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Agent-based simulator of dynamic flood-people interactions

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Abstract

This paper presents a new simulator for dynamic modelling of interactions between flooding and people in crowded areas. The simulator is developed in FLAMEGPU (a Flexible Large scale Agent-based Modelling Environment for the GPU), which allows to model multiple agent interactions while benefitting from the speed-up of GPUs. Flooding variables including terrain data are represented by a hydrodynamic Agent-Based Model (ABM) that is based on a non-sequential implementation of a robust Finite Volume (FV) solver of the Shallow Water Equations (SWEs). People movements are represented by a pedestrian ABM adopting force-based walking rules. The hydrodynamic ABM is coupled to the pedestrian ABM according to risk-to-life thresholds reported by the UK Environment Agency (EA). A hypothetical case study of a crowded shopping centre is proposed and used to assess the dynamic coupling ability of the simulator. Flooding into the shopping centre is induced based on realistic inflow conditions, and the simulator is applied considering two scenarios: evacuation without advanced warning and intervention with an advanced warning of 12 hours. Results show that the simulator can produce detailed statistics of spatiotemporal people states during evacuation, and is useful to plan safe and effective people intervention to deploy a sandbag-based temporary barriers.

Keywords: Agent-based models (ABMs), Coupled hydrodynamic and pedestrian ABMs, Microscopic analysis, Assessment of dynamic coupling ability, Evaluation of evacuation and intervention strategies.

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1. Introduction

Flooding poses omnipresent risks to people’s lives and livelihoods, and disruption to public infrastructure and transport systems that are key pedestrian hubs in urban areas (Thorne et al. 2007; Hallegatte et al. 2013). Supported by various computational methods and techniques (Penning-Rowsell et al. 2005; Lumbroso et al. 2007; Kreibich et al. 2010; Kreibich et al. 2015), flood risk management has become central to mitigate, prepare for and manage the consequences of flooding risks (Wedawatta and Inirige 2012; Penning-Rowsell et al. 2005; Aerts et al. 2018). Agent-Based Models (ABMs) can represent the synergies between social and physical dynamics and mitigation policies, therefore offer a natural platform to relate flood inundation data to the behaviour of ‘at-risk’ receptors (Zischg 2018). ABMs are found suitable for flood risk management and planning because of their capability to capture complex behaviours of receptors and their interactions with their surrounding environment situations (Lempert 2002; Batty 2003; Dubbelboer et al. 2017; Haer et al. 2017; Lumbroso and Davison 2018). However, as the incorporation of flood information within this approach relies on adopting hydrodynamic datasets at temporal intervals, current ABMs are primarily designed to analyse receptor-to-floodwater responses (Monticino et al. 2007; Dawson et al. 2011; Coates et al. 2014; Bernardini et al. 2017; Yang et al. 2018). An inherently hydrodynamic ABM that can directly interlace with other ABMs is still desired to capture dynamic interactions across flooding data and receptor responses (Abebe et al. 2019).

Most existing ABMs that are applied to study flood-induced risks and emergency responses are decoupled from the flooding data, being designed from the perspective to analyse the response of macroscale receptors at coarse scales. Brouwers et al. (2001), Brouwers and Boman (2011), and Grames et al. (2016) developed ABMs to estimate the economic consequences of floods at regional scale under different flood risk management strategies. Coates et al. (2014) and Li and Coates, (2016) developed an ABM to estimate the number of
businesses and enterprises affected by flooding to improve business responses and preparedness at a city scale. Dutta (2011) also conducted city scale assessments to study sea-level rise impacts by ABMs involving hydrodynamic and socio-economic models. Tonn and Guikema (2018) used an ABM to explore how collective individual initiatives may affect long-term flood risks at a community level in a city. Also, Dawson et al. (2011), Mas et al. (2015), Liu and Lim (2016) used ABMs involving vehicles, buildings and houses as receptors at city scale to estimate the number of injuries and casualties after flooding. However, these ABMs are not designed to analyse microscopic and emergent behaviour of receptors as such can be driven by social force models, nor are able to provide outputs informing on dynamic spatial and temporal interactions occurring between flooding and the receptors before and during the flood event.

In terms of microscale assessments, very few ABMs have been reported. Liu et al. (2009) initiated an ABM that simulates the evacuation of five people in underground flash floods to find an optimal evacuation strategy by estimating the number of casualties in different scenarios. More generally, the Life Safety Model (LSM) (www.lifesafetymodel.net) has been developed to estimate casualties and injuries during and after a flood with applications to improve emergency response management following Environment Agency’s (EA) flood incident management approach (Lumbroso et al. 2007). To the best of the authors’ knowledge, the LSM is the only available ABM for microscopic risk analysis at individual scale (Lumbroso and Di Mauro 2008; Lumbroso et al. 2011; Lumbroso and Davison 2018). The LSM relies on flood data outputs from commercial two-dimensional (2D) hydrodynamic models, imported over regular time intervals. While this approach can map flood-on-people impacts, it cannot map people-on-flood impacts: on the one hand, the hydrodynamic model is not inherent to the LSM and thus flooding information are not considered as dynamic agents; on the other hand, the LSM represents people as moving objects on pre-specified pathways whose speed is governed by a set of simple evacuation rules. The LSM cannot, therefore, model emergent people behaviours including people-on-people impacts, in part because it does not have
generalised ABM of inter-pedestrian interactions (Bernardini et al. 2017). Makinoshima et al. (2018) showed how the interactions between pedestrians and their surrounding features, such as obstacles/walls, can take part in evacuation analysis through using a force-based ABM of a flow of pedestrians within a large-scale urban environment. They used parallel computations to simulate such crowd of pedestrians, but their work did not couple hydrodynamic model information in their simulations to capture the response of individuals to floodwater. A simulator that dynamically and inherently couples a hydrodynamic ABM to a pedestrian ABM is required to genuinely account for changes in the states across individuals and water flow characteristics within a dynamically coupled modelling context.

