Modelling Mass Evacuations To Improve The Emergency Planning For Floods In The UK, The Netherlands And North America

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ABSTRACT

Whether to implement a mass evacuation of people from an area at risk of flooding can be a major issue for emergency managers. The modelling of the evacuation process generated by a forecast flood is important for those responsible for the efficient and safe movement of people during evacuations. Evacuation modelling can predict "bottlenecks" in the system before they are experienced, it can also be used to determine the impact of road closures due to flooding and the impact of phased evacuation on traffic loading. Being able to model alternative evacuation scenarios can lead to the establishment of appropriate evacuation policies and shelter strategies. With the increasing use of two dimensional hydraulic models that can provide accurate estimates of floodwater velocity and depth, and with the increased availability and accessibility of spatially-referenced population data and transport links, the modelling of mass evacuations for floods has increased. The model results can be used to assess the best locations of shelters and options for traffic management. This paper provides details of models and case studies carried out in the UK, North America and the Netherlands to estimate the evacuation times of tens of thousands of people that reside in flood risk areas. The models discussed in this paper range from "micro-models" to "macro-models". Micro-models simulate each individual person at risk, and give a detailed representation of the evacuation routes. Coarser macro-models estimate evacuation times based on key parameters such as "lumped" population groups, the distance to the nearest shelter or higher ground, the evacuation route, and the average evacuation speed. The paper provides conclusions on the suitability of different evacuation models, as well as on the scale at which these models can be applied; their suitability for evacuation planning; and the "usefulness" of the results to various actors involved in the emergency planning process.

INTRODUCTION

In recent years the awareness of the need for tools that assist with the facilitation of mass evacuation and emergency planning for floods has increased. To develop emergency management plans, information is needed on the characteristics of floods, the current infrastructure, the capacity of the infrastructure and the vulnerability of the people at-risk, thus helping to reduce the loss of life. Emergency plans allow the emergency responders to

target the people most at risk. Evacuation is a response to the forecast threat of flooding that is expected to pose a risk to life. It involves people moving to 'safe' locations, out of the flood risk area where they are able to shelter until it is appropriate for them to return. This paper will briefly outline the following:

- A review of the requirements for evacuation planning for floods based on end user consultation
- An overview of evacuation modelling for floods
- The development and implementation of evacuation and traffic management models relevant to flood event management in the Thames Estuary in the UK, the Westerschelde Estuary in the Netherlands and the west coast of Canada

USER REQUIREMENTS FOR EVACUATION MODELS FOR FLOOD EVENT MANAGEMENT

The decision to make an evacuation call is a critical issue. As part of the FLOODsite research project (FLOODsite, 2007) consultations were carried out with stakeholders to understand the factors that influence the decisions related to evacuation and emergency planning in several European countries. In some countries such as the UK residents are typically expected to "self-evacuate" following a flood warning. In the Netherlands a preventive evacuation is preferred to a "self evacuate" philosophy. To make a well-informed decision regarding how to respond to a flood event decision-makers need the following information (Lumbroso et al, 2009):

- Flood extents, depths and velocities
- Breach locations in flood defences or dams
- Location of the vulnerable receptors
- Details of the area at risk and locations that can be used as shelters
- Potential road congestion
- Estimated evacuation times
- Details of the effects of different emergency management responses on evacuation times

Mass evacuation models can be used to address the last three points above.

BACKGROUND TO MASS EVACUATION MODELS

Introduction

The modelling of the evacuation process generated by an approaching flood can identify "bottlenecks" in the system before they are experienced during an evacuation, and 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. Mass evacuation tools used for a range of hazards worldwide, (including technological hazards such as nuclear accidents) can be grouped as follows:

1. Behavioural based simulation models
2. Traffic simulation models
3. Time-line/critical path management diagrams

Behavioural based simulation models consider multiple aspects of human behaviour to facilitate the consideration of human factors that contribute to the evacuation time (e.g. such as age, awareness of the hazard, knowledge of the area at risk). In such a model people and vehicles can interact with each other or the hazard. These type of models also allow the effects of improvements in the dissemination of flood warnings or changes in the location or number of shelters to be assessed.

Traffic simulation models model the traffic flow from the 'origin' to the 'destinations using data on the road network. In evacuation modelling the origins are usually the residential areas or the locations of individuals. The destinations are the 'exits' of the threatened area. When they reach the exits, people are safe. When an island with two bridges to the mainland is modelled and only the island is flood-prone, the exits are the bridges and the origins are the locations of the houses of the inhabitants.

