Are There Better Ways to Quantify Flood Risk to Life?

S Molino[1], M Davison[2], A Tagg[2], P Cinque[3]
[1]Molino Stewart Pty Ltd, Parramatta, NSW
[2]HR Wallingford, UK
[3]NSW State Emergency Service, Seven Hills, NSW

Abstract

Risk to life is a critical consideration in flood risk management but quantify those risks has long been a vexed issue. The Australian National Committee on Large Dams (ANCOLD, 2003) recommends the methodology developed by Graham (1999) for estimating loss of life from dam failure. In the absence of other accepted methodologies this has sometimes been applied to loss of life from flooding generally but Graham himself has stressed on more than one occasion that the method has been developed purely for dam failure scenarios and is not suitable for other flood events (Graham, 2013).

At the same time, there have been developments in evacuation analysis and planning which has led to the promotion in NSW of the NSW State Emergency Service's Timeline Evacuation Model. As useful as this model is, it is coarse, it does not deal with complex road systems and traffic convergence well and it does not evaluate the consequences of evacuation failure.

In recent years more sophisticated models for the estimation of loss of life in any flood event have been created. One of the most advanced of these was developed by BC Hydro in Canada and recently commercialised as the Life Safety Model by HR Wallingford in the UK. It is an agent based model which in simple terms integrates dynamic 2D flood modelling with a flood warning dissemination model, a dynamic traffic model and consequence analysis of the interaction of floodwaters with people, vehicles and buildings to track the warning, response, evacuation and fate of each individual on a floodplain.

Molino Stewart and HR Wallingford were engaged by the NSW State Emergency Service to pilot the use of this model at Windsor on the Hawkesbury Nepean Floodplain and evaluate its utility for both evacuation planning and life risk quantification. This paper presents the findings of that work.

Background

The NSW SES is the lead combat lead agency for floods (including coastal inundation), storms and tsunami. Over the past 20 years the NSW SES has taken a more analytical approach to planning for such events which has included assessing the likely triggers for evacuations, their potential scale and the time required to effect them. To this end it has developed the Flood Evacuation Timeline Model (Opper et al, 2009) to quantify flood evacuation needs for a locality or region and to assist the NSW SES in its flood evacuation planning. Increasingly, the model has also been used to assess the evacuation implications of proposed developments. More recently the NSW SES has developed a tool and guideline to encourage more widespread and consistent use of the Flood Evacuation Timeline Model (Molino et al, 2013).

A limitation of the Flood Evacuation Timeline Model (FETM) is that each community, development or precinct must be evaluated individually to determine whether full evacuation is possible from each. Then, if evacuation traffic from several locations will be directed to the same road and potentially converge during an evacuation, further calculations must be undertaken to see whether that convergence creates delays for some evacuation traffic and whether this in turn compromises full evacuation.

The FETM tool has been set up to enable these calculations to be done for traffic leaving two localities and converging at one point. While the FETM has been used to model multiple traffic streams with multiple convergences (including in the Hawkesbury Nepean Valley where more than 70,000 may need to evacuate from several population centres (Molino Stewart, 2011)), the process is cumbersome, the results are coarse and it is challenging to present outputs in a way which is easy to communicate to decision makers. Furthermore, such modelling is really only modelling the evacuation road networks external to the area which is evacuating and assumes that the internal road networks are not a constraint to evacuation.

The guideline for the use of the FETM tool makes it clear that some, or all, of the evacuees may be unable, or unwilling to evacuate by motor vehicle even when the modelling indicates that everyone should be able to evacuate. The probability and consequences of such a failure must come into consideration when determining the appropriateness of a new development or reviewing the adequacy of emergency plans. The guideline and tool has some provision for determining whether pedestrian evacuation is a realistic fall back should vehicular evacuation fail. What the tool lacks is a robust method of estimating the fate of those who may fail to evacuate by vehicle or on foot or who may be overtaken by floodwaters in the process of evacuation.

Available Models

Several models have been developed in recent years to better model complex evacuation scenarios (not just for flooding) and others have been developed to better estimate loss of life from flooding. Some have been developed to do both.

Evacuation Models

There are many traffic models available which can be applied to evacuation analysis and planning. Pillac et al (2013) report that, "existing work in evacuation planning typically considers free-flow models in which evacuees are dynamically routed in the network. However, free-flow models do not conform to existing evacuation methodologies in which evacuated nodes are assigned specific evacuation routes." The following is an overview of three particular evacuation models which have been applied to flood evacuation in NSW in an attempt to replicate the way in which the SES triggers evacuation and designates evacuation routes.

NW SES Flood Evacuation Timeline Model

The FETM was born out of the 1997 Hawkesbury-Nepean Floodplain Management Strategy, where the NSW SES applied conventional time line project management to the flood evacuation problem. It became apparent that this approach provided a clear and concise method for examining the evacuation process.

Since that time, the approach has been refined into a model that can be easily applied to different developments.

The primary goal of the FETM is to compare the time required for evacuation with the time available for evacuation. This can be represented by the equation:

Surplus Time = Time Available – Time Required

or:

ST=TA-TR

Where the Time Available exceeds the Time Required there can be greater confidence that a community can evacuate safely by motor vehicle. Where the Time Required exceeds the Time Available it is unlikely that everyone will be able to evacuate safely by motor vehicle in all floods.

The model uses available information about flood rates of rise and flood warning to estimate the time available and empirical methods to estimate the time required for evacuation taking into consideration the time needed for people to respond to warnings, the carrying capacity of evacuation routes and the potential for delays. The method is described in more detail in Opper et al (2009) and Molino et al (2013). In essence both the flood modelling and traffic modelling components in the FETM are static models which assume average or constant values for inputs and provide an output calculated for a particular location along the evacuation route.