This paper demonstrates the development and evaluation of a unified ‘flood-pedestrian’ simulation framework that fully couples a hydrodynamic ABM to a pedestrian ABM. The hydrodynamic and pedestrian ABMs are both developed and coupled within the FLAMEGPU framework (Section 2). The hydrodynamic ABM is organised based on the formulation of Finite Volume (FV) numerical solution of the two-dimensional Shallow Water Equations (SWEs) (Section 2.1); and the pedestrian ABM follows a social force model rules that simulates interrelated behaviour of a crowd of people (Section 2.2). The dynamic interactions across the two ABMs are organised based on rules informed by EA’s risk-to-life flood hazard metrics (Section 2.3). The ABM implementation of the hydrodynamic model is validated in reproducing two well-known academic test cases (Section 3). The coupled flood-pedestrian simulator is applied to ad-hoc hypothetical test case (Section 4) to, first, evaluate the ability of the model in conducting microscopic analysis of individuals’ spatio-temporal states in floodwater and, second, to verify that the model is able to capture people responses of floodwater to an intervention process performed by a group of people. Finally, a summary and outline of key conclusions are provided.
2. Coupled hydrodynamic-pedestrian ABMs

FLAMEGPU is a framework for modelling and simulation of dynamic ABMs, empowered by the intrinsic parallelism of GPUs (Richmond et al. 2009). In FLAMEGPU, CUDA simulation programs are generated by processing three inputs as described in Figure 1: a model file (`XMLModelFile.xml`) defining agents’ descriptive information (e.g. their type, numbers, etc.); a description of agent behaviour within a source code in C (`Functions.c`) for spatiotemporal update of the state of the agents reacting to messages they receive from other agents; and, agents’ input file (`input.xml`) for initialising their state.

![Figure 1. The process of generating an agent-based simulation program on FLAMEGPU](image)

In the following, further description is provided on how dynamic coupling of a hydrodynamic ABM to a pedestrian ABM has been achieved on FLAMEGPU.

2.1 Hydrodynamic ABM

A hydrodynamic ABM is implemented on FLAMEGPU by mathematical rules, that are commonly used in standard ‘sequential’ flood model formulations (e.g. Infoworks ICM, MIKE FLOOD, TUFLOW), which are based on the FV numerical discretisation of the SWEs (Wang et al. 2011). As these algorithmic rules are well-reported in literature (Wang et al. 2011), they are briefly overviewed here focusing on how their ‘sequential’ implementation aspects can be re-implemented within the ‘non-sequential’ format of FLAMEGPU.

2.1.1 FV numerical solver of the SWEs
The selected FV approach adopts a first-order Godunov-type discretisation (Toro & Garcia-Navarro 2007), that is based on local piecewise-constant approximation of the state of the flow variables $U$ in Eq. 1 below. The selected FV approach is also supported with all robustness features (Wang et al. 2011) needed to simulate realistic aspects of flood inundation, such as flow reflections from topographic discontinuities and floodplain flow over rough terrain data with moving wet and dry zones.

On a mesh formed by quadrilateral elements, denoted by $\{I_{ij}\}_{ij}$ ($i = 1, \ldots, N_x$ and $j = 1, \ldots, N_y$), hydrodynamic ABM rules are represented by an element-wise local discretisation of the conservative form, Eq. (1), to the 2D depth-averaged SWEs written in a vectorial form:

$$\partial_t U + \partial_x F + \partial_y G = S$$

in which $(x, y, t)$ are the space-time coordinates, $U = [h, hu, hv]^T$ is vector describing the state of the flow variables, $F = [hu, hu^2 + \frac{1}{2}gh^2, huv]^T$ and $G = [hv, huv, hv^2 + \frac{1}{2}gh^2]^T$ are flux vectors relative to the two Cartesian directions, and $S = [0, gh(S_{0x} - S_{fx}), gh(S_{0y} - S_{fy})]^T$ is the source term vector containing terrain gradient terms ($S_{0x}$, $S_{0y}$) and friction terms ($S_{fx}$, $S_{fy}$) expressed by the standard Manning equation and with a roughness coefficient $n_M$. In these vectors, $h$ (m) denotes the depth of water, $u$ and $v$ (m/s) are the velocities in the $x$- and $y$-axis directions, respectively, and $g$ ($\approx 9.81$ m/s$^2$) is the gravitational constant.
Figure 2. Computational stencil of a local element $I_{i,j}$ for the approximation of the fluxes across its NORTH, EAST, SOUTH and WEST interfaces needing data shared by the four neighbours of $I_{i,j}$ (i.e. $U_R$ or $U_L$ limits in blue).