Traffic simulation models comprise micro, meso or macro types of traffic stream simulation, with simple, static or dynamic types of traffic route assignment. Micro-simulation models are based upon the detailed simulation of individual vehicle and people movements. They require the exact location of individuals. Meso-simulation is based on movements of traffic streams coupled to relatively simple evacuee route selection logic. Macro models do not consider individuals but just the general traffic flow. In macro models the number of inhabitants is lumped into an administrative area, e.g. a post code area. Dynamic traffic models differ from static models in that traffic flows can vary over time in contrast to the constant flows in static models. A static assignment model assumes steady-state traffic conditions throughout the evacuation time period. However, during highly congested periods such as those that occur during an evacuation the assumption of steady-state conditions is questionable. Furthermore, static models cannot satisfactorily describe inherently transient queues and tail backs, which contribute significantly to traffic congestion.

A time-line diagram/critical path tool is the simplest form of mass evacuation "model" available. These show the critical path of emergency response for flood evacuation. The resulting time-line can then be used to show participants in a flood planning or response activity what has to be done, when it has to be started, and approximately how long it might take during the flood scenario analysed.

Scale

There are three main scales at which evacuation models can be employed for flood event management (Mens et al, 2009):

- **Micro** – This corresponds to a scale where each individual receptor at risk (e.g. person, vehicle or property) is modelled and there is a detailed representation of the evacuation routes. A complex modelling system (e.g. an agent-based model) is often used to estimate the evacuation times for each individual receptor
- **Meso** – This corresponds to a scale that is between a micro and macro-scale. In meso models the receptors are lumped together. The evacuation time is estimated by assessing the demand for and the capacity of the evacuation routes, which are evaluated on a geographical basis
- **Macro** – In a macro model the receptors are also lumped together. The estimates of the evacuation times are based purely on the distance to the exit of the at-risk area, the capacity of the route and the average evacuation speed A macro scale model is often

used to provide an initial estimate of the evacuation time for a large area. (e.g. at a regional scale).

The type of evacuation model that is appropriate for a particular flood risk area will depend on the level of risk and the processes which the evacuation modelling is seeking to inform. For example, an emergency plan for a relatively small, densely populated at-risk area may require the use of a micro model. This is because where the potential number of people to be evacuated is large may require a detailed simulation model where the traffic and flood hazard is modelled in a truly dynamic way. However, to establish an evacuation strategy at a regional level or national scale a meso or macro evacuation model may be more appropriate. To set up a micro-scale modelling at a regional or national scale requires large quantities of data and a number of detailed assumptions to be made. At a meso or macro scale it is often important to gain an insight into the main emergency management options and the order of magnitude of time required to evacuate people for each option. Once these options have been assessed more detailed models may be used to improve emergency management strategies for specific communities or to locate shelters (Mens et al, 2009). This concept of the "appropriate level" of evacuation analysis for flood event management is shown in Figure 1.

