An agent-based model for flood risk warning.

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Abstract

This paper presents a new flood risk behaviour model developed using a coupled Hydrodynamic Agent-Based Model (HABM). This model uses the LISFLOOD-FP Hydrodynamic Model and the NetLogo (NL) agent-based framework and is applied to the 2005 flood event in Carlisle, UK. The hydrodynamic model provides a realistic simulation of detailed flood dynamics through the event whilst the agent-based model component enables simulation and analysis of the complex, in-event social response. NetLogo enables alternative probabilistic daily routine and agent choice scenarios for the individuals of Carlisle to be simulated in a coupled fashion with the flood inundation. Experiments are also constructed using a novel, 'enhanced social modelling component', comprising the Bass Diffusion Model, to investigate the effect of direct or indirect warnings in flood incident response.

From the analysis of these coupled simulations, management stress points, predictable or otherwise, can be presented to those responsible for hazard management and post-event recovery. The results within this paper suggest that these stress points can be present, or amplified, by a lack of preparedness or a lack of phased evacuation measures. Furthermore, the methods here outlined have the potential for application elsewhere to reduce the complexity and improve the effectiveness of flood incident management. The paper demonstrates the influence that emergent properties have on systematic vulnerability and risk from natural hazards in coupled socio-environmental systems.

Commented [TO1]: Technical correction Ref #1 18. '... constructed using the Bass Diffusion Model'.

1. **Introduction**

Flood hazard, or flood incident, management is a challenge that incorporates aspects of the natural sciences (hydrology, ecology, etc.), the social sciences (economics, politics, psychology, culture, etc.) and engineering. It is important for the efficiency and efficacy of decision-making processes to recognise that decision-making during floods involves what has been termed "technical complexity" (Nunes Correia, Fordham, Da Graca Raravia & Bernardo 1998). Specifically, this is the social response to the hazard, and encompasses interactions between individuals, the diffusion of decision-making and collective, during-event, behaviours (Larsen, 2005). This complexity cannot, either theoretically or physically, be eliminated when planning for flooding incidents (Assaf & Hartford, 2002; Bennet & Tang, 2017; Correia, Rego, Saravia & Ramos, 1998 and Dawson, Peppe & Wang, 2011) and can be a threat to effective planning processes (Axelrod, 1970; Nunes Correia et al., 1998). In a broader sense, this complexity is a measure of the scale of the interactions within the affected area, encompassing dynamic multi-scale interactions and adaptions between individuals, groups, infrastructures, government and the economy, all contributing to the social, political and physical aspects of flood hazard management (Dugdale, Saoud, Pavard, & Pallamin, 2009; Fordham, 1992; IPCC, 2014; Kossiakoff & Sweet, 2002; Werrity, Houston, Ball, Tavendale & Black 2007 and Wisner, Blaikie, Cannon & Davies, 1994).

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Included reference for relating diffusion concepts to the modelled process.

Recent decades have seen strong emphasis being placed on multi-scale, *participatory* methods for dealing with floods resulting in a paradigm shift from *flood defence* to *flood risk management* (Assaf & Hartford, 2002, Dawson et al., 2011, DEFRA, 2007; IPCC, 2014 and Wisner et al., 1994). Such participation means the inclusive involvement of individuals and multiple agencies in the processes of hazard management, policy implementation and post-event recovery. This emphasis is logical in that it aims to incorporate, as far as possible, the requirements of all those involved in the hazard planning process across a scale hierarchy that passes from government bodies to emergency services, and on to the affected individuals themselves. The complexity of such an ideal becomes apparent given that the intricate natures of human environments and environmental dynamics are, to a large degree, perceived as independent, and that when the two come into contact, complexity becomes amplified within a coupled socio-environmental system. For example, between 2010 and 2015, UK Government policy for flooding underwent a transformation that sought to address some of the known complexities of flood incident management (DEFRA, 2007; Eberlen, Scholz & Gagliolo 2017; The Environment Agency, 2012 & 2016). The UK Government's Department for Environment, Food & Rural Affairs (DEFRA) national framework for flood management emphasises the importance of localised decisions about flood risk and makes suggestions for developing community-based solutions to manage flood risk on a finer spatial scale. This transformation emphasised the need for innovative new approaches to managing the localised risk of flooding. This was expected to provide the foundation for better management at the larger scale as 'good practice' innovations spread across more communities. Thus, UK flood policy can be defined as moving from a top-down to bottom-up approach, often referred to as '*alternative action'* (DEFRA, 2007; Kossiakoff & Sweet, 2002).

Whilst both top-down and 'alternative action' bottom-up approaches will be likely to have divergent outcomes owing to the different emphasis each places on variables within their respective approaches, the shift towards a bottom-up strategy indicates an acknowledgement of the need for greater local participation in decision making; something which is difficult to achieve with the 'black-box' forms of assistance seen in most top-down approaches (Sabatier, 1986). Conversely, to formulate an effective bottom-up approach, the dynamics of the individual base elements, which in this model are individual people and are termed 'agents', must be specified to a relatively intricate degree of detail. This is because theory suggests individual and grouped responses will have a significant influence on the dynamics which emerge at higher systematic levels and so accounting for as much detail as possible at the individual level will have a bearing on the detail that can be developed within the descriptions of the whole system (Bresser-Pereira, Maravall & Przeworski, 1993 & Müller et al., 2013). Here, it is believed that Individual and grouped responses are defined by environmental, inter-personal interaction and interpretation (Alexander, 1980; Assaf & Hartford, 2002 and Axelrod, 1970) and that these are characteristic behaviours of sub-systematic processes which are either not present or not considered in, coarser, top-down models of physical process; despite potentially having a significant influence on the outcome of an event in which they are involved (Nunes Correia et al., 1998).

Agent Based Models (ABMs), defined as "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 whole system" (Dawson et al., 2011), provide a potential means to characterise these interactions. Essentially, this is a form of computerised model capable of simulating the emergent behaviour of complex systems. In such models, individuals and organisations are represented as 'agents' within a simulated environment (Railsback & Grimm, 2012). In recent years there has been a proliferation of ABM applications within the research community and examples of these applications relevant to flooding encompass: (i) the role of social media in flood evacuation processes (Du, Cai & Sun 2017); (ii) human perception, understanding and anticipation of flash floods (Morss, Mulder, Lazo & Demuth, 2016; Narsizi, Mysore, & Mishra, 2006); and (iii) the effectiveness of simultaneous and staged flood evacuation strategies (Chu, 2015; Dawson et al., 2011; Zarboutis & Marmaras, 2005). A key issue for such applications is the development of realistic flooding scenarios to drive the behaviour of the modelled agents.

Hydrodynamic models can produce this information so long as they are developed with high quality terrain and boundary condition information (see for example (Neal, Schumann & Bates, 2012)~~)~~, but to date ABM applications have not taken full advantage of the latest developments in flood inundation modelling. ~~The only study to date to~~To date, the most comparable models to the HABM that have driven an ABM with a hydrodynamic model ~~was~~ are those~~at~~ of Dawson's (Dawson et al., 2011), Lumbroso's (Lumbroso et al., 2011) and Medina's (Medina, Sanchez & Vojinovic, 2016), with Abebe's coupled flood agent-institution modelling framework (Abebe at al., 2019) providing mentionable overlap also . In the example of Dawson's model,~~Here~~ a simple diffusive wave model which solves Manning's equation over a raster grid of cells was implemented within an ABM to simulate a coastal flood and

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7) Rephrasing of this section to reflect model comparability for the reader, elucidate the objective of this paper and highlight the novelty of the model considerations and approach. New references added to reference list as suggested.

showed considerable potential. However, this study initially coded the hydrodynamic model directly within the ABM meaning advantage could not be taken of recent developments in efficient numerical methods for solving the shallow water equations (Bates, Horrit & Fewtrell, 2010) and high-performance computing (*e.g.* Neal, Fewtrell, Bates & Wright 2010) architectures. As a result, computational costs were high, and this limited the domain size and resolution of the modelling that could be undertaken. Instead of directly embedding the hydrodynamic model within the ABM, a more pragmatic solution is to indirectly couple a separate, and highly optimized, hydrodynamic model with an existing ABM framework. This would allow each code to be properly optimized for the task it performs and enable each to be more easily updated as new methods become available. This is the objective of this paper, where we develop such a coupled hydrodynamic model/Agent-Based model framework (hereafter termed a Hydrodynamic Agent-Based Model, or HABM) and use this to address two currently unresolved questions relating to flood evacuation warnings. These two specific questions are:

1. During a flood, does the site-specific urban topography and morphology change the optimum evacuation warning strategy?

2. Do people (agents) respond better to direct or indirect (word of mouth) evacuation warnings for a flood event?

To date research on flood warnings and evacuation has examined the challenges and changes in thinking required to tackle the paradox of flood 'control' (Wisner et al., ch 6, 2015), the dynamic approaches required to address different forms of flood event (Berendracht, Viglione & Blöschl, 2017; Dawson et al., 2011; Gilligan, Brady, Camp, Nay & Sengupta, 2015; Smith & Tobin, 1979) and the roles of individuals and groups in flood warning and evacuative scenarios (Haer, Botzen & Aerts, 2016; Haer, Botzen & de Moel, 2016; Nunes Correia et al., 1998). However, so far, little work has been conducted on whether evacuation strategies need to be tailored to the specific geographical setting or explored whether different modes of communication (direct or indirect) affect the evacuee's response. Answering these questions is important if effective warning strategies for specific places are to be developed.

More broadly, answering these two questions encompasses the process of implementing alternative actions; these rely on positive social participation, diffusion of ideas and their implementation, and they require broader acknowledgement of, and a specific approach to addressing, the associated socio-environmental complexity (Wisner et al., 1994; Wong & Luo 2005; Zarboutis & Marmaras, 2005). The HABM framework enables us to properly explore the systematic, cross-scale sensitivity of social complexity to the physical flood phenomena and shows where the loci of *vulnerability* are within an affected system. Therefore, the goal of HABM use for this study is not to eliminate complexity from consideration, but rather to harness it as a compliment to more specific physical considerations within comprehensive hazard management strategies. This is tested by applying it to a test case in Carlisle, UK. The overall aim is to offer an assessment of the value of alternative actions within flood hazard management as a whole (Dawson et al., 2011; Müller, Bohn, Dreßler & Groeneveld, 2013).

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2. **Methods**

2.1 **Study Area**

Figure 1: The area simulated in the HABM, highlighted in red with river locations indicated for the river(s) Caldew, Petteril and Eden. (Contains OS data © Crown copyright and database right (2019))

Carlisle, Cumbria UK, and specifically the 10.3 km2 study area of the city illustrated in figure 1, is a flood prone city with a history of contemporary study (Correia et al., 1998; DEFRA 2007; The Environment Agency: 2006; 2012; 2016; Horrit, Bates, Fewtrell, Mason & Wilson, 2010; Neal et al., 2009; Neal, Keef, Bates, Bevan & Leedal, 2013). Notable flood events have affected the city since 1700, with the recent 2015 flood event having been referred to as 'unprecedented' in scale due to the river Eden's flood level rising 0.6 metres above the previous record flood level of 2005. The location of the city at the confluence of the rivers Eden, Caldew and Petteril means it is a useful source of data for hydrological research. As the county town of Cumbria, with a total population of 108,000, it is a location of significant social scale whilst also offering a case study which is suitably complex to develop new insights through modelling and simulation.

The 2005 event affected approximately 1865 properties and led to the loss of 3 lives. The event had an estimated Annual Exceedance Probability (AEP) of 0.59% (1 in 170-year return period) and was a seminal event in that it prompted significant investment in the city's flood defences. The 2005 LISFLOOD-FP data set (Horrit et al., 2010) provides a robust and reliable foundation on which to build the agent-based component of the coupled model. This data set used for the model simulation consists of a series of input files including raster grids of

Commented [TO7]: Technical correction Ref #1 Semi-colons needed between EA Reports: 2006; 2012; 2016. And after Neal et al., 2009; [Also in line 752 after 2003.] No need for 'ands' within the reference brackets; see also lines 207-8; 214; 234; 267.

floodplain friction coefficients and elevation heights in 2D, ARC-ascii format, boundary identification, time-varying boundary conditions and hydrodynamics. Since 2005, Carlisle has been subjected to further large flood events in 2009 and 2012 with the mitigative measures deployed post-2005 successfully curtailing the impact of these. Furthermore, the 2015 event, overtopped the new defences and has led the Environment Agency to produce the Cumbria Flood Plan. A novel feature of this is that it introduces and promotes community-based flood resilience measures on a large scale for the UK. It is the essence of these measures that prompted the development of the coupled model with a view to better understanding the dynamics on which these measures were based (DEFRA, 2007; Dugdale et al., 2009; The Environment Agency: 2006; 2012; 2016).

2.2**. The flood modelling component: LISFLOOD-FP**

For a viable exploration of different individual responses to flooding, detailed, accurate and dynamic simulations of the flood at Carlisle were required. LISFLOOD-FP (Bates & De Roo, 2000; Bates et al., 2010; Neal et al., 2009; 2012), is a 2D hydrodynamic model specifically designed to simulate floodplain inundation in an efficient manner over complex topography, as is the case in urban areas. LISFLOOD-FP is capable of simulating grids of up to 10^7 cells for dynamic flood events with airborne laser altimetry defining the DEM of the affected area. From this, the LISFLOOD-FP model can accurately simulate the dynamic propagation of flood waves by predicting water depths in each grid cell through a series of time steps, and over the complex topographic forms within floodplains. The ABM element of the coupled model can then operate from this reliable foundation, enabling exploration of different hypotheses for social reactions and responses to the detailed, accurate and dynamic physical outputs generated by LISFLOOD-FP; by adding the related elements of policy and systematic change (Wheater, 2006; Wilson & Atkinson, 2005). Whilst LISFLOOD-FP was the chosen hydraulic model for the HABM, similar 2D-hydraulic models could resolve flow problems to similar degrees of accuracy and this would mean that these alternative models could be utilised in place of the LISFLOOD-FP with the HABM modelling framework (Hunter et al., 2008; Landstrom, Whatmore & Lane, 2011; Neal et al., 2012).

