Use of agent-based modelling in emergency management under a range of flood hazards

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Abstract. The Life Safety Model (LSM) was developed some 15 years ago, originally for dam break assessments and for informing reservoir evacuation and emergency plans. Alongside other technological developments, the model has evolved into a very useful agent-based tool, with many applications for a range of hazards and receptor behaviour. HR Wallingford became involved in its use in 2006, and is now responsible for its technical development and commercialisation. Over the past 10 years the model has been applied to a range of flood hazards, including coastal surge, river flood, dam failure and tsunami, and has been verified against historical events. Commercial software licences are being used in Canada, Italy, Malaysia and Australia. A core group of LSM users and analysts has been specifying and delivering a programme of model enhancements. These include improvements to traffic behaviour at intersections, new algorithms for sheltering in high-rise buildings, and the addition of monitoring points to allow detailed analysis of vehicle and pedestrian movement. Following user feedback, the ability of LSM to handle large model 'worlds' and hydrodynamic meshes has been improved. Recent developments include new documentation, performance enhancements, better logging of run-time events and bug fixes. This paper describes some of the recent developments and summarises some of the case study applications, including dam failure analysis in Japan and mass evacuation simulation in England.

1 Background to Life Safety Model

With improvements in 2-dimensional modelling of flood flows, associated with increasing computer power and visualisation, the use of agent-based modelling to investigate receptor behaviour and fate has become more widespread. One such agent model is the Life Safety Model (LSM) which was developed originally for dam break assessments and for informing reservoir evacuation and emergency plans [1, 2].

HR Wallingford became part of the LSM user community in 2006, when we started to use it as part of the major EC research project FLOODsite (www.floodsite.net), to investigate evacuation along the Thames Estuary. Since the beginning of 2012, we have formally taken over the responsibility for its future development, licensing and promotion on behalf of British Columbia Hydro and Power Authority ('BC Hydro'). In this role we undertake a programme of agreed model developments, jointly-funded by our two organisations, as well as support a number of commercial and academic users, according to their respective licence agreements.

The model is able to use a range of industry-standard 2D hydraulic model outputs. These flow models provide a grid of predicted water depths and velocities at each time step. In addition, census, building and road datasets will be required to set up the 'virtual world' comprising a series of receptors; this is depicted in Figure 1.

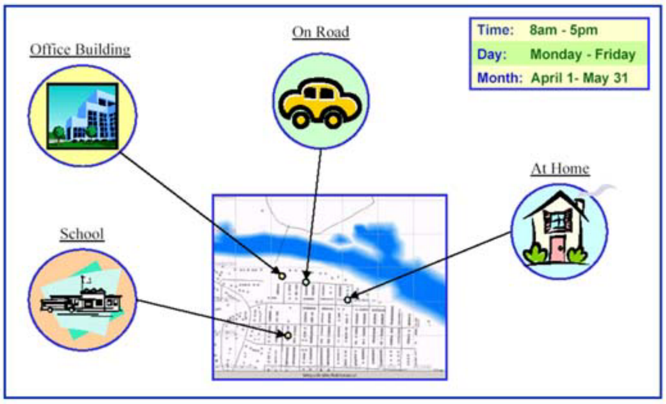

Figure 1. Components of the 'virtual world'

The LSM simulates the "fate" of these receptors, which are described by their position at each time step through the simulation. Receptors are objects that can be affected by a hazard, such as a flood, and in the case of LSM comprise people (individuals and groups), vehicles and buildings. The outputs of the LSM simulation are an estimation of receptor impacts (such as loss of life and building collapse), as well as a dynamic, computer-generated visualisation of the results. Each receptor can be allocated a set of properties that defines its behaviour, so that different scenarios can be simulated. For example, if a summer vacation period is being simulated, a school

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may be out of session, and students will not be located there during the day. In addition, the study area may also experience an influx of visitors, so the population is increased temporarily. So it is important to consider time varying properties of a receptor since it represents the varying risk. Other time-varying properties include the ability of the receptor to withstand the effect of the flood wave, and how it would react to the approaching wave, with and without a formal evacuation warning.

