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Recent developments in loss of life modelling for flood defence and dam break risk assessments

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43rd Defra Flood and Coastal Management Conference, Manchester University, 1 to 3 July 2008

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RECENT DEVELOPMENTS IN LOSS OF LIFE MODELLING FOR FLOOD DEFENCE AND DAM BREAK RISK ASSESSMENTS

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Key Words

Loss of life modelling

Abstract

To date the work done in the UK to assess the loss of life as a result of flooding has been limited, with the "Risk To People" model being the most commonly used tool to assess flood fatalities. However, it is an empirical, generalised model that does not use detailed information on each individual receptor in its "broad scale" estimates of loss of life.

For a more accurate assessment of loss of life an agent-based model is required. An agent-based model simulates the interactions of autonomous receptors with a view to assessing their effects on the system as a whole. It can model the simultaneous operations of multiple agents (in this case people and vehicles) with floodwater, in an attempt to re-create and predict the actions of complex phenomena such as those that occur in a flood emergency.

A prototype, agent-based Life Safety Model (LSM) has been used to estimate the loss of life for two embayments in the Thames Estuary. The LSM models individual receptors (e.g. people and cars) and their dynamic interaction with the flood wave. This is done by integrating transport routing models with the results of two dimensional hydrodynamic modelling. The LSM estimates fatalities from: drowning; exhaustion; building collapse; and vehicles being swept away.

The LSM offers a scientifically robust method of assessing the residual risk behind flood defences and for dam breaks in terms of injuries and lives lost. Importantly, it allows the comparison of different emergency management strategies that could assist in reducing the loss of life during future flood incidents. The model was validated against historical data from the 1953 Canvey Island flood.

INTRODUCTION

Flood defence and dam safety risk assessments require credible loss-of-life estimates to enable dam owners and the Environment Agency to manage the risk from these structures effectively. Estimates of loss of life can be used to evaluate existing and residual risks against tolerable guidelines; to assess the risk reduction benefits associated with structural and non-structural risk reduction measures; and to

estimate the cost effectiveness of life safety risk reduction measures to aid in their justification and prioritisation (Bowles et al, 2003). In addition, an accurate understanding of loss of life and injuries as a flood event unfolds is valuable for developing and improving emergency plans for areas at risk. Despite the global impacts of floods there are a limited number of methods to estimate the loss of life and the

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evacuation times for flood events. Loss of life modelling can be performed at different levels of detail as follows:
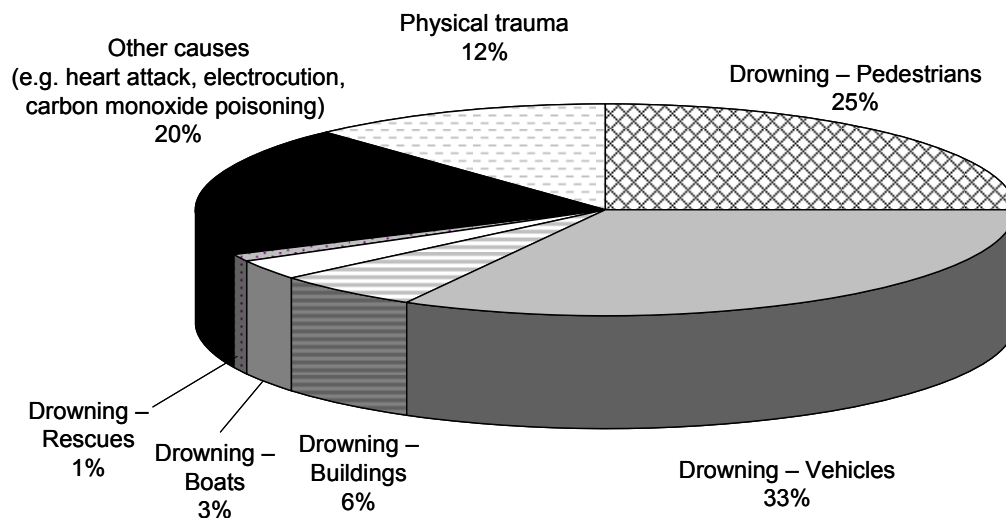
- **Macro or overall event level** where one mortality rate is applied to the whole of the exposed population;
- **Meso or group/zone level** where mortality rates are estimated for groups of people or specific zones;
- **Micro or individual level** where the circumstances and behaviour of each individual is modelled to estimate each person's probability of dying.