TUFLOW Integrated GIS

Wallace et al (2010) describe a GIS based evacuation assessment tool which was developed by BMTWBM to integrate with two dimensional dynamic flood model outputs from TUFLOW. It was reported that "evacuation capability can be assessed for different flood scenarios as well as multiple evacuation sectors, routes and centres within an automated framework…To enable this integration, an assessment tool was developed to quantify evacuation capability based on the SES timeline approach. This new tool enables more efficient evacuation planning for Floodplain Risk Management Studies, makes better use of existing flood model output, and provides more user-friendly GIS output for floodplain managers, emergency managers and planners alike."

This modelling offered several distinct advantages over the traditional static application of the FETM:

- It integrates with the dynamic two dimensional flood model to capture route closure information
- It calculates evacuation capacity on a time step basis making it more dynamic than the traditional application of the FETM
- It enables analysis of complex, multiple evacuation centres and routes
- It produces outputs as time series records for each population centre, route, junction and destination in both spreadsheet and GIS format.

Since publication of that paper there does not appear to have been publication of any results of application of the model to flood evacuation scenarios in NSW or elsewhere nor more information regarding further development of the tool.

Conflict- Based Path-Generation Model

More recently Pillac et al (2013) have developed a dynamic evacuation model which models the evacuation problem as a population(s) at one or more threatened nodes having to reach one or more safe nodes along one or more available pathways which can be cut at different times during the evacuation. The primary objective is to get all of the evacuees to a safe node within the capacity of the road network. A secondary objective, which the authors define, is to, "evacuate them as late as possible, as this leaves more time to potentially refine the threat scenario and hence avoids unnecessary evacuations."

They took three approaches to the modelling with the first being a free flow model which allowed evacuees to follow whichever (open) evacuation path they chose. The second ensured that those from a particular evacuation node followed a designated evacuation route. The third is what they describe as a "Conflict-Based Heuristic Path Generation" model which reduces computational complexity, and therefore increases computational speed, by separating the generation of evacuation paths from the scheduling of the evacuation.

These models were applied to an evacuation of 70,000 people from the Hawkesbury Nepean floodplain and demonstrated that evacuation of the entire threatened population can only be achieved if evacuation is commenced very early in the flood.

Life Loss Models

DSO-99-06 Procedure

The Australian National Committee on Large Dams (ANCOLD, 2003) recommends the US Bureau of Reclamation DSO-99-06 Procedure which is a methodology developed by Graham (1999) for estimating loss of life from dam failure. This is an empirical method base on the results of analysis of 16 dam failures which resulted in a total of 450 deaths around the world. It applies a fatality rate per head of population at risk to estimate the total number of lives lost taking into account the dam failure event, the number and location of people exposed to the event and the availability and efficacy of planned warnings and evacuations. This approach is not applicable to flooding which has not been generated by dam failure and assumes that evacuation is not constrained by transport network capacity.

Jonkman

Lang (2009) describes this as and empirical method for estimating loss of life from flooding of low lying delta areas. It uses fatality rates which have been derived from UK, US and Japanese case studies and uses an event tree approach to characterise warning and evacuation possibilities. It was applied during the FLORIS Project to estimate the consequences of flooding in the Netherlands but has had limited application elsewhere. It has been reported that the fatality rates in New Orleans were significantly different to the case studies upon which this method was based.

Combined Models

LIFESim

This was first developed by Utah State University but is now being developed by the United States Army Corps of Engineers (USACE) (Aboelata and Bowles 2005). It is not yet publically available. This model distributes the population at risk into three zones: chance zone (high damage); compromised zone (moderate damage); and safe zone (low damage) and applies an empirically based fatality rate to the population which finds itself in each zone when the floodwaters arrive.

It uses flood routing to categorise the various zones. It then uses inputs on topography, distribution of buildings and populations at risk, characteristics of warning and mobilisations, and the road network to distribute the population at risk horizontally and vertically depending on whether they are likely to move to a different part of the floodplain or move to a higher location in the building in which they are in. This is done via a series of decision trees within the database which is the interface of LIFESim. As such, it includes a quasi simulation of evacuation.

HEC-FIA

The HEC-FIA (Flood Impact Analysis) software package was developed by the USACE to analyse the consequences from a flood. It calculates damages to structures and contents, losses to agriculture, and estimates the potential for life loss. The loss of life calculation method is essentially a simplified version of LIFESim. Its simplifications include assumptions that mobilisation ends once the defined flood depth is reached, people move towards the edge of a hazard zone at a constant speed of 10km/hr and the distribution of compromised, chance and safe zones is based on flood depth. It essentially takes an empirical approach to evacuation.

Life Safety Model

The Life Safety Model (LSM) has evolved from work pioneered by British Columbia Hydro in assessing life safety risks downstream of its dams. HR Wallingford, under licence from British Columbia Hydro, has developed the LSM into a dynamic model that represents:

- the rise and spread of floodwaters
- the receipt of warning messages
- the response of occupants to the warning
- evacuation traffic flows
- the fate of those who fail to evacuate before the arrival of floodwaters.

It models the evacuation and fate of each individual household based on their exact spatial location and the available road network over time. Time series output from the model can be viewed as animations and well as in tables.

More information about the model can be found at http://www.lifesafetymodel.net.

Windsor LSM Pilot

In 2013 the NSW SES commissioned Molino Stewart and HR Wallingford to pilot the use of the LSM in Windsor in the Hawkesbury Nepean floodplain.

Windsor was chosen 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 – residential and others
- There are proposals for additional major development as well as ongoing creeping growth through infill development
- Flooding is not complex, it is essentially the same level rising across the entire area
- There is one evacuation route through the town and out
- The Hawkesbury Floodplain Risk Management Study and Plan (HCC, 2012) recommends the duplication of this evacuation route
- The FETM evacuation modelling done to date indicates that there are capacity issues on the evacuation route for the current level of development if a 9 hour warning time is assumed
- There are proposals for future development outside of Windsor which will have evacuation traffic which may converge with (and therefore block) Windsor evacuation traffic.

Windsor lies on the Hawkesbury River floodplain approximately 50km North West of Sydney Figure 1 in the Hawkesbury local government area (LGA). It is principally an urban centre with:

- old and new residential dwellings
- predominantly detached cottages but an increasing number of medium density residential developments – mainly townhouses
- a large commercial area with shopping strip, two mini-malls, car yards, district hospital, council chambers and other commercial developments
- an industrial area with a mixture of light industrial premises.