The model uses generalised event logic to determine the location of each receptor, whether it is aware of the flood wave, whether it is trying to find a safe haven, what happens if it encounters the flood, and whether the object survives or not. A loss function related to each receptor (e.g. people, buildings, and vehicles) specifies the ability of a receptor to resist the impact from the flood wave, in terms of depth and velocity, and how these can change during an event. This approach, based on flood depth and velocity, is common in many countries for emergency management assessments. There can be instantaneous loss when an individual encounters fast-flowing water, or a group who have sought safety in a building can suffer loss if the building collapses, or experience cumulative loss via a slow deterioration in health if they are exposed to the flood water for a significant length of time, resulting in hunger or cold.

As a flood event evolves, the interaction of receptors with the flood wave will impact the ultimate loss of life and injuries. The timing of the event and the decisions made by individuals can determine whether or not they can escape the flood wave. As the flood progresses, escape routes can be eliminated by rising water, and with advancing time roads can become congested with evacuees.

Figure 2 provides a conceptual summary representation of how the LSM is applied, combining 2D water flow with a 2D ‘people flow’.

For a given population at risk, LSM can:

- Estimate the potential loss of life and building loss from an extreme flood event
- Produce a series of virtual representations of how a flood emergency could evolve
- Support emergency management analysis, which aims to develop and test mitigation strategies that could reduce the potential life loss (this could include provision of warnings and safe havens, designated evacuation routes).

This paper outlines the model developments undertaken over the past few years as part of a programme of work agreed by the core user community. The current functionality and use of the model is then demonstrated by several contrasting applications from around the world.

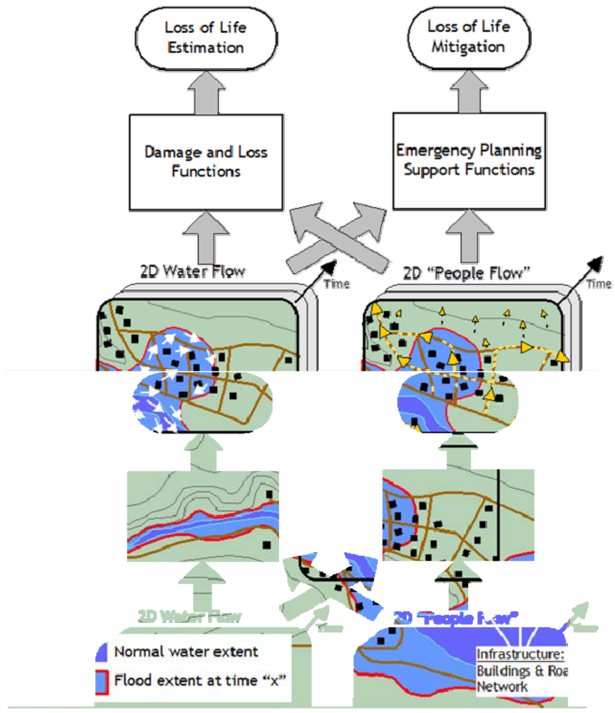

Figure 2. High-level concept of LSM simulation (from BC Hydro 2006)

2 Recent model developments

Working with BC Hydro and other core users, the LSM has been enhanced over the past few years to include a range of new features. These include:

- Building losses due to high water depth and low velocity
- A mechanism for loss of life when buildings fill with water but are not destroyed
- A mechanism for people to shelter in buildings when the water depth reaches a threshold
- Improved traffic flow
- Improved traffic monitoring and monitoring the number of people that reach each safe haven
- Ability to run the model without any hydrodynamic output: ‘running in the dry’
- A 64 bit application for modelling large geographic areas and populations.

The following sections provide further explanation of some of these features.