2.3. **The social modelling components: HABM & NetLogo**

With LISFLOOD-FP producing an accurate representation of the flood at Carlisle, the related elements of flood incident policy options and agent behaviour were implemented through the separate ABM program of NetLogo (Railsback & Grimm, 2012; Wilensky & Rand, 2015). The HABM (figures 3 to 7), uses water depth output files from the LISFLOOD-FP at each model time-step within a simulated version of the affected area (figures 5 - 7). For the simulation of the Carlisle study area, a Digital Elevation Model (DEM), identical to that used by LISFLOOD-FP as an input data set was used to provide a realistic topography for the flood-impacted area in NetLogo (NetLogo, 1999; Wilensky & Rand, 2015). In addition to the simulation of the flood event and physical landscape, NetLogo was used to generate a virtual population of *agents* to occupy the virtual version of Carlisle. Using a pseudo-random, number of generator and deterministic agent scheduling algorithms directed through probabilistic routines (Nunes

Correia et al., 1998; Wilensky & Rand, 2015; Wong & Luo, 2005) this then simulated the population's interaction with the environment and response to the flood event. This simulated interaction allows the possibility of identifying *emergent properties* likely to arise at the complex interface between the social and environmental systems. These emergent properties have a significant impact on objective 1, in that they occur subtly and at locations that significantly influence human responses within the coupled physical and social systems. This significance is found in the HABM's capacity to reveal systematic emergent phenomena through the simulated co-evolution of a socio-environmental system, operating here through a flood event that has impact upon the basic daily routine (figure 2) and the complex co-existent entities *i.e.* the more complex, responsive *configuration* of evacuating groups (figures 3 & 4). This then has a further impact on hypotheses regarding *risk*, *vulnerability* and *resilience*, with the HABM providing an opportunity to analyse and evaluate these terms, from a sub-systematic perspective. Here, *sub-systematic* is a term used to describe the development of individual (micro) to community (meso) level characteristics in response to the flood onset, with greater scope than has previously been possible with traditional approaches to flood incident management (Borschev & Filippov, 2004; Chen & Zhan, 2008; Gilbert & Troitzsch, 2005; Guo, Ren & Wang, 2008; Guyot & Holiden, 2006; Landstrom et al., 2011; Namatame & Chen, 2016, Sanders & Sanders, 2004; Srbljinović & Škunca, 2003; Wei, Zhang & Fan, 2003)).

2.4. **The enhanced social modelling component: Bass Model**

For objective 2 of this paper, and in planning for effective flood impact management on a broader scale, we must incorporate elements from a whole range of *activities* (Axelrod, 1970; Berendracht et al., 2017). These include the spatial and temporal variations in phenomena (flooding in this instance), the non-linear relationship between small perturbations at a sub-systematic level and large knock-on effects at a system-wide scale (the macro-level), the understanding that these effects can extend beyond the physical impacts of the phenomena and change social behaviours and routines within an affected area, thus changing the characteristic function of the system as a whole. This suggests that objectives 1 and 2 are intimately connected and so there is a need to consider the social dynamics and reflexive nature of the human system in response to the flood event within the framework of the hazard system to determine the sensitivity of the incident management response (Davies, 1979). To better understand this relationship between human system and environmental phenomena (figure 2), the ABM was used to provide choices to the simulated agent population of Carlisle as part of a synthetic daily routine (figures 3 & 4), further details of which are to be found in section 3 of this paper. These agent choices and the routine were combined to synthesise the dynamics of the socio-environmental interface and from this, estimates were made for the influence that agent choices have on the characteristics of the system being simulated. In the Carlisle HABM, the agents were given the choice of carrying out their normal, linear, routine during the flood scenario, of becoming warned and taking immediate action to evacuate, or of assessing this warning based on social interaction with other agents in the immediate vicinity, and then acting post-interaction(figure 4). The scenario of becoming warned and *evacuating immediately* is used in the HABM to reflect the government policy instruction of 'what to do in a flood scenario' in the most direct form. Within the model (DEFRA, 2007), this instruction is programmed as '*pre-preparedness'* and it describes an adoption and undertaking of actions beyond the 'normal' daily routine, both modelled and real (Chen & Zhan, 2008; Chu, 2015).

The Bass Diffusion Model provides a tool for interpreting the impact of these choices and actions, by representing agents who adopt certain actions at a given time. The model, originally conceived for marketing economics, is used to inform understanding of the diffusion of frequently purchased or *adopted* products, and is based on a principle derived from the following relationship (Bass, 1969):

$$\frac{f(t)}{1-F(t)} = p + \frac{q}{M}\left[A(t)\right]$$

This states that "The portion of the potential market that adopts at time *t*, given that they have not yet adopted, is equal to a linear function of previous adopters" (Bass, 1969; Davies, 1979). The basic premise of the model provides insight into interaction between adopters of the *product* within a population; it then classifies these adopters as '*innovators*' or '*imitators*'. In the HABM, the 'material product' concept of the Bass Model is replaced with the a priori product of 'knowledge' regarding an imminent flood event, this is to say that agents within the model can simply be set to act out evacuative measures immediately at the start of the simulation and in all of the timesteps leading up to the flood inundation, if they choose to stay. These 'innovative' agents are also freely able to communicate these measures to proximal neighbouring agents who can then choose to imitate these informed agents; or carry on with what they are doing. it should be stated that the sociological dynamic of *innovation* and *imitation* is proliferated within the model by communication between agents who are proximal and so this simple binary distinction could be regarded as a potentially useful one for representing the apparently complex communication dynamics of a social system in a relatively simple manner.

In the specific instance of the HABM, the *innovators* are set as *pre-prepared* prior to the flood simulation onset and the *imitators* are those who would not be prepared, but who are given the choice to adapt their routine at each timestep, based upon contact with the innovators. This situation, describing people who are in possession of knowledge regarding the flood event and then communicating it to those who are not, could have an impact on all aspects of response and evacuation, as it is a crucial component of the boundary between the processes of *warning* and *response* (Axelrod, 1970; Chen & Zhan, 2008; Chu, 2015). With specific reference to the Bass Model terminology, there are three parameters (or representative coefficients), that define the compatibility with the HABM, these are:

- **(***M***)** - The potential *market*, these are the ultimate number of potential adopters, i.e. the population. This constitutes the number of members of the social system in which word-of-mouth communication from past adopters is the driver of new adoptions. The Bass

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Model assumes that *M* is constant, though in practice and over longer periods, M is often slowly changing according to population change and product memory.

- **(*p*)** – The coefficient of innovation, so-called because its contribution to new adoptions does not depend on the number of prior adoptions. Since these adoptions are due to some influence outside the social system, the parameter is also called the 'parameter of external influence.'

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- **(*q*)** – The coefficient of imitation has an effect that is proportional to cumulative adoptions A(t), implying that the number of adoptions at time t is proportional to the number of prior adopters. In other words, the more that people talk about a product, the more other people in the social system will adopt it. This parameter is also referred to as the 'parameter of internal influence'.

The other variables in the Bass Model relationship and calculated from *M*, *p*, *q* and *t*, are:

- *f(t)* - The portion of M that adopts at time t,
- *F(t)* - The portion of M that have adopted by time t,
- *a(t)* - The adopters (or adoptions) at t,
- *A(t)* - The cumulative adopters (or adoptions) at t.

The outcomes of the coupled application of these three components (sections 2.1, 2.2 & 2.3) towards the two objectives are further illustrated in section **4** and are discussed further in section **5**.

Of further interest here is how to qualify the communication taking place within the HABM. In sociological terms, the imitative process involved is broadly one of inter-agent communication and collective response. According to the sociologist Gabriel Tarde and his Laws of Imitation (Tarde, 1903), as applied to 'groups of people', innovations must undergo a process of diffusion over time to gain a foothold and become a component in the decision-making process linked to the innovation, be this *adoption* or *rejection*. Tarde's process involved in the diffusion of innovation has undergone some revisions in the decades since being first proposed and can now be defined through the following five steps:

- First Knowledge,
- Attitude formation,
- Adoption or rejection,
- Implementation,
- Confirmation of the decision.

Via the Bass Model, the HABM for Carlisle allows a simulated engagement with the first four steps of Tarde's process, the fifth being confirmed in the representation of the first four activities as the simulation advances over time. This interpretation of social imitation and adoption was used as a basis for investigating the influence of these processes in an event where time is relatively constrained and the stakes of action are high, such as during a flood onset. The values for this process of adoption were taken from the change in overall un-prepared population in Carlisle transitioning to a 'prepared state' based upon contact with a 'pre-prepared', or innovative, agent. This transition was represented by the percentage of the population in possession of the appropriate knowledge for effective flood evacuation who then reported this change back as an agent-orientated change of state throughout the simulation of the flood. This rate of change of state is then fed into the Bass Model functions to produce diffusion curves like those seen in figures 8a & b and discussed in further detail in sections 4 and 5.

3. **Core model construction and system dynamics**

Given the complexity caused by the incorporation of these diverse elements within considerations of a flood hazard system, the benefits of a standardised flood incident management strategy based on an understanding of these dynamics might not be immediately apparent. Further management of complexity might necessarily arise through the required interactions between the individuals and organisations who might very well have conflicting interests linked to contrasting elements in their expertise or experience (Hart, Nilsson & Raphael, 1968; Hornor, 1998). Furthermore, the feedbacks within a flood hazard system, particularly an urban one, can lead to a spectrum of dampening and amplification of behaviours within the system, the dynamics of which could be influential on outcome, yet difficult to account for in a standardised flood incident management strategy (Assaf & Hartford, 2002; Dawson et al., 2011; Rasmussen, Pejtersen and Goodstein, 1994.) It is here where the HABM concept reaches out to the concepts of phenomenology, poststructuralism, structuration theory, structural functionalism and symbolic interactionism to inform the conception of a modelling framework that incorporates the important social notions of these disciplines and thus anchors the modelling element of the HABM to the cardinal philosophical and sociological concepts underlying it and the outputs produced. The appeal of this approach lies primarily in the novelty of the undertaking in addition to the application of concepts from disciplines such as sociology, philosophy and psychology, which complement the model by offering access to new terminology and theoretical bases for better representing social systems, focussed on *relatedness* rather than *boundedness* between the dimensions and the whole (Alexander, 1980) ; within a coupled modelling framework. Here, the benefit of a more holistic representation can lead to the development of a more effective and holistic understanding of how to manage social dynamics, responses and functions within physical models where they can have further impact on effective planning for and outcomes from the whole system and the components comprising that system (Smith & Tobin, 1979; Zarboutis & Marmaras, 2005).

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With these details in mind, and urban systems being the primary interest in this paper (figure 2), the first step beyond bringing together the initial HABM components was to devise a conceptual format that describes the key dimensions of the urban system within a parameterised and reproducible framework. In this paper they will be primarily referred to as *dimensions*, alternatively they can be called '*sets'* (or *centres* (Alexander, 1980), and can be broadly subdivided into three separate systems, that of the *Environment*, *Community* and *Built Infrastructure* (UNISDR, 2015; Wisner et al., 1994). Networks existing between these dimensions, resulting from the co-evolution of the dimensions, are characterised by the immediate practical and physical influence that each has on the behaviour of the other to create an operational whole. Conceptually, this is analogous to the notion of the *Brunnian Link* in mathematics and the poststructural, psychoanalytical concept for *experience* or *jouissance*, proposed by Jacques Lacan's *Borromean Rings* construct in the 1970's (Zupančič, 2000). An urban system, concomitant with our physical perception and experience of it, can occur at the nexus of the topological sets illustrated in figure 2. Whilst these constituent dimensions could be deliberated in terms of scale, dynamic or boundary and seemingly experienced separately from one another by individuals or groups, it is important to understand that for the present analysis, the function of the urban system within the HABM framework arises in the form of the aforementioned Brunnian link. This is as an "extended and unbroken continuum of connections wherein the whole is necessarily unbroken and undivided" so that life may be supported, experienced and proliferated therein (Alexander, 1980).

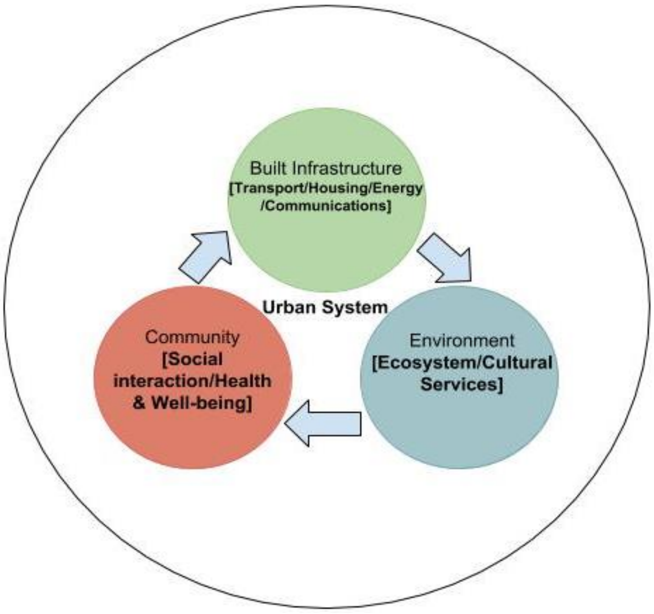

Figure 2: A simplified schematic illustrating the key centres of an urban system. Conceptualised from [Axelrod, 1970, Wisner et al., 1994] and the terminology given within the Sendai framework 2015-2030 [UNISDR, 2015].

