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THE DEVELOPMENT OF A LIFE SAFETY MODEL TO ESTIMATE THE RISK POSED TO PEOPLE BY DAM FAILURES AND FLOODS

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Abstract
Dam owners face important decisions about the ways in which finite resources should be allocated to ensure the continuing safe operation of ageing dams. Dam safety risk assessments depend on credible estimates of loss of life for hypothetical failure events to aid in quantifying risk and making decisions concerning how structures are maintained. This paper briefly describes the development of a model, called the "Life Safety Model", to provide a physics based, dynamic model to estimate loss of life and evacuation times that can result from extreme flood events. The Life Safety Model has an agent-based simulator that enables the model to represent a myriad of probable scenarios which could result from a flood event. Unknown variables such as the effectiveness of warning, road capacity, and time varying population density can be tested in a range of scenarios. The Life Safety Model uses results of flood water depth and velocity from two dimensional hydraulic models such as Telemac 2D over the course of the event, to represent the flood hazard. Unlike many other models and methods of this kind the Life Safety Model includes a dynamic interaction between the receptors and the flood hazard. The paper describes the application of the model to the Malapasset Dam disaster that occurred in 1959 in the south of France. The application of the Life Safety Model to this disaster demonstrated that the model was capable of making accurate estimates of loss of life from an actual flood event.

1 Introduction

High hazard, low frequency events have the potential to cause considerable damage to property and loss of human life. Some events are outside human control, such as hurricanes, tornadoes, earthquakes, and precipitation-induced floods. Some events are a direct result of human or engineering failures, such as plane crashes, toxic chemical spills, or accidents at nuclear reactors. Dam failures generally fall in between these extremes, sometimes resulting from faulty design under otherwise favourable environmental conditions and sometimes failing despite superior engineering, after being overwhelmed by an extreme flood, earthquake or latent geotechnical defect (McClelland & Bowles, 2002).

In the context of flood risk management, "risk" is defined as the product of the probability of the hazard occurring and its consequences on "receptors". In the context of this paper the term receptors is used to refer to entities in the floodplain that may be harmed (e.g. people, properties, vehicles, habitats). The evaluation of the risks posed to people by floods has become increasingly important over the past decade with policy decisions on flood risk management not being made purely on economic factors, but also taking human and environmental concerns into consideration.

Dam owners are facing increasingly difficult decisions about the ways in which finite financial and human resources should be allocated to ensure the continuing safe operation of ageing dams. Without such investment dam failure is not only a possibility but can be an expected consequence of lack of proper maintenance and diligence by a dam owner. In the USA, historically, some of the largest disasters have resulted from dam failures. In 1889, 2,209 lives were lost when the South Fork Dam failed above Johnstown, Pennsylvania. The 1928 St. Francis Dam failure killed 450 people. During the 1970s, the failures of the Buffalo Creek Dam in West Virginia, Teton Dam in Idaho and the Toccoa Falls Dam in Georgia collectively cost 175 lives and more than US$1 billion in losses (Dam Safety Coalition, 2005). The failure of a stepped masonry spillway at Ulley dam, near Rotherham, UK, during a flood on 25 June, 2007, and the ensuing evacuation of people at risk were a timely reminder of the risks that dams can pose and the importance of assessing evacuation times and the probability of fatalities. Ulley reservoir was completed in 1873, and the average age of British dams is now about 110 years (Mason, 2008).

Dam safety risk assessments depend on credible estimates of loss of life for hypothetical failure events in order to quantify risk and make decisions about the construction, rehabilitation, or removal of dams. As a consequence there has been an increasing requirement to quantify the estimated number of fatalities and injuries that could result from the failure of dams and major flood events. Until recently improvements in "life loss" estimation had been one of the most intransigent aspects of the field, causing some decision makers to seriously doubt the credibility of analysts' estimates (McClelland & Bowles, 2002). Over the past 15 years a number of methods and models have been developed to assess loss of life as a result of dam failure and severe flooding. This paper provides a brief review of the loss of life models that have been developed, based on work by Johnstone & Lence (2009), and focuses on the development of a micro-scale Life Safety Model that can be used to assess the risks to people posed by dam breaches, required evacuation times and measures, (such as safe refuges or improvements in the dissemination of warnings), that can reduce the risk.

BC Hydro is a Canadian electricity utility based in the province of British Columbia, who is responsible for the operation of 27 hydroelectric facilities comprising several "high" or "very high consequence" dams (CDA, 2007). These are dams where the consequences of failure could result in large losses (e.g. hundreds of deaths and tens or even hundreds of millions of dollars of economic and social losses). In 2001 BC Hydro commenced work on a Life Safety Model to provide a physics-based, dynamic model to:

- provide credible estimates of loss of life using transparent auditable methods;
- use readily available government and commercial Geographic Information System (GIS) based data sets;

and

- provide results and animations that can improve the emergency response and plans for such disasters.

The first part of this paper provides some background to the Life Safety Model, the second part provides a comparison of loss of life models for dam risk assessments and the third part provides details of the application of the Life Safety Model to the Malpasset Dam Disaster in France.