Until recently, most of the loss of life models for floods were based on a statistical analysis of fatalities and injuries from historical events. To date the work done in the UK to assess the loss of life and evacuation times for flood risk areas has been limited to macro or meso level estimates. The "Risk To People" model, developed as part of a Department for the Environment Food and Rural Affairs (Defra) research project, is the most commonly used tool in the UK to assess flood fatalities (Defra, 2005). However, this meso-level method is based on an empirical, generalised model that does not use detailed information on each individual in its "broad scale" estimates of loss of life. There are several limitations to empirical approaches to loss-of-life modelling as follows:

- Floodwater depths, velocities and travel times that affect the fate of people and vehicles are based on large-scale average values;
- Factors that change with time are often not represented;

- The population at risk is often considered to be heterogeneous for the entire inundation area or for large sub-areas of it. Empirical methods do not represent, at a detailed level, the many attributes (e.g. age, health) that are important determinants of loss of life;
- Evacuation is not considered as a separate process and the benefits of those who move to safe havens are often not explicitly included;
- The effectiveness and rates at which the flood warning message is disseminated are not taken into account.

Empirically based loss-of-life models tend to apply one mortality rate to an area and do not take into account the cause of death. Research carried out by Jonkman analysed 13 flood events in Europe and the USA that resulted in 247 reported flood-related fatalities. Each event occurred in the past 20 years and involved relatively few deaths. Jonkman considered the events to be representative for extreme events in most Western European countries (Jonkman, 2007). The results are shown in Figure 1. Drowning accounted for some 67% fatalities. Vehicle-related drownings were found to occur most frequently as result of people attempting to drive across flooded bridges, roads, or rivers. Physical traumas account for 12% of the fatalities, most of which occurred whilst people were in their vehicles. Other causes of death included heart attacks during evacuation and return, electrocution during clean up and deaths from fires following a floods.

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(Source: Adapted from Jonkman, 2007)
Figure 1   The main cause of deaths during floods

To provide a more accurate assessment of loss of life and evacuation times an agent based model is required. An agent-based model is a computational model that simulates the interactions of autonomous receptors with a view to assessing their effects on the system as a whole. It can model the simultaneous operations of multiple "agents" or receptors (in this case people and vehicles) with the floodwater, in an attempt to re-create and predict the actions of complex phenomena such as those that occur in flood emergency. The modelling of the evacuation process generated by an approaching flood is included within such a model. This is important for those responsible for flood event management planning. It can identify "bottlenecks" in the escape network before they are experienced in an evacuation, it can also be used to determine the impact of road closures due to flooding, the impact of phased evacuation on traffic loading, and many other possible consequences of an evacuation event. In the UK there has been little work undertaken for evacuation modelling specifically for flood event management.

This paper describes the application of a recently developed, agent-based, micro-level Life Safety Model (LSM). This work was undertaken as part of Task 17 of the EC funded research project FLOODsite. Rather than relying on very scarce and possibly unrepresentative observations on life loss caused by large floods, the LSM is designed to generate insightful information about this complex phenomenon by observing the simulated behaviour of a physically-based virtual representation of the inundation area and its inhabitants as they mobilise to escape flooding. Details of the LSM are described below.

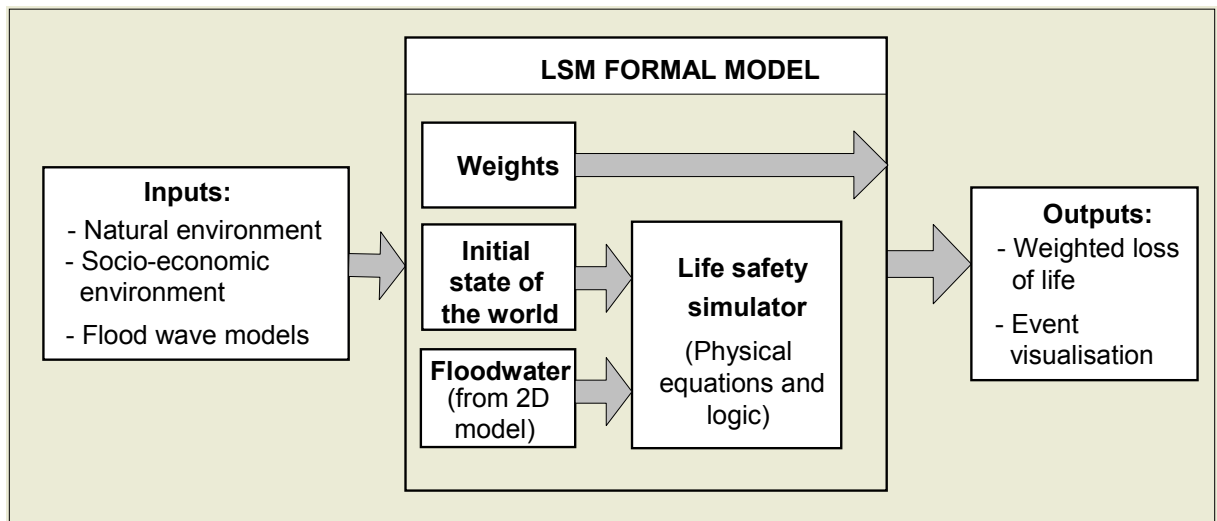## THE BC HYDRO LIFE SAFETY MODEL (LSM)

Background

The LSM is a piece of prototype software developed by BC Hydro in Canada that previously had only been used to carry out dam break risk assessments for small communities (e.g. less than 3,000 people) in British Columbia. The LSM allows dynamic interaction between the receptors (e.g. people, vehicles and buildings) and the flood hazard. The LSM requires a significant amount of data including:

- The location of individual properties, vehicles and people;

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- Flood depths and velocities from a two dimensional hydrodynamic model of the flood event;
- Details of the road network and other pathways.