Specifically, this link is a mathematical and topological term used to describe the triviality and non-triviality of connection between the sets. As applied to the HABM system concept, when disconnected from the complete, interconnected, system set, the system no longer exists and cannot be experienced by people within it. Utilising the terminology applied within mathematical topology, the individual systems become '*trivial*' when disconnected from one another and '*non-trivial*' when all are in contact within the dimensions of the systematic whole. Thus, the individual systems are experienced in combination with one another, where the boundaries, existing between these systems, would not be as discrete as those shown in figure 2. This would suggest an overlap in the systems whereby experience and interactions between these systems and people, *life*, occurs at the nexus of the three. A simplified scenario to support this understanding for Carlisle would be one where a *community* requirement for an advance in *built infrastructure* as a response to perceived, or experienced, *environmental* risk from flooding; something which could be considered an *emergent* characteristic from the onset of the flood hazard system. Consequently, were the topologies of each of the three dimensions existent separately, and not connected in a manner as suggested in figure 2, interactions between the elements of the three system sets, including the manifestation of physically *hazardous* phenomena, would not be possible (Alexander, 1980; Axelrod, 1970; Berendracht et al., 2017; Du et al., 2017; Dugdale at al., 2009; Eberlen et al., 2017; Fordham, 1992; Guyot & Honiden, 2006; Holland, 2014; Liu et al., 2015; UNISDR, 2015).

Thus, the simulations of the dynamics of Carlisle's urban system for the HABM focused on establishing the linked characteristics between the three dimensions to model a non-trivial system. The use of an ABM enables this through a focus on the community dimension, through simulation of activities and interactions which may then be used as metrics for change according to a specific environmental event, in this instance the 2005 flooding of the Rivers Eden, Petteril and Caldew. To perform these simulations, a correspondence between the conceptualised urban system, representing the three inter-linked elements of figure 2 and the modelling framework illustrated in figure 3, was developed. Figure 3 is a schematic of this correspondence and represents the overlying workflow of the HABM for simulations of the 2005 Carlisle flood. The layout for this figure was used to support workflow and model structure in relation to effective representation of the urban system shown in figure 2, within the ABM platform. The Layout of figure 3 is such that the structure of each set from figure 2 corresponds with the processes taking place in NetLogo to represent that set. In sum:

- The environmental set is simulated using the LISFLOOD-FP outputs and the site DEM,
- The Built infrastructure is emulated using census data sets and street network information,
- The community or social set overlaps both the built and environmental systems and is driven by the agent-orientated, probabilistic choice and interaction flowchart illustrated in figure 4**.**

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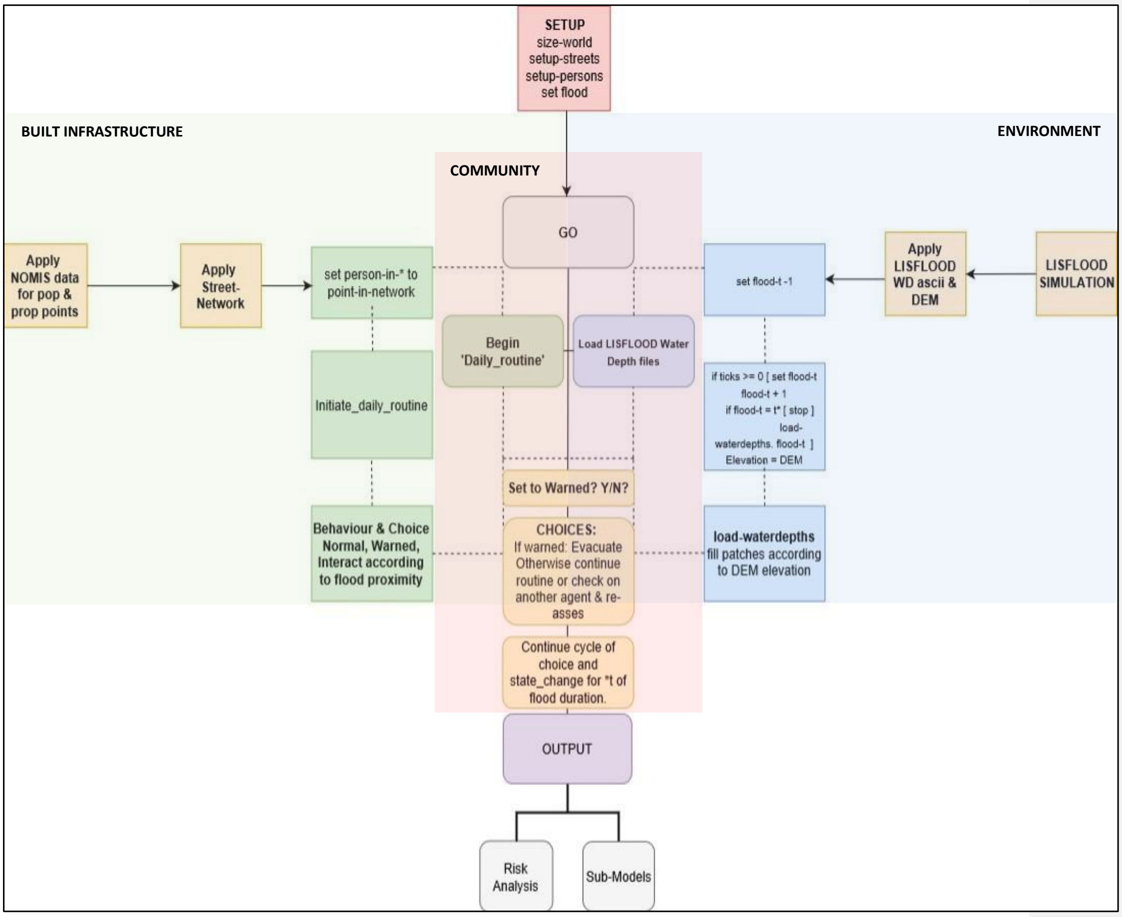
The details of the diagram in figure 3 are the cardinal NetLogo commands that overlap between the system sets and so enable the simulation of the three dimensions within the HABM. This establishes a tangible link between the conceptual complexity of the urban system experienced by people with that experienced by agents, who represent people, within the simulated version of the urban system. This transferral from a conceptual topological figure to a logical modelling schematic was an important step which was taken to link the modelling system to the physical system being modelled. Whilst the format presented in figure 3 is not particularly novel in the sense of workflow or process for an ABM, it is relatively novel in the sense of how it illustrates this link between a conceptual construct of a system, figure 2, and the workflow steps required in simulating this system and representing dynamics



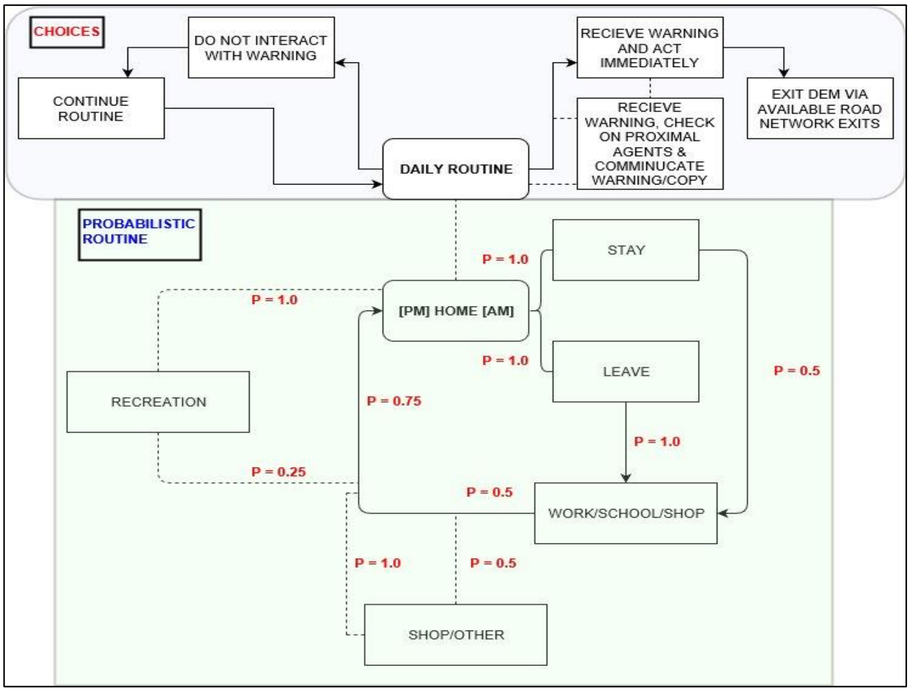
that can provide an analogue for events that occurred during an historical physical event, such as that in Carlisle during 2005.

Figure 3: The core components of the HABM, an indication of the model cycle for these components, and the elements of the urban system (**figures 1 and 2**) that they demonstrate. The schematic follows a similar format to that of a Euler diagram [Whitehead & Russell, 1913], whereby the three centres of the urban system are shown to contain the respective components of the model representing their function within the HABM. These are (from right to left): Built Infrastructure, Community, Environment.

Figure 4 further extends this conceptual approach through to the community element of the modelled system in offering simulated agents the choice to engage with a basic, probabilistic, daily routine within the simulated system as well as engage in emergency response actions following flood onset. This further enhances the realism of the simulated population of Carlisle and provides an analogue for how variations in the physical interaction with a flood might affect the evacuation response (Morss et al., 2016; Müller et al., 2013). The routine and decision tree format, formulated through the ODD (Overview Design concepts & Details) protocol (Wilensky & Rand, 2015), with a view to potentially producing '*emergent*' behaviour for the modelled system, was initially referenced from the synthetic daily routine and transport model used for simulating storm-surge evacuation by Dawson (et al., 2011). The adopted elements of this routine were the basic formatting seen in figure 4, whereby probabilities were assigned to activities for the agents in the model. Of note here is that a discrete transport model was not included in this model for these initial findings as it was felt that there has already been recent and significant advances in this area of interest (for example: Coates et al., 2014; Pyatkova et al., 2019; Mostafizi, Wang & Dong, 2019). The activities of interest were engaged with on a point-to-point basis as the agents navigated through the simulated system of Carlisle until flood onset. With onset, the agents within the simulated system can then choose to engage with the emergency routine or continue with the elements of a daily routine until the next timestep. As there is already a wealth of evidence available (see for example: Assaf & Hartford, 2002; Berendracht et al., 2017; Chu, 2015; Du et al., 2017; Dugdale et al., 2009; Eberlen et al., 2017) to suggest that the time of event onset is influential in event outcome, this time-dependency was not implemented within the simulations for Carlisle. This choice was made in favour of developing streamlined simulations that emphasised agent-agent interactions between event onset and end. However, time-dependency is something which is easily implemented within NetLogo if desired and indeed was implemented in later iterations of the HABM for different applications. In addition to this agent-agent focus, non 'pre-prepared' agents may also engage with 'pre-prepared' agents in the model and initiate emergency action based upon their interaction, demonstrating a synthesised form of communication and response. The development of this step in the modelling procedure was crucial to allow interpretation of the influence of an adopted policy directive on inter-agent interaction and choices made during the onset of the flood event which may ultimately not be time-dependent in nature

Commented [TO14]: Narrative enhancement Ref #2 Clarification of why transport model was not included. References added to reference list.

(DEFRA, 2007;Landstrom et al., 2011; Liu et al., 2015; Morss et al., 2016; UNISDR, 2015; Waldorp, 1993).



<u>**Figure 4:** An overview of the agent choice & probabilistic routine tree used to guide agent processes through the simulated environment of Carlisle. Informed by reference to (Bennet & Tang, 2017) & (Dawson et al., 2011).</u>

The format of figure 4 was beneficial in this instance as it offers a basic format for agents operating within the model of Carlisle, a format by which they can navigate along the street network in a manner reflective of what might be expected during an average day in Carlisle. The probabilistic format of the routine ensures that upon each timestep agents will be at specific points within the network. Whilst this attenuates the representative complexity of the model, it is believed that it offers enough complexity of choice and action to reflect the potential reality of a complex social and flood onset situation within Carlisle. The probabilities shown in figure 4 were adapted slightly from the original synthetic routine proposed by Dawson et al. to be more generalised and, for computational efficiency within NetLogo, were implemented to be acted out on each time step, rather than continuously over flood onset.

In section 4, figures 5 to 7, the product of the co-action between the components of figures 2, 3 & 4 can be seen. These figures illustrate the model in a preliminary state of simulation and so the full agent population is not in action. Whilst the largely autonomous processes of NetLogo, outlined in section 2, influenced the extent to which the simulated agents engaged with the routine and the choices provided, the implementation of a routine acted to attenuate not only the representative complexity of the situation, but the outright stochasticity of the NetLogo agents also. This means that whilst the agents would be interacting with 'commands' *e.g.* 'leave home point' or 'stay at home point for t(n)', these commands are not too far removed from a realistic analogue of basic choices a human might make on a given day (Bernardini, Camilli, Quagliarini & D'Orazio, 2017; Chu, 2015; Dawson et al., 2011) with the possible actions of the daily and emergency routines being more reflective of general and reactive behaviours expected during a flood onset (Du at al., 2017; Dugdale et al., 2009). The spatial distribution of the agent population within the HABM was informed with national UK Census statistics for Carlisle. However, as census data does not identify individuals against specific addresses, the distribution of agents within the simulated HABM environment was implemented in a slightly more utilitarian manner than the demographic-based distribution seen in Dawson (Dawson et al., 2011), by using a linear function of the population of Carlisle with agents being allocated to home points within the model according to building footprint (Bennet & Tang, 2017; Borschev & Filippov, 2004; Dechter & Pearl, 1986).