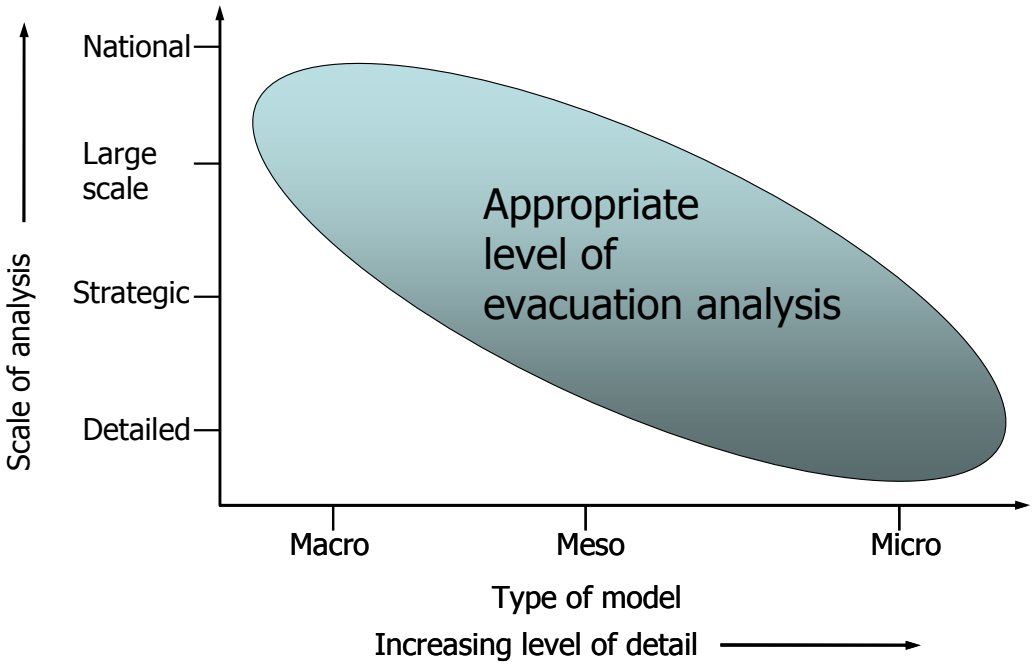


Figure 1 Appropriate level of evacuation analysis

MASS EVACUATION MODELS FOR FLOOD EVENT MANAGEMENT

Introduction

This paper discusses three existing mass evacuation models that have been implemented in the UK, the Netherlands and North America to assess mass evacuation times for floods:

- Life Safety Model (LSM)
- The INtegrated DYnamic traffic assignment model (INDY)
- The Evacuation Calculator

Life Safety Model (LSM)

The Life Safety Model is a detailed micro-modelling tool that can aid in assessing risk to people and evacuation times from a range of flood events including: fluvial floods; flash floods; dam breaks and breaches of flood defences. The LSM can also be used to assist in the location of shelters and safe havens (BC Hydro, 2004). It uses a physics-based approach to simulate the physical interactions of people, vehicles and buildings in a major flood event. For a given population at risk, LSM will:

- Estimate evacuation times
- Estimate the potential loss of life due to an extreme flood event
- Produce a spectrum of virtual representations of how a flood emergency could evolve
- Provide an estimate of the potential number of buildings that will collapse
- Support emergency analysis activities that aim to support the development of mitigation strategies that could reduce the potential loss of life

The LSM uses information on the flood warning process, the behaviour of people, the strength of houses, as well as the stability and characteristics of persons and cars. It requires detailed data on the location of buildings and inhabitants, and their possible escape routes. The velocities and depths of the floodwave at a suitable temporal and spatial interval are also required as an input to the model. . The LSM is relatively data intensive and hence may be best suited for local scale planning. The LSM provides animations of the flood event as it unfolds that can help planners improve their emergency management plans.

INtegrated DYnamic traffic assignment model (INDY)

INDY provides a method to assess mass evacuation times for floods using a dynamic traffic model. The model allows the analysis of traffic scenarios on transportation networks. INDY is able to predict traffic conditions over time, to identify the locations where congestion is expected and to estimate the corresponding delays.

INDY requires data on the road network, the number of cars and their origin and destination. It calculates different options and routes. Applying INDY at a regional scale is possible, but time consuming.

The Evacuation Calculator (EC)

The Evacuation Calculator (EC) was developed to calculate how much time is required for evacuation and to determine the effect of traffic management during the evacuation process on the required evacuation time. The EC focuses on the trip production and distribution, and is based on a static traffic assignment model. The road network in the EC is simplified to driving distances stored in an "origin-destination matrix" combined with an average driving velocity. The EC is suitable for macro scale applications. Several important assumptions are required to be made when applying the model including:

- Number of people present in the area at risk
- Number of people who respond to warnings
- A departure profile indicating how quickly people leave after they receive an evacuation order
- Average velocity of cars

- The exit strategy that people choose. For example, do people go to the nearest "exit"; or are the people distributed over the exits in an "optimal" way that results in the shortest evacuation times. This is based on distances to exits and exit capacities.

Table 1 provides an overview of the above mass evacuation models.

Table 1 Overview of mass evacuation models used in flood risk management

Model name	Scale	Background	Countries where model has been applied
Life Safety Model	Micro	Life Safety Model includes traffic model and loss of life model	Canada, France, the Netherlands, UK, USA
INtegrated DYnamic traffic assignment model	Meso	Based on a dynamic assignment traffic model	The Netherlands
Evacuation Calculator	Macro	Based on a static assignment traffic model	The Netherlands

The sections of this paper below briefly describe the application of the above models in various case studies in the Netherlands, UK and North America.