On each element $I_{i,j}$, the flow variables in $U$ are approximated as piecewise-constant data, denoted by $U_{i,j}^n$, with $n$ indicating the present time iteration. Then, the following element-wise FV discretisation of Eq. (1) can be used to evolve $U_{i,j}^n$ to time iteration $n + 1$:

$$U_{i,j}^{n+1} = U_{i,j}^n - \frac{\Delta t}{\Delta x} (F_{\text{EAST}} - F_{\text{WEST}}) - \frac{\Delta t}{\Delta y} (G_{\text{NORTH}} - G_{\text{SOUTH}}) - S$$

Eq. (2)

In Eq. (2), $\Delta t$, $\Delta x$ and $\Delta y$ denote the time step, element size (i.e. for a square grid here) all of which being globally accessible to any local element $I_{i,j}$ under consideration. In contrast, to achieve local spatial evaluations of incoming and outgoing inter-elemental fluxes and the discrete source terms (i.e. $F_{\text{EAST}}$, $F_{\text{WEST}}$, $G_{\text{NORTH}}$, $G_{\text{SOUTH}}$ and $S$ in Eq. (2)), further access to the piecewise-constant data of the neighbouring elements is required. That is, as shown in Figure 2, access to the four inter-elemental limits, i.e. $U_L$ and $U_R$, of the approximate solution is further needed to evolve each $U_{i,j}^n$ to time iteration $n + 1$, in particular after ensuring robust discretisation of the topography with wetting and drying treatments (Wang et al. 2011) and incorporating an approximate Riemann solver (Harten et al. 1983). Although accessing the neighbouring piecewise-constant data can be performed through direct memory lookups for a ‘sequential’ implementation of Eq. (2) over the mesh $\{I_{i,j}\}_{i,j}$, this is not the case within the framework of FLAMEGPU that requires operating Eq. (2) within a ‘non-sequential’ implementation. This alternative implementation is detailed in the following (Sec. 2.1.2) with particular focus on algorithmic process of describing the grid interaction within an agent-based methodology required to simultaneously elevate all $U_{i,j}^n$ by one time iteration in FLAMEGPU.

2.1.2 Non-sequential implementation using dynamic messaging
On FLAMEGPU, using the indexing $i, j$ is no longer possible, and instead $U^n$ is discretised by a population of quadrilateral ‘flood agents’; and therefore, $i, j$ is translated into fixed $x, y$ coordinates that are stored in the memory of each flood agent as a set of constant variables. The state $U^n$ of all the flood agents is concurrently evolved in time iteration $n + 1$ by executing a transition function (Chimeh and Richmond 2018), which applies Eq. (2) to evolve all flood agent once at a time as described in Figure 3. To do so, piecewise-constant data of the neighbouring flood agents are broadcast to the local flood agents as messages (containing $U$ and $(x, y)$ coordinates). After the messaging process, all local flood agents will be able to locally evaluate $F_{EAST}, F_{WEST}, G_{NORTH},$ and $G_{SOUTH}$ and $S$ from within their local dynamic memory.

Figure 3. A grid of $3 \times 3$ flood agents concurrently elevating their present state ($U^n$) to the next state ($U^{n+1}$) one iteration in time. A local flood agent in the centre (coloured in ‘dark blue’) is the representative of any flood agent on the grid concurrently receiving messages (represented by ‘white message icons’) containing the inter-elemental limits (i.e., $U^n$ and $(x, y)$ coordinates) from its neighbours required for each local flood agent to complete Eq. (2). The ‘curved red arrows’ show that these messages are accessible to the local flood agent at the same time.
2.2 Pedestrian ABM

The pedestrian ABM simulates a crowd of pedestrians moving in an area that act upon a set of navigation rules implemented on FLAMEGPU (Karmakharm et al. 2010; Karmakharm & Richmond 2012). In this ABM, a grid of ‘navigation agents’ forms a map indicating the location of exits, obstacles, and walls, above which ‘pedestrian agents’ walk toward their goal destination (e.g. one of the exits), which is randomly assigned to them once they are generated. The behavioural rules of pedestrian agents are governed by a directional steering force that evaluates their next state (new location) in each subsequent iteration based on social repulsive forces and navigational repulsive forces. As these forces are exerted on pedestrian agents, their walking speed may increase or decrease to avoid collisions with other pedestrians, walls, or obstacles. However, their walking speed here is limited to 1.4 m/s to consider human average walking speed in normal condition (Wirtz & Ries 1992; Mohler et al. 2007).

![Diagram](image)

Figure 4. A diagram outlining the communication network organising the interactions between flood agents and the two types of pedestrian agents (evacuee and responder); the ‘blue’ rectangle represents a flood agent broadcasting a message (‘blue’ arrow dashed-line) containing water flow information to an evacuee pedestrian agent (‘brown’ rectangle) which responds to this message as shown within the ‘white’ dashed rectangle on the left; also an evacuee pedestrian agent (‘brown’ rectangle) broadcasts a message containing its coordinates as $x$ and $y$ (‘brown’ arrow dashed-line) to a flood agent which responds to this message as shown within the ‘white’ dashed rectangle on the right.
2.3 Dynamic coupling

The hydrodynamic and pedestrian ABMs are now coupled to form one ABM, hereafter called flood-pedestrian simulator. This simulator is designed to locally capture the interactions between pedestrian and flood agents as the hydrodynamic and the pedestrian ABM exchange messages. The implementation of the dynamic coupling between the ABM is described in the following, see also Figure 4, for two types of pedestrian agents: evacuee and responder.