Figure 2 provides a conceptual view of the architecture of the LSM. The core of the system is the LSM simulator that requires two inputs: an initial state of the world (which describes modelling receptors such as people, buildings, cars, roads) and the flood wave. The simulator output includes an estimate of loss of life and dynamic computer-graphics visualisations.

(Source: BC Hydro, 2004 and 2006)
Figure 2   High-level architecture of the Life Safety Model

The system models the "fate" of a set of receptors, which are described by their position at each time step through the simulation. Each receptor can have a set of properties that describes its normal location/condition during a week, such as travel times, school/work hours, and weekend activities. Other time-varying properties include the ability of the people, vehicles and buildings (i.e. the receptors) to withstand the effect of the floodwater. The LSM also models how people would react to the approaching wave, with and without a formal evacuation warning. Before any loss-life-modelling can be carried out the following has to be undertaken:

- Two dimensional hydrodynamic modelling of the flood area to produce a time dependent grid of depth and velocity;

- A "virtual world" needs to be set up representing the initial state of the area of interest before the flood occurs.

The representation of the population at risk and their associated vehicles, buildings and other infrastructure are encompassed in what is termed a "People's World". The various inputs to and affects on this world such as the flood wave itself, flood warning systems are realised via a set of submodels that can collectively operate on the People's World. Each of the LSM submodels can operate in parallel on this virtual world snapshot. Figure 3 shows a representation of the People's World in the LSM. At the beginning of a simulation all the people at risk are either located in a building or in a vehicle on the road network. A number of different People's Worlds can be set up depending on the time of day, day of the week and the time of the year.
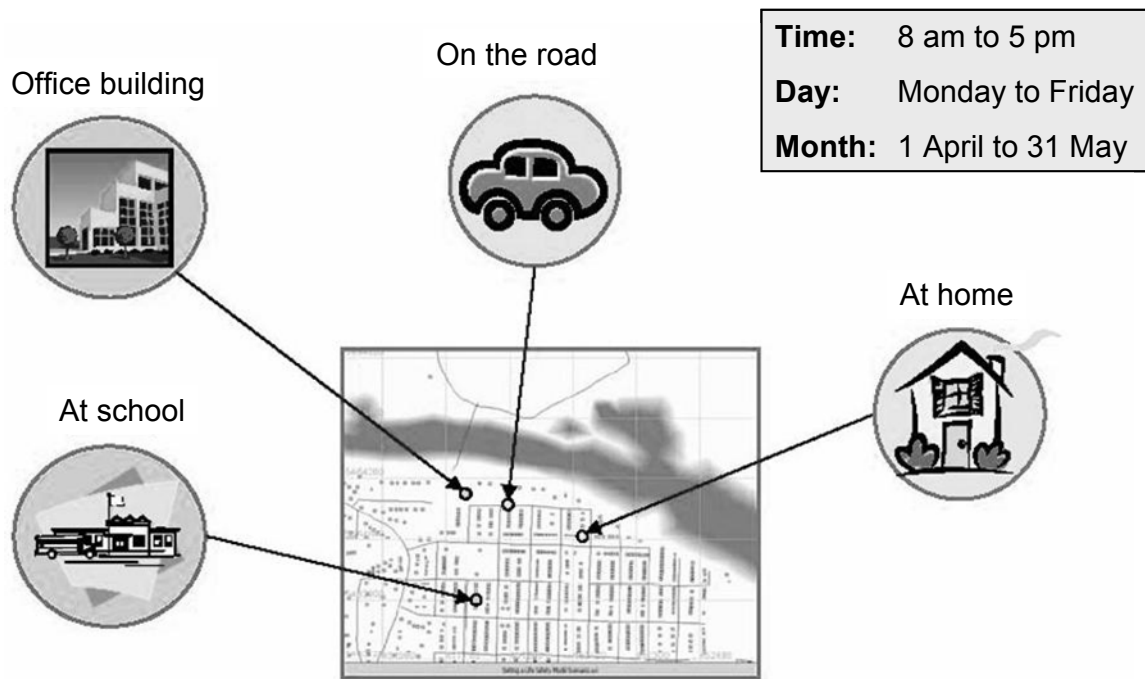
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Figure 3   Representation of the "People's World" in the LSM

The LSM uses a generalised event logic to determine the location of each person, whether they are aware of the flood wave, whether they are trying to find a safe haven, what happens if they encounter the flood, and whether they survive 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. A generic example of a loss function is shown in Figure 4. There can be instantaneous loss when an individual encounters fast-flowing water, or a group who have sought safety in a building can suffer cumulative loss if the building collapses or a slow deterioration in health if they are exposed to the flood water for a significant length of time, as a result of hunger or cold.