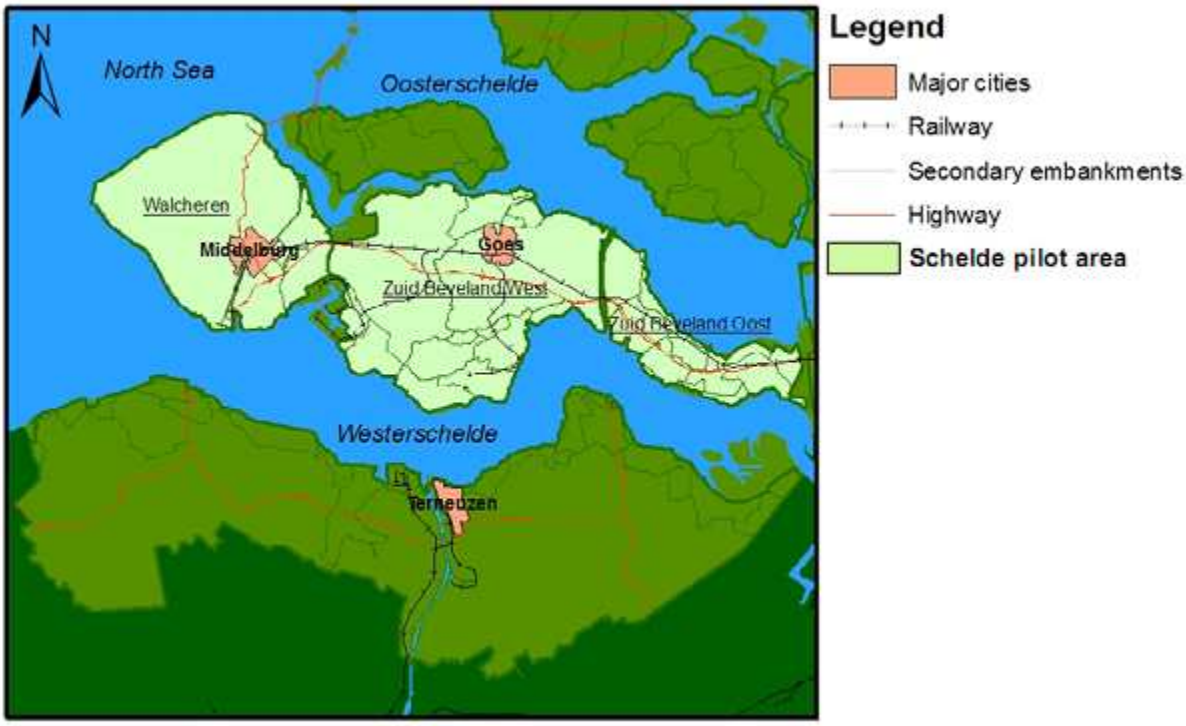
APPLICATION OF MASS EVACUATION MODELS IN VARIOUS CASE STUDIES

The Netherlands

INDY and the Evacuation Calculator (EC) were applied in a case study in the Netherlands that focused on an area consisting of three former islands, (Walcheren; Zuid-Beveland West; and Zuid-Beveland East) in the west of the country in the Westerschelde Estuary, shown in Figure 2. The islands are surrounded to the west by the North Sea, to the south by the Westerschelde Estuary, to the north by the Oosterschelde and to the east the Kreekrak and Rijn-Schelde Canals. The threat of flooding mainly occurs from the North Sea and Westerschelde Estuary. The embankments along the Westerschelde are between about 8 m to 11 m above mean sea level. Flood protection standards have been set to protect against a 1 in 4,000 year storm (i.e. a 0.025% annual probability). The area has approximately 200,000 inhabitants, most of who live in the cities of Goes, Middelburg and Vlissingen.

The EC is not very detailed and was applied at a macro-scale. It gives an insight into situations where the whole area needs to be evacuated. INDY allows modelling to be carried out at a more detailed level. INDY was applied at a meso-scale. It allows smaller areas to be assessed in more detail. None of the models model individual movement of persons, only the flows of the total number of inhabitants from each post code zone is described in the model.

Both models provide estimates of travel times based on a number of assumptions related to the behaviour of people. This behaviour is not modelled explicitly and thus needs to be assumed. The most important assumption is the time that it takes people to leave their homes and the direction that they go into. The effects of what may happen if people leave more quickly or go in another direction may be studied with these models. In both INDY and the EC it is not possible to include shelters or safe havens within the area at risk to which people can be directed.