2 Background to the Life Safety Model

2.1 Development of the model

When work commenced on the development of the Life Safety Model an assessment of existing tools for assessing the risk to people from dam failure and floods identified that many models were based on empirical methods that were often based on relatively limited experiments or historical events. Results from many of these models rely on subjective measures which can lead to a considerable variation in the results (Jonkman et al, 2003) depending on the assumptions made by the users. Moving from general empirical models, the focus of the Life Safety Model was to develop an approach that would provide the ability to simulate receptors in a floodplain and base their interaction with a floodwave on fundamental physical equations. This led to the development of an "agent-based" simulator that can assess the "fate" of individual receptors in the flood plain. The Life Safety Model uses output from commercially available two dimensional hydrodynamic models (e.g. Telemac-2D, TuFlow) and couples it in a GIS environment with a simulator that models the interaction of receptors (i.e. people, buildings, and vehicles) in the flood. Dynamic simulations linking the movement and interaction of receptors with the floodwave can be performed. The interaction of these receptors was based on fundamental physics: mathematical models of "human toppling" defining the stability of people in water (Lind & Hartford, 2000); or damage to buildings in floods (Clausen & Clark, 1990) and the stability of vehicles in water.

Although the Life Safety Model was originally developed to provide a method to determine more credible loss of life estimates resulting from catastrophic dam breaches, the model has demonstrated value beyond this singular task. The model can be applied to a range of flood events including: fluvial floods; coastal events and floods generated by tsunamis (Johnstone & Lence, 2009; Lumbroso & Di Mauro, 2008). As a result of the richness of detail provided by the model, it has proved to be a valuable tool in modelling and assessing evacuation plans and the feasibility of implementing these plans. Through modelling and visualizing the movement of individual people, the Life Safety Model is able to show how a flood emergency may unfold. Characteristics of the specific flood site that create challenges in an evacuation such as bottlenecks in evacuation routes can become apparent as the simulation unfolds.

In 2004, BC Hydro released their first fully functional version of the model in collaboration with the Canadian Hydraulics Centre, which falls under Canada's National Research Council. Following a decision by the Canadian Hydraulics Centre to cease its participation in the Life Safety Model, BC Hydro established a research and development agreement with HR Wallingford. However, there was also significant interest in the Life Safety Model in the USA and other many other parts of the world. The United States Bureau of Reclamation (USBR) is an additional partner in the development of the model. Along with heading the developmental improvements of the Life Safety Model, HR Wallingford continues to apply the model on projects related to emergency planning for floods and dam breaks worldwide. BC Hydro is also working to advance the model through funding research by the Technical University of Delft in the Netherlands and the University of British Columbia in Canada in identifying communities that are "shelterable and evacuable", in ranking the needs of these communities, and in applications to tsunami preparedness and emergency management. The University of British Columbia is also working on adapting the Life Safety Model so that it can be used to look at the impact of dam breaks on the environment (e.g. fisheries). The model is also currently being tested by the University of New South Wales in Australia.

2.2 Functionality of the model

Developing the Life Safety Model as an agent-based simulator enables the model to represent a myriad of probable scenarios which could result from a flood event. Unknown variables such as the effectiveness of warnings, road capacity, and time varying population density can be tested in a range of scenarios. To provide this range of assessment, the Life Safety Model was developed to represent the following:

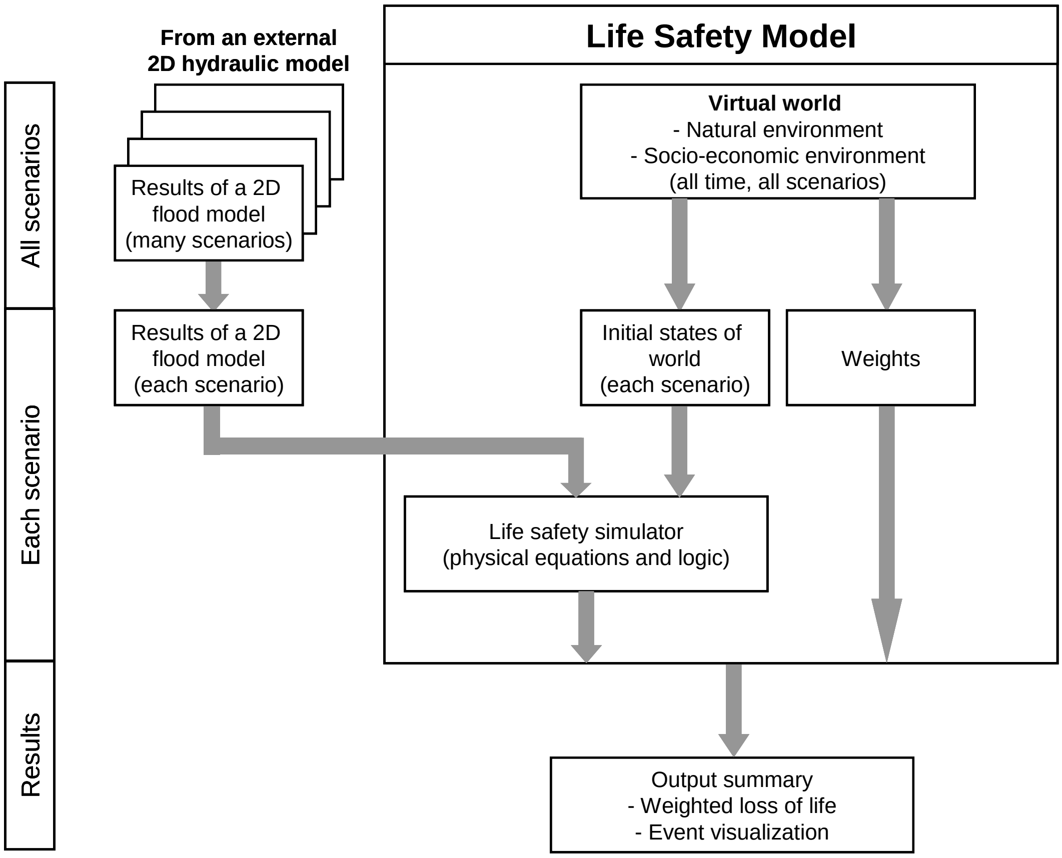
- The number of people that are killed or injured by an inundation. The time-varying properties of the flood in terms of its depth and velocity affect people's survival capacity, and also the speed at which they move. Should a person be caught in the floodwave their chance of survival depends on the velocity and depth of the flood at a particular point in time (i.e. above a certain threshold level people will be drowned or be swept away by the water). However, the effect of continuous exposure to water is also modelled with the effects of exposure also being represented in the number of fatalities.
- The movement of vehicles is modelled by a simple traffic model. This allows the effects of traffic jams and other bottlenecks to be taken into account when the evacuation time is estimated.
- The dynamic interaction of the floodwave with vehicles. If people are leaving the area at risk in a car the engine will stop once the vehicle has encountered a certain depth of water or if the combination of velocity and depth is high it would get swept away in the floodwater.
- The capacity of each building to withstanding the floodwater. Depending on the characteristics of the building and the flood, buildings can: suddenly collapse; fail progressively as a consequence of continuous exposure to the flood; or remain intact.
- People being modelled as individuals and also as groups (e.g. families) so they do not separate during an evacuation. The speed at which a group moves is influenced by every member of the group.
- The speed of the dissemination of flood warnings: People can receive warnings from a "warning centre" and also by "word of mouth" from other people who are aware of the impending floodwave.
- The evacuation of people along roads or footpaths, toward refuges is predetermined by the user. The refuges can be areas of high ground, buildings resilient to the flood wave with more than one storey or specially adapted shelters.

Figure 1 provides a conceptual overview of the components of the Life Safety Model. The key system inputs include representations of the natural environment (e.g. topography, water bodies), the socio-economic environment (i.e. people, buildings, vehicles, roads), and temporal results from a two dimensional flood wave model. The core of the model is the Life Safety Model Simulator which requires two inputs as follows:

(i) An initial state of the "virtual world" in the model. This describes the initial position and number of receptors including: individual people; groups of people; types of buildings; vehicles, roads; safe havens; warning centres.

(ii) The results of depth and velocity from a two dimensional model of the flood at a suitable time step over the duration of the event.

The simulator output includes an estimate of loss of life and dynamic computer-graphic visualisations. Loss estimates from multiple runs can be used to produce a weighted estimate of loss of life. Animations of different scenarios can help planners to compare how emergencies might unfold with and without planning and mitigation (Johnstone et al, 2005).



(Johnstone et al, 2005)

Figure 1 A conceptual overview of the components of the Life Safety Model

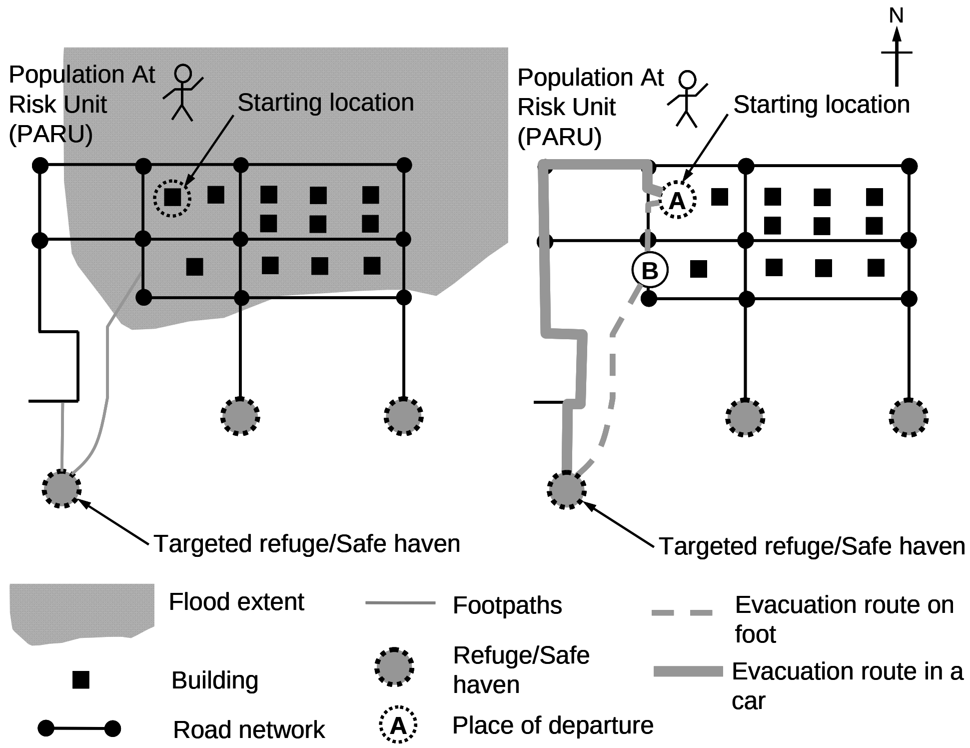
2.3 Modelling the fate of people, vehicles and buildings at risk