2.1 Modelling of building loss

At every time-step the model determines if each building is still standing or has been destroyed. It does this by extracting the depth and velocity from the hydrodynamic output grid, and computing the ‘impact’ parameter DV (depth * velocity). These are compared with strength parameters set by the user for each building, and if exceeded will indicate the building is destroyed. In the original version, building loss occurred through either instantaneous loss when the DV reached a critical value, or by cumulative loss as the building is exposed to water for an extended period. This could equate to impacts such as erosion of the foundations, hydrostatic pressure on walls or doors, bombardment by water-borne debris, or simply loss of structural integrity through extended wetting. The updated version includes a further loss mechanism, such that when the flood depth is greater than the height of the building, the building is destroyed [3]. The status of the building can now be defined by four states:

0 = Standing
1 = Destroyed - Depth
2 = Destroyed - DV
3 = Destroyed – Cumulative loss.

This formulation is illustrated in Figure 3 and is seen as a more realistic outcome under very deep floodwater. The parameters delineating the zones shown in Figure 3 can all be specified by the user for each building; this also applies to the corresponding diagrams for vehicle and people stability. The maximum height of each building sets the upper limit on water depth beyond which total failure is assumed. The curved boundary between the two zones is set by the critical depth * velocity value (BDVC) which is set for each type of building, based on published values [4-6].

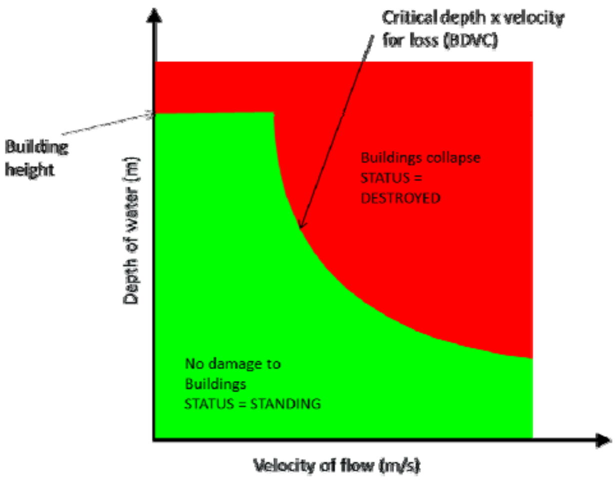

Figure 3. Building loss function

2.2 People-building interactions

Buildings generally provide the main opportunities for safe havens within a modelling domain. Therefore the way in which the affected population use them is important in assessing the potential fatalities. When evacuees arrive at a building, there is a realistic time interval for them to enter and disperse. The original formulation did not allow groups to split to fill any remaining spaces if the building could not accommodate them all. This had the result of available spaces within but with people still queueing outside. The latest version has allowed arriving groups to split to ensure that buildings do fill up, so that the next available safe haven can be recalculated and the remaining group members to set off in that direction.

In the original model decision logic, once a person or group was aware of a flood they would start to evacuate from their starting-point, using the most appropriate route and means of transport, looking for the closest safe haven. In some circumstances this had the unfortunate outcome that people would leave a building and enter floodwater with a high DV and instantly perish. Whilst this could happen in some situations, because people may not appreciate the danger through lack of previous contact with floodwater, we believe that most people would decide that their home is a safer option (especially if it has upper floors that are likely to remain dry). Such vertical evacuation is a key element of any emergency plan [7]. The model was therefore updated to allow for more ‘intelligent’ decision-making from those surrounded by water.

If a building is destroyed by whatever set of conditions then it is assumed that any people inside are also lost. In addition, there can also be loss of protection where people drown inside the building if the flood water rises high enough. To account for this loss mechanism the water depth is compared to the height of each floor and if the water depth is greater than the height of the floor plus a foundation height the people in the building are considered drowned, as shown in Figure 4.