As a flood event evolves, the interaction of receptors with the flood wave will impact on the ultimate loss of life. 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.

The internal logic of the LSM can be explained by considering how an individual might experience a flood event. Figure 5 shows a person located in a building at the start of a flood event. Assuming that the area will be heavily inundated by floodwater, the person would be killed if caught in the building without warning in the location denoted by A in Figure 5. Three possible safe havens are shown to which the person can evacuate on foot or in a vehicle. Taking into account the "costs" to reach each haven, the south-west alternative is optimal for both foot and vehicle escape. However, if the person attempts escape on foot, they will be overwhelmed at point B. Under the third scenario, the person survives due to a combination of sufficient warning and the use of a vehicle to reach point C. The ability to generate and assess the outcomes of multiple scenarios is a key capability of the LSM (Johnstone, 2005).
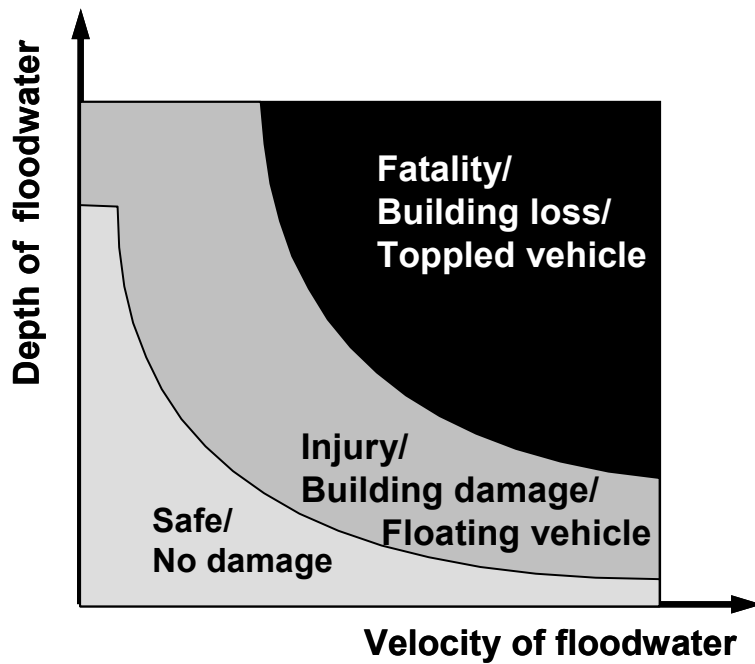
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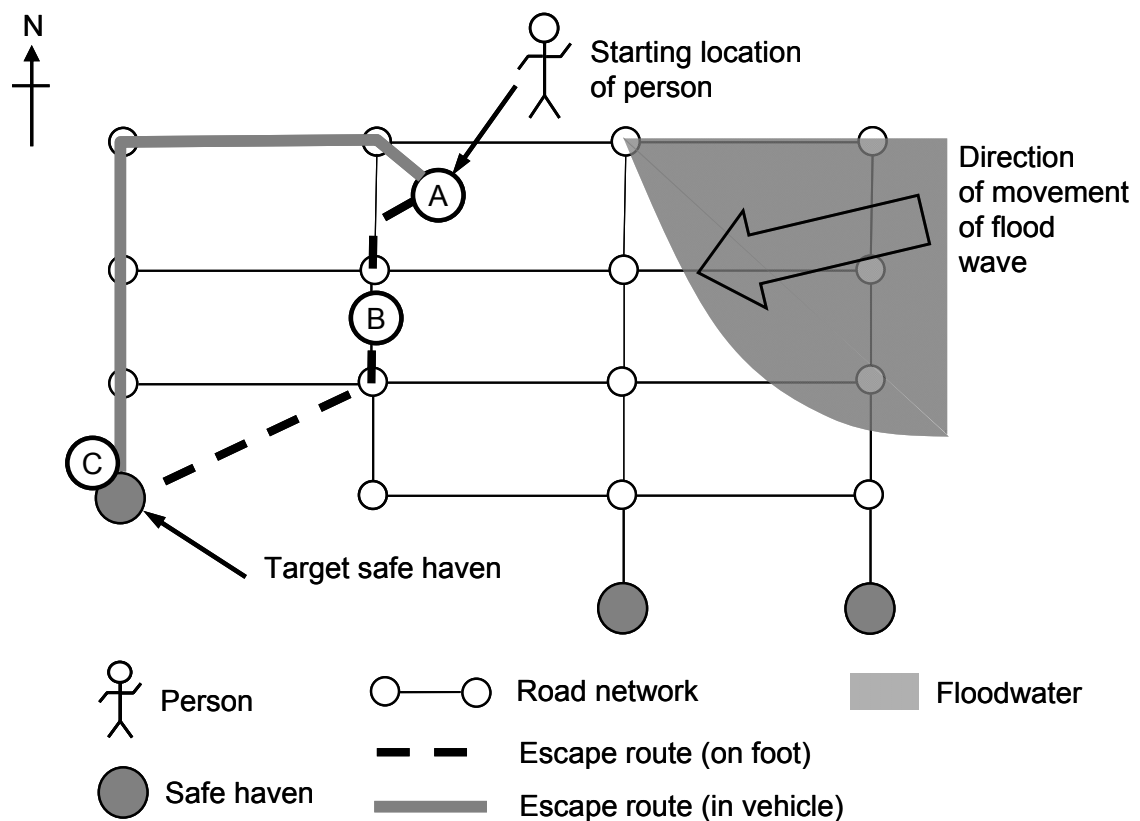
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Figure 4   Generic example of a loss function used in the LSM