At the heart of the model is its ability to establish the "fate" of each individual person. Each individual can be assigned parameters relating to how they react to the flood including:

- how an individual is warned of the flood;
- how long it takes for an individual to become aware of the flood;
- once aware of the flood if the individual remains in place or how long they take to evacuate;
- by what method they evacuate (i.e. by car or on foot);
  and
- how "resistant" the individuals are to the floodwater.

Should an individual remain in their building, the characteristics of the building will determine if the building will provide sufficient shelter to protect the individual. If the individual evacuates, characteristics of the site such as available evacuation routes and density of traffic can influence whether or not the individual successfully reaches safety.

Figure 2 depicts how the specific characteristics of the floodwave scenario and individuals, (known as Population At Risk Units (PARUs)), being modelled can have an impact on their survival or "fate". An individual may choose to evacuate from their designated Point A by the longer evacuation route by car, (the thick grey line in Figure 2), a more direct route by foot (the grey broken line in Figure 2), or choose to seek refuge in their building (Point A). 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. Given the rate of rise and magnitude of this flood, this event suggests the individual was able to escape by car, instead of being overwhelmed by the flood at Point B when travelling by foot. In this particular case, if the building is destroyed by the flood, the individual in that building would not survive. Other scenarios might suggest that congestion on roads would render vehicular evacuation to be a less optimal choice. The benefit of the Life Safety Model is that such site specific scenarios can be modelled dynamically and assessed.



(Johnstone et al, 2005)

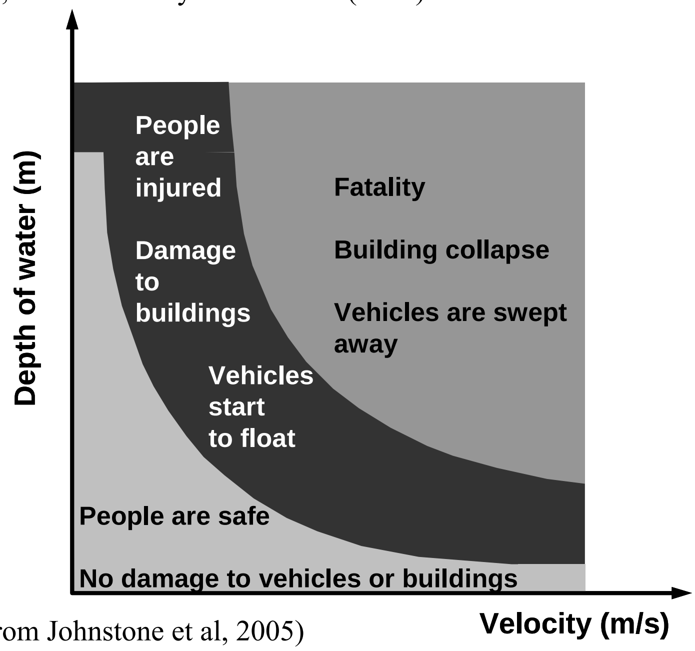
Figure 2 Schematic diagram illustrating how a Population at Risk Unit’s (PARU’s) choice of evacuation can have an impact on their survival

In the model road and footpath networks provide temporal routes of escape from flood waters for both vehicle and pedestrian traffic. Vehicles are restricted to roads. Pedestrians can escape via roads and footpaths. These networks form the basis of a traffic and pedestrian model that is used to assess evacuation times. The Life Safety Model takes into account the road network, considering the different kinds of road in terms of their capacity with respect to the number of vehicles/km/lane. In the Life Safety Model the road capacity is related to the vehicle’s velocity by means of the widely used Greenshield linear speed-concentration formula. In a road network using the Greenshield equation, as the traffic density increases the traffic flow increases to some maximum value, but a continual increase in density will cause the flow to decrease until “jam density” and zero flow conditions are reached (Greenshield, 1935). All roads and footpaths are assumed to be bi-directional. This means there can be an equal flow of traffic and pedestrians in both directions. Vehicles cannot pass each other in their designated lane. This rule simulates the traffic bottlenecks that may occur on congested escape routes. A vehicle can move to an adjacent lane on multi-lane roads if that adjacent lane is unoccupied (BC Hydro, 2004).