In terms of the Bass Model variables discussed earlier, (**M**) is represented by 108,000 agents (in the final simulations), the total population of Carlisle (The Environment Agency, 2016); (**p**), here, represents the 50% estimate by the EA for the population of Carlisle currently deemed as 'signed up to flood warnings' or *pre-prepared* and in possession of the, defined within the HABM as *innovative*, knowledge to respond to the flood upon onset (The Environment Agency, 2012). The coefficient (**q**) roughly equates to 30% which represents the one-third likelihood of those who encounter the innovators (**p**) adopting the innovation as defined by the Bass Model in a scenario where the rate of adoption between innovation and adaptation is linear or *seamless* (Bass, 1969). Despite this somewhat ideological perception of human communication (Jakkola, 1996), this rate of conversion was kept consistent in the instance of the Carlisle simulations as no evidence was found to suggest that social factors were present within Carlisle that would adversely affect it (widespread prejudice, social unrest, a despotic government etc.). In total 200,000 simulations were performed using this methodology within the NetLogo BehaviourSpace tool. These differed through scaling of 'pre-preparedness' between 0 and 100% and the outputs of interest from these simulations were the rate of change from '*un-prepared*' to an '*evacuative*' state, based upon agent contact and the number of potential casualties linked to the change of preparedness (%). Finally, regarding the status of 'potential casualties' within the HABM, this is a term and metric of the HABM used to describe agents physically impacted by the flood. This term does not account explicitly for 'death', rather it is a measure of those agents who may become cut-off from a clear escape route or inundated during evacuative procedure and actual agent fatality was extremely rare during the simulations. The simulation of fatality was defined differently to physical fatality in that it was only presented when an agent's grid cell became inundated, to a third of an agent's height, for one time-step, having had all escape routes cut off (Assaf & Hartford, 2002; Landstrom et al., 2011; Roland & Moriarty, 1990).

Commented [TO15]: 2i) Narrative enhancement Ref #3 Source included for reference on implementation of behavioural patterns within modelled systems.

Commented [TO16]: Technical correction Ref #1 127. Put 'Dawson' in the bracketed reference. [also line 570.]

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4. **Results**

Figures 5 to 7 are examples of these simulated flood sequences for the 2005 Carlisle flood by the HABM, showing inundation areas and agent locations, both prior to the flood (figure 5) and at later stages (figures 6 and 7) after flood onset and agents have been variously alerted. The time taken to model this process in NetLogo, over one complete event simulation, ranged from 45 seconds (2019) to 3 minutes 30 seconds (2017). -The side panels on the left-hand side of the figures outline the basic controls for the model, whilst the charts on the right show model predictions for *potential casualties* in relation to populations and *pre-preparedness*, which is an apriori knowledge of the flood, as previously stated. These figures are representations of the modelled culmination of the concepts discussed in sections 1, 2 and 3 and illustrated in figures 2 to 4 within the NetLogo interface.

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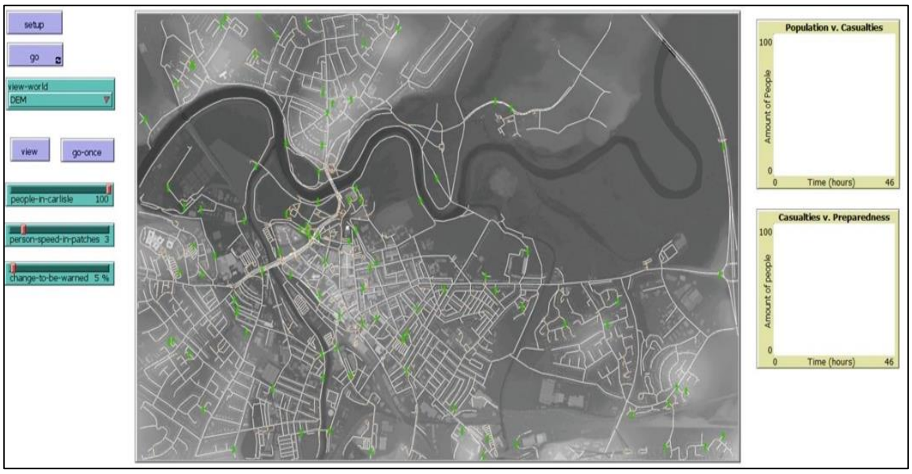

Figure 5: An overview of the preliminary HABM. Shown here as an example are agents engaging in the daily routine (green) prior to the initiation of the LISFLOOD-FP flood inundation. These figures represent only a small proportion (<1000 agents) of the full agent populations (~ 108,000 agents) simulated for the final results of the simulations

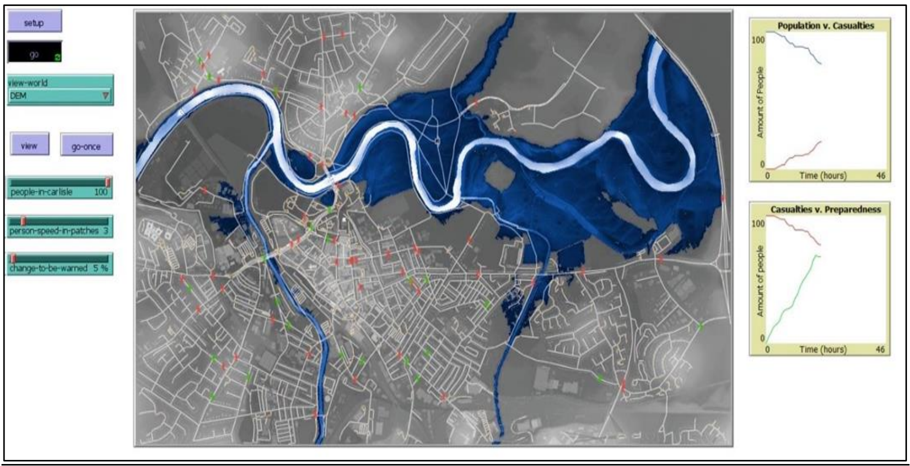

Figure 6: Agents marked in red are those whom have become aware of the incoming flood and are taking evacuative action. Changes in agent colour on the GUI (Graphic User Interface) indicate that members of the sample population are transitioning to a 'potential casualty' as the flood encroaches their vicinity but also that the likelihood of casualty occurring will diminish over time as the message of 'preparedness' diffuses through the population.

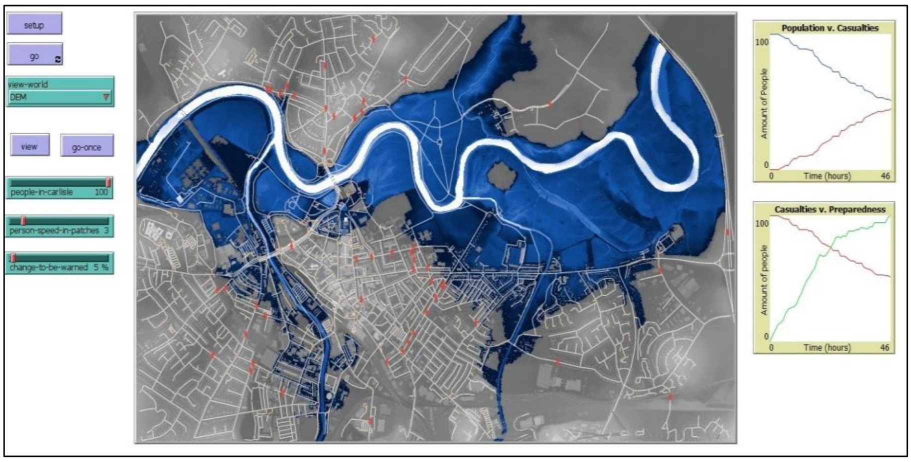

Figure 7: Further to preparedness and potential casualty, an indication of areas in which people are likely to stay, areas from which people are most likely to move as well as the areas through which people are most likely to pass may be observed within the HABM GUI and are indicated further in **figure 10**.

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In applying the Bass model to the Carlisle HABM, two diffusion curves were produced (figures 8 a & b). These represent inter-agent communication regarding the adoption of policy instructions to either evacuate the area immediately, i.e. to adopt an innovative instruction, or to follow an imitative one after checking with nearby agents and only then deciding how to respond. The coefficient (**q**) is typically represented by a much smaller value than 30% in traditional applications of the model (Mahajan, Muller & Bass, 1990). However, owing to the elevated risk involved in adopting, or not adopting, the product of evacuative knowledge during a hazard scenario, the traditionally small value of (**q**) has been scaled up significantly. This is to represent a one-third likelihood (~30%) of those who encounter the innovator (**p**) agents, receiving the flood warning by communication and adopting directly from them. Whilst this is a manipulation of the Bass Model function, it remains consistent with the Bass Model theory, stipulating that human adoption of a process or product is more likely to happen based upon internal systematic influence, or *imitation*, rather than through external influence on the social system, or by *innovation.* Wherein the available choices may be reduced to 'yes', 'no' and 'maybe', probabilistically represented as roughly one-third each for a given scenario (Dechter & Pearl, 1986; Hart et al., 1968; Hornor, 1998; Mahajan et al., 1990; Massiani & Gohs, 2015; Sultan, Farley & Lehmann, 1996).

The fundamental difference between (**p**) and (**q**) is generated from this external-internal distinction. Aligning this further with the sociological notions of Tarde, (**p**) is a representation of an external factor that requires a change in operation of the internal system dynamics (**q**) over time, thought of as an attunement, harmonisation or, in more traditional terms that may be thought of as an *acceptance* (Tarde, 1903). This means that for an innovative process (**p**) to become a naturalised component of the internal system dynamics (**q**), a significant amount of time may be required for innovation to lead to imitation when there is a *risk* involved (~~63~~ Wheater, 2006). In this application, the Bass model gives an indication of this duration based on the relative probabilistic magnitudes of (**p**) and (**q**) for a population of 108,000 agents. The overall significance of this application is that it allows conclusions to be made as to how influential external policy protocols are for the population in relation to their internal 'sense' during flood event response (Massiani & Gohs, 2015;~~,~~ Sultan et al., 2003).

The curves illustrated in figures 8a and b are the separate curves for the process of adoption based upon the optimised Bass Model values for the coefficient of innovation (**p**) at 50% and coefficient of imitation (**q**) at approximately 30% over 200,000 simulations for the Carlisle model. The three separate lines are illustrations of the three different iterations of the model's standard differential equation as functions of continuous and discrete time (~~5~~ Bass, 1969). Correspondence between the curves represents an agreement between the model's functions and the data being plotted. Broadly, the curves show that the innovation of external directive, seen in figure 8a (**p**), is more effective at promoting an immediate evacuation as a lower number of the simulated population changing state over time would suggest that a large proportion of the original innovators choose to act in the early onset of the flood and evacuate the area without hesitation. The negative aspect of this function is that there will be less agents available to communicate the innovative process ~~of (**q**)~~ and influence the less prepared agents and so this process of innovation will take longer to diffuse throughout the agent population leading to less agents taking appropriate action and exposing themselves to potential danger.

The curve for figure 8b, (**q**), is the internal function for evacuative measures, which is reliant on agent-agent interaction and suggests that the internal dynamics for the adoption of evacuative measures, that is to say the adoption of the same actions as the agency directive

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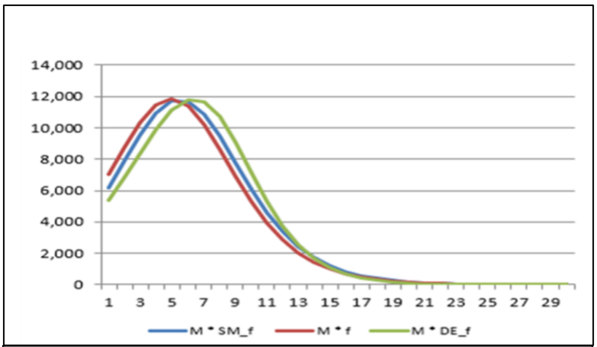
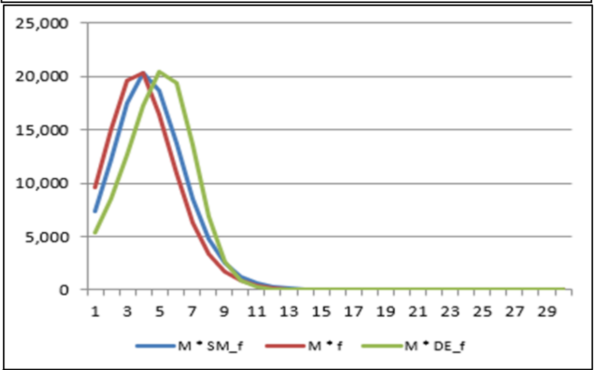
Commented [TO22]: Technical correction Ref #1 659. Semi-colon needed after 2015.

Commented [TO23]: Technical correction Ref #1 654. Give cited reference, not just its number. [Also line 665] but not directly from the external directive (e-mail, text alerts etc.), according to communication between agents, within the total flood affected population of Carlisle, is more influential over a shorter duration than the operation of (**p**). The variance between the three lines would suggest that there is some disagreement between the baseline functions of the Bass Model differential equation and those for discrete and continuous time for (**q**) and it is believed that this is likely related to the unusually high value attributed to the 30% likelihood of agents *agreeing* to imitate the innovative agents and become imitators, as well as the general stochasticity related to the reliance on 'proximal contact' for communication between agents, which is likely but not guaranteed in any situation; particularly in one as frenetic as that involving a flood.



Y-axis: Population of Carlisle, **X-axis**: Time (hours.)



Y-axis: Population of Carlisle, **X-axis**: Time (hours.)

Figures 8 a & b: Example Bass diffusion curves for p or innovation -(top), and q, or imitation (bottom), at Carlisle. Illustrated are the curves for the continuous time Bass Model functions (blue/ M*SM_f & red/ M*f) for discrete and incremental time-steps and the Bass Model differential equation (green/ M*DE-f). The Y-axis for both curves represents the maximum number of individual agents with potential to respond in accordance with the type of warning given and action taken.