(Source: Johnstone et al, 2005)
Figure 5   Fate diagram for a person in the LSM

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Application of the LSM in a UK environment

Work was carried out by HR Wallingford to test the LSM in a UK environment. The aims of testing the LSM in the UK were as follows:

- To assess the possibility of employing the LSM for dam risk assessments and flood event management planning, rather than its original purpose of emergency planning for dam breaks;
- To assess whether it was possible to use the prototype version of the LSM to estimate evacuation times for people using data readily available in the UK;
- To test if the LSM could be applied to 40,000 individual receptors in the UK. This number of receptors is an order of magnitude greater than it had been applied in the past;
- To see whether it was possible to compare the results of the LSM in terms of evacuation times with other evacuation models developed for the project;
- To assess the accuracy of the estimates of loss of life and building collapse provided by the LSM.

APPLICATION OF THE LSM TO CANVEY ISLAND

Background

Canvey Island, shown in Figure 6, is an island in the Thames Estuary, covering an area of 18.5 km². The mean high water mark of the Thames Estuary at Canvey Island is higher than most of Canvey Island's land. The first sea defences were constructed in 1623 and Dutch settlers formed the first Canvey Island communities of the modern era. The population did not expand rapidly until the 1920s, with 1,795 inhabitants in 1921 but over 6,000 in 1927 during which time the number of buildings rose from 300 to about 1,950 (Barsby, 1997). In 2001 its population was estimated to be approximately 37,000 (Office for National Statistics, 2002).
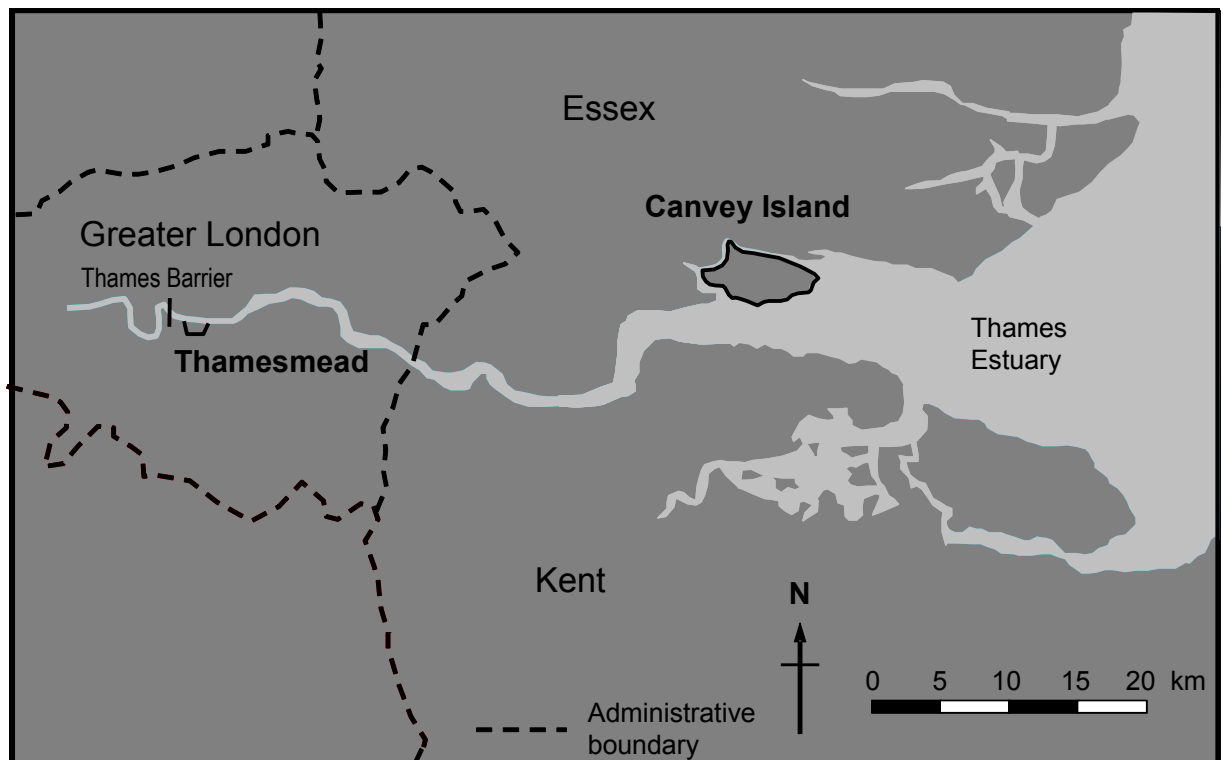

