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Approaches for Estimating Flood Fatalities Relevant to Floodplain Management

WRL Technical Report 2015/09
September 2016

By G P Smith and P F Rahman

Water Research Laboratory
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1. Introduction

Loss of life is often considered the most important indicator in the public perception of the severity of natural disasters. Limiting loss of life is a key focus for the floodplain management process and is highlighted in current national best practice in floodplain management (AEMI, 2014) (https://ema.infoservices.com.au/items/HB7-2ND).

It follows, that the ability to quantify potential loss of life from flooding disasters is important for floodplain management. Understanding disaster impact and risk factors for loss of life can aid in anticipating the consequences of future disasters and help in developing risk reduction strategies. Methods to identify areas more likely to have populations at risk to loss of life are already available, but the ability to quantify potential loss of life in these areas would enable more focussed planning for future events and also assist resource allocation in a post disaster context.

This report summarises techniques available for estimating the potential for loss of life on floodplains and the ability of these techniques to consider changes in the number of potential fatalities due to floodplain management measures or changes in the scale of floodplain development.

2. Scope

The aim of this study is to review currently available literature to seek an understanding of methods for estimating flood fatalities resulting from flooding. Importantly, the methods for estimating flood fatalities should be able to be based on data sets readily available from a typical floodplain management study. A description of typical floodplain management datasets is available in AEM Handbook 7 (AEMI, 2014).

The scope of work identified from the study brief includes:

- *Identification of the different types of techniques available for assessing the relative scale of potential fatalities that may be of relevance to flood risk and the ability for these techniques to consider changes in potential fatalities due to management measures or changes to the scale of floodplain development.*

- *These techniques may include but not be limited to techniques that are used for dams and other water related infrastructure. Several techniques known to be used include:*
    - *Population at risk, a pseudo metric that is used in some dam break cases. From a flood risk management perspective, this may be able to be improved to identify populations at risk in areas with more difficult evacuation issues rather than a simple overall population at risk metric.*
    - *Agent based modelling which models propagation of floodwaters over the landscape, includes traffic network modelling, and considers human behaviour and interaction with the flood inundation. This is being used in some complex flood situations to provide an indication of areas where evacuation may be difficult and where lives may be at a particular risk.*
    - *However, there are likely to be other approaches uncovered that will be identified by the project and should be considered.*

- *A desktop review of above identified potential techniques to identify:*
    - *their limitations;*
    - *the assumptions made;*
    - *their information needs;*
    - *the scale (in terms of size of problem) in which there use may be feasible and practical;*
    - *the usefulness in different types of studies from simplistic to complex.*

3. Overview of Loss of Life during Floods

Every year floods cause enormous damage and loss of life on a global scale. An analysis of global statistics showed that inland floods (river floods, flash floods and drainage floods) caused 175,000 fatalities and affected more than 2.2 billion people between 1975 and 2002 (Jonkman, 2005). The consequences of other types of floods such as coastal floods and tsunamis are not included in these statistics.

The consequences of flooding encompass multiple types of damage such as environmental losses, economic damage and loss of life. However, loss of life is considered the most important loss type in the public perception.

Based on the available information and previous analyses of loss of life during floods (Tsuchiya and Yasuda, 1980; Bern et al., 1993; McClelland and Bowles, 2002; Ramsbottom, 2003; Jonkman, 2014) the main factors that influence mortality are summarised below:

- The events with the largest loss of life occurred unexpectedly and without substantial warning. Many of the high-fatality events also occurred at night (Netherlands and UK 1953, Japan 1959), making notification and warning of the threatened population difficult;

- Timely warning and evacuation prove to be important factors in reducing the loss of life. Even if the time available is insufficient for evacuation, warnings can reduce the loss of life. Warned people may have time to find some form of shelter shortly before or during the flood;

- The possibilities for shelter are a very important determinant of mortality. Buildings can have an important function as a shelter, but possibilities to reach shelters will depend on the level of warning, water depth and rise rate of the water;

- The collapse of buildings in which people are sheltering is an important determinant of the number of fatalities. Findings from different events (Bangladesh 1991, Netherlands 1953) show that most fatalities occurred in areas with vulnerable and low quality buildings;

- Water depth is an important parameter, as possibilities for shelter decrease with increasing water depth. Low-lying and densely populated areas, such as reclaimed areas or township areas behind levees, will be most at risk;

- The combination of deeper water depths and rapid rise of waters is especially hazardous. In these cases people have little time to reach higher floors and shelters and they may be trapped inside buildings;

- High flow velocities can lead to the collapse of buildings and instability of people. In different cases (Netherlands and UK 1953, Japan 1959), many fatalities occurred behind dike (levee) breaches and collapsed sea walls, as flow velocities in these zones were high;

- When exposed to a severe and unexpected flood, children and elderly were more vulnerable. This suggests that chances for survival are related to an individual's stamina and his or her ability to find shelter.

A summary of fatality statistics from various forms of flooding disasters are provided in Table 1.

Table 1: Statistics of Reported Mortality for Selected Hazard Types (1900 – 2009) (after Johnstone, 2012)

	Number of Disaster Events	Loss of Life (LOL)						Analysis / Comparisons			
		Cumulative Mortality	Mean Mortality	Std Dev.	Skew	Kurt	Maximum	% of All Events with Loss of Life		% of All Mortality with Loss of Life	
								≥10	≥100	≥10	≥100
Disaster Type	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
Cyclone/Storm Surge	1,057	1,333,873	1,262	12,004	18.4	401	300,000	79%	50%	99.5%	98.6%
Tsunami	34	241,390	7,100	38,758	5.8	34	226,408	94%	56%	100.0%	99.8%
Dam/Dike/Levee Failure	129	105,980	822	7,480	11.3	128	85,000	56%	33%	99.8%	98.9%
Volcano	83	95,979	1,156	4,147	5.8	36	30,000	70%	41%	99.9%	98.7%
Extreme / Flash Flood	358	59,978	168	1,610	18.0	333	30,000	71%	16%	99.2%	88%
Industrial Accident	51	3,448	127	530	7.0	49	2,500	47%	6%	97.3%	84%
Wildfire	127	3,477	27	94	9.1	93	1,000	43%	4%	93.1%	50%
All Disaster Types	**1,839**	**1,844,125**	**1,003**	**10,765**	**20**	**463**	**300,000**	**72%**	**37%**	**99.6%**	**98.3%**

Most methods to estimate loss of life during flood can be categorised into one of two types:

1. **Empirical models** are based on statistical analysis of historical information. From historical flood records, relations can be derived between the characteristics of the flood and the fraction of the people at risk that will lose their life.

2. **Agent based (physical) models** are based on a deterministic analysis of physical processes during a flood. These models use a time varying quantification of flood behaviour (flood depth, velocity, inundation area) cross correlated with flood exposure criteria/thresholds, for example the instability of people in a flood flow or the structural strength of buildings, to determine a flood fatality estimate, often on an individual by individual basis.

McClelland and Bowles (2002) give a comprehensive historical review of loss of life methods for dam break floods. While focussed specifically on fatalities due to dam break, this summary provides some pertinent conclusions for flood fatalities generally.

> *'Empirical models have evolved, growing from an effort to capture life loss through a single regression equation to an effort to divide events into smaller, more homogeneous components that can be compared to similar components. In this way, it is possible to develop historical life-loss relationships specific to each set of similar components. … As for contributions, every useful dam-failure life-loss model addresses the following components:*
>
> *1. The probability of failure given assorted loadings. It is preferable to consider every conceivable loading, breaking the loadings into ranges with similar consequences.*
>
> *2. Flood routing that yields credible estimates of travel times, depths, and velocities. It is preferable if these can be approximated at every point and not merely as large-scale averages.*
>
> *3. Quantification of Population at risk (PAR). It is preferable to be able to subdivide this into subPAR with common attributes, describe the distribution of PAR in the flood zone, and assign different values to PAR according to temporal variations in the time of day, week, and year.*

4. Warning time. It is preferable if this accounts for the detailed chain of events that must occur before a message can first be disseminated on a mass scale. It is also preferable if the analysis describes not only the difference in timing between the first warning and the arrival of the flood, but also the rate of warning propagation, the extent to which the warning penetrates a community, and the ability of the message to mobilize an evacuation without causing panic.