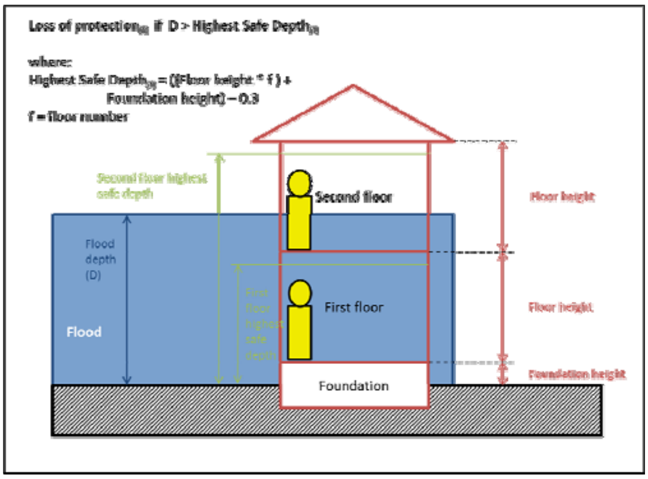

Figure 4. Loss of protection in buildings

The purpose of a multi-storey building is to allow people to shelter in place rather than attempting to evacuate across flood water. A new refinement to the model was to reproduce the drowning of individuals who are ‘trapped’ on any particular storey and unable to escape higher. Clearly when the floodwater reaches the top elevation of the house all occupants are assumed to drown; this was a feature of certain fatalities on Canvey Island resulting from the 1953 storm surge where in-situ sheltering was limited due to the prevalence of single storey buildings [8].

The overall outcome of the improvements on the people-building interactions is that the status of each person or group can take one of the following states:

0 = UNAWARE
1 = AWARE – Have been warned of the flood and preparing to respond
2 = EVACUATING – Evacuating on the road and trail network
3 = SAFE – Arrived at a Safe Haven
4 = TOPPLED – Made unstable by the flood and effectively immobilised
5 = DECEASED – DROWNED – Drowned by DV

6 = DECEASED – EXHAUSTION – Cumulative loss due to physical exhaustion

7 = DECEASED – BUILDING DESTROYED – Deceased in destroyed building

8 = DECEASED – BUILDING DROWNED – Drowned by D in building

9 = DECEASED – TOPPLED VEHICLE – Deceased in lost vehicle.

2.3 Improved traffic modelling

The model uses a simplified traffic model based on Greenshields' density/speed relationships [1935], with distance travelled being a function of lane speed, vehicle density and timestep. Although the model has been calibrated/verified against the Malpasset dam failure [6, 9] and the storm surge on Canvey Island [8, 10], there is little empirical data on traffic movements during similar evacuation events with which to check the accuracy of the model. Therefore with each new study the project team reviews the 'realism' of the predicted behaviour; for traffic movements this concerned suitable timesteps and road segment lengths.

As with any timestepping model the time step length can influence results. The time step must be small enough to accurately resolve the movement of objects (people and vehicles) through the impact zone and allow interaction with the flood hazard. If the time step is too large relative to the speed of movement, the objects can appear to 'jump' or move too far within a time step before they next interact with the flood, which can affect estimates of loss of life. Table 1 shows the distance that objects would move under free-flow conditions during a time step as a function of the travel speed and the time step.

Time step (s)	Distance travelled (m)			
	1 km/hr	10 km/hr	50 km/hr	100 km/hr
1	0.8	2.8	13.9	27.8
5	4.2	13.9	69.4	138.9
10	8.3	27.8	138.9	277.8
30	25	83.3	416.7	833.3
60	60	166.7	833.3	1666.7

Table 1. Distance moved on a road segment based on timestep and travel speed

The model time step can also influence:
- traffic flows at intersections;
- the ability of vehicles to enter the road network from buildings;
- entry into Safe Havens;
- hydrodynamic conditions.

LSM provides the modeller with the statistics needed to review initial results and confirm suitable values for the space and time scales.

Overall, a forensic analysis of sample simulations has resulted in better traffic logic that reduces the models sensitivity to parameters such as timestep length, and provided recommendations for the spatial and temporal resolution of the model domain.

2.4 Running large model data sets

LSM is a micro-based model that simulates the behaviour of individuals and therefore the input data file sizes can be significant for large population centres. However, what has been found to provide more of a data handling challenge are the output files from the hydrodynamic simulation, which could cover very extensive areas in great detail (as required for hydraulic stability). For example, one study involved a cascade of dams and the desire to investigate potential failures along the cascade. This required a very large hydrodynamic model domain to produce the flow routing along the river valley. Memory issues occurred when running the LSM. As a result, the change to a 64 bit model build now allows LSM to run much larger models than the 32 bit version. Model data sizes are discussed further in the Discussion section.