(Source: Lumbroso et al, 2009)

Figure 2 Location of the Dutch case study site

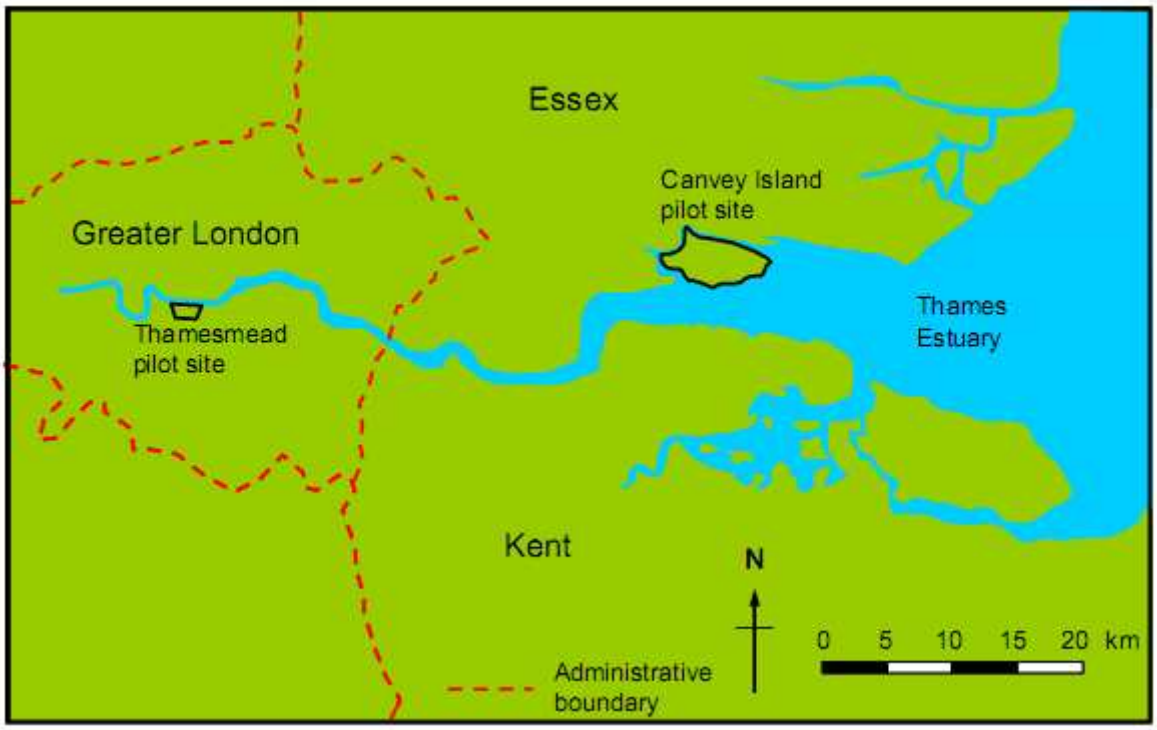
As no observed historical data on mass evacuations exists for this area the model results could not be compared with actual evacuation times. However, the results of the INDY model are considered most realistic, because they are based on the actual road network and dynamic traffic modelling, whereas EC simulates the network based on assumptions regarding the departure profile, direction people go to and evacuation velocities.

Both the models applied in the Dutch case study predicted that it would take at least 22 hours to evacuate the whole study area, when the evacuation is "well managed" (i.e. there are no unexpected events and people leave "efficiently"). This indicates that it would not be possible to complete the evacuation of the area within the lead time of the forecast of an extreme event, which is usually six hours to a day. This indicated to emergency planners that alternative strategies need to be found such as the possibility of people sheltering in adjacent tall and robust buildings or only evacuating the areas at greatest risk.

The UK

In the UK the Life Safety model (LSM) was applied to Canvey Island and Thamesmead both of which are located in the Thames Estuary, shown in Figure 3. Canvey Island is an island in the Thames Estuary, covering an area of 18.5 km². It is formed on a flat, low-lying alluvial fan that has an average height of approximately 1 m below the mean high water level. The location of Canvey Island is shown in Figure 1. Canvey Island is protected from the sea by a network of flood defences. In 1953, the island was inundated by the "Great North Sea Flood" that breached the island's flood defences and resulted in the deaths of 58 people and the

destruction of several hundred houses. The LSM was used to recreate the consequences of the 1953 flood.



(Source: Lumbroso et al, 2009)