The town is built on a ridge which runs between Rickabys Creek on its west and South Creek on its East. Both creeks drain to the Hawkesbury River which runs along the northern end of Windsor. Urban development occurs on land ranging from about 13m AHD to about 26m AHD.

Flooding

Flooding on Rickabys Creek is unlikely to reach areas of urban development in Windsor but flooding on South Creek may impact on some of the lower lying properties along its floodplain.

The greatest flood threat to Windsor is from the Hawkesbury River. The River level at Windsor is most frequently at about 0.5m AHD and has a slight tidal influence although it is about 100km upstream of the ocean. However, due to topographic constrictions downstream, the river can rise to considerable heights during floods. Windsor has the oldest and most continuous record of flood levels in Australia. Table 1 summarises the major flood events which have been recorded and their estimated probabilities.

Table 1 Windsor Flood History

Chance per year	**Windsor (m AHD)**	**When occurred**
1 in 5	11.1	1992, 1986, 1975, 1956, 1952 & 11 other times
1 in 30	13.3-14.5	1990, 1978, 1964, 1956 & 12 other times
1 in 40	15.0	1961, 1799
1 in 100	17.2	None has occurred since records began
1 in 200	18.6	1867
1 in 500	20.3	At least once before 1788
1 in 1,000	21.7	No record
1 in 10,000	26.4	Probable Maximum Flood (PMF) - No record

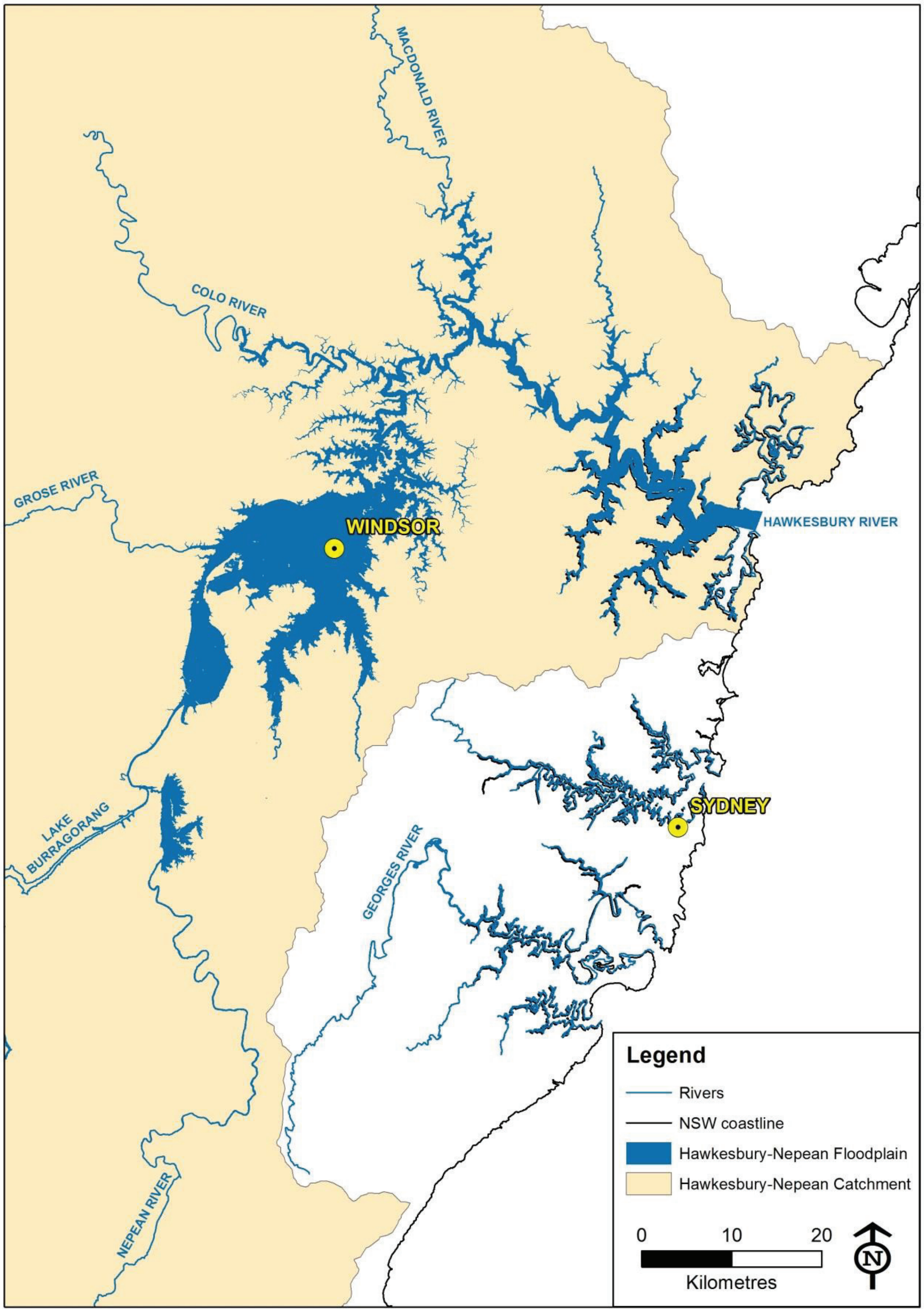

Figure 1: Windsor

Evacuation

The roads in and out of Windsor cross the Hawkesbury River, South Creek or Rickabys Creek floodplains and therefore are flooded before there is significant flooding of the urban areas of Windsor.

The NSW SES Flood Emergency Plan for the Hawkesbury Nepean River (NSW SES, 2008) recognises that:

- Windsor can be isolated by floodwaters for some days
- Windsor can be completely overwhelmed by floodwaters
- Early and complete evacuation of Windsor is necessary if it is forecast that the town will be significantly impacted by flooding.