Table 1. The status and walking speed of people in water flows according to water depth and velocity pairing spanning the EA (2006)’s flood hazard matrix.

| Flood categories | Severity          | HR From | HR To | Status of pedestrian agents in floodwater | Pedestrian agents walking speed |
|------------------|-------------------|---------|-------|-------------------------------------------|-------------------------------|
| -                | Safe for all      | 0       | 0.75  | (1) Safe                                  | Brisk walk (1.8 m/s)          |
| Class 1          | Danger for some   | 0.75    | 1.5   | (2) Disrupted                             | Brisk walk (1.8 m/s)          |
| Class 2          | Danger for most   | 1.5     | 2.5   | (3) Disrupted                             | Slow walk (1.0 m/s)           |
| Class 3          | Danger for all    | 2.5     | 20    | (4) Trapped                               | No walk (0.0 m/s)             |

Evacuee agents represent individuals evacuating a flood, whose behaviour is informed by the characteristics of water flows broadcasted locally by flood agents to pedestrian agents (i.e., via a message containing \( h \), \( v \), and \( u \); see (1) and (2) in Figure 4). The evacuee agents respond to these messages by increasing or decreasing their walking speed depending on their local ‘status in water’ (see Table 1). The status of each evacuee agent in water is parameterised according to EA (2006)’s flood hazard matrix through pairing of \( h \) and velocity magnitude \( V \) for rating flood hazard, as Hazard Rate (HR) = \((V + 0.5) \times h\) where \( V = \max(|u|, |v|)\). Herein, the HR is considered while ignoring the effect of debris (EA 2006). Also, once a positive \( h \) is
broadcasted by any flood agent in the domain, evacuee agents will no longer be entering the
domain, and those already in the domain will be leaving to a specific goal destination (e.g. an
emergency exit).

**Responder** agents represent individuals taking part in an intervention process to
construct a temporary flood defence barrier, here assumed to be by sandbagging. The barrier is
represented by topography variable ($z$) stored in the memory of the flood agents, and is updated
in response to the action of the responder agents. In order to update $z$, each responder agent has
to complete an iterative process consists of four main subsequent steps as shown in Figure 5.
In the first step (Step 1), the responder agent is directed to a temporary goal destination
informed by a navigational agent (e.g. location for the sandbag storage). Once the responder
agent reaches the storage, Step 2 consists of picking up a sandbag, followed by Step 3 aimed to
subsequently redirect the responder agent to a new temporary goal destination (e.g. a pre-
specified location for defence barrier where they should drop the sandbag). Finally, as the
responder agent arrives at latter destination, Step 4 consists of informing the flood agent at its
same location ($x$ and $y$) to increase its $z$ value. The increment in $z$ value is related to the spatial
dimension of a sandbag and resolution of the grid used for the flood agents. This increment is
added in a horizontal order until forming a longitudinal barrier that is one layer high, and the
process restarts to form as many layers in height as desired (i.e. this is specified by the user in
the *input.xml* file, Figure 1).
Figure 5. Four main steps of a process completed by each responder pedestrian agent to increase \( z \) stored in the memory of a flood agent; flood agents here are represented by the 3 \( \times \) 3 ‘blue’ grid, the ‘green’ dashed-line represents the direction towards the temporary goal destinations that are shown as ‘red’ dots.

3. Verification of the hydrodynamic ABM implementation on FLAMEGPU

Two academic dam-break tests are selected to verify the FLAMEGPU implementation of Eq. (2) in evolving flood agents. The first test considers a classical radial dam break flow involving symmetric 2D water propagation over a flat, frictionless, and initially wet domain. The second test also considers 2D dam break flow propagation, but propagating over a rough, initially dry and closed domain including three topographic humps. FLAMEGPU simulations for both tests are run on a grid of 128 \( \times \) 128 flood agents and using adaptive time step based on a CFL number equal to 0.5. Simulation results are compared to those produced by a sequential flood model counterpart implemented on MATLAB and with reference predictions reported in the literature.

(a) 1D diagonal cross-sectional profiles of water depth and discharge at \( t = 1.4 \) s

(b) 1D diagonal cross-sectional profiles of water depth and discharge at \( t = 4.7 \) s
Figure 6. Comparing the profiles of water depth and discharge simulated via the hydrodynamic ABM (red line) against MATLAB (blue circle-marked line) and the reference solution (solid black line). The profiles on the left represent water depth \((h)\) and on the right are the profiles of water discharge both along the radial direction.

3.1 Radial dam-break flow

This test (Toro 2001) involves the symmetrical propagation of a circular, tsunami-like, wave over a flat and frictionless domain enclosed by walls. This test is often used to verify the implementation of newly developed shock-capturing numerical flood models, to verify their ability to capture different types of shallow flow transitions and to produce symmetrical profiles (Wang et al. 2011; Kesserwani et al. 2018). The wave propagation happens after instantaneous removal of an imaginary cylinder-shaped dam located in the centre of a 40 m × 40 m square domain, causing a circular wave moving outwards from the centre (Toro 2001). The thin 2.5 m radius circular wall of this dam retains a column of water 2.5 m deep. The rest of the domain outside the dam is covered with 0.5 m of still water. A reference solution can be obtained by solving the SWEs along the radial direction (Toro 2001) by a second-order accurate scheme over a fine mesh of 1001 × 1001 cells (Wang et al. 2011; Kesserwani et al. 2018).