Figure 6   Locations of Canvey Island and Thamesmead

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In 1953 the island was inundated by the "Great North Sea Flood" that breached flood defences and resulted in the deaths of 58 people and the destruction of several thousand houses (Kelman, 2002). The likelihood of flooding of the access routes to and from Canvey Island will increase following sea level rise. Access to Canvey Island is currently only possible by two roads both of which are connected to the same roundabout. Any disruption to these routes would hamper evacuation and severely limit access.

At present, Canvey Island is protected by a concrete sea wall that rises approximately 3 m to 4 m above the high tide level. However, it has been found that whilst substantial, these defences show signs of deterioration such as cracks in the concrete, and the degradation of seals between slabs (Kelman, 2002). The current standard of protection at Canvey Island of 0.1% (1 in 1,000 years) will be reduced to 0.5% (1 in 200 years) by 2030 owing to sea level rise and the land in the south of the UK sinking.

On Canvey Island, it has been estimated that 30% of properties are bungalows and 45% of flats are situated at ground floor level. There is thus a large risk to life and property with limited opportunities to temporarily move to a higher level (Kelman, 2002). It is possible that a majority of the island would be inundated if a major storm surge occurred and led to significant overtopping or breaching of defences.

Available data

One of the key tests of using the LSM in the UK was to assess whether there was sufficiently readily available data to utilise the model. The readily available data for Canvey Island comprised the following:

- **Population data** was available from the Office for National Statistics at an Output Area level. Output Areas contain an average of around 125 houses;
- **Number of vehicles** was available at an Output Area level is available from census data;

- **Topographic data** in the Thames Estuary LIDAR survey data was available with a vertical accuracy of approximately ±25 mm;
- **The locations of properties** were available in the form of a national property data set that provides geo-referenced details of each of the properties in England and Wales;
- **The road network** was digitised from street and Ordnance Survey maps.

These data were used to construct a "virtual" representation of the modelled areas that were used by the LSM. The majority of the effort expended in the work was related to setting up the virtual representation of the areas of interest.

Hydrodynamic modelling of the 1953 flood

In order to model the 1953 Canvey Island flood a historical analysis was undertaken to reconstruct the situation that existed at that time. Important sources of information included: historical maps of the island; articles from 1953 newspapers; books (e.g. Barsby, 1997); police reports; and the results of physical modelling carried out in 1954 (e.g. Allen et al, 1954). This information was used to assist in assessing the height and location of the 1953 flood defences, to update the digital terrain model, to reconstruct the tidal shape and to assess the incoming flood volume associated with the breaches that occurred. The modelling of the 1953 inundation was carried out using the two dimensional software package TuFlow with a 20 m x 20 m regular grid.

The results of the hydrodynamic model indicated that the 1953 flood covered most of Canvey Island. The model showed that the water depth was 3 m to 4 m at the point closest to the breach with a mean depth of between 0.8 m to 1.0 m. The modelled volume of the 1953 flood was estimated to be 12.6 million m^3. This compares well with a 1953 flood volume for Canvey Island of 11.7 million m^3 that was estimated by the Kent and Essex River Board shortly after the event (Allen et al, 1954).