The application of the NSW SES FETM to Windsor showed that evacuation would need to be triggered using flood predictions based on forecast rainfall well in advance of a flood developing.

The Flood Emergency Plan divides Windsor into subsectors for the purposes of evacuation and all of these subsectors use local evacuation routes within Windsor to take them to Day St which leads onto Jim Anderson Bridge as shown in Figure 2.

From here traffic is directed through Mulgrave and Vineyard onto the regional evacuation route which follows Windsor Road then Old Windsor Road to the M7 which leads onto the M2. From the M2 evacuees can make their way to the main evacuation centre which will be established at the Olympic Stadium at Homebush. Not all evacuees are expected to reach Homebush with the majority of them expected to find temporary accommodation with family or friends or by other means.

The regional evacuation route is shown in Figure 3.

Model Set Up

The steps involved in setting up and running the Life Safety Model (LSM) are:

- Buildings – The physical location of occupied buildings to provide a start location for the population groups and vehicles.
- Population data – Use census data to define household groups and distribute to physical building location.
- Number of Vehicles – The number of vehicles evacuating from each property are distributed to the building locations.
- Road network – Digitise a simplified road network containing the evacuation route and minor roads leading to it. The number of lanes and free flow speed limits are required.
- Hydrodynamic data – 2D depths, water levels, velocity for a number of time intervals covering the flood event. The time interval depends on the duration and rate of rise of the flood event.
- Run the model for the base scenario.
- Create emergency management scenarios to be tested.