Figure 6 compares the outputs produced by the hydrodynamic ABM to those of the sequential implementation on MATLAB and the reference solution, in terms of water depth \((h)\) and flow discharge \((q)\) cross sections along the radial direction at times \(t = 1.4\) s and \(t = 4.7\) s (i.e., as in Toro (2001) and Wang et al. (2011)). At \(t = 1.4\) s (Figure 6.a), a front shock wave propagating away from the centre towards the boundary is expected to be formed and the water depth in the centre drops to below the initial water depth outside the dam; whereas, at \(t = 4.7\) s (Figure 6.b), the propagating shock wave reaches close to the boundaries, a hump-shaped water surface is formed in the centre of the domain after the collision of depression waves moving inwards. As can be seen in Figure 6, these profiles of water depth and discharge are seen to
preserve the expected radial symmetricity at both output times $t = 1.4$ s and $t = 4.7$ s. Also, the hydrodynamic ABM outputs are identical to those produced by the sequential flood model, while both being in good agreement with the reference solution. The clear discrepancies relative to the reference solution are expected, given that it was computed on a mesh resolution that is approx. 8 times finer and using a higher order numerical solver. Nonetheless, this solution is reproduced by the hydrodynamic ABM at the same predictive quality as the sequential model counterpart, indicating a sound functioning of the hydrodynamic ABM on FLAMEGPU.

3.2 Dam-break flow over rough terrain with flooding and drying

The hydrodynamic ABM is further applied to reproduce dam-break flows over a rough terrain with wetting and drying, in order to verify the robustness of its implementation for handling realistic aspects of flooding. This test assume a dam-break wave propagating over a $75 \times 30$ m closed domain (i.e. by four imaginary walls) with an initially dry floodplain including three humps (see Figure 7). The imaginary dam is here located along $x = 16$ m locking an initial body of water with a height of $1.875$ m. The roughness of the domain is represented by Manning coefficient $n_M = 0.018$ s/m$^{1/3}$.

Figure 7-left shows the simulated water surface elevation produced at the same output times as the results in Huang et al. (2013), which are shown in Figure 7-right. At $t = 6$ s, the front wave passes over the small humps and it collides with the large hump that causes water accumulation and a raise in water level. At $t = 12$ s, the water passes either side of the large hump and it reaches the dry areas downstream, while more accumulation of water can be seen behind the large hump. At $t = 30$ s, the moving water covers the entire domain and the peaks of the small humps are seen to be dried again. At $t = 300$ s the water volume becomes stored, motionlessly after the flow is damped by friction effects, in the domain. As illustrated in Figure 7, the outputs delivered by the hydrodynamic ABM are very similar to those of Huang et al. (2013), showing the model ability to capture wave reflections, wetting and drying processes,
and conserve mass as the dam-break flood settles hindered by friction effects. This indicates that the hydrodynamic ABM is suitable for applications involving realistic flood scenarios.
4. **Verification of the simulator’s dynamic coupling**

In this section, an ad-hoc hypothetical test case of a flooded shopping centre is proposed to evaluate the capability of the flood-pedestrian simulator in modelling the interactions between people's actions and floodwater flows. This test assumes a shopping centre encompassing a crowd of walking pedestrians exposed to flooding, and distinguishes two scenarios. The first, termed hereafter ‘Scenario 1’, assumes that there is no early warning and evacuation plan and focuses on analysing the dynamic changes in people status, behaviour and position in line with the change of floodwater flow propagation. The second scenario, termed hereafter ‘Scenario 2’, focuses on analysing strategies of people responses to reduce the flood risk upstream of the emergency exit, hence assuming an intervention to deploy a temporary flood barrier followed an early evacuation for the pedestrians.

![Figure 8. An illustration of the shopping centre: the open area is represented by a blue grid with sets of stores located on west and east shown by brown colour, the amber lines represent the entrance doors, the emergency exit is the entrance door located at the north-west corner, the green pedestrians symbolise evacuating people, the black pedestrians are the emergency responders.](image)
responders in (b) who pick up sandbags from the sandbag storage represented by an amber rectangle on the west side, and the orange dashed rectangle linking west-side stores to the east-side stores represents the proposed sandbag barrier.

The area of the shopping centre is $332 \text{ m} \times 332 \text{ m}$ (see Figure 8), chosen considering the average area size of UK’s 43 largest shopping centres (Globaldata Consulting 2018; Tugba 2018; Sen Nag 2018; Gibson et al. 2018). A set of stores are located at the east and west side of the shopping centre, which are separated by corridors linking the entrance doors to an open area. Through these corridors, pedestrians can enter the open area and walk toward their destinations. The open area is assumed to be occupied by 1000 pedestrians. There are 7 hypothetical entrance doors allowing people to enter and/or leave the area with an equal probability of 1/7. The flood propagation occurs from the southern side (Figure 8) assuming a river inundation (e.g., as happened in Sheffield 2007 floods when Meadowhall shopping centre was flooded from River Don). As the flooding starts in Scenario 1, pedestrians evacuate to an ‘emergency exit’ located at the northern side of the shopping centre (Figure 8.a) in response to an emergency announcement. The emergency exit’ is accessible via one of the exits and remains open during evacuation.

