Use of Agent-based Modelling to Validate Hurricane Evacuation Planning

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ABSTRACT
Justification for evacuation and evacuation planning is sometimes questioned and there is a need develop approaches which justify the planning and associated expenditure. To this end, it was decided to carry out a pilot evaluation of the impact of a Hurricane Storm surge flooding on Brunswick, GA using a dynamic Agent Based Model that represents people's interactions with a flood and provides estimates of the number of people that are likely to be killed as a result of a flood event, as well as the time that is required for them to evacuate the area at risk. Climate change increase of 3ft in mean sea level would increase the population at risk in Brunswick by 20% for a category 4 hurricane. The modelling shows that for a category 4 hurricane managed evacuation can significantly reduce the number of fatalities.

INTRODUCTION
USACE teams work with FEMA and other federal, state and local partners to develop Hurricane Evacuation Studies under the National Hurricane Program (NHP) (see http://www.fema.gov/region-iii-mitigation-division/national-hurricane-program). Justification for evacuation and evacuation planning is sometimes questioned and there is a need develop approaches which justify the planning and associated expenditure.

To this end, it was decided to carry out a pilot evaluation of the impact of a Hurricane Storm surge flooding on Brunswick GA using an agent-based model (ABM). An agent-based model (ABM) is a type of computer models for simulating the actions and interactions of autonomous agents (e.g. people, vehicles, animals, spread of diseases) with a view to assessing their effects on the system as a whole.

An Agent Based Model for flood hazards can estimate:

- The evacuation time
- Fatalities and injuries
- Vehicles swept away
- Buildings destroyed

How the number of victims is affected by:

- The closure of roads
- The efficiency of the dissemination of warnings

- The use of safe havens

The results can help to increase understanding of the risk by people who live in the flood zone and improve Flood Risk Management and Emergency Plans.

The Life Safety Model (LSM), is a dynamic ABM that represents people's interactions with a flood and provides estimates of the number of people that are likely to be injured or killed as a result of a flood event, as well as the time that is required for them to evacuate the area at risk.

BACKGROUND TO THE MODEL

Over the past 15 years a number of methods have been developed that can be applied to estimate the loss of life as a result of flood events. Many of these methods and models were based on empirical methods that were often based on relatively limited experiments or historical events. They often rely on subjective measures that can lead to a considerable variation in the results.

Moving on from these general empirical models, the focus of the Life Safety Model (LSM) is to develop an approach that provides the ability to simulate receptors (i.e. people, buildings, and vehicles) in a floodplain and base their interaction with a flood wave on fundamental physical equations. This led to the development of an "agent-based" simulator that can assess the "fate" of individual receptors in the floodplain.

Determining loss

The LSM uses output from commercially available two dimensional hydrodynamic models (e.g. Telemac-2D, TuFlow) and couples it in a Geographic Information System (GIS) environment with a simulator that models the interaction of receptors in the flood. The interaction of these receptors is based on fundamental physics including mathematical models of "human toppling" defining the stability of people in water or damage to buildings in floods and the stability of vehicles in water. Figure 1 shows diagrammatically how the model determines the state of an object in relation to the water depth and flow velocity at its location.