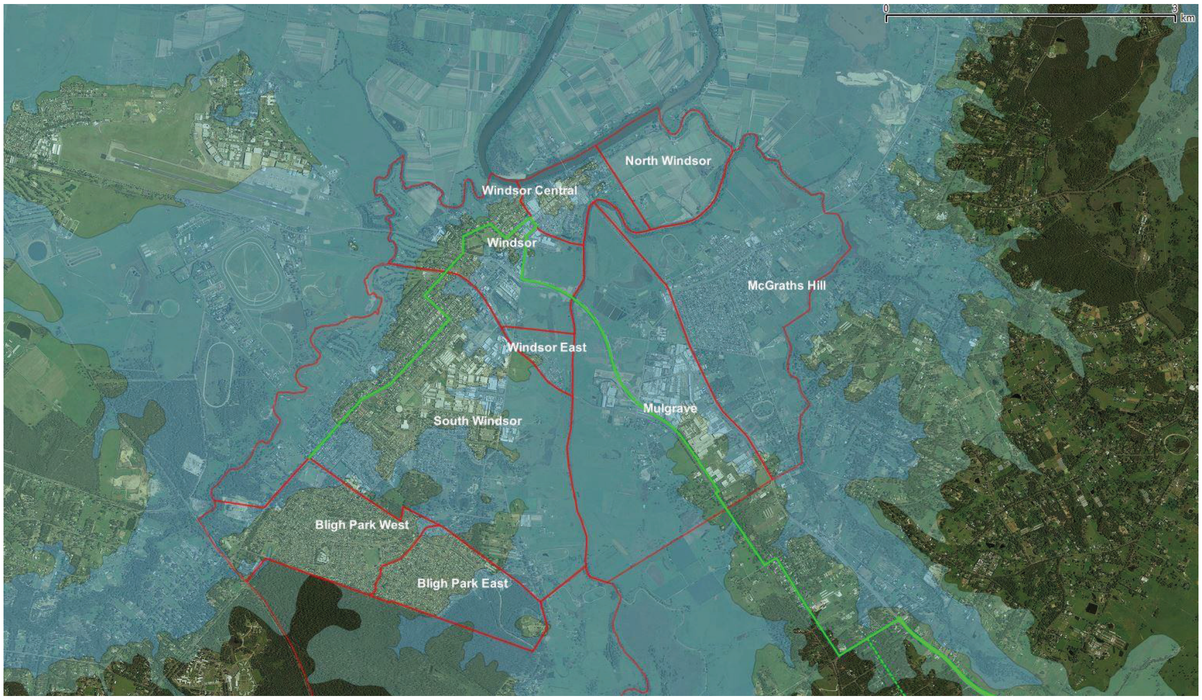

Figure 2: Windsor Sub Sectors and Main Evacuation Route

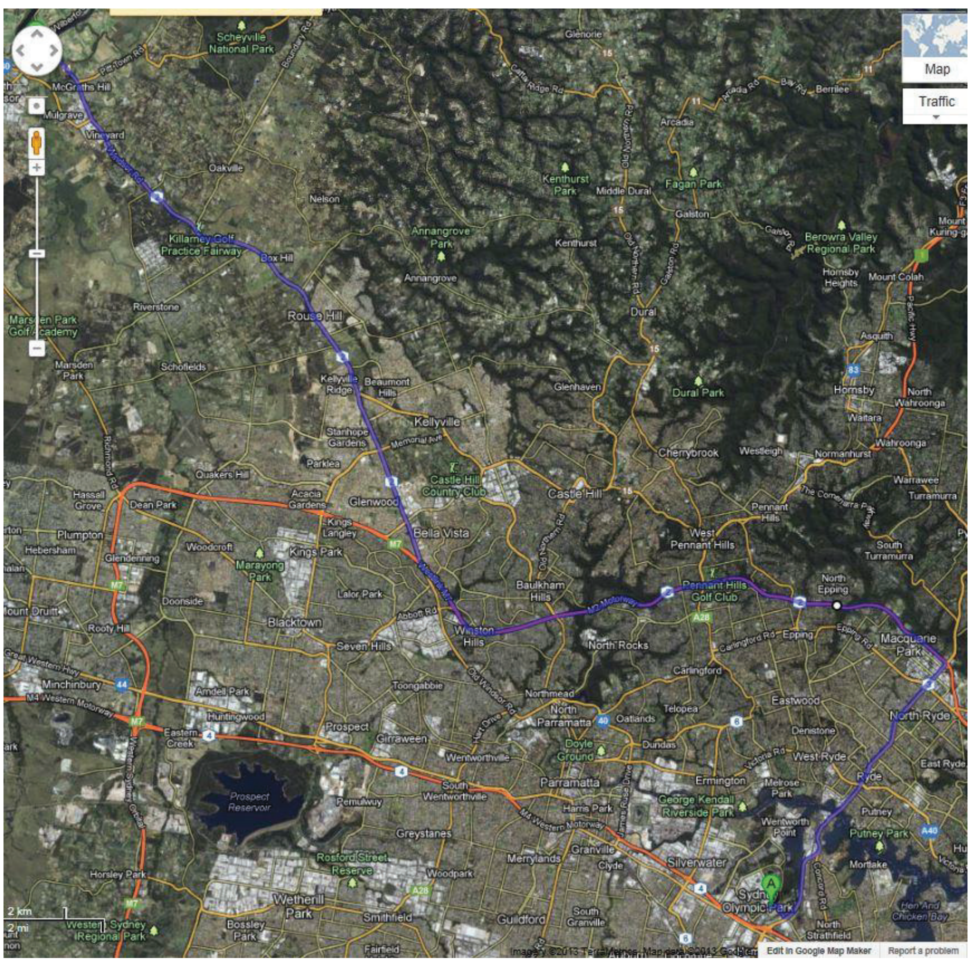

Figure 3: Regional Evacuation Route

For this pilot study the physical location of all buildings had been logged as part of the Hawkesbury Nepean Valley Flood Management Review and the residential population and vehicle data was available from the Australian Bureau of Statistics. The SES was able to supply a detailed digitised road network with information about levels, speed limits and available lanes for evacuation.

What was problematic was the flood modelling. A recent MIKE-11 model was available which had been developed for the Hawkesbury Nepean Valley Flood Management Review, however, LSM needs a two dimensional model to be able to demonstrate its full functionality. There was an older RMA-2 model of the Windsor floodplain but this is one of the few two dimensional flood modelling programs with which LSM is not yet compatible. It was therefore decided to undertake the evacuation modelling without integrating a flood model and manually interpreting the results by comparing them to a flood hydrograph.

Assumptions

Several assumptions were made in setting up the model. The main assumptions were:

- Only evacuation from residential dwellings would be modelled at this stage
- All households with their own car will self-evacuate (about 90% of the dwellings) and that all cars will be evacuated
- The remaining 10% of households will require public transport/assistance and it has been assumed that there will be one bus for every 30 people in these households
- People would leave their homes randomly throughout Windsor but their departure times could be described by an S shaped departure curve with total time of 8 hours and P50 of 4 hours as shown in Figure 4. This is consistent with the approaches taken in the Netherlands (Tagg et al., 2012) where evacuation planning is a major exercise.
- The maximum traffic flow was set at 600 vehicles per hour per lane to match NSW SES recommended values. This was done by setting a target free flow speed of 48 kph and the maximum density at 50 vehicles per km.

With regard to the S shaped departure curve, the underlying assumption behind this curve is that reaction to an evacuation order will be immediate but slow at first, then accelerate as people see others leaving. It will then taper off as the most resistant to evacuation leave it until the latest possible time. In this way it varies from the assumption within the SES FETM (See Figure 4) which assumes that there will be:

- a one hour warning acceptance factor (WAF) – the time taken for people to accept the warning,
- a one hour warning lag factor (WLF) the time taken for people to prepare to evacuate
- a constant rate of evacuation which matches the road capacity (assuming that door knocking can be undertaken at the same rate)
- a traffic safety factor (in the case of Windsor this would be 2 hours) to account for traffic delays due to contingencies such as car accidents, breakdowns, downed electricity wires or trees or water across the road

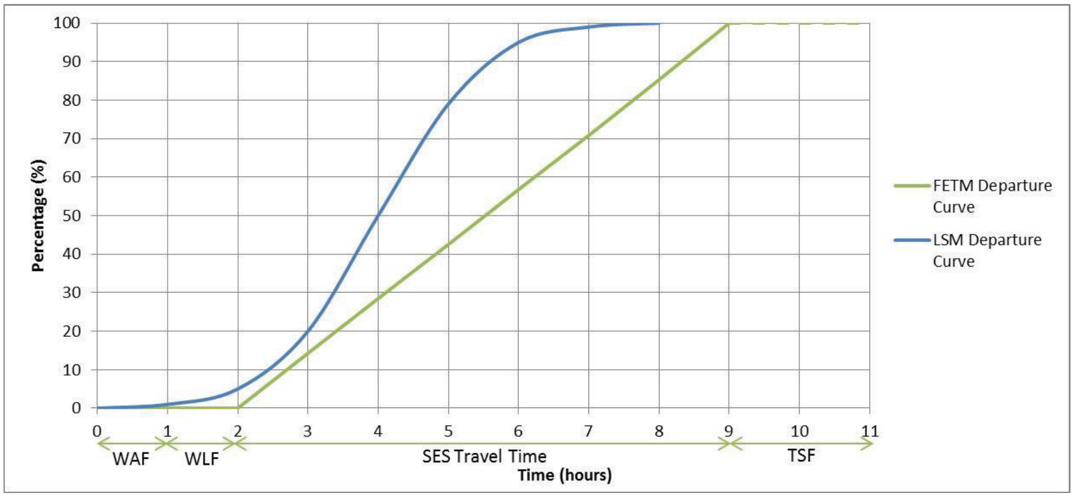

Figure 4: Departure Modelling Assumptions in LSM and FETM for Windsor

Results

The model was run for the base case scenario which was a night time evacuation in which all dwellings, but no non-residential buildings, would be occupied. In the absence of a 2D hydraulic model, data was extracted from the dynamic traffic modelling to graph when people are ready to leave their homes, when they cross the point where the evacuation route rises above the PMF and when they would arrive at the Sydney Olympic Precinct at Homebush.

This is shown in Figure 5 which clearly shows that although everyone has departed or is ready to depart by hour 8, everyone has not left the floodplain until about hour 9.5 and everyone has arrive at Homebush about another hour later.