5. Evacuation. It is preferable to identify not only the number of people who escape flooding based on the warning time, but where the remainder are located when the flood arrives and whether or not those locations provide a degree of safety.

6. Loss functions that describe the rate of life loss in every unit that has been defined, whether this is on the level of PAR, subPAR, or locations within subPAR. It is preferable for these functions to be validated empirically so that they can be used with confidence.'

4. Empirical Methods for Estimating Flood Fatalities

This section provides a comprehensive collation and review of individual methods for the estimation of loss of life due to flooding. A review of literature has been undertaken to identify methods used in different countries and for different types of flooding; including dam failure flooding, river flooding, coastal flooding, and tsunami-induced flooding. These methods relate the mortality[1] in a flooded area to flood characteristics and possibilities for warning and evacuation. Much of the work presented here is summarised from Jonkman and Vrijling (2008).

4.1 Dam Failure

Dam failure floods are often characterised by a violent, deep and fast flowing surge of water passing down a gorge (where dams are often built) onto a wider, populated floodplain. While dams sometimes fail unexpectedly and catastrophically (e.g. due to earthquake), they can also fail in combination with a flood event (e.g. when the dam wall is overtopped during a flood), which imposes additional flood hazard to the already inundated floodplain. The following methods characterise flood fatalities related to dam failure.

4.1.1 Ayyaswamy et al., (1974)

Ayyaswamy et al. (1974) prepared a report for the United States Atomic Energy Commission to evaluate the probabilities and consequences associated with potential dam failures. This study individually assessed eleven dams with relatively large populations at risk in earthquake prone California. The analysis of risk to life was assessed based on:

1. The volume of water leaving the dam in the event of complete dam failure;
2. The dimensions of the flood wave;
3. Flow routing of water in the channel below the dam; and
4. Water depth for various chainages downstream.

The authors concluded that all those who do not evacuate would perish in the flood and any evacuations would only reduce 10-20% of the expected mortality. This high mortality was due to the limited time (warning) between dam failure and the time of arrival of the flood wave near the population at risk. The main limitation of this method is that it is only applicable to instantaneous earthquake prone dam failures, as other types of failures may warrant the use of longer warning periods and higher survival rates. DeKay and McClelland (1993) point out that the mortality rates predicted in this study far exceeds the loss of life observed during actual dam break events, as no dams with populations at risk of greater than 10,000 have failed without warning. This finding also highlights the dangers of extrapolating beyond limited data.

4.1.2 Pate'-Cornell and Tagaras (1986)

Paté-Cornell and Tagaras (1986) used casualty ratios in which loss of life was expressed as a portion of the population at risk. This model was similar to that first developed by Ayyaswamy et al. (1974). In this model, the authors assumed a fatality between 50%-90% in the main path of the flood and 0%-15% closer to the peripheries of flood extent (rather than assuming a 100% fatality rate at depths of 10 feet). The authors used census data in conjunction with inundation area maps to estimate the total population at risk. The casualty ratio was defined as a proportion of the inhabitants who might be killed upon dam break assuming a weighted average of night and day occupancy ratios in the zones at risk. Like Ayyaswamy's model, this model also

[1] Mortality is defined by the number of fatalities divided by the number of exposed people.

relied on intuitive estimates of fatality rates without true empirical support, however it was the intention of the authors to demonstrate the importance of incorporating risk not offer a refined model (McClelland and Bowles, 2002).

4.1.3 Stanford/FEMA Model

(McCann et al., 1985) of Stanford University, under contract for the Federal Emergency Management Agency (FEMA), developed a model to estimate the loss of life using factors such as distance from the dam, depth of floodwaters and the quality of the warning. This model aimed to estimate the loss of life in various reaches of an inundation area rather than a simple total of the entire area. The authors proposed that the loss of life is a function of the percentage of the people exposed to the flooding, the fraction of the people who remain in the area at the time of inundation, the length of time of exposure to the flood and the distance between rural and urban residential areas. The equation for loss of life was defined as:

$$L = \sum_{i}\sum_{j} f(d_j)\, h(m_i) P_{ij}$$

where

L	= the number of lives lost in the flooding event
$f(d_j)$	= the proportion of the population at risk in reach i remaining in flooded zone j at time of arrival of flood wave
h	= is a function of the quality of evacuation warning and of the distinction between urban and rural areas
P_{ij}	= the population at risk in flood zone j, of reach i, miles from the dam
d_j	= the depth of flooding in zone j
m_i	= the river miles from dam to reach i (a surrogate for flood travel time)

The specific numerical estimates of the proportion of the population in the various flood zones are listed in Table 2 and Table 3.

Table 2: Suggested Parameters of Stanford/FEMA Loss of Life Model. Loss of life as a Proportion of Threatened Population

Depth of Inundation d_j (feet)	Proportion Loss of Life $f(d_j)$
2	0.00
4	0.05
6	0.20
8	0.40
10	0.60
12	0.80
>12	0.85

Table 3: Threatened Population as a Proportion of Population at Risk [i.e. $h(m_i)$]

Distance (m_i)	Residential Area Warning System		Rural Area Warning System	
	None	Good	None	Good
<10	0.80	0.50	1.00	0.70
20	0.50	0.20	0.80	0.40
30	0.10	0.00	0.20	0.10
50	0.00	0.00	0.10	0.00

The most obvious shortcoming of this model is that the authors present subjective estimates of the model parameters without empirical calibration. The authors acknowledged that the travel time is a more meaningful way of dividing the population at risk but choose distance downstream for convenience, as this was a surrogate measure of the available warning time. They also acknowledged that loss of life could not be related to flooding depth alone (as velocity plays an important role). However, they ignore velocity in their analysis to simplify the model.

4.1.4 Institute for Water Resources (Lee et al., 1986)

The Institute for Water Resources (1986) model was a modified version of the Stanford/FEMA approach, and relied on professional judgment to estimate fatalities. The difference between this approach and the Stanford/FEMA model is that the authors estimated the threatened population at risk by taking into account the warning times for each sub-group of population at risk, instead of the distance from the dam. The authors also suggested that the population at risk would also vary depending on the time of day, season and transient, as shown by the example in Table 5. The estimate of the loss of life using this model was defined as:

$$L = \sum_i \sum_j f(d_j)\, g(w_{ij}) P_{ij}$$

where

$g(w_{ij})$ = the proportion of population at risk in reach i remaining in flooded zone j at the time of arrival of the flood wave

w_{ij} = the warning time for population in reach i in flood zone j

Table 4: Threatened Population as a Proportion of Population at Risk, expressed as a Function of Warning Time

Warning Time, W_{ij} (hours)	Residential Area Warning System		Rural Area
	Poor	Good	
0.00	1.000	0.800	1.000
0.50	0.400	0.100	0.800
1.00	0.250	0.050	0.400
1.50	0.150	0.010	0.200
2.00	0.080	0.002	0.080
2.50	0.030	0.001	0.030
3.00	0.005	0.000	0.005
3.50	0.001	0.000	0.004

Table 5: Example of Table for Population at Risk in Specified Flood Zones in Reach for Different Flood Event, by Season of Year and Time of Day