3 Example model applications

This section summarises some of the case study applications of the LSM, including dam failure analysis in Japan and mass evacuation simulation in England.

3.1 East Coast storm surge and mass evacuation (England)

The East Coast of the UK is at risk from large scale inundation in a low probability extreme storm surge. In such a situation, up to 400,000 people may need to evacuate away from the coast, and a key issue was how to use the local road network to optimise a successful evacuation. In the last few years, therefore, the relevant Local Authorities have commissioned studies to inform the development of plans for mass evacuation of the low lying areas in such a scenario. These studies considered two study areas: Lincolnshire & Norfolk and Humberside [7]. Three levels of modelling were used: a static, macro model (the Dutch *Evacuation Calculator)* to gain insight of the effectiveness of different strategies; a meso-dynamic traffic model (OmniTrans) to identify local bottle necks in the road network; and the agent-based, micro model (Life Safety Model) to investigate individual people behaviour at the local or micro scale. This tiered approach provided detailed and valuable insight of the issues associated with data collection and the modelling assumptions, and how the uncertainties associated with these could be addressed.

The LSM was used, therefore, as part of a tiered traffic modelling approach to investigate how long it would take for mass evacuation of the area in advance of a major storm surge (such as happened in 1953). The basis of the modelling was to achieve a safe evacuation in sufficient time before conditions deteriorated with the arrival of the storm, as a later evacuation was considered dangerous and could lead to higher fatalities. The 'micro' modelling carried out by LSM for the east of the City of Hull showed that congestion would take place on the local road network, which had not been modelled in the other two approaches because they concentrated on the capacity of the main routes away from the flood zone. This modelling made use of the feature of running the model without any hydrodynamic modelling, which saves time and expense, and also means that testing of evacuation plans can proceed independently of any particular storm conditions. Overall, LSM produced consistent evacuation times to the other traffic models. Figure 5 illustrates the predicted congestion in part of Hull.

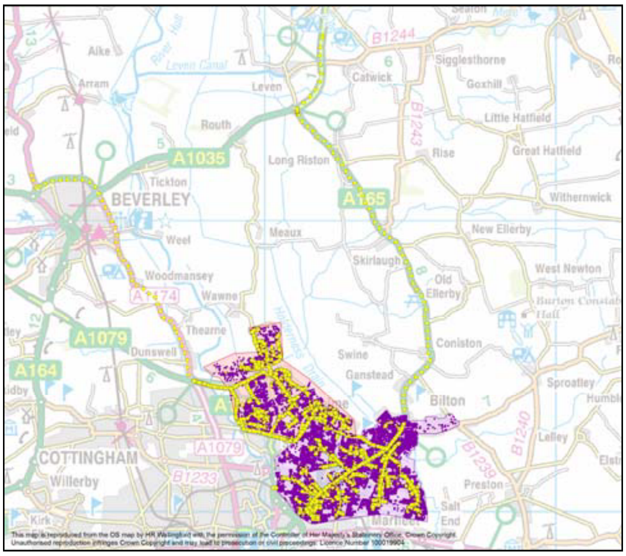

Figure 5. Predicted congestion on the roads in East Hull

In summary, the two evacuation studies in England have been successful in that both authorities have now defined dedicated evacuation routes as part of their emergency procedures. In case of a future major event, constraints of road system and evacuation timeframe are now better understood from the modelling studies. In the case of Lincolnshire, this is supported by dedicated signage approved by the Department of Transport (see Figure 6), and this has raised the profile of the role of evacuation in the local area, with increased media and public consultation.

Figure 6. New evacuation route signage in Lincolnshire

3.2 River flooding in New South Wales (Australia)

An LSM study was commissioned by the State Emergency Service of NSW in May 2013. This was to act as a pilot study to demonstrate the model's capabilities for the community of Windsor. Windsor was chosen as the pilot location because:

- It is a self-contained population centre which needs to be completely evacuated in extreme floods.
- There is reasonably good data on the locations of each of the existing buildings.
- There are proposals for additional major development.
- There is one evacuation route through the town and out onto the main highway.
- A previous macro assessment of evacuation times has identified that there are capacity issues on the evacuation route.