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Results for the 1953 flood

The results of the reconstruction of the 1953 flood event agreed well with the available historical data. The BC Hydro LSM model indicated that approximately 90 to 110 fatalities had occurred during the 1953 event. This number is dependent on the "resilience factors" applied to both people and buildings. The actual number of people that died in 1953 was 58, mostly as the resuly of drwonings. The number of buildings destroyed during event is unclear. However, the anecdotal evidence available seems to be similar to the LSM model results. Figure 7 shows the results of the loss of life modelling using the LSM for the 1953 flood. Of the 13,000 people living on the island in 1953 the model indicated that there would be 104 fatalities, 54 the result of drowning and 50 as a result of exhaustion. The LSM also indicated that some 130 people would be "toppled" (i.e. knocked over) by the floodwater. This figure can be used as a proxy for the number of injuries that are likely to occur.
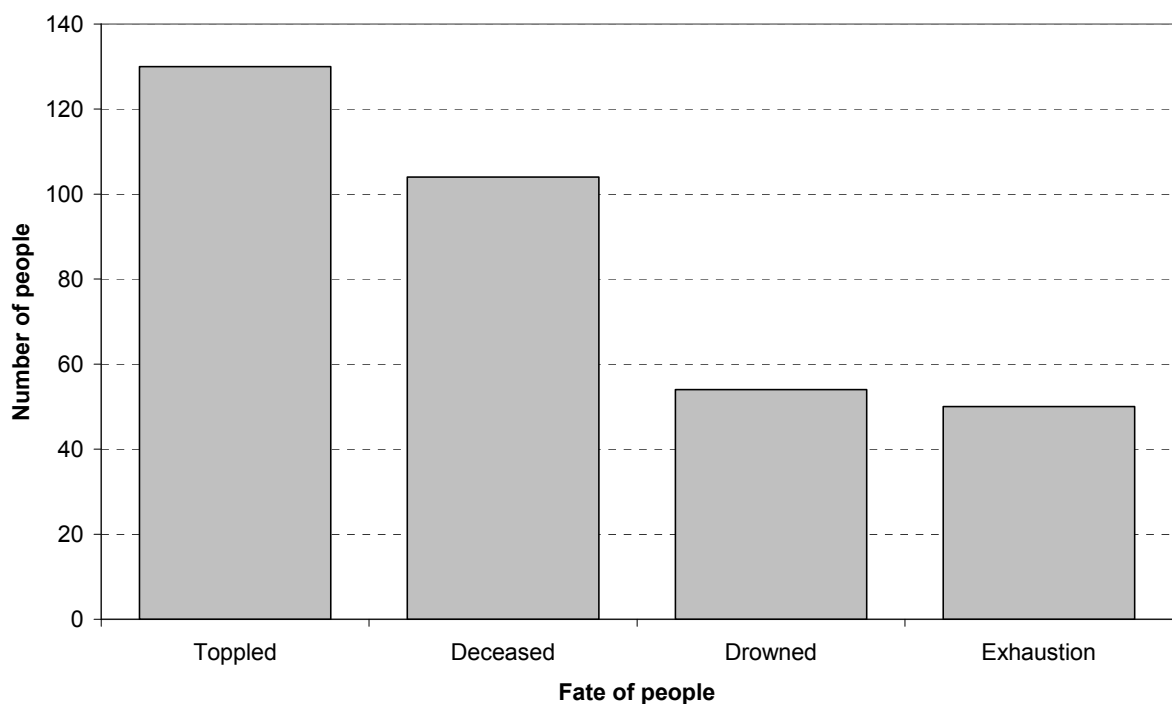

Figure 7   Typical results of modelling the fate of people for the 1953 Canvey Island flood

APPLICATION OF THE LSM TO THAMESMEAD

Having validated the LSM on Canvey Island, it was also applied to the Thamesmead embayment located downstream of the Thames Barrier (Figure 6), which has a population of 43,000. Sixty different scenarios were modelled for the Thamesmead embayment. These included different rates of warning; numbers of road closures and safe havens. For the 60 different scenarios modelled the number of fatalities varied from a minimum of 406 to a maximum of 2,378 people. The average number of fatalities was found to be 1,296. There are approximately 43,000 people that are exposed to the flooding in the Thamesmead embayment, so the LSM model indicates that on average about 3% of the exposed population will suffer fatalities.

Research by Jonkman indicates that the expected number of fatalities is usually between 0.7% and 1.3% of the exposed population. This is shown in Figure 8.

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However, in these cases many of the population have evacuated before the hazard occurred. For Thamesmead the "worst case" of everybody being at home was assumed. In the historical data collected by Jonkman many of the people had already been evacuated from the exposed area so it is expected that in the case of Thamesmead where it was assumed that no evacuation would occur prior to the flood event that the percentage of fatalities would be much higher