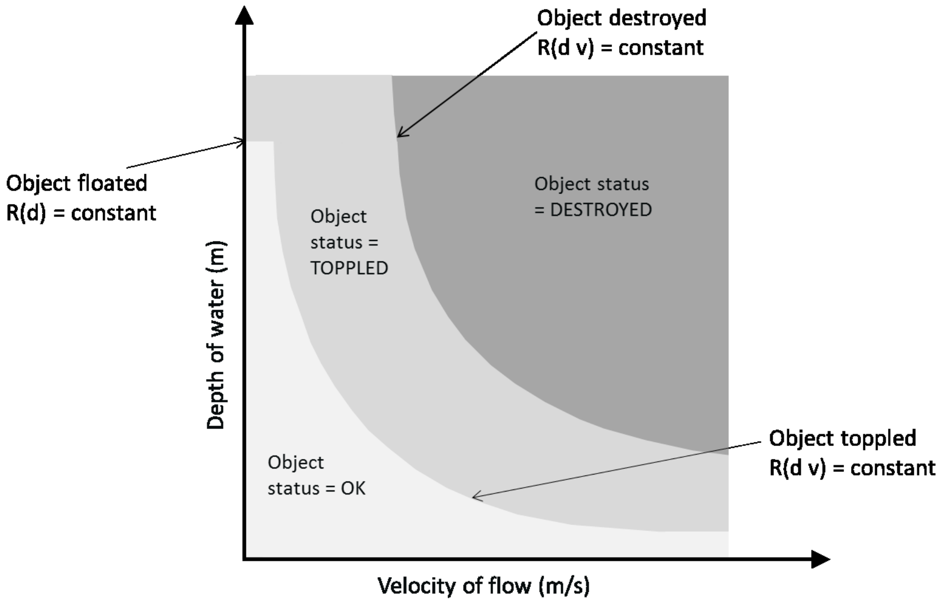


Figure 1 Object states related to water depth and flow velocity

Agent behaviour

Awareness of the 'agents' is influenced by the type of warning system:

- Warning in advance of flood
- Late warning
- No warning

The following responses are options

- Planned evacuation out of the area at risk
- Evacuation to local 'safe zones'
- Vertical evacuation

Examples of the how agent awareness and response can affect the outcome of a particular agent or object are shown in Figures 2 and 3.

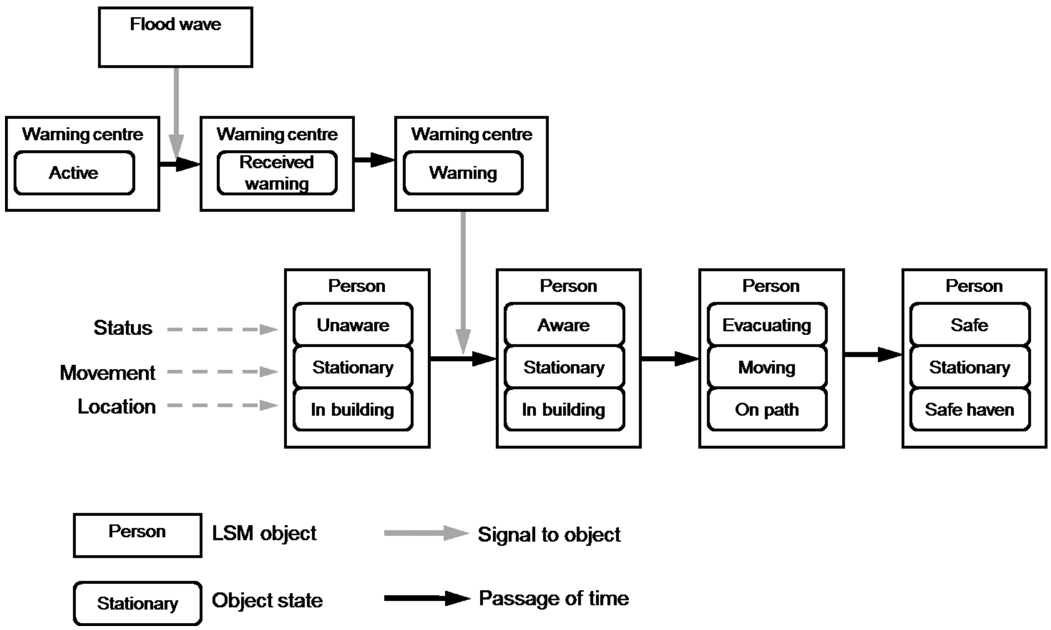
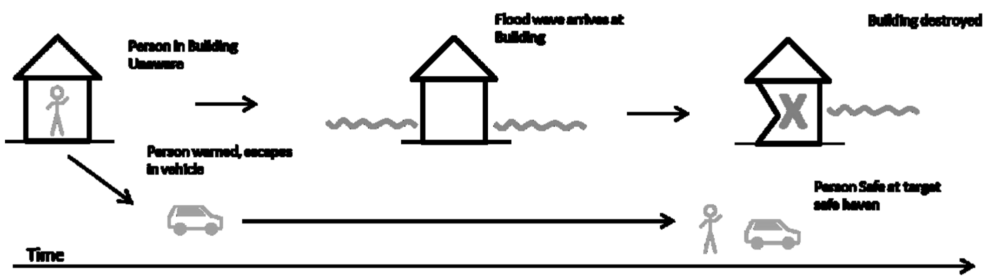
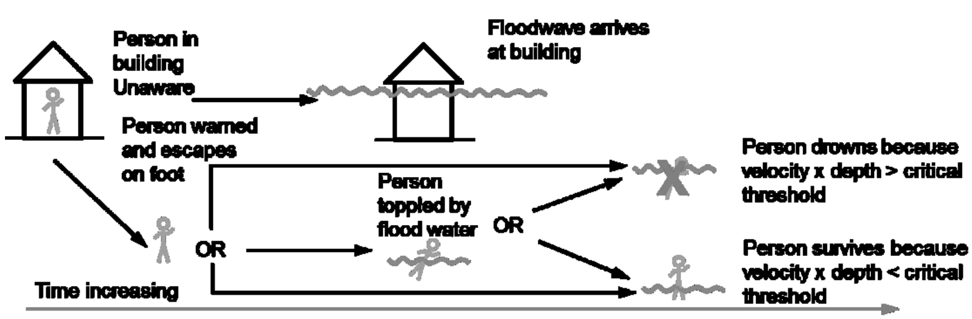