Flood Event	Flood Zone (interval in feet)	Permanent Population		Seasonal Transient Population								Daily Transient Population	
				W		S_p		S		F			
		D	N	D	N	D	N	D	N	D	N	D	N
.10 PMF Peak Stage = 4 (ft)	0-4	50	75	2	0	2	0	40	10	2	0	0	0
	4-8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	8-12	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	12-16	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Total	50	75	2	0	2	0	40	10	2	0	0	0
.25 PMF Peak Stage = 8 (ft)	0-4	50	75	2	0	2	0	40	10	2	0	0	0
	4-8	70	100	0	0	2	0	20	5	2	0	0	0
	8-12	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	12-16	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Total	120	175	2	0	4	0	60	15	4	0	0	0
.50 PMF Peak Stage = 12 (ft)	0-4	50	75	2	0	2	0	40	10	2	0	0	0
	4-8	70	100	0	0	2	0	20	5	2	0	0	0
	8-12	60	95	0	0	7	2	50	15	7	2	100	20
	12-16	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Total	180	270	2	0	11	2	110	30	11	2	100	20
.75 PMF Peak Stage = 20 (ft)	0-4	50	75	2	0	2	0	40	10	2	0	0	0
	4-8	70	100	0	0	2	0	20	5	2	0	0	0
	8-12	60	95	0	0	7	2	50	15	7	2	100	20
	12-16	300	400	0	0	4	0	40	5	4	0	50	10
	16-20	500	800	0	0	5	1	350	65	10	4	40	10
	Total	980	1470	2	0	20	3	500	100	25	6	190	40

0-4 = flood zone begins at bank full stage
D = day time (between 0800 and 1600 hours)
N = night time (between 1600 and 0800 hours)
W = Winter
Sp = Spring
S = Summer
F = Fall
Ft = feet
n/a = not applicable
PMF = probable maximum flood

4.1.5 United States Bureau of Reclamation (Brown and Graham, 1988; McClelland and Bowles, 2002)

The United States Bureau of Reclamation (USBR) flood loss of life model derived a simple numerical relationship for the loss of life based on the total population at risk and warning time. An official presentation of this method was published as a technical memorandum in 1986. Subsequently, Brown and Graham published "Assessing the Threat to Life from Dam Failure" in 1988 which was officially published as an interim guideline in 1989 (McClelland and Bowles, 2002).

The model proposed a nonlinear relationship for population size and the loss of life for warning times of less than 1.5 hours, as it assumed that larger communities with greater communication and public safety resources have a facilitative effect on warning dissemination. The model proposed that the effect of the nonlinear relationship diminishes for warning times greater than 1.5 hours, as the communicative advantages ascribed to larger population centres are no longer significant when there is adequate time to evacuate the entire population. The authors also presented a situation in which the warning time is less than 15 minutes for which they proposed a loss of life of 50% of the population. The formulations for loss of life in this model is as follows:

$$\mathrm{LOL} = 0.5(\mathrm{PAR}) \quad \mathrm{WT} < 0.25 \text{ hours}$$
$$\mathrm{LOL} = PAR^{0.56} \quad 0.25 < \mathrm{WT} < 1.50 \text{ hours}$$
$$\mathrm{LOL} = 0.0002(\mathrm{PAR}) \quad \mathrm{WT} > 1.50 \text{ hours}$$

where:

LOL	= the loss of life
PAR	= the population at risk
WT	= warning time

The USBR model used empirical calibration of historic failure events and acknowledged that loss of life estimates were influenced by factors beyond the warning time and population at risk. McClelland and Bowles (2002) highlighted that the data set (whilst an excellent start) was limited and lacked statistical sophistication.

4.1.6 Lee et al. (1986)

The Lee et al. (1986) method is similar to the model presented by USBR as they both report a reduction in fatalities with increasing warning time and suggest a nonlinear relationship between populations at risk and warning time. This study considered a wider range of events (47 events) and different data sets (including riverine flooding) to estimate its model parameters. The authors also propose a logic procedure which requires estimates of loss of life and the population at risk to be limited (between zero and one) to replace the ordinary least squares regression which can sometimes lead to unreasonable or negative loss of life estimates. Lee et al. (1986) propose the following formulation to estimate loss of life:

$$\frac{L_{ij}}{P_{ij}} = p(x_{ij} y_{ij})$$

where

L	= the number of lives lost in the flooding event
i	= reach
j	= the flood zone
$\underline{x}$	= a vector of variables affecting the ratio of deaths to threatened population including; the number of residences damaged, depth of the flood, velocity of the flood, discharge, breach of dam, topography of inundation area, special characteristics of the population, vulnerable facilities, type of structures, number of bridge crossings in inundated area.
$\underline{y}$	= a vector of variables affecting the size of the threatened population relative to the population at risk including: warning time, experience and knowledge of flooding in the local area, existence of hospitals and retirement homes, time of day, proportion of elderly and young population, effectiveness of the evacuation plan and systems, evacuation traffic and the urban and rural situation.
P_{ij}	= the probability of loss of life of an individual in each reach i at flood zone j
p	=population at risk

DeKay and McClelland (1993) points out that this model incorrectly treats individual outcomes as independent of one another and highlights that it is inappropriate to treat individuals as "independent trials in a binomial experiment".

4.1.7 DeKay and McClelland (Bureau of Reclamation 1993)

Under another USBR contract, DeKay and McClelland (1993), of Utah State University Institute of Dam Safety Risk Management, improved on the previous version of the USBR model by adding more historical events. The authors expanded on the work begun by Brown and Graham (1988) and Lee et al. (1986) and introduced "flood force" as an additional predictor of loss of life. They proposed a separate equation for high force floods (such as near canyons where flood waters are likely to be fast and swift, or in areas where more than 20% of the buildings are damaged or destroyed) and low force floods (such as wide floodplains where floodwaters are likely to be shallower and slower). DeKay and McClelland (1993) apply a logic transformation to preclude the predicted fatalities from being negative or greater than 100%. They used the following equation for the computation of loss of life during high and low force floods:

$$LOL_{HF} = \frac{PAR}{1 + 13.277\ (PAR^{0.440})e^{2.982(W_t)-3.790}}$$

$$LOL_{LF} = \frac{PAR}{1 + 13.277\ (PAR^{0.440})e^{0.759(W_t)}}$$

where

LOL_{HF}	= the loss of life in a high force flooding event
LOL_{LF}	= the loss of life in a low force flooding event
PAR	= populations at risk
Wt_{HF}	= warning time (hours) during a high force flooding event
Wt_{LF}	= waring time (hours) during a low force flooding event

The authors suggested that warning time is of more significance during high force conditions. They suggest this might be because people in a more hazardous condition may take warnings more seriously and evacuate more quickly than people who are likely to be exposed to a less treacherous flood. In both functions the loss of life decreases very quickly when the time available increases.

It should also be noted that the empirical data set used by Brown and Graham (1988), and DeKay and McClelland (1993) under represented severe flooding events compared to this method. As a result, the equation for high mortality is deficient when used to predict life loss for dam failures that result in truly catastrophic flooding (Graham, 1999).

4.1.8 Graham (1999)

In 1999, the U.S. Bureau of Reclamation began using a model developed by Wayne Graham (Graham, 1999). This model presented a framework for the estimation of loss of life due to dam failures by recommending fatality rates based on the severity of the flood, the amount of warning and the understanding of the flood severity by the population. The model presented expected mean values for the potential loss for life for each of the fifteen possible categories represented in Table 6.