The initial state of the virtual world can have people who are unaware that a flood has commenced in it moving on foot and in vehicles. These “unaware” people move back and forth on the road and footpath networks until they become alerted to the flood hazard. People in buildings who have not received a flood warning do not move from them (BC Hydro, 2004).

Once a person in a building has become aware of the flood, those that have decided to evacuate will start their journey towards the nearest perceived safe haven.

The Life Safety Model uses generalised event logic to determine the location of each person at each time step, whether they are aware of the danger, whether they are trying to find a refuge, what happens if they encounter the flood in terms of their survival. The Life Safety Model includes damage and loss functions for people, vehicles and buildings. These specify whether the receptor survives the flood or not. These functions describe the ability of the receptor to resist the impact from the flood wave, in terms of depth and velocity. There are number of loss functions. For example, there are instantaneous loss functions in cases where an individual person is swept away in fast-flowing water, or has sought refuge in a building that suddenly collapses. Figure 3 shows the form that some of these loss functions take. Recent work to extend the theoretical formulation of the building loss function to model the structural failure of one-storey and two-storey wood frame homes as a function of the hazard load path through various building components, and to add breaching and buoyancy to the loss-of-protection mechanisms, is described by Becker et al (2010).



(Modified from Johnstone et al, 2005)

Figure 3 Schematic diagram illustrating the form of the loss functions for people, vehicles and buildings

The model further mimics the dynamic interaction of the receptors in the floodplain by simulating how the receptors can be weakened by flood events. With prolonged exposure to flood waters, an individual can become weakened by the inundation either through exhaustion from withstanding flowing waters or hypothermia. The strength of buildings can decrease as they are continually exposed to hydrodynamic loads. The model simulates this loss in strength by effectively lowering the critical values of the loss functions shown in Figure 3 for each receptor with respect to time and the severity of flood exposure.

3 Comparison with other loss of life models

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 a dam failure and flooding. These include the UK Department for Environment, Food and Rural Affairs method (DEFRA, 2003), USBR or ‘Graham’ method (Graham, 1999, USBR, 2005), HAZards United States (HAZUS) produced by the US Federal Emergency Management Agency (FEMA, 1999; Joyce and Scott, 2005), LifeSim (Aboelata &

Bowles, 2005), the TU Delft method (Asselman & Jonkman, 2003) as well as the Life Safety Model (LSM). A comparison of these models carried out by Johnstone and Lence (2009) is provided in Table 1. The first column lists the characteristics of the model that were assessed, and the remaining columns denote whether the model incorporates this capability in an explicit or implicit manner, or does not appear to provide the functionality at all.

Table 1 Characterisation and comparison of loss of life models and methods for use in dam and flood risk assessments

Functionality	Name of model					
	DEFRA	**USBR**	**HAZUS**	**TU Delft**	**LifeSim**	**LSM**
Purpose						
Loss estimation						
Fatalities/injuries	▲	▲	▲	▲	▲	▲
Economic			▲	▲		
Community response						
Evacuation times		Δ		▲	▲	▲
Use of refuges					▲	▲
Dissemination of warnings					▲	▲
Type of flood event						
Dam failure		▲	▲	▲	▲	▲
Flood defence failure	▲	▲	▲		▲	▲
Fluvial floods	▲					▲
Flash floods						▲
Coastal floods/Storm surges				▲		▲
Tsunami						▲
Receptors modelled						
Individual people					Δ	▲
Groups of people	Δ	Δ	Δ	Δ	Δ	▲
Buildings	Δ	Δ	Δ	Δ	Δ	▲
Vehicles					Δ	▲
Roads and paths				▲	▲	▲
Modelling approach						
Empirical	▲	▲	▲	▲	▲	▲
Physical				▲		▲
Time dependent					▲	▲
Dynamic interaction between receptors and flood wave						▲
Spatial resolution						
Macro	▲	▲				
Meso			▲	▲		
Micro					▲	▲
Flood wave hydraulics						
Severity scale	Δ	Δ			Δ	
Physics based						
Water depth			▲	▲	▲	▲
Flow velocity				▲	▲	▲
Momentum				▲		▲
Kinetic energy						▲
Rate of rise				▲		▲

Note: ▲ explicitly represented in the method or model
Δ implicitly represented in the method or model
(Source: Modified from Johnstone and Lence (2009))

Of the methods detailed in Table 1 the Life Safety Model offers one of the most scientifically robust and flexible method for not only assessing the risk from floods caused by dam breaks but also other types of floods. The analysis suggests that the earlier models cannot be extended to produce the loss estimates or to support emergency response planning, and they do not consider important factors such as social vulnerability, mobilization and the movement of traffic. The Life Safety Model is also the only model that explicitly considers the dynamic interactions between the receptors and the flood hazard over the duration of the event. Many of the simpler loss of life models only develop aggregated, macro-resolution estimates of fatalities. Although these can be useful for making very high level decisions, they are not as helpful for detailed emergency planning as the results and visualisations provided by the Life Safety Model. The next part of this paper details the application of the Life Safety Model to the Malpasset Dam disaster in the south of France.