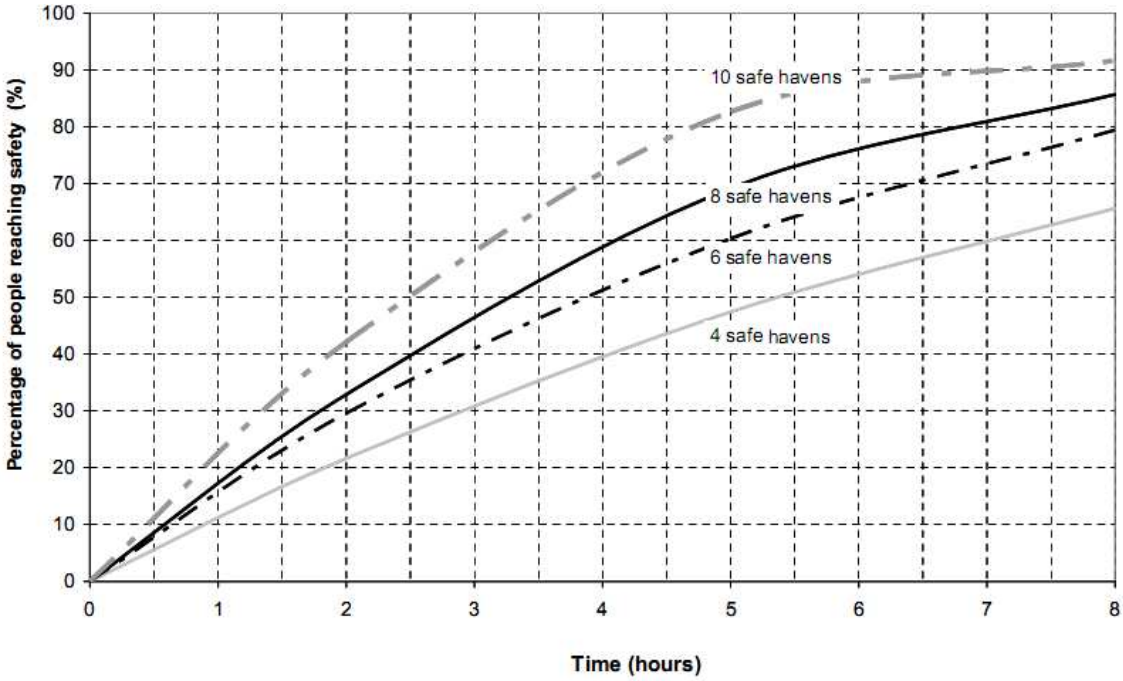
Figure 3 Location of the UK case study sites

Data from the 1951 census were used to assess the population of the island in 1953. Historical maps were used to assess the distribution of the properties on the island at the time of the flood. The results of the reconstruction of the 1953 flood event agreed well with the available historical data. The LSM model indicated that approximately 100 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. The number of buildings destroyed during event is unclear. However, the anecdotal evidence available seems to be similar to the LSM model results. Having validated the LSM on a historical case study the LSM was applied to Thamesmead.

Thamesmead is a "new town" constructed in the late 1960s in London on an area of marshland. It covers an area of approximately 12 km^2 and has a population of around 43,000. The majority of Thamesmead is at a level of between -1 m AOD and 1 m AOD which is below the "normal" high tide level. The area is defended by a flood embankments and walls. These provide protection against the 1 in 1,000 year (0.1% annual probability) flood level. A number of breach scenarios of the defences were considered when the LSM was applied to the Thamesmead case study area.

In Thamesmead over 60 different scenarios were tested and assessed using the LSM, these included different combinations of the following: numbers and locations of safe havens; number and location of road closures; and changes in warning dissemination rates.

Typical results of the modelling are shown in Figures 4. Figure 4 shows how the percentage of people that are safe varies with the number of safe havens that are available. For example five and a half hours after a breach of the flood defences has occurred with four safe havens in place about 50% of the people have reached safety. However, with ten safe haves in place almost 90% of the people have reached safety a similar time after the breach. This indicates the usefulness of the tool in assessing the number and location of safe havens in Thamesmead, as well as evacuation times.



(Source: Lumbroso et al, 2009)

Figure 4 Effect of the number of safe havens on the percentage of people reaching safety and evacuation times in Thamesmead

The case study in the UK showed that the LSM has the potential to be used to inform emergency plans for heavily defended areas (e.g. London, some coastal areas) and dam risk assessments in the UK. The effect of the following can be assessed for different flood events: evacuation times; location and the number of safe havens; effect of road closures; rate of dissemination of warning; time of day and the location of the population; and the number of fatalities and injuries.

Canada

The west coast of North America is at risk from a potential tsunami generated from a number of source zones including the Aleutians, Japan, and South America. Communities from Northern Vancouver Island in Canada, southwards to Mendocino County in Northern California, would be the first to feel the effects of the associated onshore waves (Clague et al., 2003; Atwater et al., 2005). Arrival times for the first wave are estimated to be on the order of 30 minutes to one hour after the seismic event, with associated run-up heights on the order of 10 m to 15 m. A tsunami on the west coast of North America combines a set of factors that could create a truly catastrophic event.