Table 6: Fatality Rates Derived from Dam Breaks as a Function of Flood Severity, Warning and Understanding (after Graham, 2010)

Flood Severity	Warning Time (minutes)	Flood Severity Understanding	Fatality Rate (Fraction of people at risk projected to die)	
			Suggested	Suggested Range
HIGH	No warning	Not applicable	0.75	0.30 – 1.00
	15 to 60	Vague	Use the values shown above and apply to the number of people who remain in the dam failure floodplain after warnings are issued. No guidance is provided on how many people will remain in the floodplain.	
		Precise		
	More than 60	Vague		
		Precise		
MEDIUM	No warning	Not applicable	0.15	0.03 – 0.35
	15 to 60	Vague	0.04	0.01 – 0.08
		Precise	0.02	0.005 – 0.04
	More than 60	Vague	0.03	0.005 – 0.06
		Precise	0.01	0.002 – 0.02
LOW	No warning	Not applicable	0.01	0.0 – 0.02
	15 to 60	Vague	0.007	0.0 – 0.015
		Precise	0.002	0.0 – 0.004
	More than 60	Vague	0.0003	0.0 – 0.0006
		Precise	0.0002	0.0 – 0.0004

The paper provided guidance on selecting “Flood Severity” based on flood depth and or/the proportion of the discharge generated by the flood to the mean annual discharge of the system. Graham suggests that the discharge can be easily estimated and it is an indicator of the safe channel capacity and therefore the severity of the flooding.

McClelland and Bowles (2002) highlight that Graham’s definition and division of warning time limits the flexibility of the model and potentially misses the most important aspects of both warning and evacuation dynamics. They conclude that Graham’s model is biased by the necessity to subjectively decide how many zero-life-loss events to include or exclude when averaging historic fatality rates. Given the limited dataset focussing on dam failure flood waves upon which it is based, the Graham (1999) model is not recommended for estimating loss of life from natural flooding (ANCOLD 2003).

In 2010, Graham updated the 1999 method for estimating the loss of life, and suggested that there is a higher likelihood of loss of life for residents within close proximity to the dam collapse compared with those situated further downstream. This is because the behaviour of floods in the upstream areas is much more extreme than in downstream areas (Lee et al., 2015).

The aim of this publication was to apply the method by Graham (1999) and to supplement the results with considerations on flood impact on the population living in the area at risk of the possible dam break. The paper considered three additional factors:

1. Damage parameter (defined by flood depth – velocity product)
2. Population vulnerability (i.e. age of population)
3. Living conditions (i.e. one or two storey buildings).

The loss of life is estimated by:

$$LOL = PAR \times FAT_{BASE} \times IMPACT \times CORRFAT$$

where

LOL = the loss of life caused by the dam break flood
PAR = the population at risk
FAT_{BASE} = the base fatality rate for PAR (after mean values in Table 7 of Graham, 1999)
$IMPACT$ = additional factor to account for flood severity, living environment and vulnerability impact derived from using public population information on PAR
$CORRFAT$ = correction factor to take the warning efficiency and possible emergency / rescue action into consideration in each sub area (re-arranged values from Table 7 of Graham (1999))

4.1.9 British Columbia Hydro Loss of Life Model (Hartford et al., 1997)

British Columbia Hydro, a large dam owner in Canada, developed a conceptual framework for modelling the response of people to a dam breach flood and its impact on the people and buildings. A method was developed for the estimation of loss of life due to dam failures, which took into account the hydraulic characteristics of the flood, the presence of people in the inundated area and the effectiveness of the evacuation. The model used census data to distribute population based on building use and categorised the daily, weekly, and yearly occupancy factors to determine the temporal distribution of population. The model simulated the escape of population away from the flood path and estimated survivability based on water depth and velocity and individual characteristics.

Whilst this model provided an approach to estimate spatial and temporal distribution of population under the risk of a dam failure, it did not represent interaction among individuals and depicted the environment as one-dimensional with escape routes perpendicular to channel flow. The model was also largely based on expert judgement.

Later developments to the model (Life Safety Model) included two-dimensional considerations (Assaf and Hartford, 2001; 2002), which integrated outputs from a flood simulation model with a virtual world made up of individual entities representing people, buildings, vehicles, and roads (agent based models). This is discussed further in Section 5.

4.1.10 RCEM - Reclamation Consequence Estimating Methodology (USBR, 2014)

The Reclamation Consequence Estimating Methodology (RCEM) was released by the U.S. Bureau of Reclamation in 2014 to supersede Graham (1999). The main update of RCEM compared to Graham (1999) is that the prescribed fatality rates of the RCEM vary continuously with the depth times velocity product (DV) of the flood making the method less sensitive to changes in flood severity.

RCEM determines loss of life estimates through a prescribed series of tasks which parameterise the likely modes of dam failure, the variability of flood behaviour parameters across the floodplain, the PAR, the preparedness of the flood impacted communities through consideration of the time of day and the season, the amount of warning time and the ability of the PAR to respond and evacuate.

Central to the method is a set of fatality rate curves based on collation and analysis of historical flood events where fatalities occurred. The flood fatality data relates mainly to dam failure flooding, though some natural flood events are included. The fatality rate curves relate the intensity of flooding (DV) to the fatality rate and are further classified by the perceived warning time available to the flood affected community. The figures, reproduced below are classified by communities having '*Cases with Little or No Warning and Cases with Partial Warning*' (Figure 1) and '*Cases with Adequate Warning and Cases with Partial Warning*' (Figure 2).

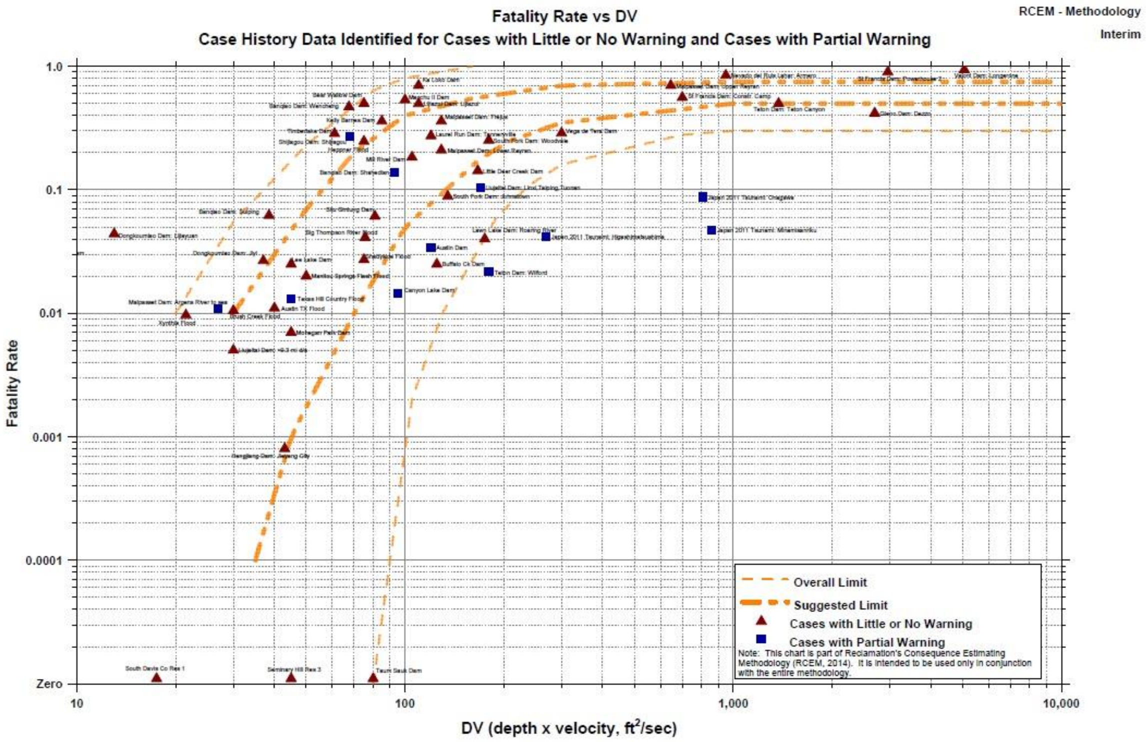

Figure 1: Flood Fatality Curves – Little or No Warning (after Barendregt et al., 2005)