This bridge between sociological and theoretical concepts of process diffusion, or between internal and external components, provides insight into the relationship existent between

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policy and responsive behaviour. Furthermore, the Bass Model's use in the analysis of flood response dynamics is a broadly useful one, providing quantitative evidence of behaviour, in the form of diffusion curves (figures 8a & b) and, for the dynamics of during-event agent communication, thus implementing Tarde's sociological laws into the modelling process. In addition, it represents both the 'innovative' *i.e.* individual response to policy direction, and the 'imitative' processes related to this direction, which certainly have influence on the micro, and potentially macro, scale human responses to flood events (Bernardini, 2017, Guyot & Honiden, 2006).

As the flood depths in the Carlisle dataset were relatively shallow beyond the river channel during the early time-steps, very few agents were presented with a potentially fatal scenario that they could not escape from, registering them as a '*potential casualty'* instead of a fatality. Broadly, a *fatal* scenario in this instance was determined by total cell inundation surrounding an agent and preventing them from leaving. Whilst there are examples of models utilising depth and velocity as determinants for a fatal scenario (Chen & Zhan, 2008; Chu, 2015; Dawson et al., 2011) these were not functions implemented in this preliminary model but were implemented in the later iterations of the HABM. Whilst the HABM should not be regarded as a full predictive tool, it does enable the visualisation of individual and group interactions, which might lead to potential casualty over repeated simulations. This is a valuable insight given that it is often difficult to identify comparable levels of detail from historical examples and their related data for micro-scale factors that are influential in event outcome.

According to figure 9, once overall 'preparedness' of the agent population of Carlisle exceeds 30%, either through increased social interaction or directly from policy instruction, the likelihood of 'casualty' resulting from the flood scenario actually increases. This was an unexpected outcome and might, at first, seem counter-intuitive but is thought to be attributable to ~~the~~ Carlisle's urban '*fabric*' (topography and morphology)~~ of Carlisle~~. When agents select to respond to the flood collectively and all at the same time, congestion of exit routes leads to an overall reduction in of movement away from flood inundated areas, so increasing agent exposure to the hazard (Wei et al., 2003; Werrity et al., 2007). This possibility is a valuable new insight produced by the HABM. Figure 9 illustrates the range of results from the 200,000 simulations of the 2005 Carlisle flood. Across these simulations, the percentage of the population pre-warned of the flood event was varied between 10 and 100 %. The current DEFRA estimation for Carlisle is that 50% of the population (~ 54,000 people) are classed as 'prepared' for a flood (termed 'population warned' or 'pre-prepared' in the HABM simulations~~.~~). The population warned within the HABM will initiate evacuative behaviours, according to policy instruction, within the first hours (~ 1-3 timesteps) of the flood inundation taking place and are able to communicate this action to surrounding agents from the outset of the simulation, largely by-passing the time required for the autonomous decision-making process during the event and engaging directly with the apparent agent preference for imitative behaviour.

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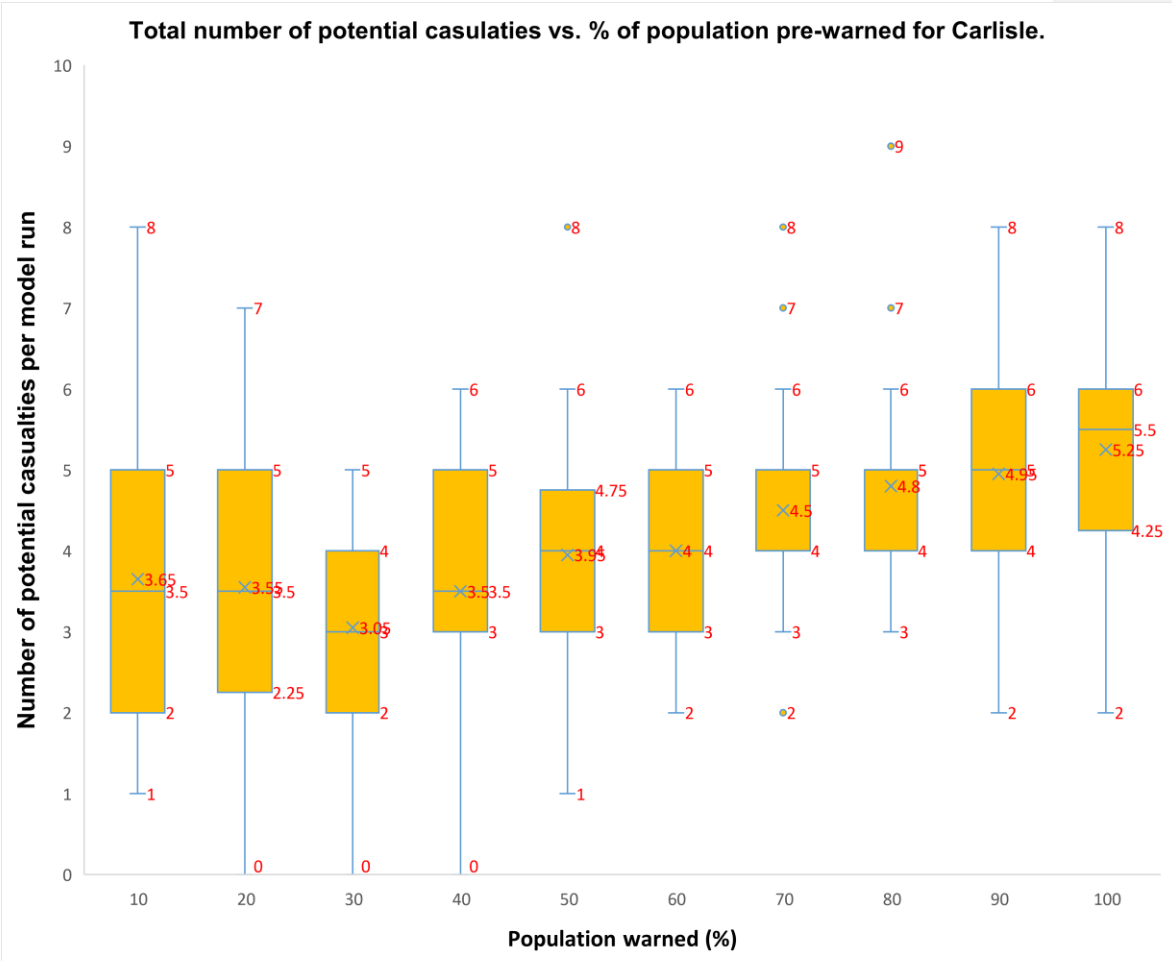

Figure 9: A box chart illustrating the range of values, sampled from 1000 agents (the most computationally stable sample size for batch runs on the available architecture) within the full agent population (108, 000), for the total number of potential casualties vs. % of population pre-warned for Carlisle from 200,000 simulations.

To assume that a higher percentage of pre-prepared agents would lead to an overall reduction in potential casualties would be a logical assumption to make (Axelrod, 1970; Chen & Zhan, 2008; Dawson et al., 2011; The Environment Agency, 2016). As highlighted by figures 9 and 11, overall potential casualties for the simulated population of Carlisle shows an *increasing* trend for higher percentages of pre-warned agents, particularly above 80% preparedness. As already mentioned, this reflects the way in which Carlisle has been constructed around the confluence of the river(s) Eden, Petterill and Caldew. It highlights the deficiencies of this urban structure when a large inundation event forces significant numbers of agents to evacuate through a limited number of escape routes (figure 10), (Gilligan et al., 2015; Sanders & Sanders, 2004).

According to the HABM results, Carlisle's agent population has a distinct 'preference' for evacuation to the south-west of the city, along the arterial A595. This preference was established through visual assessment of the simulations and was likely determined by the number of sub-routes that had access to the A595 and that were not cut-off by flood waters. Indeed, the most densely populated areas of Carlisle are divided into four distinct areas by the three rivers shown in figure 1 and so this preferred escape route is only immediately available to those who are either pre-prepared, reside within the immediate vicinity of the A595, or who live or work to the west of the Eden and Caldew. As the flood progresses beyond the first 5-6 hours of propagation, the number of escape routes diminishes yet the number of agents prepared to evacuate has increased significantly. This creates a backlog in the system whereby more agents choose to stay in their immediate vicinity or to evacuate at the same time as everyone else, exacerbating the system congestion and increasing agent exposure to the flood inundation. Whilst agent choices do vary from simulation to simulation according the choices of their routine and the type of agents they make contact with, this pattern of evacuation occurs across the whole set of simulations, and so could be taken as an indicator of likely choices made by the population of Carlisle if a flood happened today.

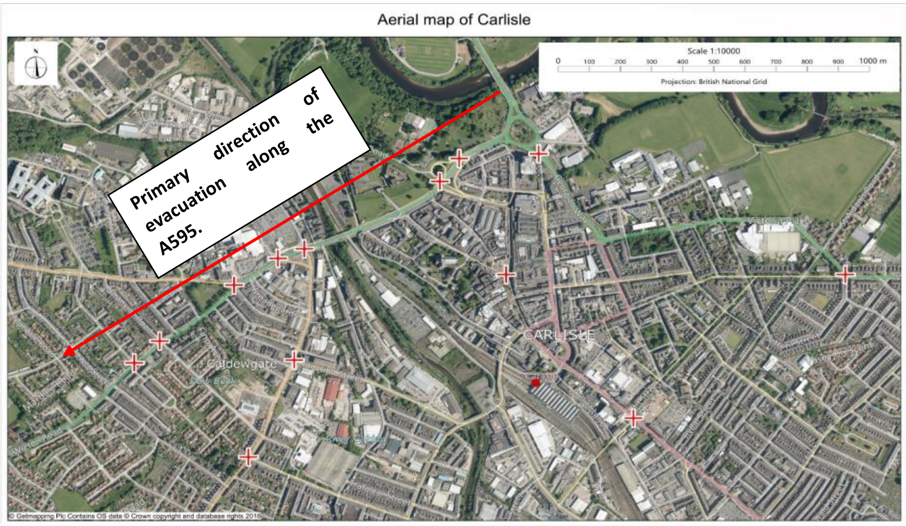

Figure 10: An aerial image of Carlisle illustrating the preferential direction for escape to the south west along the A595. Further illustrated are the most prominent chokepoints (**red crosses**) for reduced evacuative flow of people between 80 and 100% preparedness. These points were identified from the HABM as the nodes in the street network overlay which have the most consistently high densities of agents throughout the range of simulations. (Contains OS data © Crown copyright and database right (2019))

As is illustrated in figure 11, with less than 30% preparedness, agents within the HABM show a preference for evacuation away from Carlisle during the earlier stages of the flood onset and so the social response to the flood is slow when there are fewer people in Carlisle to disseminate the message of evacuation. This finding further reinforces the results presented in the diffusion model (figures 8 a & b). Without a threshold number of the population being aware of the impending flood there is less likelihood of contact with unaware agents. This means that the response dynamics are more reliant on the innovative procedures of policy uptake and arbitrary choice, both of which are shown to be less likely to produce a *successful* evacuation outcome. The transition from micro to macro level response, from individual agent interaction up to a large group response to changes in the environment, is realistically a much more complex process than that illustrated in the HABM model. Thus, as a starting point for testing hypotheses related to transitory-scale flood hazard response, it is a useful tool for exploring the related and inherent complexity of the socio-environmental interface present during a flood event (Wilensky & Rand, 2015; Wisner et al., 1994; Wong & Luo, 2005).

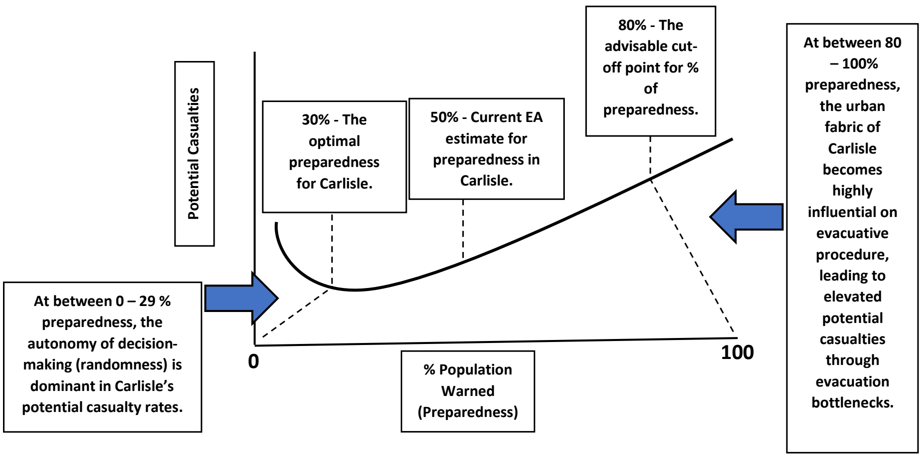

Figure 11: A representation of the key results shown in Figure 9 together with concepts that can be associated with them. It is expected that these percentages will vary with model parameterisation and changes in the area modelled.

5. Discussion

From further interpretation of figures 8 a & b, 9, 10 and 11 it is reasonable to infer that the agents within the HABM, representing the local population of Carlisle, demonstrate a further *preference* for basing their response to a flood event on interaction with their surrounding neighbours, a social response, rather than acting directly from policy instruction. The 2005 event in Carlisle significantly overtopped existing defences, meaning that local and possibly larger scale *management* actions would have been of little consequence to the event dynamics and so it is here where the social response becomes influential in the risk and resilience dynamics of the event (De Groot and Schuitema, 2012; Kinzig et al., 2013). With respect to these dynamics of response, the rate of innovation (Figure 8a) impacts less of the

Commented [TO27]: Narrative enhancement Ref #2 Clarification of how societal actions, simulated within the HABM, have impact on the event outcome.

