g. storage for temporary defences) can help identify locations that are more robust under a wide range of flood scenarios or precautionary measures that can be taken by emergency services when responding to flood emergencies.

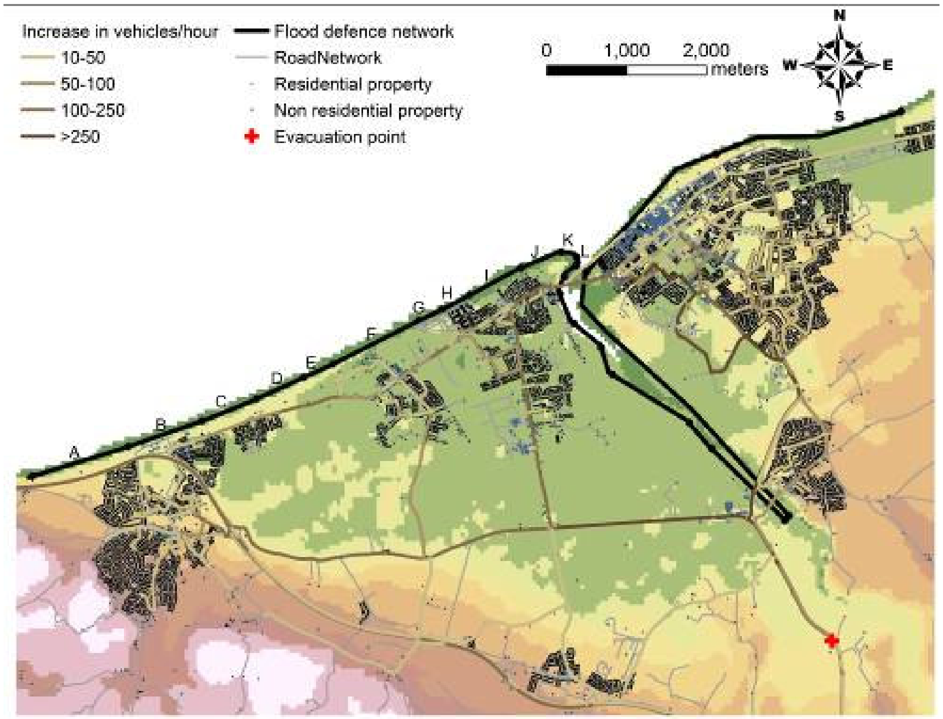
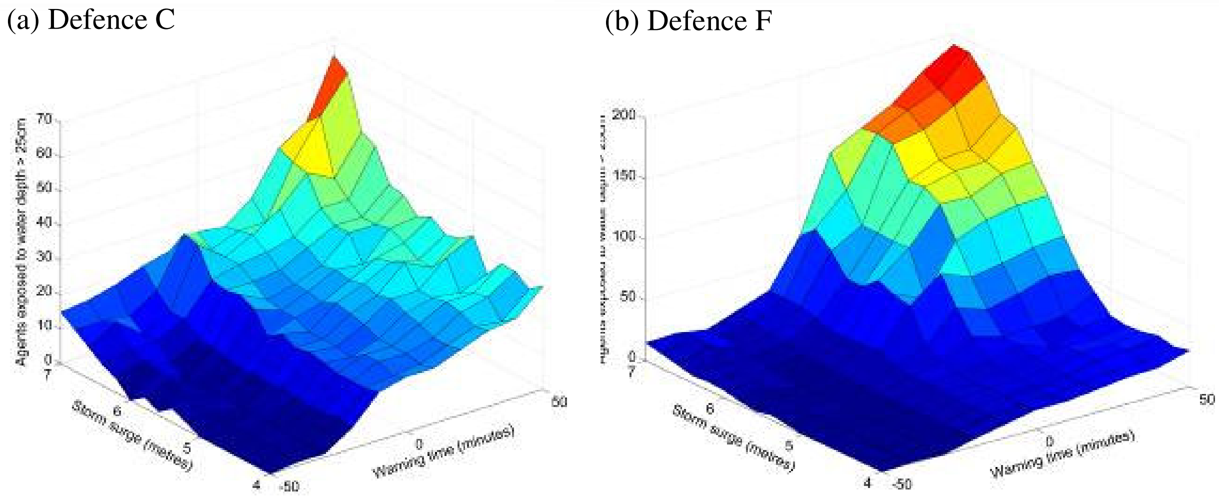


Figure 11 Additional road traffic as a result of a flood evacuation to a single shelter in the Southeast of Towyn.