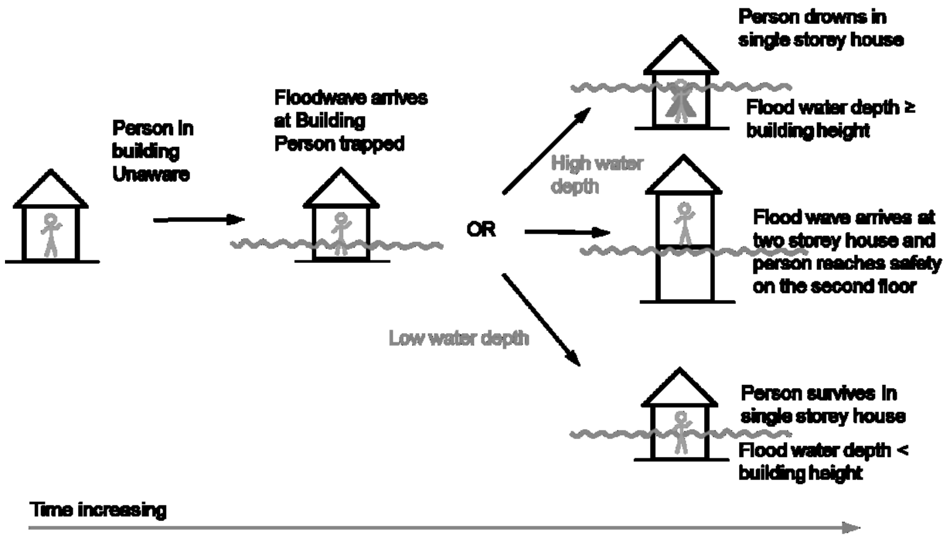
Figure 2 An example of the linkage between awareness and response behaviour in the model



Scenario A - Advanced Warning escape in vehicle



Scenario B - Warning escape on foot



Scenario C - No Warning

Figure 3 Three examples of different agent responses and interaction with flood water

Validation

The LSM has been validated previously on a number of historical floods including the Mapasset Dam disaster that occurred in France in 1959 (Johnstone and Garrett 2014) and the Great North Sea Flood of 1953 that inundated Canvey Island in the Thames Estuary resulting in the deaths of 58 people (Lumbroso et al., 2011) with the number of fatalities comparing favourably with those recorded.