Figures 6 to 10 are snapshots from the dynamic model and show that the 1.5hour delay in leaving the floodplain is caused by traffic congestion on the evacuation route within Windsor which in turn causes queuing along this route and back onto the roads leading onto this route. In these figures the purple dots are the dwellings which have not yet evacuated and the yellow dots are evacuating vehicles.

From viewing the dynamic model outputs, it appears that queuing builds from about the 2.5 hour mark to a maximum at about 6.5 hours and then dissipates over the next three hours.

The LSM is simulating the evacuation of 4,210 cars and 26 buses and suggests that they would all be able to leave the floodplain within about 9.5 hours of evacuation being ordered.

If evacuation of the whole town is ordered 9 hours before the main evacuation route is cut then the LSM suggests that only about 95% of the residents would have time to depart.

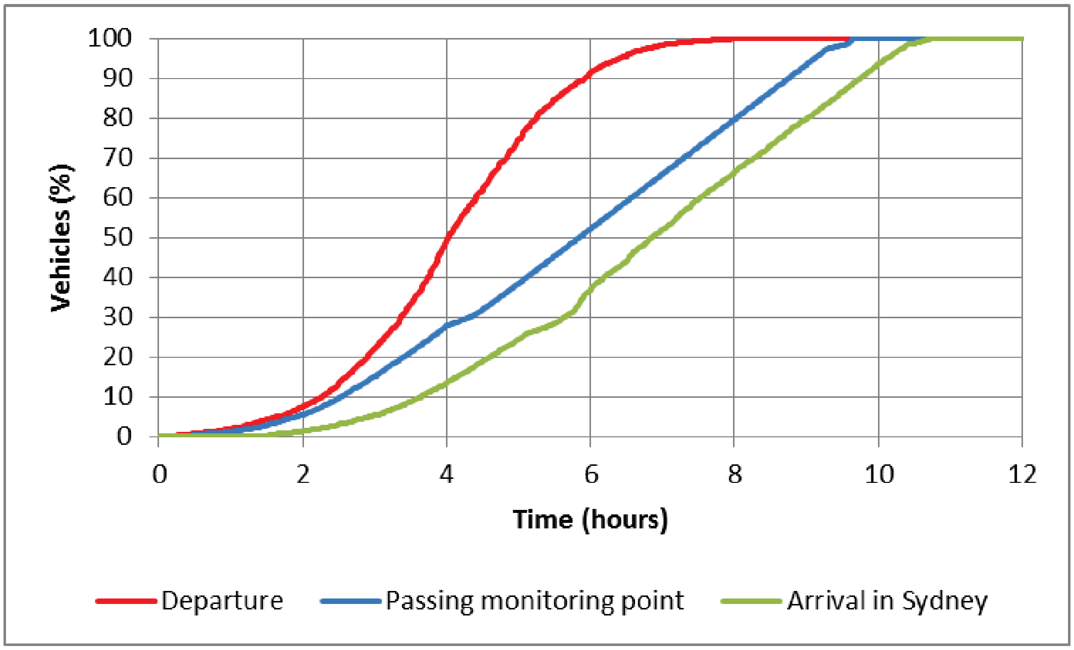

Figure 5: Windsor LSM Departure and Arrival Curves

Figure 6: Windsor LSM Snapshot at 2 hours

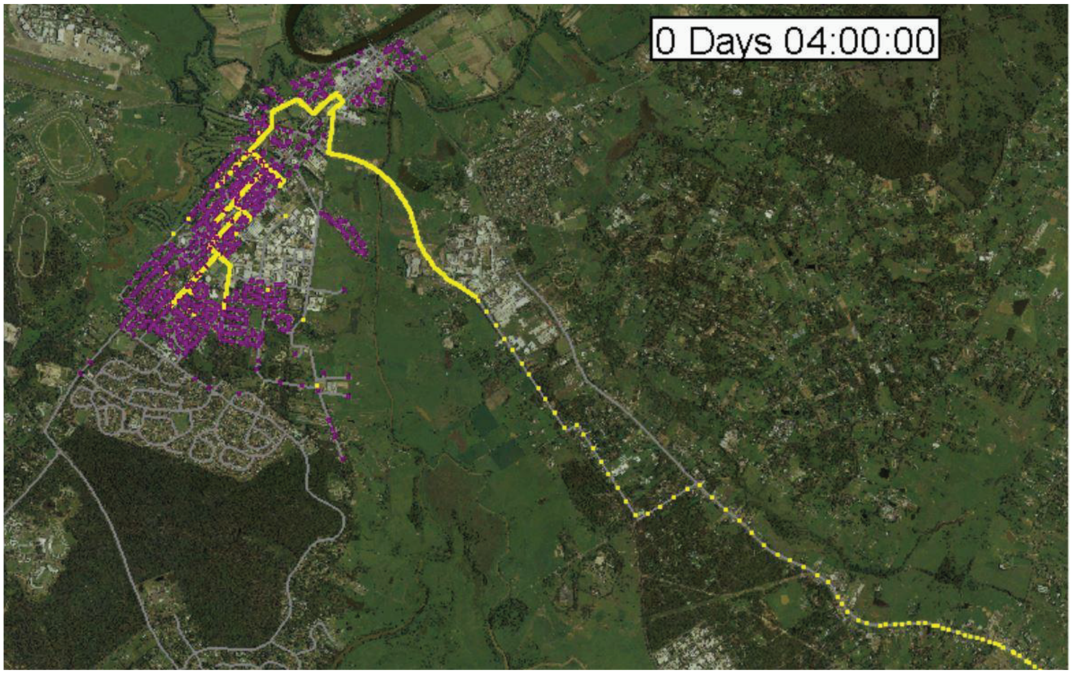

Figure 7: Windsor LSM Snapshot at 4 hours

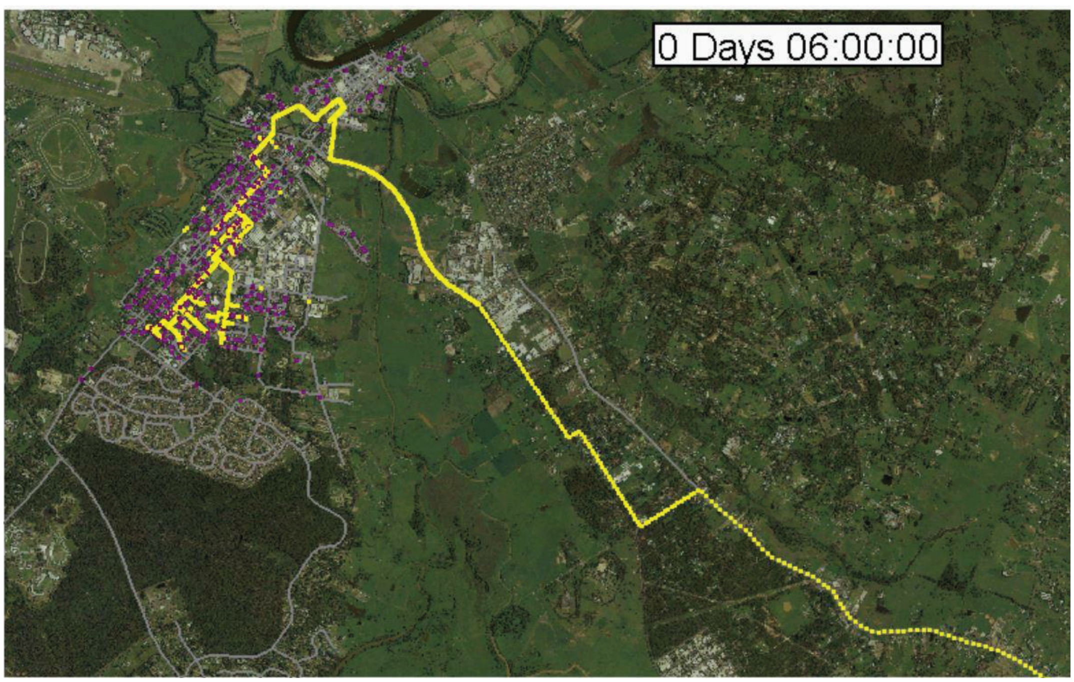

Figure 8: Windsor LSM Snapshot at 6 hours

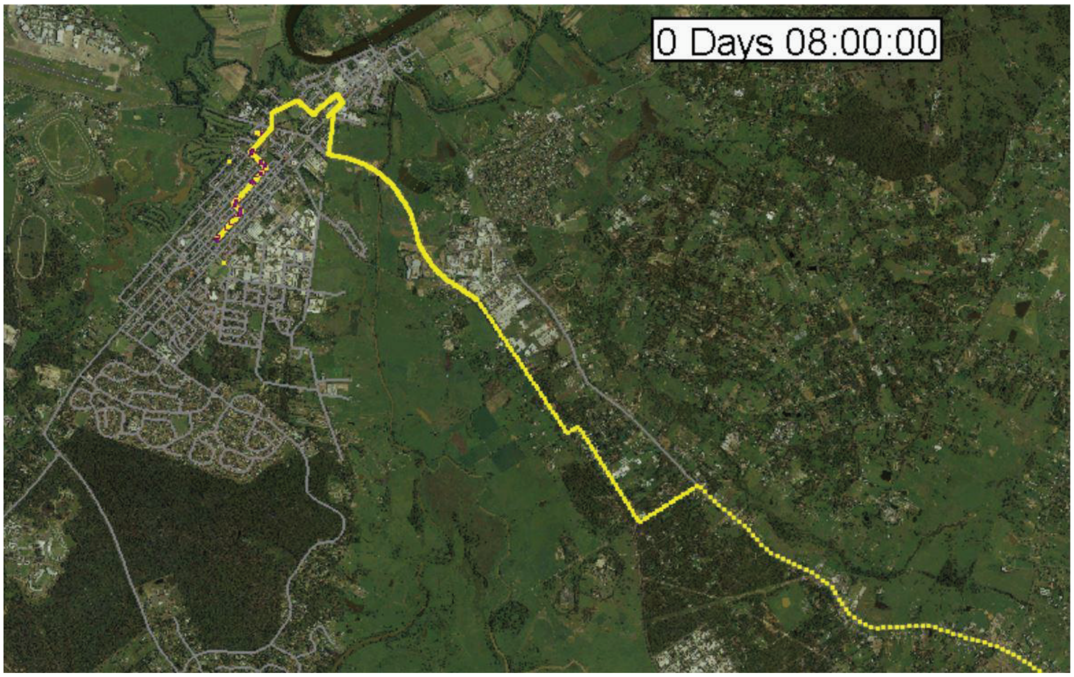

Figure 9: Windsor LSM Snapshot at 8 hours

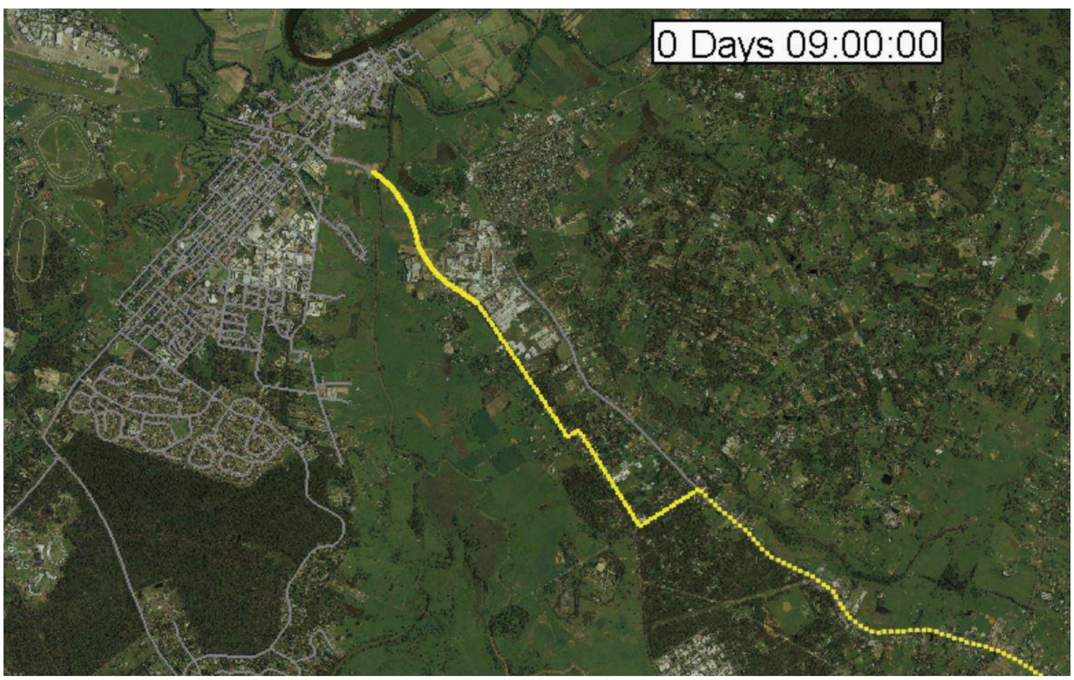

Figure 10: Windsor LSM Snapshot at 9 hours

If the FETM were used for the same number of vehicles, it would suggest that:

Warning Acceptance Factor	=	1hr
Warning Lag Factor	=	1hr
Travel Time = 4,210 / 600	=	7hrs
Traffic Safety Factor	=	2hrs
Total		**11hrs**

The FETM is suggesting an additional 1.5 hours is needed to evacuate Windsor compared to the LSM results. However, this is because the FETM includes a factor for traffic delays which is not included in the LSM. If the TSF is ignored in the FETM and the results compared to the LSM, the LSM suggests that it would take 0.5hours longer to evacuate Windsor than is suggested by the FETM. This is most likely due to the slowing of traffic flow caused by congestion and queuing within the town which cannot be modelled by the FETM.

Were a two dimensional flood model available for integrating into the LSM at Windsor, the LSM would evaluate the fate of any people who were unable to evacuate before they were overtaken by floodwaters. This would depend the magnitude of the flood which was modelled and allows pedestrian evacuation to be modelled as a default when vehicular evacuation has failed. In the case of Windsor, after the evacuation route is cut it would be possible for some residents to walk up to the highest parts of town which were above the reach of the 1867 flood but which would be completely inundated in more extreme events.

Figure 11 shows how the LSM can graphically represent the fate of evacuees when a two dimensional flood model is used. This figure shows the situation approximately 1.5 hours after a sudden dam failure causes flooding. People become of the need to evacuate because they either see the floodwaters or see others evacuating. The legend is generally self-explanatory but the pale dots represent all of the buildings which have been evacuated.

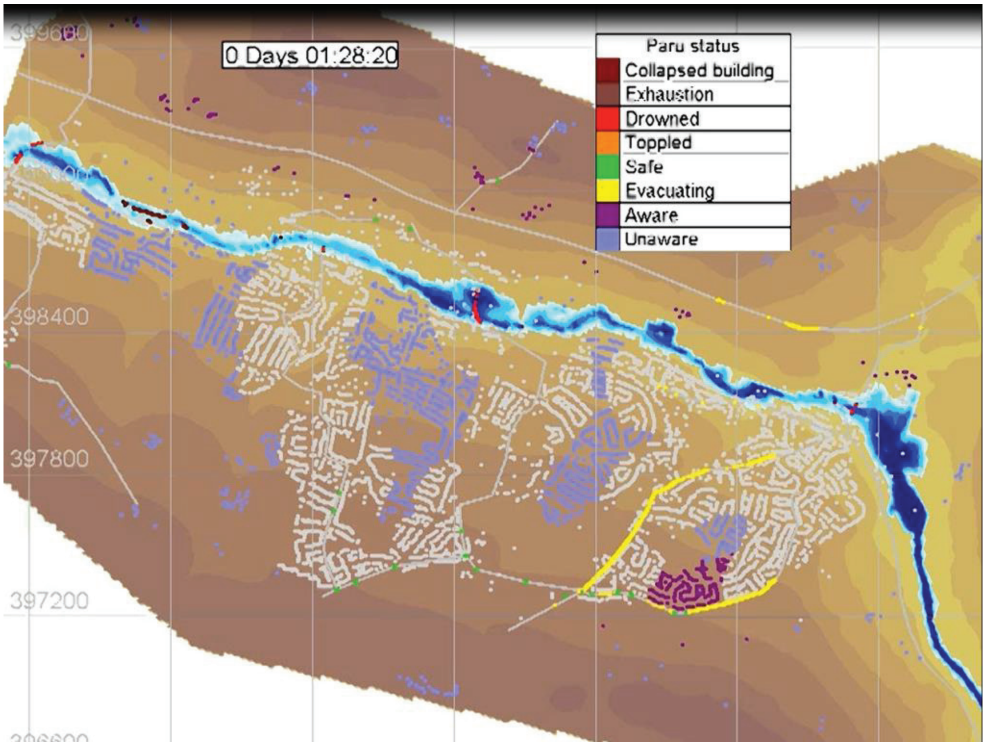

Figure 11: LSM Output for a Sudden Dam Failure Flood

Conclusions

While there are several models available which either model flood evacuation or loss of life, there are few which are able to model both. The Life Safety Model appears to be a versatile and robust model for evacuation analysis and planning and life safety analysis because it can:

- fully integrate with two dimensional flood models
- model different warning dissemination mechanisms
- model vehicular and pedestrian evacuation
- model individual buildings and vehicles with spatial accuracy
- replicate NSW SES warning, departure and travel assumptions
- test alternative evacuation modelling assumptions
- model the entire road network including networks internal to evacuation nodes
- model traffic convergence within and outside of evacuation nodes
- show results dynamically and visually in a way which helps communicate convergence, queuing and evacuation failure
- model the fate of those who fail to evacuate and provide a defensible estimate of loss of life
- undertake sensitivity analysis quickly

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