After the Indian Ocean tsunami in December 2004, the British Columbia Provincial Emergency Program (in partnership with the Canadian Federal Government) established the Tsunami Integrated Preparedness (TIP) programme part of which was a study was initiated to investigate methods to estimate flood wave arrival times, onshore run-ups, flow velocities, and losses, and to support emergency preparedness and evacuation planning (Johnstone & Lence, 2009). This work was also supported by Geomatics for Informed Decisions (GEOIDE), a National Centre of Excellence supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), and the British Columbia Hydro and Power Authority.

The community at risk selected for the study was the District of Ucluelet, a community of approximately 2,100 local citizens that doubles in size during the tourist season. The community sits on a peninsula with its western and southern limits facing the ocean, and its eastern edge forming a protected inlet. Two potential tsunami scenarios were modelled. The first was used by the Washington Department of Natural Resources in a study of tsunami hazards along the Washington State coastline (Walsh et al. 2000), which describes a magnitude 9.1 event. The second is a modified version of the first, in which the vertical deformations are scaled by a 60% factor to reflect the notion that a modern day event might only dissipate the strain built up during the 300 year period since the last event in 1700. The estimated lead times for both scenarios is less than 40 minutes.

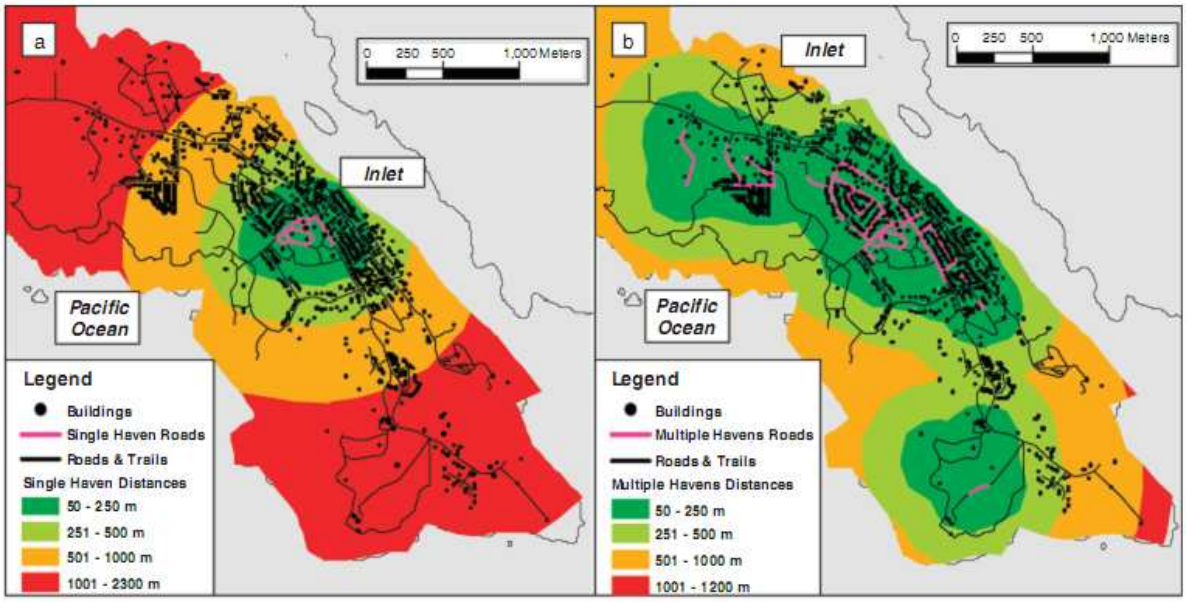
A study using the LSM was carried out to investigate evacuation scenarios in which 100% of the population were aware and chose to evacuate, the mobilization times were short, and everyone understood the evacuation route system. Four evacuation scenarios were specified based on two travel modes (i.e. vehicle only and pedestrian only) and two sets of safe havens (i.e. a single centralized safe haven, and a distributed set of multiple safe havens based upon the safe elevation line derived from the flood wave).

Figure 5a and b present an example of a simple spatial analysis of the differences in the travel distances between the single and multiple haven options. Figure 6 shows of the population at risk, which is summarized as a function of distance to the nearest safe haven. The figure shows that by simply changing the number of available havens in the LSM, the population within 500 m of a recommended safe area increases from 50% to 96% of the total population at risk. However, an approach which only considers distance to safety cannot estimate the possible reduction in losses, nor can it assess whether evacuation is feasible (Johnstone & Lence, 2009).