The Hawkesbury Nepean Valley in which Windsor sits has one of the highest risk floodplains in Australia with significant urban development up to 3.5m below the 1% flood level. The PMF can reach almost 9m above the 1% flood level and the largest flood recorded occurred in 1867 and was about 2m above the 1% flood level. To help quantify the time and resources needed to safely evacuate the Valley, the New South Wales State Emergency Service (NSW SES) developed the Timeline Evacuation Model which compares the time available for evacuation with the time needed for evacuation. However use of this can become very complicated when there are several population centres to consider, and this is why the LSM was chosen to see if it could assist in the issue of evacuating multiple towns under major flood conditions.

Due to a lack of a suitable hydrodynamic model, simulations have been 'in the dry', pending receipt of the flood model outputs. This has looked at the time needed for everyone to reach safety (the Olympic Stadium in Sydney) prior to the flood arriving. Running the model 'dry' avoids the need for 2D flood modelling output, and can be used to test existing evacuation plans.

Based on an assumption of everyone leaving their home within an 8-hour period after the issuing of the warning, LSM predicted that everyone would leave the floodplain within 9.5 hours, and reach the safe haven one hour later (see Figure 7).

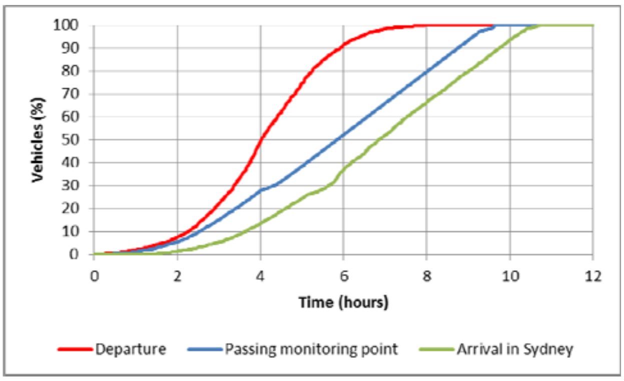

Figure 7. Departure and arrival curves for Windsor traffic

This result uses the same assumptions as in the Timeline Evacuation Model, but because this assumes an additional safety factor, allowing for accidents and broken-down vehicles, the total time to evacuate Windsor is 11 hours by this second method. Discounting this factor shows that LSM predicts an extra 0.5 hours to evacuate, which is due to predicted congestion and queueing in the town, which cannot be simulated by the TEM approach (see Figure 8).

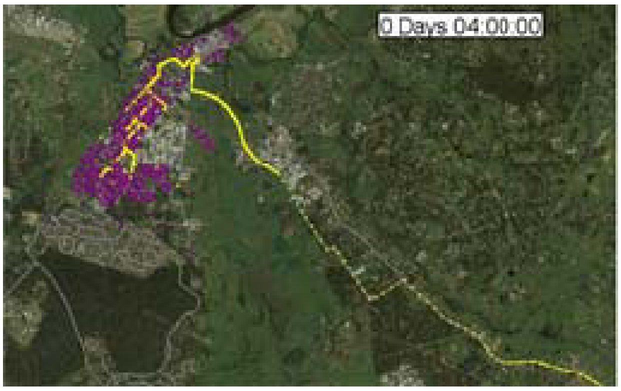

Figure 8. LSM snapshot at 4 hours

3.3 Dam risk assessment (Japan)

The use of a suite of models, covering dam beak, flow routing and loss of life, was demonstrated for a major dam in Japan. As with other LSM applications the 'virtual world' was set up using road and building data from open streetmap. The building locations were further revised using maps obtained during the site visit and satellite images (Google Earth). The population at risk for the village immediately downstream was provided by the dam owner and confirmed during a site visit from other available information.

A series of simulations were carried out, investigating the theoretical failure of the dam assuming high and low erodibility of the construction, and with and without the issuing of a warning (assumed to be 30 minutes after initiation of a breach. These results are summarised in Table 2.