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Carlisle population over a greater duration compared the rate of imitation (Figure 8b). It is believed that this could be because there is a higher number of the influential, *aware* or *pre-prepared*, agents leaving the vicinity of the flood prior to, or in the early timesteps of, flood onset and so the message of adoption from these agents becomes less likely to diffuse through the rest of the population (seen in figures 5 to 7). Conversely, when the remaining proportion of the population begin to experience the effects of the flood and a greater number of this population's daily routine becomes disrupted, a greater number of this population will transition to the choice scenario (figure 4) and begin *checking* with those agents around them about what an appropriate response will be. This proliferates the imitative process of evacuation and so would explain why the rate of imitation is more influential over a shorter period, particularly when the compact social network of Carlisle, facilitated by a relatively constrained urban topology and morphology; is considered.

A likely explanation of the slightly better correspondence between the curves of Fig. 8a compared to Fig. 8b is that they represent a direct instruction at the outset of the simulation and so there is less time for choice to be considered, with agents taking direct action as soon as possible. The issue with this is that the agents carrying the innovative knowledge will encounter less agents as the event unfolds over time, having taken evacuative action from the outset and left the area where the rest of the agents may not have encountered the flood inundation yet and are therefore continuing with their daily routine. Consequently, when the function of **(q)** is considered, a more effective and efficient process for diffusing the evacuative information amongst the modelled population of agents is seen. To understand why this is the case one must consider the dynamics at play in a broad sense, **(q)** is a descriptor for internal influence and, within the HABM, is reliant on agent-agent interaction whilst **(p)** is the innovative directive from a distal governmental agency which is reliant on engagement from the population and so to simplify this process as much as possible for these simulations, this directive was designated as an instruction to 'take evacuative measures immediately'. Worthy of note here is that, for the applied parameters, the Bass Model is considered a pessimistic forecasting tool with more optimistic alternatives, which have potential for application in similar scenarios, being based on the shifted Gompertz and Weibull distributions, both of which have superior forecasting and theory testing capabilities but do not offer such a balance between normative and non-normative interpretation, necessary for this format of analyses, as is the case with the use of the Bass Model (Jakkola, 1996).

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Within the HABM specifically, the format for agent distribution and seeding is more generalised, and the framework of the daily routine is more direct, than in comparable models. This is, in some ways, a concession in relative precision, justified by the sustainable operation of the model within the NetLogo format (Rasmussen et al., 1994; Wilensky & Rand, 2015; Wong & Luo, 2005). Furthermore, with the primary application of this model being concentrated on the development of understanding regarding the complex nature of human interaction with the urban and natural environments, under extraordinary or unusual circumstance, the production of interpretable metrics using a new, interdisciplinary tool is considered to be a significant first step in enhancing understanding in this area. The general form of complexity explored in this paper has certainly been subject to greater scholarly interest in recent times and this has been evident through the proliferation of publications on the subject and related phenomena, particularly through the last decade (Liu et al., 2015). As a result of this, complexity science has increasingly undergone a process of extension into quite different scientific fields (Alexander, 1980; Axelrod, 1970; Wilesnky & Rand, 2015)**.** This process, whilst a necessary element of scientific progress, has in some way acted to separate theory from application and has led to a diminished emphasis on cross-disciplinary applicability, leaving potentially useful scientific tools isolated or limited by the technological capability of the time. This has furthered the highly fragmented development of agent-based models and modelling frameworks (Axelrod, 1970; Müller et al., 2013; Namatame, 2016). These largely fall into one of two polar groups: those which over-emphasise a very specific use through a reductive process of refinement to meet validative expectations, or those which place themselves at the extremity of validation because of the physically unimaginable complexity that is being modelled (Ormerod & Rosewell, 2009). It is here, despite any shotcomings, where the ~~truth~~ value of the HABM is found; at the point of bifurcation between these groups (Assaf & Hartford, 2002; Eberlen & Scholz,2017; Guo et al., 2008; Liu et al., 2015; Morss et al., 2016; Nunes Correia et al., 1998; Waldorp et al., 1993; Wei et al., 2003; Werrity et al., 2007).

The provision of a probabilistic framework (F~~f~~igure 4) for the 'pseudo-random', this being a term which describes the large array of numbers underlying the agent's movements (i.e. leave, stay, etc.), within the model environment (~~,~~ which are effectively~~in effect~~ limitless but are also bounded by the fractal (self-replicating) 'stochasticity' of the model layer implemented within NetLogo), ~~agents to interact with (i.e. leave, stay, etc.),~~ has great importance for the general and trans-disciplinary application of the methods in this paper. This is particularly the case in the absence of empirical certainty for how the real population of Carlisle might individually act on the day. But the framework provides some necessary, general, parameters for human response in the event of a flood and so greatly reduces the possibility of an entirely chaotic modelling scenario, whilst also maintaining a realistic representation of choices that represent systematic functions of the community, infrastructure, and environmental dimensions within the urban and flood hazard system. Finally, it allows reproducibility for the HABM where components of future hydro-sociological models could simply be substituted for those of the HABM (Landstrom et al., 2011, Sabatier, 1986; Wong et al., 2005).

In reality, the social elements of the complexity explored here are as unpredictable as they are dynamic: this challenges forecasting behaviours in addition to their understanding. As evidenced in this paper, the social elements are represented by many different participants who adapt and influence one another, interacting in intricate ways that continually reshape their individual and collective responses. When performed collectively, these interactions form systems which are characterised by multi-scale interactions between the micro (individual) to the macro (demographic, economic and governmental). The collective coalescence of multi-scale interactions have been termed 'Complex Adaptive Systems' and they have a significant underpinning from research focused on their inter-disciplinary and methodological design so as to better understand the significant challenges presented by

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Source included to elucidate the difficulties of striking balance between the ability to validate and verify a model in a social context and representing physical phenomena to a further degree.

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902. 'value' rather than 'truth' perhaps.

Commented [TO32]: Technical correction Ref #1
907. Not bold. Need to check house style (especially whether 'figure' should have a capital letter). This long sentence at the start of the paragraph needs recasting, too.

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923. their understanding.

their complexity (Dugdale et al., 2009; Gilligan et al., 2015; Holland, 2014; Liu at al., 2015; Morss et al., 2016.)

Ultimately, the design of, “holistic risk management strategies requires an accurate understanding of the level of risk across the various layers of society. One important remaining limitation in our understanding of flood risk is the way individuals perceive and respond to risk. Even if we manage to model population density and flood inundation with increasing accuracy, assumptions about peoples’ risk reducing behavior, willingness to relocate, and access to information play a key role in the actual level of risk” (Jongman, 2018, pg. 2). Individual perception is an extremely complex phenomena and representing this from event and systematic complexity is paramount for developing further understanding of the nature of the physical-social interactions discussed here, so that evacuations may be better organised and the greatest number of lives may be saved in the event of a complex event, like a flood (Berendracht et al., 2017). Consequently, the non-linear characteristics associated with complex adaptive systems, including influential systematic processes such as heterogeneity, phase transition and emergence, require that our methods, such as those illustrated in the HABM, also attempt to represent the general complexity of adaptive systems. Given that such systems exist as macro networks of partially connected micro structures (fundamentally via individuals interacting in different groups which adapt to changes in the surrounding environment), the methods must then also include microscale models which are able to simultaneously simulate cross-scale operations, interactions and responses amongst multiple participants (Assaf & Hartford, 2002; Dawson et al., 2011), to provide interested parties with access to more representative insights of what is and could be unfolding in reality.

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Finally, during the 2005 flood, as modelled by the HABM for this paper, three deaths occurred. During the 2015 flood event in Carlisle, the River Eden exceeded the 2005 flood level by 600mm, yielding only one fatality but with a much greater economic impact (The Environment Agency, 2016). Even with the generalised ‘potential fatality’ metric implemented into the HABM, set as such due the low number of actual fatalities which occurred during the 2005 event, if the results of the model’s simulations are to be believed; then there is a much greater potential for a fatal impact within the flood inundation area than that which presented itself during the actual events of Carlisle in 2005 and 2015. Here, the true importance of the HABM and Bass Model results is that they offer a counter-intuitive scenario to be further deliberated, one which could prove significant for flood hazard management in Carlisle and risk management overall.

6. Conclusion and future development

This paper began by proposing two specific questions:

1. During a flood, does site-specific urban topography and morphology, change the optimum evacuation warning strategy?

2. Do people (agents) respond better to direct or indirect (word of mouth) evacuation warnings during a flood event?

These questions were formulated to explore the UK governmental shift towards alternative, bottom-up, action for addressing flood vulnerability and risk, as especially affected by agent response and urban morphology. These objectives simplify what is a very complex scenario and so with respect to this complexity, a methodological framework for addressing these two objectives was formulated and demonstrated, producing results via a coupled hydrodynamic and agent-based model: the HABM. This model was used to explore the complexity of human responses and behaviours during a flood event with a view to better specifying the two basic elements of the flood hazard system, a physical flood interacting with a human urban system. From this investigation, a range of implications were uncovered by the model simulations of response and behaviour. Based upon observation of these implications, some practical recommendations can be made for flood warning delivery and strategy as follows:

- Agents operating within a system of change show a preference for action via a socially *imitative* process as opposed to one which operates from *innovation*. This would suggest that bottom-up approaches towards warning and evacuation would benefit from incorporating measures that harness this understanding of group processes.
- Owing to the influence of site topography on the outcomes of social response, and the creation of potential congestion points within affected sites, a phased response to flood events should be an actionable option within flood warning strategy and delivery.
- During the process of issuing a flood event warning, the geography (topography and morphology) of the affected site can significantly influence the success or failure of the evacuative process and so due attention to this influence should be given during planning. This reaction phase involving the response and movement of people does not normally receive much attention and likely should.
- Whilst it might be a desirable goal to achieve a 100% preparedness within a flood-prone area, the results from the HABM simulations suggest that this may not be necessary, or even desirable. Simulations support the idea that the 50% estimate of the EA for Carlisle is the best value for efficient evacuation, owing to the social dynamics and the topography of the site. The design of 'optimal' impacts for a ranging of percentages of prepared people, and for sites with differing layout and population dynamics, needs to be critically considered in future flood response strategies.

There are significant questions that arise from these recommendations which require further analysis. Enhanced development of the HABM and the related themes will look to provide this further analysis in the form of the following:

- The nature of the agent decision-making process in locations where interaction is concentrated, e.g. is social response hastened where there is a higher population density?

- The nature of agent response with respect to the physical attributes of the flood event, e.g. attenuation of the flood hydrograph & variations in flood volume influencing the process of evacuation.
- Different urban morphologies: will these give dramatically different results to those produced for Carlisle?

Whilst not a predictive tool, the implications of the results herein outlined, coupled with such future developments of the HABM, are useful in providing greater scope for including and quantifying relevant operative factors that are involved in flood vulnerability, risk and resilience as related to urban systems. The HABM offers a dynamic method for simulating important actions linked to these, with the potential to enhance quantitative analyses in support of the decision-making process for flood hazard management. This paper demonstrates that such quantification can involve not only flooding itself, but also potential human responses. These may exacerbate the risk if they are not accounted for during planning, or they may be diminished through improved response planning. Other hazard environments may similarly be analysed using the approach here outlined, providing many points of further discussion and consideration for stakeholders involved with risk assessment. The HABM can be a welcome and useful analytical tool for supporting and expanding on these points whilst moving forward.

Data availability: The population data was accrued and modified from the 2011 aggregate NOMIS (ONS) database found at: https://www.nomisweb.co.uk/census/2011
This was cross-referenced with the supporting flow data found at: https://wicid.ukdataservice.ac.uk/
Building footprint data was taken from OSM, copyrighted to OpenStreetMap contributors and available from: https://www.openstreetmap.org/
The LISFLOOD dataset for Carlisle can be requested directly from Dr. Jeffrey Neal with further details on the LISFLOOD-FP available at: http://www.bristol.ac.uk/geography/research/hydrology/models/lisflood/
Bass Model curves were informed by information found on The Bass's Basement Research Institute webpage, © 2008, 2009, 2010 Bass's Basement Research Institute, at: http://www.bassbasement.org/BassModel/Default.aspx
The prototype Netlogo code for this model is currently still being used and modified as an active component of Thomas O'Shea's PhD thesis but it will be made available via open-source repository on the NetLogo Modelling Commons page at: http://modelingcommons.org/account/login under the title of this paper.

Author contributions: Thomas O'Shea wrote this paper with assistance and input from Paul Bates and Jeffrey Neal.

Competing interests: The authors declare that they have no conflict of interest.

Acknowledgements: The authors are indebted to Professor John Lewin, Toon Haer and his colleagues at the IVM, VU Amsterdam, Professor Nobuhito Mori and his colleagues at the Research Division of Atmospheric and Hydrospheric disasters, DPRI, Kyoto and our Bristol colleagues, Laurence Hawker and Jeison Sosa Moreno for their helpful thoughts on the pre-developmental stages of the HABM network.

Financial Support: Thomas O'Shea is supported by the EWS Educational Trust Exceptional Contribution Award. Paul Bates is supported by a Royal Society Wolfson Research Merit Award and Jeffrey Neal is supported by a NERC fellowship for interdisciplinary research on flooding in Vietnam.

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RC1 – Response

The authors would like to extend their sincere thanks to the referee for their time and considered thoughts on the submission. All comments and corrections have been thoroughly considered, with our respective action and/or response to these outlined below (in red.)

General comments

This paper recognises the complexity of hazard situations and responses, but also that adaptive actions overall may be simulated from individual or 'agent' behaviours through using agent-based models (ABMs). On the physical side, hydrodynamic behaviour can have an equivalent concern for the local through detailed topographic modelling and floodwater routing. The paper demonstrates how combining the two, through an innovatively developed approach coupling hydrodynamic and agent-based models (named here HABMs), allows site-specific procedures for warning provision and evacuation to be usefully designed. This is accomplished through simulating populations and exploring their alternative behaviours to see which might be of most benefit for responses to flooding events given the local geography – as in the case of Lancaster, UK, flooding described here. An interesting feature of the approach is that the human behavioural aspects are here justified by appeal to social theory, just as the (now better-established) hydrodynamic modelling is justified and rests on physical theory.