Figure 12 plots the number of agents exposed to water depths of greater than 25cm as a function of storm surge level and warning time. These might be described as a exposure functions, and are basically monotonic (i.e. increasing with storm surge height and lower warning time). However, they are quite ‘jagged’ because they are constructed from only a single model run at each combination of storm surge and warning time and do not therefore account for the uncertainties shown in Figure 9. These exposure functions can be used to quantify the risk to people using Equation 5 as they correspond to the term: $A(W_{FP}>0.25\text{m})$. Data on defence fragility and the probability of storm surges is the same as Dawson and Hall (2006). The risk associated with the failure of each defence is summarised in Table 5. The benefits of an effective flood warning system (including appropriate dissemination and response) are demonstrated to reduce the risk almost fourfold, or an expected reduction of 0.073 agents exposed per year.


(a) Defence C

(b) Defence F

Figure 12 The relationship between agents exposed to water depths greater than 25cm, the storm surge level and the warning time (-ve warning time means the warning was issued before the flood which begins at 8am) for (a) Defence C and (b) Defence F.

Table 5 Expected number of agents exposed to water depths greater than 25cm, disaggregated by defence, for situations where a warning is issued in advance of a flood and when no warning is given. Darkest cells represent the highest expectation (≥5×10$^{-3}$), with the lightest representing cells with the lowest expectation (<1×10$^{-3}$).

| **Defence** | **A** | **B** | **C** | **D** | **E** |
|---|---|---|---|---|---|
| No warning | 2.3×10$^{-3}$ | 9.9×10$^{-3}$ | 4.6×10$^{-4}$ | 1.8×10$^{-5}$ | 5.7×10$^{-3}$ |
| Warning | 2.7×10$^{-4}$ | 3.2×10$^{-3}$ | 1.6×10$^{-4}$ | 1.1×10$^{-6}$ | 1.8×10$^{-3}$ |
| **Defence** | **F** | **G** | **H** | **I** | **J** |
| No warning | 1.0×10$^{-3}$ | 1.8×10$^{-3}$ | 1.4×10$^{-2}$ | 4.2×10$^{-2}$ | 1.3×10$^{-2}$ |
| Warning | 4.1×10$^{-4}$ | 4.6×10$^{-4}$ | 5.6×10$^{-3}$ | 1.0×10$^{-2}$ | 3.5×10$^{-3}$ |
| **Defence** | **K** | **L** | **M** | **N** | **Total** |
| No warning | 1.9×10$^{-3}$ | 2.1×10$^{-3}$ | 1.3×10$^{-3}$ | 3.3×10$^{-3}$ | **0.099** |
| Warning | 9.6×10$^{-5}$ | 2.3×10$^{-5}$ | 1.7×10$^{-4}$ | 3.4×10$^{-4}$ | **0.026** |

## 5 Conclusions

The methodology described in this paper presents a novel approach to support the appraisal of flood event management. The methodology couples a hydrodynamic simulation with an agent based model of human response to a flood. The ABM has demonstrated that it can provide insights not obtainable from other methods. However, it is important to recognise the potential pitfalls of using an agent based model. This is not a predictive tool in the sense of simulating the behaviour of individuals precisely, its value is in studying the aggregate response of the whole system and all its agents. The philosophy behind this work is basically optimistic about the potential for quantified modelling of flood incidents, but humble about the limitations of any modelling activity, particularly when it involves complex socio-technical systems. Uncertainties surrounding flood incidents may be large, but by exploring a range of events and parameterisations we can identify options that are as far as possible robust to uncertainties.

Consideration of human behaviour will probably not be a new concept to many natural hazard managers as scenario approaches are well accepted. However, whereas scenario studies are often constrained to a limited number of realisations, the ABM captures the dynamics of both the natural and human system over the duration of a flood event enabling a wide range of different responses to managing flood events to be tested. The ABM delivers insights into emergent features such as evacuation routes prone to congestion, which could not be extracted from the other methods reported in Table 2. As in scenario, and other approaches, the implications of different model parameterisations are made transparent and their validity can be argued amongst stakeholders. In this case, the probabilistic nature of the model parameterisation captures some of the uncertainties associated with the process of quantifying certain variables.

The methodology has been tested in Towyn, North Wales. The results of the case study have shown how the model can be used to evaluate the effectiveness of flood event management measures such as flood warning and the location of shelters. The model can be used to construct exposure functions that quantify the exposure of the population to flooding for different events. These can be used to quantify the risk to people associated with defence failure, and the contribution of different defence sections thereby providing a vital appraisal tool for flood managers. As well as supporting flood incident management, it can be used in policy analysis by testing changes in flood frequency, flood defence investment and floodplain occupancy.

The methodology uses only nationally available spatial and demographic data sets and could therefore be readily applied elsewhere in the UK. Much of this data is collected as standard in other countries. However, whilst it might be acceptable to generalise some behaviour rules others would need to be re-evaluated on a case by case basis. Further work will focus on adding more agents such as engineers and emergency services to enable a fuller range of flood event management responses to be tested. These might include bridge conditions, resource availability as well as the siting of evacuation shelters explored here. This model therefore represents a first step towards the development of an operational tool for guiding the design of flood incident management plans.

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