In Scenario 2, a percentage of the crowd acts as ‘emergency responders’ tasked to deploy a local flood barrier in response to an advanced flood warning of 12 hours. The barrier is 168.6 m long and 2.59 m wide (Figure 8.b) and can be built by placing horizontal layers of sandbags (as explained in Sec. 2.4). Each sandbag size is on average 40 cm long, 30 cm wide, and 25 cm high following standard recommendations (Williamson 2010; Hellevang 2011; Padgham et al. 2014). This means that at a modelling resolution of 2.5 m, 3640 sandbags are required to construct a barrier that is one-layer high, which is a sensible number according to online tools (e.g., Sandbag Wall Calc 2019) and the EA recommendations for estimating sandbag numbers (EA 2009). Note that this was the maximum resolution affordable considering
that memory storage needs to be tripled to simultaneously represent navigation, pedestrian and flood agents. The sandbags are assumed to be stored in a truck that is parked at one of the entrances (see Figure 8.b). Each emergency responder is set to wait 30 s at the location of the storage to pick up a sandbag, and to undergo another wait of 30 s to safely drop it at the flood barrier area. This is in addition to the time required to walk the 100 m distance between the storage location and the barrier location.

![Inflow hydrographs produced based on inflow discharge (Q) changing over time (t): for Case 1 (green), the duration of inflow takes 1 hour and the discharge reaches its peak of 20 m³/s after 30 minutes; for Case 2 (blue), the duration is now halved to 30 minutes and therefore the inflow discharge reaches its peak of 40 m³/s after 15 minutes; for Case 3 (amber), the duration is again halved to 15 minutes causing doubled peak discharge of 80 m³/s happening after 7.5; for Case 4, the duration of inflow is further halved and reduced to 7.5 minutes that causes the highest peak discharge of 160 m³/s after 3.75 minutes.](image)

**4.1 Flooding cases with associated HR analysis**

Floods are generated by inflow hydrographs based on a peak discharge $Q_{peak}$ and an inundation duration $t_{inflow}$. As can be seen in Figure 9, the flooding cases are assumed to release the same volume of water $V_{inundation}$ into the shopping center, based on varying $Q_{peak}$ and $t_{inflow}$. To ensure that the floods generated by these hydrographs are close to reality, $Q_{peak}$ for one hour of flooding
is calculated by the initial depth \(h_{\text{inflow}}\) and velocity \(v_{\text{inflow}}\) for Norwich case study of river inundation (EA 2006) where \(h_{\text{inflow}} = 1\) m and \(v_{\text{inflow}} = 0.2\) m/s. This forms Case 1 of flooding inflow with \(Q_{\text{peak}} = v_{\text{inflow}} h_{\text{inflow}} B\) (Chow 1959; White 2011), where \(B\) is the length of inflow assumed to be 100 m long. Cases 2, 3 and 4 are set to represent more severe flooding than Case 1, with their \(Q_{\text{peak}}\) derived by successive halving of \(t_{\text{inflow}}\) on the basis that \(V_{\text{inundation}}\) remains constant, i.e., leading to the flood spreading over a shorter duration (Figure 9).

Figure 10. Changes in maximum HR during the 60-minute flood period over the shopping centre relative to Case 1, Case 2, Case 3 and Case 4 floods, induced by the hydrographs in Figure 9. Maximum HR for Cases 1 and 2 remains below 1. For Case 3, the maximum HR fluctuates considerably within the first 10 minutes reaching around 1.8 after 5 minutes, but remains predominantly below 1. For Case 4, the maximum HR is notably above 1 in the first 15 minutes with a peak reaching to almost 6.8 after only 5 minutes.

To analyse HR for the four selected flooding cases, the hydrodynamic ABM is applied with the inflow hydrographs of Figure 9, respectively, introduced from the breach at the southern boundary. Northern boundary is considered open whereas eastern and western boundaries are walls. The bed roughness is defined by Manning coefficient \(n_M = 0.011\) s/m\(^{1/3}\) representing a clear cement (Chow 1959). The simulation is done for 128 × 128 flood agents, resolution equivalent of 2.5 m. Figure 10 shows the time history of the maximum HR for Cases
1-4 within one hour of flooding, clearly indicating that Case 4 is the worst-case flooding scenario. Hence, it is selected for further analysis later based upon Scenarios 1 and 2 defined previously.

### 4.2 Dynamic simulation of flooding and people interaction for Case 4

The flood-pedestrian simulator is configured with $128 \times 128$ flood agents, a grid of $128 \times 128$ navigation agents and a population of moving pedestrian agents. Given the memory needs for dynamic message broadcasting and storage of agents across the three grids, 2.5 m was the maximum affordable on a 1 GB Nvidia Quadro K600. As the time-step of the hydrodynamic ABM was smaller than the 1.0 s time-step of pedestrian simulator, it governed the simulation when the domain is wet.