The authors appreciate the referee's acknowledgement of their attempt to innovate an approach towards the development of useful designs for warning provision and evacuation that harness the detailed elements of physical and social theory together. The authors agree that physical theory is, currently, the better-established format for justifying action with respect to warning provision and evacuation but also believe that there are influential degrees and actualities of the warning and evacuation processes which are not yet, or cannot be, accounted for within physical theory. It is here where the authors hope their attempts to illustrate the potential influence of these unaccounted factors, through the lens of urban flooding and the HABM framework, find the greatest value.

Specific Comments

The promotion of new quantitative approaches that combine physical understanding of hazards with possible actualities of human responses to them is surely to be welcome. Until recently there has commonly been an academic gap between the two: (1) improved modelling of physical phenomena and their dynamics on the one hand, but (2) 'top-down' imposition of (mostly hard engineering) solutions at affected sites without exploring what their populations might be doing, or could best be doing, in response. Localized decision-making is likely to improve greatly if those involved have good understanding of what best to do in the situation they confront – rather than putting schemes to the vote at some higher political level, the advantages or disadvantages of which are little understood on the ground. 'Participatory methods' have to be better than this. Coping with hazards is at heart a human cognitive activity, and so how people at different participatory levels can behave, or get informed as to how better to behave, should be beneficial.

The authors roundly agree with this assessment and hope the essence of this agreement can be felt from reading the submitted paper. De Groot and Schuitema (2012) suggest, quite robustly, that there is a distinct link between the acceptability of environmental policies, social norms and the characteristics of those policies, further to which, Kinzig (et al., 2013) suggests that the insufficient insight on the coevolution of these norms and policy instruments is what compromises the ability of decisionmakers to craft effective solutions to society's most intractable environmental problems. The authors recognise the growing annual losses attributable to the environmental problem of flooding as an extension of this lack of insight and as having a solution in the analysis, evaluation and development of participatory methods which are equally informed by both physical **and** social theory. This paper and example therein serve as a vehicle for this sentiment and the authors hope the approach outlined in the paper serve as a catalyst for the development of further hybrid narratives that are necessary for the advancement of effective participatory methods and policy.

Technical Corrections

The referee's direction for technical corrections throughout the submission are very much appreciated by the authors and these have been implemented within an updated version of the manuscript to be uploaded following the period of interactive discussion.

18. '... constructed using the Bass Diffusion Model'. x

118. Omit last comma in cited references. x

127. Put 'Dawson' in the bracketed reference. [also line 570] x

171. Dawson et al., 2011; Müller, . . . x

183. Semi-colons needed between EA Reports: 2006; 2012; 2016. And after Neal et al., 2009; [Also in line 752 after 2003.] No need for 'ands' within the reference brackets; see also lines 207-8; 214; 234; 267.

304. 'imitators' x

305. a priori. x

323. Chen & Zhan, 2008; x

334. One quote mark only needed. x

394. Dawson et al., 2011; also, no full stop after 1994 within the brackets. x

487. Comma after information [to be consistent with elsewhere]. x

587. Add full stop to sentence after bracket. x

627. How does the map show 'areas through which people are most likely to move' as the caption suggests? That's made more visible in figure 10. x

651. Why a semi-colon here? Perhaps: '…traditional terms that may be thought of as an acceptance'. x

654. Give cited reference, not just its number. [Also line 665]. x

659. Semi-colon needed after 2015. x

719. Last sentence of caption incomplete. x

751. Omit 'of'. x

758. Full stop after bracket, not before it. x

846/7. (Figure 8a), (Figure 8b) [add the word 'figure', and not in bold].

875. 'being based on shifted Gompertz…' x

902. 'value' rather than 'truth' perhaps.

907. Not bold. Need to check house style (especially whether 'figure' should have a capital letter). This long sentence at the start of the paragraph needs recasting, too.

923. their understanding.

940. Readers might appreciate a page number for this quotation.

Lettering sizes on Figures 2, 3 and especially the side panels of Figures 5-7 are on the small size.

References:

De Groot, J.I.M. & Schuitema, G., How to make the unpopular popular? Policy characteristics, social norms and the acceptability of environmental policies. Environmental Science & Policy, 19-20, 100-107, DOI: https://doi.org/10.1016/j.envsci.2012.03.004, 2012.

Kinzig, A.P., Ehrlich, P.R., Alston, L.J., Arrow, K., Barrett, S., Buchman, T.G., Daily, G.C., Levin, S., Oppenheimer, M., Ostrom, E. & Saari, D., Social Norms and Global Environmental Challenges: The Complex Interaction of Behaviours, Values, and Policy. BioSciences, 63-3, 164-175, DOI: https://doi.org/10.1525/bio.2013.63.3.5, 2013.

RC2 – Response

The authors would like to extend their sincere thanks to the referee for their time and considered thoughts on the submission. All comments and corrections have been thoroughly considered, with our respective action and/or response to these outlined below.

This paper proposed an innovative approach to represent the complex human behaviour during flood evacuation in Carlisle by combining a hydraulic model (LISFLOOD-FP) and an Agent-Based Model (NetLogo). I have really liked the idea of using the Bass Diffusion Model to represent the agent's behaviour during flooding. The results of this study demonstrated the importance of using a holistic approach to flood management purposes. Overall, I have enjoyed reading the paper and I found the manuscript well written, clear, and results are properly described and discussed. For this reason, I do recommend a minor revision before this paper can be accepted in NHESS. However, I still have a few comments which I hope will be useful to the author to strengthen the manuscript.

The authors appreciate the referee's kind comments and recognition of our efforts to holistically frame the dynamics of flood events using a combined socio-hydrological modelling tool. In sum, we have found the referee's thoughtful comments useful in strengthening the revised manuscript, to be uploaded following this period of interactive discussion.

1) It looks to me that one important aspect of the ABM is not included in your approach, i.e. the traffic model. In fact, during the evacuation process, traffic congestions can play a crucial role before the

agents select to respond to the flood all at the same time. However, it is not clear to me what are the dynamic characteristics of the agents 'movement (e.g. speed) and how are the road features included in the ABM. In fact, evacuation strategies may change based on the direction, capacity, and maximum allowed speed of the road network in Carlisle.

The authors do agree with the referee that traffic models offer an important aspect to ABMs and can have impact on the response to flooding. In the first instance, it was felt that there was already a wealth of models that had implemented traffic flows in ABMs. We wanted to focus on developing something different and whilst traffic dynamics have been implemented in the latter iterations of the HABM, this was a matter of course rather than interest and has little impact on the novelty of findings outlined in this paper. Simulations were run where the dynamics of agent movement varied between 1m/s and 3.5 m/s, to represent 'walking' up to a 'brisk pace'. The exit from the DEM is the action towards which 'warned' agents will move. Not all agents will do this, some will just move to a safe distance and then re-interact with the routine in the following time-step. This is thought to best represent the dynamics of human response that people would give to a flood like that seen in 2005 Carlisle – slow onset and propagation. The road features were implemented from open street maps and these provided the avenues upon which agents could move and interact with the environment.

2) Why did the authors couple LISFLOOD-FP with the ABM if societal actions will not influence flood propagation (at least in this study)? Of course, the proposed coupling framework can allow simulating more complex situations, e.g. placing sandbags or other tools to protect from flooding, but it will drastically increase computational costs. I assume that such costs may reduce if the raster files are uploaded within the NetLogo framework each simulation time step. Moreover, what is the computational time for 1 simulation?

This flood event was a 1 in 150-year event which significantly overtopped the existing defences meaning that local and even large-scale management actions would have been of little consequence to the event dynamics. Furthermore, we are concerned with the process of in-event, societal response to the flood propagation. Of primary interest here was the modelling of communication dynamics. Whereas placing sandbags can indeed be defined as a routine, antecedent response that influences flood propagation, we suggest that the characteristics of responsive action (the patterns of inter-agent communication and subsequent action) taken by agents to the flood and in the simulations would not be present if the flood did not happen and so is analogous to the process of innovation. Here, we are framing response by adopting the terminology used by the governmental guidelines for flood planning in the sense of human, individual and community, 'plans' and we offer some insight into how the concepts and patterns of individual and community communication and response can be represented within an ABM. The time taken to model this process, over 1 complete simulation of the flood, without any variance in the parameters and dependent on the computer system used, has ranged from 45 seconds to 3 minutes 30 seconds. We found that implementing a dynamic flood wave within NetLogo exponentially increased computation time and thus moved to importing raster files which offered relatively faster simulations, overall and at each time step, of the dynamics and interactions of interest.

3) How the working locations for all the agents are assigned? From what I could understand from the manuscript, the daily routine is randomly assigned at each simulation based on the census information of the specific commercial area in Carlisle for 2005. Is this valid also for the working locations?

The daily routine is present throughout the whole simulation for all agents to carry out. Yes, this is valid for the working locations also and is sourced from the census flow dataset.

4) When an agent receives the warning and decides to act immediately it will then exit the DEM using available network road. Is this a realistic situation? If yes, please provide a reference to support your choice.

With respect to the ABM outlined in this manuscript, we chose to develop and focus on the aspects of community, individual choice and action. This was justified through reference to the UK Government's ‘personal flood plan’. To ensure that these aspects were as dynamic as possible we recognised that we needed to give the agents the choice to ‘respond’ to the flood propagation based on proximity to flood waters and/or on inter-agent communication but also the choice to not respond and continue with their daily routine. Being ‘pre-warned’ simply gives an agent the option to immediately seek an exit from the DEM as they are aware of the impending flood. In terms of this being a realistic response, the authors inferred this process of moving away from the flood waters as being realistically representative of a choice people would make based upon reference to The Environment Agency’s ‘Flooding: what to do before, during and after a flood’ document from 2015. This will be added as a reference in the updated document.

5) Can you provide an example of the “innovative knowledge to respond to the flood upon onset” that a pre-prepared agent can use? (line 579) Maybe I have missed some details.

Upon deliberation, the authors suspect they might have explicated this in a clearer fashion for the reader. An example would here be classed as knowing how and when to leave along a particular route that leads to safety Here, we explain that the knowledge of the flood and thus the requirement to respond in a fashion which is beyond that of the daily routine is innovative in its own right, or at least is analogous to the essence of an innovation. This is different to undertaking an action which you might class as an implementation of a ‘hard-engineered’ innovation and is linked to the terminology of The Bass Model and Tarde’s terminology for the laws of imitation. The format of human response and communication is necessarily innovative owing to the relatively infrequent unification of human and natural environments in the format of a flood event.

6) Besides for the DEFRA estimation for Carlisle at line 756-758, did you evaluate the model results with other observation data (e.g. tweets or report for some specific parts of the city)? I have found some (maybe useful) information in this webpage http://www.intrescue.info/hub/index.php/carlisle-floods-8th-january-2005/

This is a very useful source. However, it seems that the information in this source does overlap with that provided within the DEFRA reports, which were used to inform the dynamics of interaction within the HABM. We feel that the information contained in the source provided by the referee could be useful for informing and developing a sub model routine for agents who choose to remain in their properties during flood propagation. Aside from DEFRA, local and national tabloid accounts were used in cross-referencing event timelines and these were found to be useful in the absence of twitter or indeed any digital footprint of note for the event in 2005.

7) The authors stated that “The only study to date to drive an ABM with a hydrodynamic model was that of Dawson (et al., 2011).” This is not totally correct. Also, in Medina et al. (2016) an ABM and a hydraulic model were coupled to test large scale evacuation strategies in coastal cities under threat of imminent flooding due to extreme hydro- meteorological events. Moreover, other studies coupled ABM with a hydraulic model for flood risk management purposes (Abebe et al., 2019).

This statement has been revised to indicate that there are indeed other examples of ABMs driven by hydrodynamic models. In making this statement, the authors were referring to a model which they felt would be directly comparable by scale and computability, this could have been made clearer. We also feel that these references are good additions to the paper and so they have been included in the revised manuscript.

8) Try to improve the quality of figures 8 and 9

Yes, this will be implemented in the revised manuscript.

References:

Abebe Y.A., Ghorbani, A., Nikolic, I., Vojinovic, Z. and Sanchez, A. (2019) A coupled flood-agent-institution modelling (CLAIM) framework for urban flood risk management, Environmental Modelling & Software, 111, 483-492.

Medina, N., Sanchez, A. and Vojinovic, Z. (2016) The Potential of Agent Based Models for Testing City Evacuation Strategies Under a Flood Event, Procedia Engineering, 154, 765-772, https://doi.org/10.1016/j.proeng.2016.07.581.

RC3 – Response

The authors would like to extend their sincere thanks to the referee for their time and thoughts on the submission. All comments and corrections have been thoroughly considered, with our respective action and/or response to these outlined below.

"This paper attempts to present an integrated hydraulic-ABM model for modelling individual behaviour during flooding. Human interventions could significantly affect flood risk even during an event, especially in densely populated urban areas. This research represents an encouraging attempt to develop an approach to model human activities in the city of Carlisle during a flood event in 2005, which is an innovative and necessary step forward in flood risk assessment. But at its current form, the paper is difficult to follow, and it is not clear what the core focus and innovation is. It must be substantially revised and improved before accepting for publication. Hope the following comments will help the authors revise their paper."

Author response: The authors appreciate the referee's acknowledgement that this is indeed an encouraging attempt at developing an innovative and necessary step in the field of flood risk assessment. As outlined in the responses below, the authors have sought to address the referee's concerns and to clarify further the core focus and innovation of the paper.

The major concerns:

1. What is the major novelty or focus of this work? Is it the 'new' modelling framework? Or is it the application of the model to understand human activities during a flood event in the case study?