The LSM indicated that the time required for 43,000 people to evacuate the Thamesmead embayment varied between approximately 5 and 8 hours, depending on the number of safe havens assumed and the capacity of the road network. These evacuation times were compared against evacuation times estimated using other methods and found to be realistic.
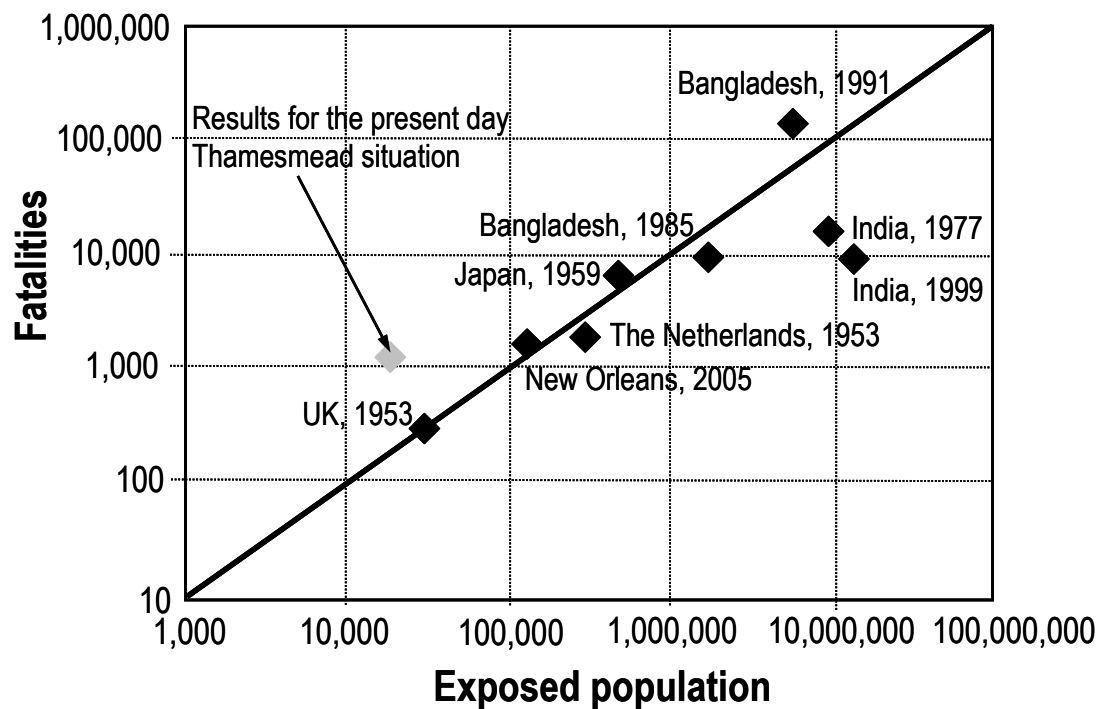

(Source: Adapted from Jonkman, 2007)

Figure 8   Results of Thamesmead modelling compared with historical data

CONCLUSIONS

The LSM offers a scientifically robust method of assessing residual risk behind flood defences and downstream of dams in terms fatalities. Although time consuming to set up the LSM computes not only the injuries and loss of life for each method but also evacuation times. The LSM model is the only loss of life model that has a dynamic interaction between the receptors (e.g. people, vehicles) at risk and the flood hazard. Other loss of life and evacuation models generally only provide first order of magnitude estimates of fatalities and

evacuation times. These could be useful for high level planning but are unlikely to be helpful for detailed emergency planning, flood defence or dam break assessments.

Importantly, the LSM allows the comparison of different emergency management strategies (e.g. the use of safe havens) that can assist in reducing the loss of life during future floods and dam breaks. The model was validated against historical data from the Canvey Island flood in 1953, during which 58 people lost their lives. The LSM was then applied to Thamesmead to estimate loss of life and evacuation times for a range of

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scenarios. It is crucial that the Environment Agency and dam owners employ the best reasonably obtainable scientific information to assess risks to health, safety, and the environment to improve emergency planning and minimise loss-of-life.

ACKNOWELDGEMENTS

REFERENCES

Allen, F. H., Price, W.A. & Inglis, C.C. Model experiments on the storm surge of 1953 in the Thames Estuary and the reduction of future surges Proceedings of the Institution of Civil Engineers 1954 Vol 4 Pt III pp 48-83

Barsby, G Canvey Island, Tempus Publishing Limited, Gloucestershire, UK, 1997

BC Hydro, Life Safety Model (LSM) formal description engineering report E299, October 2004

BC Hydro, Life safety modelling environment V2.0 beta User manual, August 2006

Bowles, D and Aboelata, M Evacuation and life-loss estimation model for natural and dam break floods, Extreme hydrological events concepts for security pp363-383, 2003

Defra, R&D outputs: Flood Risks to People Phase 2 FD2321/TR1 The Flood Risks to People Methodology, March 2005

Johnstone, W.M., Sakamoto, D., Assaf, H. & Bourban, S. Architecture, modelling framework and validation of BC Hydro's virtual reality life safety model International Symposium on Stochastic Hydraulics 2005, 23 & 24 May 2005, Nijmegen, The Netherlands

Jonkman, B Loss of life estimation in flood risk assessment - Theory and applications Dissertation submitted for the degree of Doctor of Philosophy, June 2007, Technical University of Delft, The Netherlands

Kelman, I Physical flood vulnerability of residential properties in coastal, eastern England, Dissertation submitted for the degree of Doctor of Philosophy, September 2002, University of Cambridge, UK

Lumbroso, D, Gaume, E, Logtmeijer, C, Mens, M & van der Vat, M Evacuation and traffic management, FLOODsite Task 17 report number T17-07-02, March 2008

Office For National Statistics, The 2001 census in England and Wales [WWW] http://www.statistics.gov.uk/census/

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