4 The application of the Life Safety Model to the Malpasset Dam disaster

4.1 Background to the disaster

The Malpasset Dam was built for irrigation, the storage of drinking water and flood control. It was located in a narrow gorge of the Reyran River valley, in the Var Département in southern France approximately 12 km upstream of the town of Fréjus. The dam was a double curvature arch concrete dam 66.5 m high with a crest length of 223 m (Herzog, 1999). In the winter of 1959, torrential rains filled the new dam for the first time. On 2 December 1959 the Malpasset dam suddenly failed releasing nearly 55 million m^3 of water (Alcrudo & Gil, 1999). Investigations showed that key factors in the failure of the dam were the pore water pressure in the rock, and the nature of the rock. Under the increasing pressure of rising water, the arch separated from its foundation and rotated about its upper right end. The whole left side of the dam collapsed, followed by the middle part, and then the right abutment (Goutal, 1999). Figure 4 shows a photograph of the dam after its failure. There were some 6,000 people at risk living downstream of the dam (McClelland and Bowles, 2002). Although various sources quote different values, the official death count was estimated to be 423 fatalities. The majority of these occurred in the town of Fréjus (Goutal, 1999).

Figure 4 Photograph of Malpasset Dam taken in 1988 looking upstream

4.2 Application of the Life Safety Model to the Malpasset Dam disaster

The Malpasset Dam failure provided a suitable case study for validating the Life Safety Model because:

- Data were available concerning the dam break from Électricité de France (EDF), including a calibrated, two dimensional, hydrodynamic model of the resulting floodwave;
- In addition to field observations for peak flood levels there were also times available for the passage of the flood wave. These were estimated as the result of the failure of three electricity transformers;
- Data from a 1:400 scale physical model study undertaken by EDF in 1964 were available (Morris, 2001);

and

- Reliable records of population at risk and those impacted by the flood were available.

The following key stages were carried out before the construction of the Life Safety Model of the disaster was commenced (Johnstone et al, 2003):

- Data gathering and data pre-processing were performed to collect available information and assess its applicability. Data collected included: digital photography; cartographic data; and written accounts of the event;
- An inventory of the data sets was developed;
- The available hydrodynamic model was analysed to extract the flood characteristics used in the Life Safety Model. These are: depth, velocity, and depth x velocity with respect to time;

and

- Data interpretation was performed to identify the characteristics of the flood and its "lethality" based on topographic and flood characteristics; and the impacts of the location of the population at risk.

4.3 Hydraulic model of the Malpasset Dam break

The hydrodynamic model used was a Telemac two dimensional (2D) model developed by the Laboratoire National d'Hydraulique du France (Hervouet & Petitjean, 1999). This model was developed to validate the ability of the Telemac 2D model to simulate dam breach floods. The benefit of using this breach event is that well documented information was available to calibrate the model. The following information was recorded in 1959:

- The reservoir level was known as it was being tracked during the first full filling of the dam;
- Aerial photography of the site post event provided a visual record of flood extents;
- Power loss at transformers along the flood path provided timing of the flood propagation;
- Extensive media coverage of the event provided additional photographic and written accounts of the disaster.

For the purpose of this Malpasset Life Safety Model validation study, the only alteration of the model was to translate the model co-ordinates into the Lambert co-ordinate system consistent with other GIS based map data available for the region.

4.4 Setting up the virtual world for the Life Safety Model

An extensive library of data was gathered to develop the data necessary to recreate the 1959 Malpasset dam breach event (Johnstone et. al, 2003). A brief summary of some of the data acquired is given below:

- Topographic data was sourced through France's Institut Géographique Nationale (IGN). A 1:25,000 scale digital GIS base map provided topography, hydrography, buildings, roads, and neighbourhood names;
- IGN aerial photography from 1955 and 1960 were used to provide images of the region before and after the flood event;
- Numerous published books and articles were collected to provide source data for the event;
- Personal communication and inquiries were performed to gather further data.

To recreate the flood event, the modern digital topographic and infrastructure data were "back-cast" to create a virtual representation of the town of Fréjus and its surrounding areas as it existed in 1959. The historical aerial photographs, additional oblique airborne photos, and local maps were used to approximate the building stock and road network that existed at that time. The distribution of the population at risk as prepared through a placement of individuals based on building properties, eye witness accounts of the event, records indicating where lives were lost, and the approximate location of structures based on geo-corrected aerial photography.