	Warning issued	No warning
Low erodibility		
Fatality rate	7%	74%
Buildings destroyed	29%	29%
High erodibility		
Fatality rate	5%	76%
Buildings destroyed	33%	33%

Table 2. Japan case study summary results

This shows that issuing a warning that the dam is failing could significantly reduce the potential number of fatalities. The slightly lower number of fatalities with the 30 minute warning in the high erodibility breach scenario is due to the lower flow between 6 and 7.5 hours compared to the low erodibility breach scenario, presumably at a time when people are evacuating (see Figure 9). The high peak outflow from the high erodibility breach scenario results in slightly higher estimated fatalities in the no warning scenario.

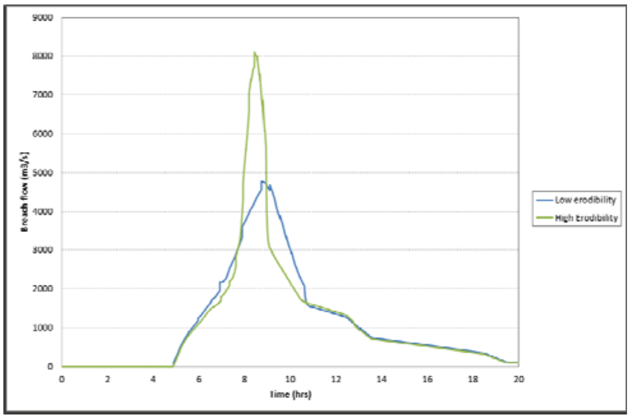

Figure 9. Predicted breach flows for different erodibilities

Using the above inundation and LSM modelling results, the level of risk posed by case study reservoir was assessed and it was found that it falls within the unacceptable zone, if no warning is issued. Where a 30 minute warning can be given, this risk can be moved to a tolerable range of failure.

3.4 River and dam failure flooding (Grand River Conservation Authority, Canada)

The LSM was applied to two pilot sites in the Grand River watershed in Ontario, to investigate the suitability of the model for consequence analysis for loss of life and building damage. The St Jacobs pilot site model was run for a dam failure scenario and the Schneiders Creek pilot site for a river flood scenario. Figure 10 shows the predicted flood extent for St Jacobs together with the location of different types of buildings.

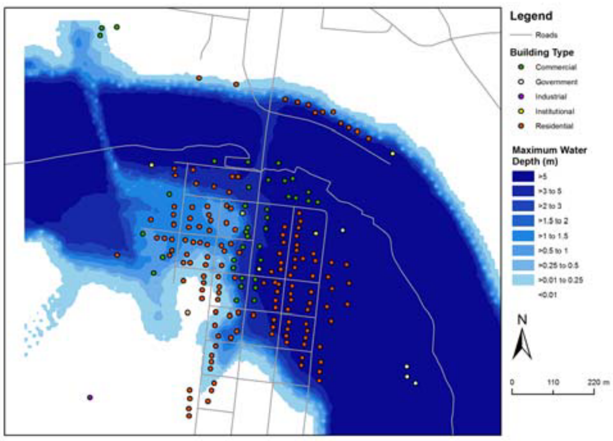

Figure 10. Location of different building types in relation to the maximum flood extent (PMF with dam breach)

Two temporal scenarios were modelled with LSM: a night simulation when everyone was assumed to be at home; a day simulation when there are a higher number of people in the model domain due to them being at work. Table 3 summarises the results.

	No warning	With warning	Delay in warning
Night scenario			
No. of people	593	593	593
% at risk	83%	83%	83%
Fatality rate (of total population)	62-68%	0%	0-70%
No. of buildings	191	191	191
% destroyed	60%	60%	60%
Day scenario			
No. of people	837	837	-
% at risk	93%	93%	-
Fatality rate (of total population)	34-76%	1%	-
No. of buildings	191	191	-
% destroyed	60%	60%	-

Table 3. Summary results for St. Jacobs pilot site

The assumed warning is given 5 hours before the PMF flood starts to inundate the floodplain, and 7 hours prior to the PMF flood peak (but approximately 15 to 20 hours prior to the breach peak arriving). It can be seen that a warning will result in a major reduction in the number of fatalities, although in the case of the day scenario, a factory close to the river can only evacuate onto a flooded road and hence a limited number of fatalities are predicted. Additional sensitivity runs were undertaken, looking at the change in fatality rate if the warning was delayed and also if the public took longer than one hour to leave their homes following receipt of the warning. These results (only for the night scenario) are summarised in the final column and Figure 11 illustrates the variation.