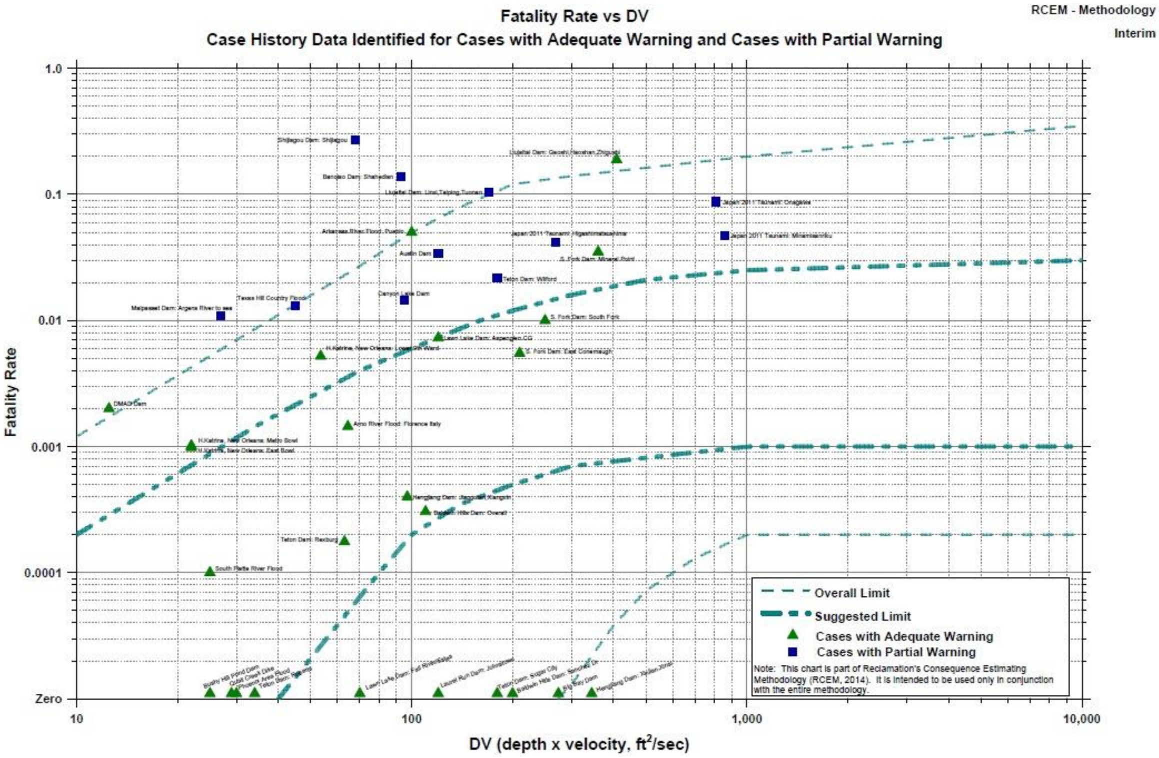

Figure 2: Flood Fatality Curves – Adequate Warning (after Barendregt et al., 2005)

Application of the method requires subjective input by the practitioner, particularly when it comes to determining a PAR classification for warning time which is not defined and acknowledged as likely varying from case to case based on the local floodplain conditions, the warning systems in place and the preparedness of the flood affected community.

4.2 Riverine and Coastal Floods

Whilst riverine floods may be fast flowing and violent, especially in smaller, steeper catchments prone to flash flooding, riverine floods are generally less extreme in flow behaviour than dam failure flood waves. In addition, timely warning that a catastrophic flood is about to occur is more likely for riverine flooding caused by extreme rainfall events that can be monitored and forecasted in advance. Similarly, inundations due to coastal storm surges can be reliably forecast and warnings can be provided in advance. Because of these subtle differences in flood behaviour between riverine flooding and coastal flooding, these mechanisms have been considered separately by many authors when estimating loss of life. The following section summarises methods for estimating loss of life related to riverine and coastal floods.

4.2.1 Friedman (1975)

One of the earliest studies in this field was undertaken by Friedman (1975). He linked the number of fatalities in a flooded area to the number of damaged residencies. He based his analysis on annual flood tabulations collected by the American Red Cross annual flood tabulations. Friedman suggested a casualty rate of one per 170 damaged dwellings for normal floods and one per 85 dwellings for flash floods.

4.2.2 *Allen and Hoshall et al., (1985)*

Allen and Hoshall et al., (1985) used the same technique as Friedman (1975) but with additional details regarding the population, employment, and the type and occupancy of buildings. Casualties were estimated for two periods of the day, an "at work or school" period and an "at home" period. The method changed the population distributions between the day and night time such that some of the population in housing units is redistributed to businesses based on employment records.

4.2.3 *Duiser (1989) and Waarts (1992)*

Duiser (1989) and Waarts (1992) collected data from official reports regarding the loss of life caused by a storm surge on the North Sea that resulted in flooding in the Netherlands, the United Kingdom and Belgium and caused a total of 1,835 deaths. Duiser (1989) proposed a model that related the local mortality fraction to the flood depth. More data on the 1953 floods had been added by Waarts (1992). He derived a general function for flood mortality (F_D) as a function of water depth (h) as follows:

$$F_{D1} = 0.665 \times 10^{-3} \times e^{1.16h}$$
$$F_{D2} = 0.40 \times 10^{-3} \times e^{1.27h}$$

where

F_{Di} = mortality fraction of the inhabitants of the area inundated (i = 1,2)
h = water depth (m)

Waarts also proposed a more refined method that accounted for the effects of warning and evacuation, high flow velocities and the collapse of buildings. However, not all factors of this method were based on historical data (Jonkman et al., 2008b). Jonkman et al. (2003) questions the widespread applicability of this method as it only relied on data from the singular storm event and highlights that many changes to flood warning systems and building stability have occurred since 1953.

4.2.4 *Vrouwenvelder and Steenhuis (1997)*

Vrouwenvelder and Steenhuis (1997) proposed an extended method that was based on Waarts' written in Dutch and as such the summary of the formulations presented here is after (Jonkman et al., 2008b)

This paper takes into account three causes of drowning:

1. Fatalities due to building collapse (f_b);
2. Fatalities near the breach, caused by wave attack (FR);
3. Fatalities due to other factors (f_o)

Combination of the above factors yields the total number of fatalities as follow:

$$N_d = (f_o + p_b f_b + p_s f_s)(1 - f_e)N_i$$
$$f_s = \alpha \times 10^{-3} \times d^{1.8} \times r$$

Where

N_i = the number of inhabitants
f_e = the evacuated fraction of the affected population
N_d = the total number of fatalities
p_b = the probability of dike breach nearby a residential area
p_s = the probability of storm (1 for a coastal flood, 0.05 for a river flood)
f_s = the probability of collapsing of a building during a given storm

α = material factor
d = flood water depth in meters
r = shelter factor – see Vrouwenvelder and Steenhuis (1997)

4.2.5 *Dutch Ministry of Transport (HKV 2000-2005)*

A technical report commissioned by the Dutch Ministry of Transport entitled the "Standard method for predicting damage and casualties as a result of floods" in the Netherlands (Kok, 2005) describes a method to estimate loss of life. As this report is written in Dutch, the summary of this method presented here is taken from Jonkman *et al.* (2008b). The functions of this method are partially based on the analysis by Waarts (1992) of the 1953 flood. This model incorporates the impacts of rapidly rising flood waters in its computation of flood fatality and presents the following relationship of mortality:

$$F_D = 0 \quad h < 3m \ \ OR\ w < 0.3\ m/h$$

$$F_D = \min(\max(8.5e^{0.6h-6} - 0.15; 0) . \min(\max(8.5e^{1.2w-4.3} - 0.15; 0), 1))$$

$$F_D = 1 \quad h > 6.25\ m \ \ AND\ w < 2.0\ m/h$$

where
F_D = mortality fraction of the inhabitants of the area drowned
w = the rate of rise of flood water (m/h)
h = the flood-water depth (m)

Jonkman et al., (2008b) highlight that this method includes the same limitations as the function presented by Waarts (1992), and the outcomes of the calculations (i.e. the number of fatalities) are influenced to a large degree by the value chosen for the rate of rising of the water.