CASE STUDY: BRUNSWICK GA

Hurricane surge hazard

The last significant hurricane landfall in Glynn County, Georgia was in 1898 which caused a 16 foot storm surge in downtown Brunswick and caused the storm surge of record for most points in northeast Florida and southeast Georgia (Sandrik and Landsea, 2003). During which nearly 200 people lost their lives in the vicinity of Brunswick and on the islands near the mouth of the Altamaha River (Ho, 1974).

Sandrik and Jarvinen (1999) re-created the 1898 event using the SLOSH model to estimate peak water levels to be 19.8ft or 6m at Glynn Avenue and 18.1ft on the East River. The water level hydrograph from the SLOSH model is reproduced in Figure 4.

The Georgia Hurricane Evacuation Study (USACE, 2013) used the MOMS to define the evacuation areas for different categories of storm, the maximum surge heights for locations in Glynn County are given in Table 1. The water level of the 1898 storm surge is similar to the MOM water level for the Category 4 storm in Brunswick.

Table 1 Maximum surge heights for locations in Glynn County

Location	TS	CAT 1	CAT 2	CAT 3	CAT 4	CAT 5
Jekyll Island Beach Front	6.6	9.5	14.3	18.8	22.8	26.4
Jekyll Island Wharf	6.6	9.4	14.6	19.0	22.8	26.7
St Simons Lighthouse	6.7	9.5	14.9	19.5	23.3	26.9
Torras Causeway Bridge	6.8	9.6	15.3	19.9	23.6	27.6
Downtown Brunswick	**0.9**	**4.9**	**10.7**	**15.9**	**20.6**	**24.1**
Little St Simons Island	5.6	8.2	12.8	17.9	22.0	25.8
U.S. 17 at Joe Frank Harris Terminal	1.4	4.3	10.1	15.0	19.5	23.1
Oak Grove Island	5.7	8.4	14.7	20.1	24.1	28.6
Altamaha River at U.S. 17	6.8	9.7	15.5	21.0	25.2	28.6