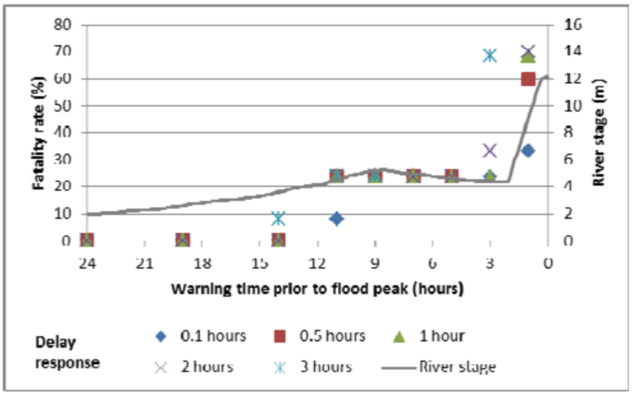

Figure 11. Variation in fatality rate with warning and response delays

The second pilot application of LSM, Schneiders Creek, is an urban water course, with a very fast response time. The creek flows through an urban area for a 1.2 kilometre reach with about 90 buildings; a combination of primarily industrial and residential. The event modelled is the Regulatory Flood event, for which the results of the LSM case study would inform floodplain management redevelopment plans and emergency preparedness. The LSM was run with two safe havens located outside of the maximum flood extent, one on each side of the river. The model has been run with and without a flood warning scenario, where the flood warning is issued 4 hours before the peak of the flood and 2.5 hours before the flood starts to inundate the floodplain. Table 4 presents the summary results.

	No warning	With warning
Night scenario		
No. of people	676	676
% at risk	3%	3%
Fatality rate (of total population)	1%	0%
No. of buildings	263	263
% destroyed	0%	0%
Day scenario		
No. of people	2085	2085
% at risk	10%	10%
Fatality rate (of total population)	3%	0%
No. of buildings	263	263
% destroyed	0%	0%

Table 4. Summary results for Schneiders Creeks pilot site

Again, a flood warning could ensure there are no fatalities, irrespective of whether it is a day or night-time scenario, provided that the warning can be issued with enough time to allow the population to respond before the flood peak arrives. The LSM could be used further to check the assumed evacuation routes and the minimum time required for a successful flood warning.

4 Discussion

Within the last few years the LSM has been used to investigate a range of flood-related issues, and has been successful in informing evacuation plans, life loss estimates, and reservoir risk designations (see above). The increased use in consultancy and research projects has been further supported by purchase of the model, with commercial licences now held in Canada, Italy, Australia and Malaysia. Interest has developed from both a need for agent-based approaches, but also with the realisation of the increasing flood risks in all countries due to climate change.

In Canada there is an initiative to produce improved floodplain mapping of flood hazard, associated with a need to consider Special Policy Areas where existing dwellings lie in the floodplain. It is for these reasons that the Grand River Conservation Authority has been investigating the use of the model to support the production of robust evacuation plans. A key consideration in Canada is the need of the warning agency issuing the flood warning, and the municipality enacting their emergency plan, to warn residents and get them out of harm's way. Such action needs to be well-organized, and to err on the side of public safety and not to dither making decisions. Further pilots are possible and GRCA has purchased a copy of the model to support this. Similarly in Australia, the positive application of the Windsor pilot, allowing for a comparison with the existing TEM approach, means that it was also adopted for use in a new housing development, to check if the new houses could be safely evacuated in a reasonable timeframe, without affecting the evacuation of surrounding communities. This is the first time that the model has been used as part of the planning process, and illustrates that the use has moved on significantly from application solely for dam break risk assessments.

Finally, an informal workshop in early March 2016 discussed the various life loss and evacuation methods in use around the world, and the outcomes of this useful discussion will feed into a new programme of model enhancements so that LSM continues to support emergency management requirements in the widest sense.

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