4.2.6 *Jonkman (2001)*

Jonkman (2001) proposed a method for the determination of loss of life for sea and river floods in the Netherlands; as this paper was presented in Dutch, the summary of this method is reported from (Jonkman et al., 2002). This model combines both physical and empirical relationships to determine a value of mortality for a given flood event. The method uses the functions derived by Waarts, evacuation time, and the stability criteria determined by Abt et al., (1989) to determine probability of drowning as a function of the water depth for a given flood for people in and outside buildings due to high stream velocities. This is represented as:

$$P_{d|i}(u) = \mathrm{P}(u > u_{cr}\ |\mathrm{i}) = \emptyset_N\left(\frac{u-\mu}{\sigma}\right) \text{ with } \mu = 1.8\ \mathrm{m/s} \ \ and\ \sigma = 0.48\ m/s$$

where
u = stream velocity (m/s)
$P_{d|i}(u)$ = probability of drowning as a function of u, given flood i
$\mathrm{P}(u > u_{cr}\ |\mathrm{i})$ = probability that the stream velocity u is larger than the critical stream velocity (u_{cr}), in which people drown given flood i
$\emptyset_N\ (x)$ = formal distribution of variable x

In this model, the probability of a successful evacuation is dependent on the time available for evacuation. This is calculated as follows:

$$P_{e|i}(t) = \mathrm{P}(t > t_{cr}\ |\mathrm{i}) = 1 - e^{\frac{-t}{20}}$$

where

t = time available for evacuation (hours)

20 = constant hours

$P_{e|i}(t)$ = probability of a successful evacuation as a function of evacuation time for a given flood pattern i

$\mathrm{P}(t > t_{cr}\ |\mathrm{b})$ = probability that y is larger than the critical evacuation time (t_{cr}) given flood pattern i

Thus, the resulting probability of drowning in a flood, given an evacuation is expressed as:

$$P_{d|i,evac}(x,y) = \left(1 - \mathrm{P}_{e|i}\big(t(x,y)\big)\right) \times \left(\mathrm{P}_{d|i}\ \left(\mathrm{u(x,y)} + \mathrm{P}_{d|i}\mathrm{h(x,y)}\right)\right)\ for\ P_{d|i,evac}(x,y) \leq 1$$

4.2.7 Asselman and Jonkman (2003)

Asselman and Jonkman (2003) used historical data from the 1953 flood event in the Netherlands to propose a flood mortality function related to the hydraulic circumstances (maximum water depth, maximum velocity and the rate of rising of water) of the flood. The authors categorise the deaths from the 1953 flood into the following three reasons; fatalities due to rapidly rising water; fatalities due to high flow velocities and fatalities due to other causes. The authors completed statistical regression between water depth and mortality to present the functions for mortality due to rapidly rising water and mortality due to other causes. They suggest that other causes of death (such as hypothermia and fatigue) can be indirectly correlated to water depth.

The authors proposed a function to represent fatalities due to rapidly rising water and fatalities due to other causes:

$$f(h)_{rise} = 9.18 \times 10^{-4} \times e^{1.52h} \qquad f(h)_{rise} \leq 1$$

$$f(h)_{other} = 1.41 \times 10^{-3} \times e^{0.59h} \qquad f(h)_{other} \leq 1$$

The authors assumed a simple criterion for mortality due to high velocities based on Reiter (2001) work on the building damage due to water depth and flow velocity. The authors assume that most people remain indoors during the flood and that persons will drown when the buildings collapse. As such they suggested the following criterion for mortality:

$$h \times v \geq 7 \text{ and } v \geq 2$$

where

h = water depth (m)

v = flow velocity (m/s)

$f(h)_{rises}$ = the fraction of inhabitants killed by rapidly rising water

$f(h)_{other}$ = fraction of casualties in areas with an increase in water depth of less than 1m/hour

The authors also consider evacuation and adopt a simple conceptual model by (Barendregt et al., 2005) as shown in Figure 3.

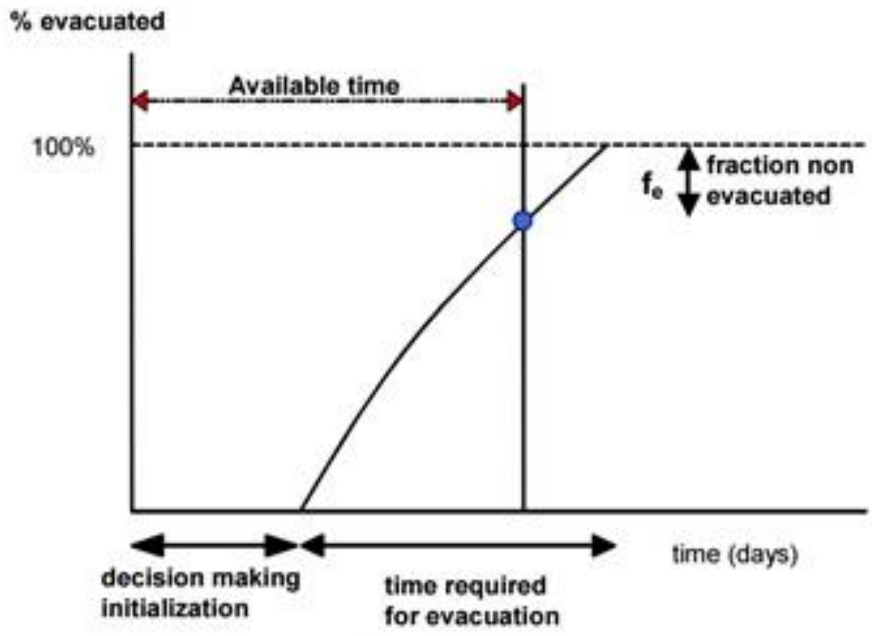

Figure 3: Evacuation Curve (after Barendregt et al., 2005)

4.2.8 Jonkman et al., (2008a)

Jonkman et al., (2008a) proposed empirical relationships between mortality and flood characteristics, evacuation and the availability of shelter and rescue based on historical disasters from Netherlands and United Kingdom (1953), Japan (1959), Bangladesh (1991) and Japan (2002). The methods proposed by this paper were intended for floods in low-lying areas that are protected by flood defences. The authors showed that different zones could be distinguished in an area that is inundated due to breaching of flood defences. In a zone near the breach(es) flow velocities are high leading to the collapse of buildings and instability of people standing in the flow. In other zones the water depth is one of the most important characteristic and empirical functions can specify the relationship between water depth and mortality. The paper also extrapolates that an important factor in historical floods was the rise rate, as it inhibits people's ability to reach shelter on higher grounds or higher floors of buildings. The proposed hazard zones for loss of life estimation in this model are shown in Figure 4.