![Figure 11](image)

Figure 11. A stacked area chart showing the percentage distribution of the peoples’ status (see Table 1 in Section 2.3) who are still inside the shopping centre during a 13-minute evacuating time: ‘green’ area represents those exposed to very low or no floodwater, Status (1); ‘blue’ represents those slightly disrupted people by moderate floodwaters, Status (2); ‘orange’ represents those considerably disrupted by severe floodwater, Status (3); ‘red’ represents those trapped people in extremely severe floodwater, Status (4).
Figure 12. Dynamic changes in the status of people along with their location and exposed floodwater HR: ‘green’ shows individuals in dry areas, ‘blue’ represents people slightly disrupted by floodwater, ‘orange’ are people severely disrupted by water flows, and ‘red’ are people trapped in fast and deep water flow.
4.2.1 Changes in the status of people during the flood

From the flood-pedestrian simulator, time history of the statistics of people status in floodwater can be obtained as the flood evolves (see Figure 11). Figure 11 shows the percentage distribution of people’s status (see Table 1 in Section 2.3) over the first 13 minutes of flooding produced by Case 4. Before 2.5 minutes, the majority of people are walking either in dry zones, Status (1), or in very low floodwater, Status (2), whereas relatively smaller percentage of people are seen to be disrupted, Status (3). Between 2.5 to 5 minutes, the percentage of those disrupted by floodwater rises significantly and a large number of people are identified to be now trapped in water flows, Status (4). This implies that severe water flows reach to the crowd of evacuees during this period. However, after 5 minutes, although everyone is still found to be disrupted by water flows, they are able to continue evacuating the area.

Figure 12 also shows the spatial distribution of people’s status in the flooded shopping centre at six output times with a step of 2 minutes, alongside 2D contour plots of HR (Table 1). At the start of Case 4 flooding (Figure 12.a), as there is no early evacuation plan, people are seen to be scattered randomly in the open area and the corridors. After 2 minutes of the flooding (Figure 12.b), floodwater covers more than half of the domain and starts to disrupt few people while evacuating to the emergency exit. After 4 minutes (Figure 12.c), severe water flows are seen to cover the entire domain and cause disruption for everyone and made many trapped in floodwater around the centre of the open area. After 6 minutes (Figure 12.d), the HR drops down indicating slower and shallower flood flows that allow the trapped people to become disrupted again. After 6 minutes, the HR is seen to gradually decrease (Figure 12.e and Figure 12.f), showing that the flooding is no longer disruptive to people and that everyone is ultimately going to continue the evacuation process.
4.2.2 Comparison against EA’s risk-to-life method

After the simulation, the number of people at risk is extracted to allow for a comparison with EA’s risk-to-life approach (EA 2006). This approach estimates the percentage of total population at risk of death or injury (X) during and in the immediate aftermath of a flooding event. X is the product of HR and AV, where AV is a factor named Area Vulnerability. This approach is usually applied for large regions, informed by (passive) hydrodynamic model outputs of floodwater depth and velocity to estimate an average HR over certain flood hazard zones based on the thresholds in Table 1. As the shopping centre can be wholly considered a coarse flood hazard zone, a maximum HR of 6.8 (Sec. 1.1.2) is considered, assuming the worst case scenario. This leads to X = 40.8%, considering an AV = 6 that is indicative of a medium risk area based on the scoring described in Table 2 (EA 2006).

Table 2. Parameters used in estimating AV for the shopping centre

| Parameter                  | Condition for shopping centre          | Score |
|----------------------------|----------------------------------------|-------|
| Speed of onset             | Rapid; less than 1 hour                | 3     |
| Nature of the area         | Commercial and industrial              | 2     |
| Flood warning              | Good; covers the entire area           | 1     |
| **Total estimated AV**     | **6**                                  |       |

From the pedestrian ABM, the total number of disrupted people and those trapped in floodwater during Case 4 (Sec. 1.2.2) is found to be 42.4% of the pedestrian population. This prediction defines the number of people at risk and is very close to the estimation made by EA’s risk-to-life method (i.e., 40.8%). For robustness, simulation was also repeated with systematic increase of pedestrian population size up to 16000, and the discrepancy between the simulator’s and EA’s risk-to-life method’s results did not exceed 4% (Table 3). Hence, the present flood-
pedestrian simulator seems able to provide spatiotemporal statistics of flooded people whose status and behaviour changes dynamically as local floodwater characteristics change.

Table 3. The percentage of difference between the simulated number of people at ‘risk’ and EA’s risk to life method

| Population size | Discrepancy with EA |
|-----------------|---------------------|
| 1000            | 1.6 %               |
| 2000            | 0.2 %               |
| 4000            | 2.0 %               |
| 8000            | 3.5 %               |
| 16000           | 2.1 %               |

Figure 13. The time taken to deploy a local flood barrier with different heights in terms of sandbag layers. The red line indicates the starting time of the flood (Case 4). The coloured bars indicate the time required to build a flood barrier with increasing different height and considering different group size of emergency responders ranging between 5-50% of the pedestrian population.
4.2.3 Time and emergency responders required to build a flood barrier (Scenario 2)

The flood-pedestrian simulator is now applied to Scenario 2, to assess intervention strategies by emergency responders in terms of analysing options for safe deployment of a local flood barrier before Case 4 flood occurs. From a population of 1000 pedestrians, different size of group of emergency responders is explored considering 5, 10, 20, 30, 40 or 50%. Simulations are run with a view to find an optimal group size for a safe and effective emergency intervention within a 12-hour window of advanced warning before the flood occurs (Figure 13).