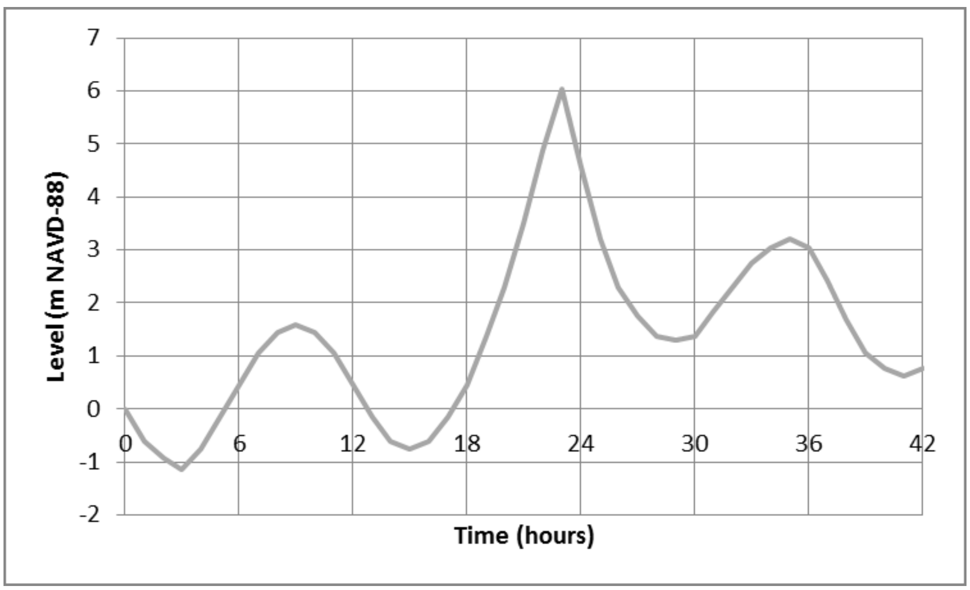


Figure 4 Storm surge water level hydrograph

Hydrodynamic model of surge

In terms of the loadings Brunswick has not experienced a significant hurricane landfall since 1898 and this event was used to assess impacts, together with an alternative event with reflecting increases in mean sea level over the last 120 years. Inundation was simulated in a 2D hydrodynamic model using a topography from USGS National Elevation Data (NED) DTM and off-shore bathymetry from the

NOAA CRM (with the vertical datum adjusted to NAVD-88) on a variable triangular mesh ($400m^2$ to $2500m^2$) with 1.5 million mesh elements. The flood hazard zone and maximum water levels in Glynn County are shown in Figure 5.

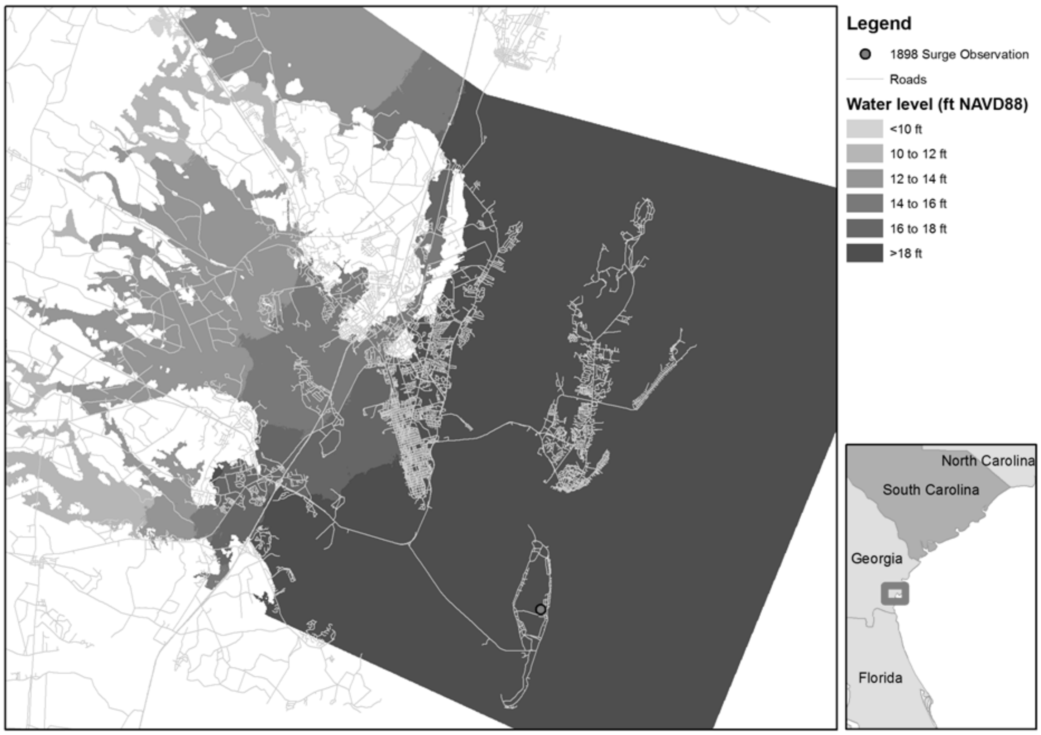


Figure 5 Maximum water levels simulated in the 2D model

The flood hazard to low lying coastal areas is likely to increase over the next century as a result of sea level rise and increase in storm intensity as a result of climate change. To assess the impact of climate change the model was also run for the same storm surge with an increase of 3ft in mean sea level. The impact of this climate change scenario was to increase the inundated area by 177.4 million m^2 and increase the water depth by on average by 2ft. The population at risk increased by 20%.