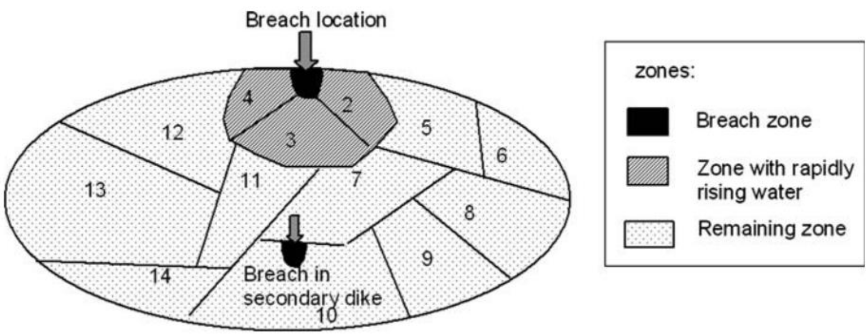

Figure 4: Proposed Hazard Zone for Loss of Life Estimation (Jonkman et al., 2008a)

A distinction is made between situations with rise rates below and above the threshold value of w = 0.5 m/h. The authors defined their zones based on the criteria shown in Figure 5:

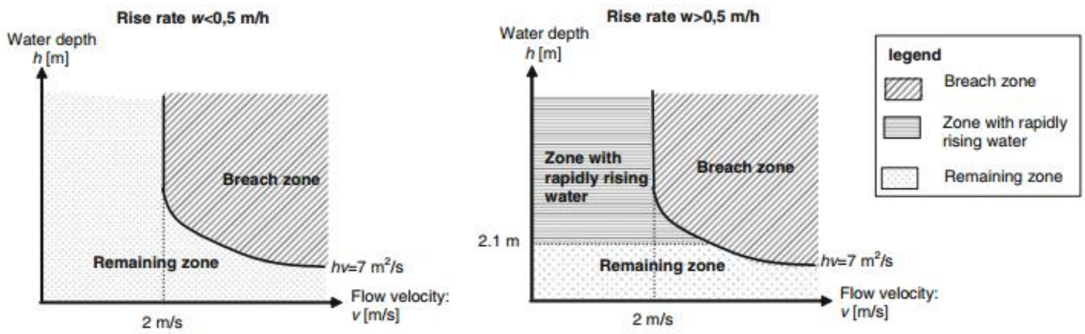

Figure 5: Area of Application of Mortality Functions (Jonkman et al., 2008a)

The paper presents the following functions of mortality based on their regressions the authors presented:

Mortality in the breach zone:

$$F_D = 1 \; if \; h \times v \geq 7 \text{ and } v \geq 2$$

Mortality in the zone with rapidly rising water:

$$F_D\,(h) = \emptyset_N \left(\frac{\ln(h) - \mu_N}{\sigma_N} \right)$$

$$if = (h \geq 2.1 \text{ and w } \geq 0.5 \text{ and } h \times v < 7 \text{ and } v < 2)$$

$$\sigma_N = 0.28 \; and \; \mu_N = 1.48$$

Mortality in the remaining zone:

$$F_D\ (h) = \ \emptyset_N \left(\frac{\ln(h) - \ \mu_N}{\sigma_N}\right)$$

$$if = (\mathrm{w}\ \leq 0.5 \text{ or } (\mathrm{w}\ \geq\ 0.5 \text{ and } \mathrm{h}\ < 2.1\ ) \text{and } (\ h \times v <\ 7 \text{ or }\ \ v\ < 2)$$

$$\sigma_N = 2.75\ and\ \mu_N = 7.60$$

where

F_D	= mortality fraction
h	= water depth (m)
v	= flow velocity (m^2/s)
w	= rate of rise of water (m/hour)
σ_N	= is the standard deviation of the normal distribution
μ_N	= is the average of the normal distribution
$\emptyset_N$	= is the cumulative normal distribution.

It should be noted that the authors reported a very poor correlation for the mortality function in the "remaining zone".

4.2.9 Jonkman (2009)

Jonkman et al. (2009) extended on the previous work (which was based on historical flood events that mainly occurred several decades ago) to analyse fatalities caused by flooding during Hurricane Katrina in New Orleans, which was relatively well documented. The data from this event was used to provide additional insight in the relationship between flood characteristics and mortality already developed in (Jonkman and Penning-Rowsell, 2008). The authors developed the following relationship of mortality:

Mortality in the breach zone:

$$F_D\ =\ 0.053\ for\ \ h \times v \geq 5$$

Mortality in the remaining zone:

$$F_D\ (h) = \ \emptyset_N \left(\frac{\ln(h) - \ \mu_N}{\sigma_N}\right) for\ h\ x\ v < 5$$

$$\sigma_N = 5.20\ and\ \mu_N = 2.00$$

where

F_D	= mortality fraction
h	= water depth (m)
v	= flow velocity (m^2/s)
σ_N	= is the standard deviation of the normal distribution
μ_N	= is the average of the normal distribution
$\emptyset_N$	= is the cumulative normal distribution

Figure 4 illustrates the outcomes of this analysis relating mortality rate to the depth of flooding for the New Orleans data.

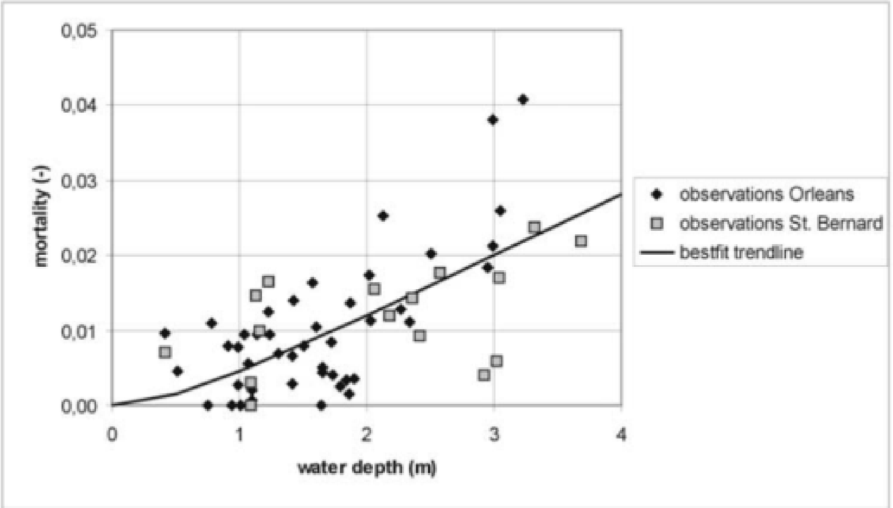

Figure 6: Mortality vs Water Depth (after Jonkman et al., 2009)

4.2.10 Zhai et al., (2006)

Zhai et al. (2006) analysed data from 269 historical flood events that occurred in Japan during the period 1947 – 2001. They derived a relationship between the number of inundated houses and the loss of life. The authors proposed that the number of flooded residencies is an indicator of the flood severity, size of the population at risk and the number of flood related injuries / fatalities. They proposed the following formula for loss of life:

$$L = S(H)$$

where

L	=	number of injuries/fatalities
H	=	number of flooded buildings
S	=	mortality function derived from database

The authors found that flood fatalities mainly occurred when more than 1,000 buildings were inundated and then increased as a function of the number of inundated buildings. They derived statistical relationships which showed considerable variation (which might be due to the influence of other factors such as warning, evacuation, flood characteristics and the actual collapse of buildings). In addition, the authors showed that when the historical data was analysed at decadal intervals, the fatality/injury coefficients decreased with time. They suggested that this is, at least in part, because of improved institutional arrangements such as flood warnings and emergency response.

4.2.11 DEFRA/HR Wallingford (Ramsbottom, 2003; Penning-Rowsell et al., 2005)

Ramsbottom (2003) developed an approach for assessing the flood risk to people, in a research project for the Environment Agency for England and Wales. The Flood Risk to People method estimates fatalities for a particular event as a function of injuries. Three characteristics are used to determine the number of fatalities and serious injuries from a flood event. These are:

1. Flood characteristics (depth, velocity, etc.);
2. Location characteristics (inside/outside, nature of housing); and
3. Population characteristics (age, health, etc.).