Author response: To broadly answer this series of questions, this work is an improvement on previously conducted work (e.g. Dawson et al., Lumbruso et al.) owing to: (i) the efficiency and flexibility of having two separate codes for the models, thus increasing the likelihood of the coupled model framework representing a more sophisticated set-up (inertial wave, 1D/2D structure for channel representation etc.) and (ii) having a hydraulic model that has been more thoroughly validated than models previously written into NetLogo. With respect to Lumbruso et al.'s paper, the Life Safety Model did not test the evacuation characteristics for 'type' of response. The focus of our work is to address these two shortcomings by offering a modelling approach which couples physical and social models where agents have a probabilistic daily routine and a choice of responses on an individual basis. This enables the exploration of different hypotheses for social reactions and responses to the detailed, accurate and dynamic physical outputs generated by LISFLOOD-FP by adding the related elements of policy and systematic change.

Specifically, we use the Bass Model of diffusion (l. 220-224) to explore hypotheses relating to flood warning and evacuation which yields interesting new insights into these processes that would be difficult to achieve in any other way. It follows from this that the framework is indeed new and by applying it to the case study for Carlisle's 2005 event we are able to illustrate human activities and understand their behaviours, structured with a logical and believable social model and driven by a firmly validated physical model. We therefore believe the work has a clear focus and is novel in endeavour, as was noted by the two other referees.

“This paper presents a new flood risk behaviour model developed using a coupled Hydrodynamic Agent-Based Model (HABM)”, which suggests the modelling framework is the key novelty in this work. But the presented HABM takes offline modelling outputs (flood depth) from LISFLOOD-FP to drive the agent-based model developed in the NetLogo framework. This is a ‘step backwards’ from the modelling approach as reported by Dawson et al. (2011), in which “a hydrodynamic model simulates the floodwave was also developed within the ABM platform and interacts directly with the agents and the built environment”.

Author response: Concerning the (excellent) work by Dawson et al., we argued in the paper that “this study initially coded the hydrodynamic model directly within the ABM meaning advantage could not be taken of recent developments in efficient numerical methods for solving the shallow water equations ... and high-performance computing…” The fundamental thought to this is that the approach taken by Dawson et al. was a great way to start to link ABMs and hydrodynamic models, but we found that it has some technical limitations because only a very simple hydrodynamic model can be coded within the ABM framework. The referee has perhaps not appreciated the limitations imposed by writing the hydrodynamic code within the ABM, so these are further outlined below:

Because they were working within the NetLogo ABM framework, Dawson et al were only able to code a very simple inundation model for 2D only domains. This was based on solving a version of the diffusion wave equations following Bates and De Roo (2000) which was (just about) adequate for the small coastal flood that Dawson et al simulated. The coding environment in an ABM framework can never be as flexible and computationally efficient as writing software in a compiler language, as we found when we tried to do exactly this at the start of our project. We initially coded our hydraulic model within NetLogo exactly as Dawson et al had done, but for the high-resolution whole city-scale test case used here the simulation took days of computer time. This is because solving dynamical equations on fine grids with numerical methods without a compiler language is extremely slow.

In addition, the lack of coding flexibility within ABM frameworks means that one cannot create more sophisticated model structures, such as hybrid 1D/2D hydrodynamic models, that are required to simulate fluvial flooding in urban areas. The only reason for having the hydraulic model coded within the ABM is if the behaviour of the agents changes the development of the inundation. This is not the case for the Carlisle flood, and neither was it the case for the coastal flood simulated by Dawson et al. In these circumstances there is no advantage to the ‘tightly-coupled’ approach and it also means that one is not able to take advantage of the latest development in hydraulic modelling. For example, we showed during a series of papers during the 2000s (Hunter et al., 2005; Hunter et al., 2008; Bates et al., 2010) that the simple diffusion wave approach used by Dawson et al suffers from a series of technical flaws meaning that to correctly simulate wave dynamics it can only be used with relatively coarse numerical grids. This is problematic for simulating floods in urban areas where it is now commonly accepted that one needs a model grid capable of resolving flow around buildings. By writing their hydrodynamic code within the ABM framework Dawson et al’s approach could not be used to simulate a whole city scale inundation event at high resolution as we do here. By keeping the ABM framework and hydrodynamic model separate we effectively solve this problem.

As a result, writing a hydraulic model within the ABM framework has no advantages for many (perhaps most) flooding applications and leads to quite a few constraints. Our approach is a step forward because it can use a more sophisticated hydrodynamic model that takes advantage of nearly 20 years of numerical developments since the Bates and De Roo (2000) formulation implemented by Dawson et al. Having an offline model is much more flexible and it can therefore be applied to a breadth of different situations to test different hypothesis, not just simple 2D coastal problems at relatively coarse resolution.

“The approach of using offline flood modelling outputs to drive an agent-based model has also been reported in the literature, e.g. Lumbroso et al. (2011) developed a life safety model to estimate risk to people imposed by dam breaks or flash floods. In their work, their Life Safety Model could use outputs from any available two-dimensional hydrodynamic models that solves the shallow water equations (e.g. Telemac-2D, TuFlow) or the simplified forms (e.g. LISFLOOD-FP).”

Author response: The authors acknowledge the referee's assertion that Lumbroso et al's work on the Life Safety Model offers a similar level of physical modelling flexibility to that of the HABM and thank the referee for drawing our attention to this. As far as the authors are aware this is one of few (Dawson's being the other) comparable modelling studies to the HABM described in our paper and we have included an acknowledgement of this in the revised manuscript.

There are clear differences in the two overall approaches. Lumbroso's model considers the notion of 'fate' based upon 'warning' and 'action', claiming to consider the notion of direct or indirect warning i.e. agent communication, in the process of warning or action. It does not substantiate the process of message adoption or suggest how this might better align with current policy direction on an individual level. There is no clarity on whether the agents carry out a routine of any kind, with the choices being given to them largely relying on linear and limited choice direction. We imagine the natural counter to this might well be to draw attention to Dawson having included a routine, with comparable physical modelling flexibility and here the HABM differs again by offering agents the choice of adopting an 'emergency routine' in addition to the standardised daily one. This means that the HABM emphasises the role of choice and models it in a more representative manner than in previous work.

Thus, in sum, with contemporary policy moving towards a more integrated approach this framework utilises the methods and conclusions of these two previous pieces of research and builds on them, adding enhanced theory and the necessarily enhanced methods, to provide an integrated approach to test new hypotheses; contributing to the overall sense of novelty.

"If the focus of the paper lies in the application of the model to understand flood-driven human dynamics in the case study. There is no strong evidence showing the model settings reflect reality and so the results and the conclusions may be misleading."

Author response: The authors would like to direct the referee's attention to the cited paper by Neal (et al., 2009) regarding this point. The primary reason why this case was chosen is because of the quality of the computer model used in the simulations. This is also covered sufficiently in figures 9 and 10 of the paper, specifically in (l.745-779) it is stated that over the simulations conducted, the number of potential casualties was aligned with that which was actual during the event in 2005. However, upon review this could be made clearer and so we wish to assure the referee that this has been done for the final submission.

2. Following the above comments, it is difficult to be convinced that the model settings can represent actual human dynamics during a flood event in Carlisle since:

Author response: The purpose of this paper is to test hypothesis (l. 144-148) and in respect of this, the human dynamics that the ABM simulates are sufficiently 'real' to produce results which are in line with those observed during the event modelled. It is also the case that all models are a simplification, but here, we believe the HABM represents suitable complexity for the scientific purposes to which it is being put.

i) the behaviour rules for individual are over-idealised and there is no evidence to back the choice of behaviour rules;

Author response: The behaviour rules are directly sourced from Dawson et al. and, upon reflection, are no more idealised than the responses seen in Lumbroso et al. As an example, in Lumbroso's paper there is no justification given for the scalar magnitude of diffusion of choice (i.e. the effect of choices made by agents, on other agents) and, where alluded to, it is not founded in the kind of arguments we outline in sections 2.3, 2.4, 3 and 4 (l. 721-729) of this paper. Again, Dawson (et. al)'s model, which is another paradigm of physical modelling, makes no substantive reference to social system representation beyond that which is basically necessary for coupled analysis. Further, with respect to agency routine, the authors would argue that Lumbroso's 'PARU' approach is more idealised in comparison to that of the framework in this paper. This particularly being so when there is little information given with respect to how these (PARU) units form and no detail given with respect to the process of choice in the formation of these 'evacuative' units. In our case the interaction rules within the HABM are based on laws of sociological diffusion (Larsen et al., 2005 – source added to revised submission), which take the agents through the five steps of Gabriel Tarde's law of imitation and invention. These are terms which are much better aligned with the reality of what behaviours individuals are likely to exhibit in social settings than anything the authors have reviewed during the process of the model development, or since.

The authors did refer to Bernadini (Bernardini et al., 2017 – source added to revised submission) during the initial stages of developing the behavioural rules alongside the framework provided by Dawson et al. as well as the Nomis and Flow data sets which were further used by the authors of this submission as a cross-reference. Combined, these sources gave rise to the general routine presented in the paper. It is hoped that with this clarification and with the additional source materials added, the referee will see that the choice of behaviour rules and routine are grounded in both legitimate evidence and theory.

ii) the communication rules between agents are also over- simplified, e.g. how are text, social media and other forms of wireless communications taken into account, which may significantly affect the simulation results;

Author response: Whilst being 'en vogue' currently, this is not the chosen focus of the paper and also, during 2005 this was much less of a factor for consideration than it is today as many networks for these forms of communication were still being developed. The 2015 Carlisle event would provide an interesting contrast to 2005 as it would be a model within which such formats for communication would presumably provide mensurable impact and thus would merit inclusion in upcoming models and study. We again stress that in the paper we are trying to test several hypotheses concerning flood warning and response, and not produce an exact facsimile of the real world. All models simplify to some extent and we would argue that this is reasonable evidence that we have included enough complexity in our model to undertake the science objectives of the paper.

iii) traffic systems and key organisations are not represented in the model which will inevitably have significant influence on the results and conclusions;

Author response: Yes, potentially they may have influence for conclusions linked to evacuative action but as is stated in this paper, the significance may be allocated at the outset of process i.e. how warning is communicated rather than how action is taken. We again note that the physical and human dynamics included in the model were chosen based on theory with a strong lineage of scholarship from other disciplines in order produce a new platform for experimentation and interpretation and practice. In this respect our view is that the HABM delivers with effect.

iv) the model results were not validated at all. Therefore, the results and the conclusions from the simulation may not be valid and may be misleading.

Author response: Were the aim of the work to make predictions and/or forecasts then yes, further validation would not only be imperative but of great value in addition to the aims and scope of this paper. However, to further reassure the referee, the authors are confident that the hydraulics modelled are well validated for the Carlisle 2005 case study, as is supported by the large body of cited works in section 2.1 of the submission and that the human dynamical routine is eminently sensible and realistic (sufficiently so to answer the questions posed in the paper). Additionally, and as the referee will be aware, ABMs are historically difficult to validate (Ormerod and Rosewell, 2006 – source added to revised submission) and whilst techniques have been introduced to improve this, the authors feel that the model offers a sufficient balance between " clear explanation and description of the phenomena" and the "simplest possible realistic agent-rules of behaviour" for the model to be considered a valid base for comparison to other models (such as those suggested by the referee i.e. Lumbroso et al. & Dawson et al.)

The authors would also argue that the level of cognition afforded to the agents operating within the model is not so high as to require significant justification beyond that provided as the process represented is of sufficient alignment to produce useful results for an intended purpose, namely to test hypothesis which would be difficult to evaluate in any other way.

Minor issues:

Author response: These issues are a precis of those outlined above and so have largely been addressed above.

1. Why the authors use the 2005 flood event but not look at the more recent 2015 event? More information would be available from different sources for the more recent event to inform and validate human activities.

Author response: As stated in the paper, the 2005 event is one which has provided a large amount of data from LISFLOOD and resulted in a large body of published information on the related phenomena. On this basis, it was felt that it provided a suitable, initial, case study for the application of the new framework – as stated in the submission. Furthermore, as stated in 2 (ii), the 2015 event will provide excellent scope for an updated model which will include the new formats for communication.

2. The paper is difficult to follow, and the authors should more explicitly explain the modelling framework, how the agents are interact(ing) and communicat(ing), and how the behaviour rules are set and why, etc.

Author response: At 32 pages, the authors feel that they have invested enough time and care to ensure the framework of the model, the formats of interaction and communication and the setting of behaviour rules are all explained in enough detail. Where necessary, we have provided further source material for the reader's reference to consolidate this detail.

3. Since the human activities do not have any impact on the flood dynamics and the agent-based model is only driven by offline flood model outputs, it is NOT a 'coupled' model.

Author response: As has been emphasised in the author's responses to all preceding assertions made by the referee, the key and novel difference of this submission is the development of a framework that offers scope to include steps seen in directly coupled models (of the same nature) as well as scope for including indirectly coupled procedures for modelling interactions from beyond the scope of those models (of different natures). The motivation here being a desire to move towards more inclusive narratives that align with the dynamic notions of vulnerability and transcend the infinite regress of 'risk-based' modelling simulacra, which seemingly feed into the 'Tower of Babel' problem and do not seem to be addressing the issues of growing disparity in modelled and realised loss; nor incorporating the growing movement in policy to incorporate fundamental elements of social science (l. 79-84 in the submission). Ultimately, were the models not coupled, no results would have been produced to represent the different aspects modelled i.e. the flood layers called into the model would not drive any response in the agent population. Therefore, the authors believe this to be associated with semiotic misunderstanding and so will move to clarify this in the final submission.

4. The title, 'an agent-based model for flood risk warning', is a bit confusing. Based on its current capacity, the model cannot be used for 'flood risk warning'.

Author response: Without a suggestion for an alternative we are unable to consider what might be a better alternative. In the most basic format, based on the physical representation of the flood and the subsequent modelled response of the population in the model, this is an agent-based model for flood risk warning.

Referees references:

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