In an effort to understand the maximum possible mitigation benefits, the team modeled a set of evacuation scenarios in which 100% of the population chose to evacuate, the mobilization times were short, and everyone understood the evacuation route system. Two travel modes were defined: vehicle-only and pedestrian-only. The multiple-haven pedestrian scenario is the most effective option with 37% of the population reaching safety within 20 minutes, and 82% within 45 minutes. The LSM simulations suggest that the other options are two to four times less effective. It is unclear whether the large subpopulation of tourists will show a preference for vehicular egress, which could increase mortality.

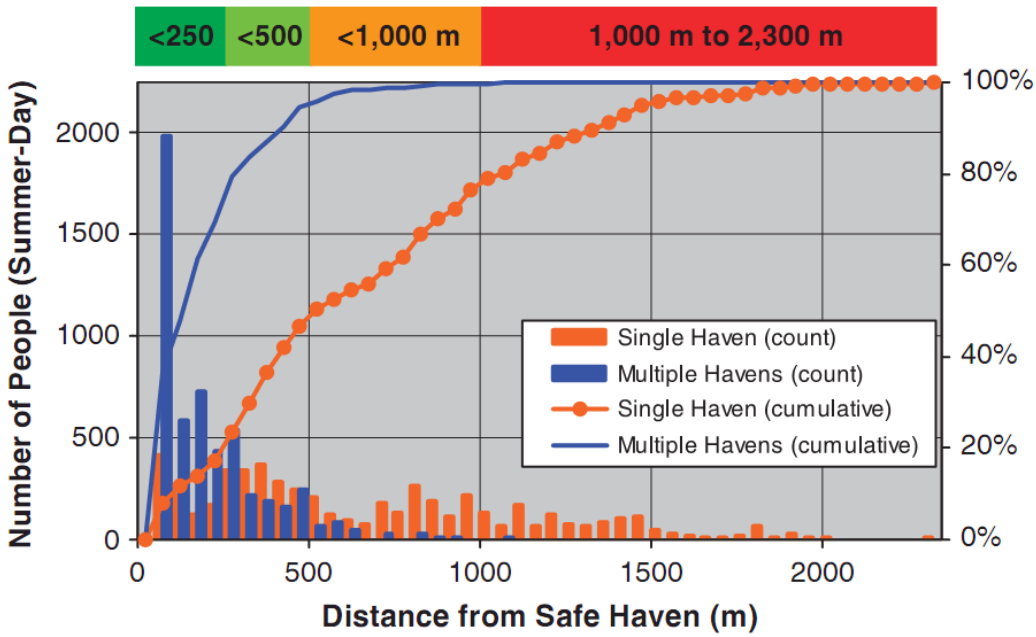
Before the initiation of this study the community did not fully understand the potential losses within each hazard zone. The original evacuation plan did not estimate traffic demand, assess the capacity of the road network, or estimate the times required to leave the hazard zones. The expanded set of candidate safe havens will make more evacuation pathways available, shorten the average distance to safety, and provide a much larger receiving area for the evacuating

population. Evacuation movements on foot will help reduce the congestion problem and increase the efficiency of movement to safety.



(Source: Johnstone & Lence, 2009)

Figure 5 **Evacuation analyses: (a) single haven evacuation distances, (b) multiple havens evacuation distances for District of Ucluelet, Canada**



(Source: Johnstone & Lence, 2009)

Figure 6 **Results from the LSM evacuation analysis showing the population at risk in a costal zone as a function of distance from safe haven(s) for summer daytime**

CONCLUSIONS

There are various scales at which evacuation modelling can be carried out. Macro-scale evacuation models are useful for obtaining first order estimates of evacuation times for

relatively large areas. Meso- and micro-scale models are needed for detailed evacuation planning. In some cases, for results to be useful there is a need for individual receptors (e.g. people, houses, vehicles) to be modelled and for additional information to be provided (e.g. loss of life and injury estimates, effects of different management plans) not just evacuation times. Micro-scale models, although more time consuming to set up than macro models, provide emergency planners and other end users with more insight into the areas at greatest risk and also provide decision makers with other risk metrics (e.g. number of collapsed buildings, loss of life, inundation of escape routes). However, to be effective such models should be applied to the whole area at risk. Further development of appropriate user interfaces will help encourage wider adoption and usage of evacuation models.

Mass evacuation models are rarely applied to improve the emergency planning for flood events and to inform flood emergency plans. This is probably because evacuation modelling for flood events often falls outside the remit of flood risk managers. This paper demonstrates that there are potential benefits for flood risk managers to incorporate evacuation modelling into their flood event management work. The application and dissemination of the benefits of using evacuation models to the emergency planning and flood risk management communities will the use of these models on a more regular basis to improve emergency planning for floods.

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