![Figure 14. Centralised floodwater depths along y-axis direction after the deployment of the local flood barrier (red dashed line) with different heights in terms of horizontal sandbag layers ranging from one to six layers.](image)

Firstly, the flood-pedestrian simulator is applied to predict the time required by the different emergency responder groups to potentially construct a local flood barrier made by as high as six horizontal layers of sandbags. Figure 13 shows the respective simulated time taken where the red horizontal line indicates the starting time of the flood (Case 4). The area below the red line is shaded in green indicating the time frame (i.e., 12-hour period) during which the emergency responders can safely take action. Clearly, the simulator sensibly predicts that the bigger the group size, higher barrier can be constructed: with 5% of emergency responders, only a one-layer high barrier is safety deployable, whereas involving 10-20% of emergency
responders make it possible to deploy a barrier that is at least three-layer high. The simulator also shows (Figure 13) that building safely the highest barrier possible (i.e. six-layer) requires involving at least 30% of emergency responders. Hence, Figure 13 suggest that safe building of a local flood barrier is possible, that is at least one-layer high within the safety time window, and that having more layer requires involving more than 5% of emergency responders.

Secondly, to study how much height is needed for the local barrier, outputs of the hydrodynamic ABM are further analysed, in terms of 1D longitudinal water depth centrelines (Figure 14). While the plots in Figure 14 indicate lower water levels downstream of the barrier with increasing height, as expected, they particularly inform that a minimum of three-layer high is needed to ensure lowering the water depth to a level where pedestrians can still walk (i.e. 0.2 m and lower, see Table 1 in Section 2.3). Hence, looking at both states of flooding and pedestrian agents, it at least three-layer high barrier needs to be deployed to ensure enough safety.

Figure 15. Cumulative percentage of maximum HR reduction with increased height of the local flood barrier in terms of number of sandbag layers. That is, a one-layer high barrier reduces the maximum HR by 91.2%, the two-layer high barrier provides further reduction of 5.3% in maximum HR, and the three-layer high barrier further reduces the maximum HR by 1.9%; higher barrier (i.e. of four-layer and more) provides no significant further reduction in maximum HR.
Finally, to further study flood velocity impact on the choice of the responder group size and on the height required for the flood barrier, analysis of the relative change in maximum HR is performed. Figure 15 shows the relative decrease in HR as the number of horizontal sandbag layers increases. Clearly, the most notable drop in maximum HR, i.e. of 91.2%, is noted after building a one-layer high barrier. Further reduction of 5.3% is seen when reaching a two-layer high barrier, followed by an extra reduction of 1.9% with the three-layer high barrier. However, this reduction is observed to stagnate around 0.4% if higher barriers is built, which seems to suggest that deploying barrier that is more than four-layer high may not be an effective choice for this case. Overall, supported by the analysis in Figure 13-15, the coupled flood-pedestrian ABM suggest involving at least 10% of 1000 pedestrian population as responders to be able to build a local flood barrier that leads to an effective and safe reduction of flood risk around the emergency exit for the shopping centre.

5. Summary and conclusions

An agent-based simulator has been developed on FLAMEGPU that dynamically couples a hydrodynamic ABM to a pedestrian ABM. The hydrodynamic ABM was formed by a non-sequential implementation of a FV shock capturing numerical formulation that is commonly used in flood modelling packages. This implementation assumed a grid of flood agents that evolve concurrently once at time in each time iteration. The pedestrian ABM was represented by a social force model governing a flow of individual pedestrians. The hydrodynamic ABM and the pedestrian ABM were coupled according to risk-to-life thresholds reported by the EA. After validating the hydrodynamic ABM on FLAMEGPU based on two academic test cases, the simulator was assessed for a hypothetical case study of a flooded shopping centre involving both people and floodwater interactions. The case study distinguished an evacuation and an intervention scenario under realistic flooding inflow condition reported by EA. For the
evacuation scenario, pedestrians were walking in the open area of the shopping centre and start walking to an emergency exit as flash flooding strike without an advanced warning. The intervention scenario included a group of emergency responders tasked to build a sandbag-based temporary defence barrier to reduce floodwater extent and magnitude upstream of the emergency exit, and within an advanced warning period of 12 hours.

The flood-pedestrian simulator was applied to simulate these scenarios with the view to evaluate its dynamic coupling ability and identify how it can be used to map evacuation and intervention statistics with unprecedented level of details. For the evacuation scenario, the simulator was able to provide microscopic analysis of each individuals’ spatial and temporal states before and during flooding, which enables to acquire statics of what actually happened to the pedestrians during the whole flooding duration and within the whole spatial domain. For the intervention scenario, the simulator provided useful information on potentially affordable labour, time needed to efficiently build a barrier within the 12 hour window, and height needed for the barrier to achieve acceptably safely level. Hence, the proposed simulator seems to have a great potential to acquire detailed statistics of flood-on-people and people-on-flood impacts prior and during flooding, of relevance to inform evacuation and intervention strategies in the context of flood community preparedness, risk mitigation and management.

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