4.5 Results of the modelling

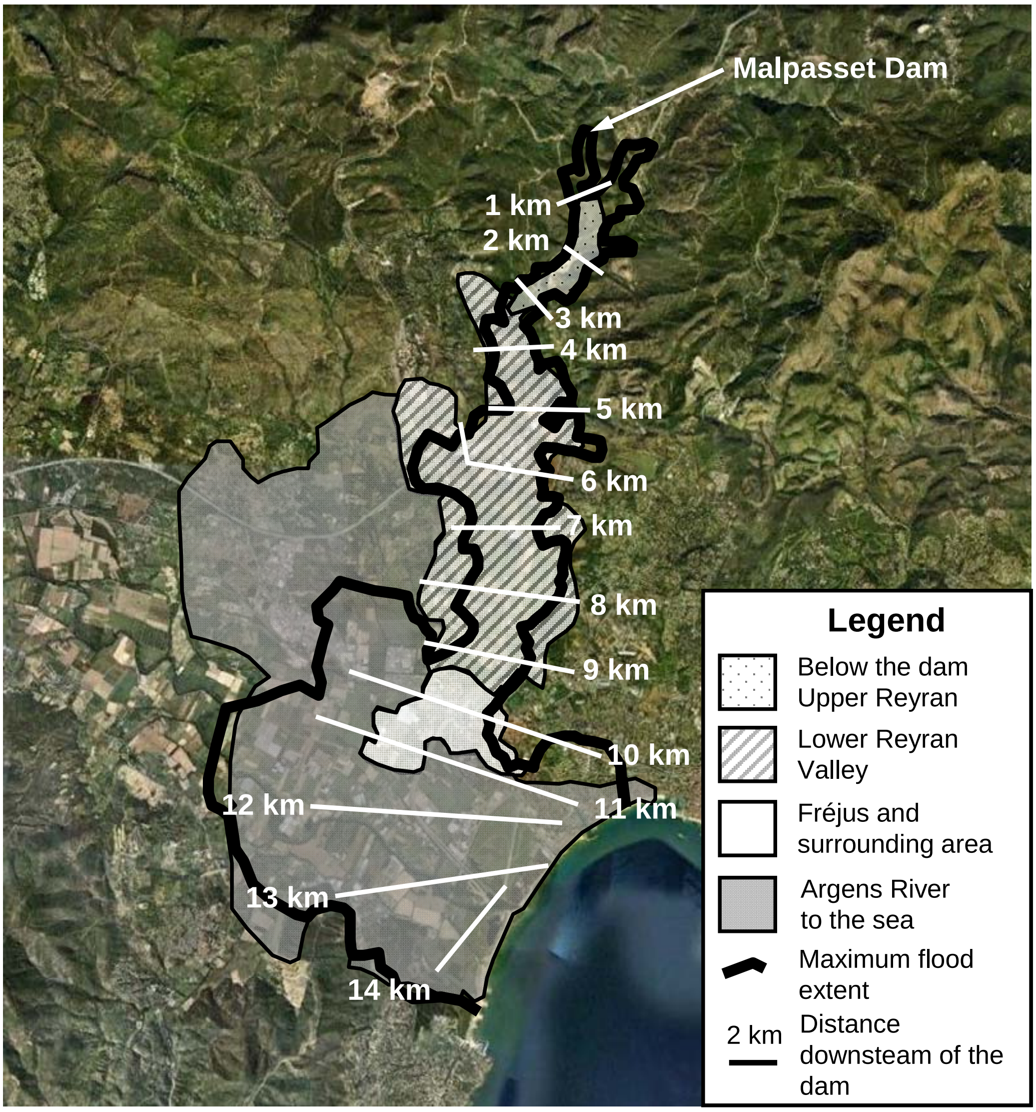
A review of the model results (Johnstone, 2005) indicate that the flood zone could be broken down into four key "Impact Zones", which are distinguishable by their flood characteristics. These are shown in Figure 5. The following flood characteristics give some indication to the effects of the flood on the population at risk in each Impact Zone:

- Impact Zone 1 - Directly below the dam, Upper Reyran
  - Narrowly confined section of the river valley, within 4 km of the dam;

- Contained 6% of the population at risk, but experienced 34% of the loss of life. This is the second-worst impact area. Few bodies of victims were recovered from this zone.

- Impact Zone 2 - Lower Reyran Valley
  - River channel section wider and less steep than Zone 1;
  - Contained 9% of the population at risk and 15% of the loss of life.
- Impact Zone 3 - Fréjus and surrounding area
  - River channel begins to expand into flood plain created by confluence of Reyran and Argens Rivers, approximately 10 km downstream of dam;
  - It contained 17% of the population at risk, but experienced 46% of the loss of life;
  - This is the worst impact area and also where many bodies were recovered. The available data did not allow the study to relate where the people were located at the beginning of the event with where their bodies were recovered.
- Impact Zone 4 - Argens River to the sea
  - This comprises the Argens and Reyran floodplain;
  - It contained 68% of the structures, but experienced only 5% of the loss of life;
  - This is important because the model had to account for a large population at risk inhabiting a large number of structures that experienced a relatively low loss of life.

The above results are also shown in Figure 6.



(Modified from Johnstone et al, 2005)

Figure 5 Malpasset Impact Zones

Observations that can be drawn from the modelled fatalities from the Malpasset event suggest that site specific characteristics of the river hydraulics can strongly influence the loss of life estimate. In the highly lethal Zone 1, a high proportion of lives can be expected to be lost. In contrast, once the flood wave spreads out across the wider floodplain of the Argens River towards the Mediterranean Sea, the combination of reduced flow depth and reduced flow velocity increased the potential for individuals to survive.

In the development of the Malpasset study, the model input parameters were tested to establish their impact on estimating loss of life. The parameters tested included:

- family size
- building and individual strengths
- building evacuation time (or choice of evacuation)
- flood awareness related to the depth of the floodwater required for people to start to react
- building and individual strength reduction factors.