LSM study of hurricane surge impacts

A 'virtual world' for Brunswick GA was created using census, topographic, building and road data. The US 2010 Census data was analysed for 1,752 populated Census Blocks in Glynn County to identify that of the total population of approximately 79,000 people;

- 20% children,
- 65% adults and
- 15% over 65

The census data on household size and family household groupings was used to distribute the population in each census block to individual buildings The USACE

(2013) identified from the 2012 Georgia Travel Guide (Georgia Department of Economic Development) that the tourist population could be 28,000 people during high season, an increase in the population at risk of 35%. In this study it was assumed that all tourists would be evacuated prior to the hurricane making landfall.

A simplified road network was derived that includes the main evacuation routes from each census block. It was assumed that the maximum free flow speed limit on all roads is 30 mph (48 km/h).

USACE (2013) conducted social surveys that indicated that in Glynn County:

- 5% may not evacuate even with an order
- 20% would not evacuate for a category 3 to 5 storm warning
- 45% would not evacuate for a category 1 to 2 storm warning

The model was run for these three scenarios of different proportions of the population that had not evacuated prior to the hurricane. These percentages have been applied to each census block to determine the population that remains during the event. This method ensures that there is reasonable spatial coverage of the remaining population through the county. The model was also run for a scenario where 100% of the population had not evacuated prior to the storm to represent a scenario with no advanced warning and emergency management.

Results were determined for scenarios with and without additional evacuation ~4 hours before start of inundation. The late evacuation is directed towards local ‘dry’ areas. The results in terms of the number of fatalities and the fatality rate are given in Tables 2 to 5.

Table 2 Results with no additional evacuation

Population Scenario	Total population	Population At Risk (PAR)	Number of Fatalities	Fatality Rate
100%	76,814	52,655	24,194	45.9%
45%	34,691	23,658	11,221	47.4%
20%	15,528	10,411	4,945	47.5%
5%	3,880	2,552	1,127	44.2%

Table 3 Results with additional evacuation ~4 hours before start of inundation

Population Scenario	Total population	Population At Risk (PAR)	Number of Fatalities	Fatality Rate
45%	34,691	23,658	69	0.30%
20%	15,528	10,411	33	0.30%
5%	3,880	2,552	9	0.40%

Table 4 Climate change scenario results with no additional evacuation

Population Scenario	Total population	Population At Risk (PAR)	Number of Fatalities	Fatality Rate
100%	76,814	63,075	38,468	61.00%
45%	34,691	28,436	17,808	62.60%
20%	15,528	12,630	7,887	62.40%
5%	3,880	3,150	1,884	58.50%

Table 5 Climate change scenario results with additional evacuation ~4 hours before start of inundation

Population Scenario	Total population	Population At Risk (PAR)	Number of Fatalities	Fatality Rate
45%	34,691	28,436	326	1.10%
20%	15,528	12,630	153	1.20%
5%	3,880	3,150	55	1.70%

The impact of climate change is to increase the fatality rate for both scenarios with and without the additional warning.

CONCLUSIONS

The model results show that there is potential for high number of fatalities in Glynn County if a category 4 hurricane similar to the 1898 storm was to hit Brunswick today. These show the importance of early warnings and evacuation prior to the storm making landfall to reduce the number of fatalities during an extreme storm surge. The modelling also indicates that if areas can be identified that would provide refuge as a last resort to people who do not to leave the hazard zone in advance of the storm, the potential number of fatalities could be significantly reduced.

The impact of climate change is to increase the water depth by on average by 2ft which led to an increase in the population at risk increased by 20%. This increased the fatality rate for the scenarios with and without the additional warning.

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