Through the tests it was possible to determine suitable values for these parameters to simulate credible results. It was noted that certain parameters could result in a significant range of results. In particular, adjustments in the rate at which building's and individual's strength was reduced resulted in higher losses. Regardless, it was noted that all reasonable parameter values tested resulted in loss estimates that were never lower than the actual losses. Table 2 provides a summary of the modelled results compared with the actual number of lives lost and buildings that were destroyed during the event.

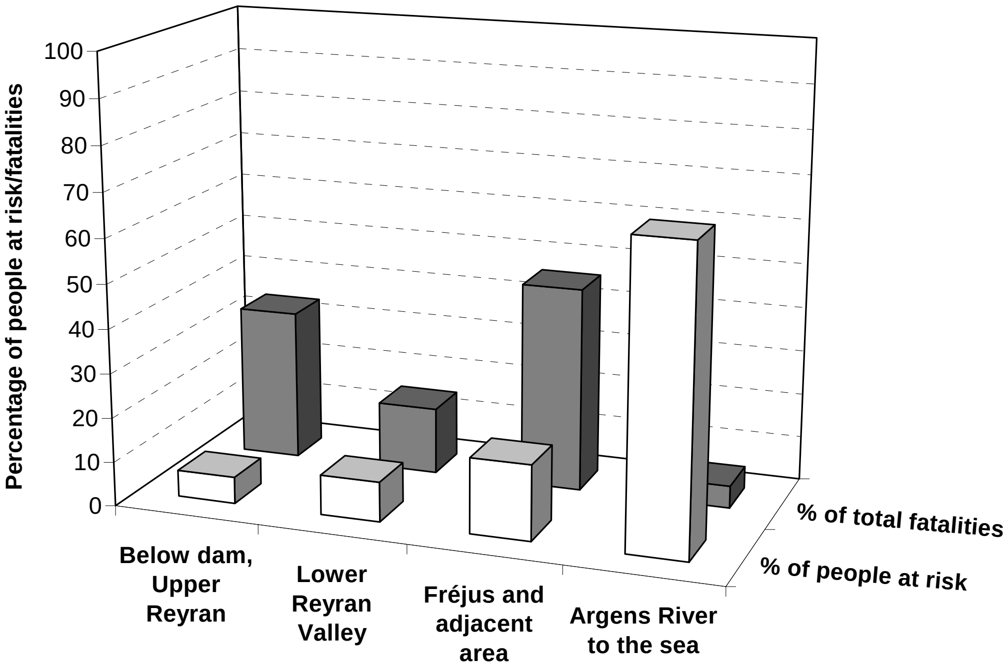


Figure 6 Comparison of the areas where people were at risk and the percentage of total fatalities

Table 2 Results of the loss of life modelling for Malpasset Dam

	Loss of life	Buildings destroyed
Estimated with the Life Safety Model	424	151
Actual number	423 to 500	158

5 Conclusions

Through the strength of its modelling processes and visualization tools, the Life Safety Model can create a dynamic representation of the "big picture" that can be used to inform those who may be affected by a dam break (e.g. people living and working downstream of the structure; emergency planners) and dams owners. The Life Safety Model can thus help to engage all stakeholders including the affected individuals, managers of infrastructure and policy makers. The Life Safety Model allows the human impact of dam failures to be forecast using physically-based methods and provides the capability to evaluate mitigations and preparedness plans (e.g. use of refuges, improvements in the dissemination of warnings).

Key strengths of the Life Safety Model include the simplicity of the core model and the transparency of the modelling process. The Life Safety Model can generate information that cannot be directly deduced from scarce historical data such as the emergent behaviour of the way a group of people react during a dam break or flood. The visualisation used in the software aids communication with community at risk, planners and decision makers which enables them to improve emergency response plans for such situations. The Life Safety Model also allows for broader sets of objectives than producing one loss estimate.

Given the results of the Malpasset study validation, the development team was able to confirm that the model is capable of estimating loss of life of the same order as an actual flood event. Although the evacuation characteristics of the model could not be tested given the fact that the imminent failure was not detected and no warning was provided, the model was capable of reproducing reasonable building and human loss estimates. Recent work by Johnstone and Lence (2009) has started to address this gap by using the Life Safety Model to support the modelling of evacuation response to tsunami. The Life Safety Model has also been validated using the flood event that occurred on Canvey Island in the Thames Estuary in 1953, (see Di Mauro & Lumbroso, 2008), in which 58 people died. The development and verification of the Life Safety Model is ongoing. The next steps in the development of the model will be to include the latest research related to the resistance of receptors to flood water, as well as making the setting up of the virtual world more efficient and user friendly.

At present in many parts of the world, emergency plans for dams and floods take little or no account of the risks to life and evacuation times. Given the age and condition of many dams and flood defences there is a need to assess these as accurately as possible. Recent events in Japan with the Sendai earthquake and tsunami on 11 March 2011 highlight the need to prepare for rapid-onset, catastrophic flood hazards. The outputs from accurate, dynamic loss-of-life models can help the organisations responsible for dam management, planners and the emergency services to improve their planning and response to major flood incidents and this will assist in reducing the probability of loss of life.

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NOTES

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