In addition, a flood hazard rating was indirectly based on the available tests for human instability and the effects of debris. The authors proposed values for the other factors, which are based on expert judgement. By a combination of these three factors, the numbers of fatalities and injuries are estimated from the following formulations:

$$N(I) = 2 \times N_z \times \frac{Hazard\ Rating\ \times Area\ Vulnerability}{100} \times People\ Vulnerability$$

where

$N(I)$	= number of injuries
N_z	= population living in the floodplain
$Hazard\ Rating$	= function of the flow characteristics of the flood (i.e. depth (m) and velocity (m/s) and the debris factor (score)
$Area\ Vulnerability$	= function of the effectiveness of flood warnings, speed and onset, type of buildings
$Area\ Vulnerability$	= function of the number of very old people (over 75) and long term sick/ disabled. This factor is expressed as a percentage.

$$Fatalities =\ 2N(I) \times \frac{HR}{100}$$

where

$N(I)$	= number of injuries
HR	= function of the flow characteristics of the flood (i.e. depth (m) and velocity (m/s) and the debris factor (score)

$$HR\ =\ d\ \times (v + 0.5) + DF$$

where

HR	= flood hazard rating
d	= depth of flooding (m)
v	= velocity of the flood water (m/second)
DF	= debris factor (=0, 0.5 or 1 depending on probability that debris will lead to significantly greater hazard)

$$Area\ Vulnerability\ (AV) = Speed\ of\ Onset + Nature\ of\ the\ Area + Flood\ Warning$$

where

AV	= area vulnerability scores (see Figure 7)
d	= depth of flooding (m)
v	= velocity of the flood water (m/second)
DF	= debris factor (=0, 0.5 or 1 depending on probability that debris will lead to significantly greater hazard)

Parameter	1 - Low risk area	2 - Medium risk area	3 - High risk area
Speed of onset	Onset of flooding is very gradual (many hours)	Onset of flooding is gradual (an hour or so)	Rapid flooding
Nature of area	Multi-storey apartments	Typical residential area (2-storey homes); commercial and industrial properties	Bungalows, mobile homes, busy roads, parks, single storey schools, campsites, etc.
Flood warning	Score for flood warning = 3 - (P1 x (P2 + P3)) where P1 = % of Warning Coverage Target Met[2] P2 = % of Warning Time Target Met[3] P3 = % of Effective Action Target Met[4]		
Area Vulnerability (AV) = sum of scores for 'speed of onset', 'nature of area' and 'flood warning'			

Figure 7: Area Vulnerability Scores (after Ramsbottom et al., 2005)

$$People\ Vulnerability\ (PV) = \%\ of\ residents\ suffering\ any\ long-term\ illness + \%\ aged\ 75\ or\ over$$

Therefore, the following formula is used to calculate fatalities:

$$N(I) = N \times X \times Y$$

where

$N(I)$	= number of deaths/injuries
N	= population within the floodplain
X	= proportion of the population exposed to a risk of death/ injury for a given flood based on the area of vulnerability
Y	= proportion of those that will suffer death and injury based on the people vulnerability

4.2.12 Priest et al., (2007)

Priest et al. (2007) prepared a report focusing on developing a methodology to estimate loss of life from flood events in central Europe. The research took as a starting point the Risk to People model developed in the UK by (Ramsbottom, 2003) and assessed the applicability of this model for flood events in Continental Europe (which tend to be more severe and life threatening). The authors gathered data on flooding events from 25 locations across six European countries to develop a semi-qualitative threshold model which combines hazard and exposure thresholds and mitigating factors in a wider European context.

4.2.13 Gouldby et al., (2012)

Gouldby et al. (2012) developed a 2D modelling framework to automate the assessment of loss of life in wide floodplain areas in the UK. The system developed uses the "Risk to People Hazard Rating" and provided an estimate of life loss from flooding related to both depth and velocity. The authors developed a methodology based upon the work of Ramsbottom et al. (2003, 2005), which is discussed in preceding sections.

4.3 Tropical Cyclone and Storm Surges

On a global scale a large contributor to loss of life is due to natural disasters and is associated with flooding by coastal events such as storm surges, hurricanes and cyclones (Jonkman and Vrijling, 2008). The number of fatalities caused by tropical cyclones depends on the intensity of the storm system, the physical protection systems (storm surge barriers) in place, and the storm surge warning systems available for a coastal community. As most storm surges occur due to meso scale weather systems and cover large areas, warning systems are typically administered at the national level, and the analyses sourced in literature focus on a similar national level. The following section presents some methods of estimating fatalities due to tropical cyclones and storm surges.

4.3.1 Boyd et al., (2005)

Boyd et al. (2005) analysed the loss of life in the city of New Orleans (USA) due to flooding after hurricane Betsy (September 1965). Boyd et al., (2005) related fifty-one fatalities directly to flooding, and proposed a linear relationship between mortality and storm surge height:

$$F_D = 0.304 \times 10^{-5} \times h$$

where

F_D	= mortality fraction
h	= water depth (m)

In later publications Boyd et al., (2005) investigated seven flood events to propose the following relationship between mortality and depth of water:

$$F_D = \frac{0.34}{1 + e^{(20.37 - 6.18h)}}$$

This relationship has an "S Shape" between flood mortality and depth (asymptotic mortality value) of F_D = 0.34. The authors suggest that almost two thirds of the population will always survive regardless of the water depth, by means of finding debris, trees, attics etc. and "*only under the most extreme situations would one expect the fatality rate to reach one.*'' *(Boyd et al.,* 2005).

4.3.2 Tsuchiya and Kawata (1981)

Tsuchiya and Kawata (1981) derived a relationship between typhoon energy and mortality. They investigated the relationship between mortality and factors such as the collapse of buildings, the time of warning and the volume of flooding (i.e. flooded area multiplied by water depth). However, no definitive method for the prediction of mortality was proposed.

4.3.3 Mizutani (1985)

Mizutani (after Jonkman and Vrijling, 2008) developed relationships for typhoons Jane and Isewan between average flood depth and mortality:

Typhoon Isewan:

$$F_D = 10^{\left(\frac{2}{3}h - \frac{11}{3}\right)}$$

Typhoon Jane:

$$F_D = 10^{(h-5.5)}$$

where

F_D = mortality fraction

h = water depth (m)

4.3.4 Adachi (2015)

Adachi (2015) established a correlation between the surge height and fatalities in the United States for a period between 1990 and 2011. The authors derived this relationship based on data available for past cyclone tracks and the corresponding annual fatalities caused by the tropical cyclones. They present a regression equation for loss of life based on this empirical analysis:

$$LOL = 0.6657(H_{max}) - 0.0709$$

where

LOL = loss of life

H_{max} = maximum surge height

4.3.5 IPET (2007)

Following the catastrophic flooding of New Orleans after Hurricane Katrina in August 2005, a method for the estimation of loss of life for hurricane-induced flooding of New Orleans has been developed in the context of the 'Interagency Performance Evaluation Taskforce' (IPET, 2007). This method assigns the exposed population into three zones (walk away zone, safe zone and compromised zone) with a typical value for the mortality rate. Local flood depths and building heights, and the age of the population were used to determine the distribution of the population over various zones (Jonkman et al., 2008b).

4.4 Tsunamis

One of the biggest and worst effects of a tsunami is the cost to human life because escaping a tsunami is nearly impossible. Hundreds and thousands of people are killed by tsunamis. Since 1850 alone, tsunamis have been responsible for the loss of more than 430,000 lives. After the Indian Ocean tsunami of December 2004, various publications have addressed the loss of life caused by this tragic event (e.g. Nishikiori et al., 2006; Rofi et al., 2006). These studies reported mortality fractions (F_D) in the affected areas between 0.129 and 0.17 of the population at risk. Whilst these investigations presented very relevant information related to tsunami, they did not directly address the relationship between mortality and the characteristics of the tsunami wave and the consequent inland flooding. The following section summaries the methods proposed in literature to estimate fatalities due to tsunami events.

4.4.1 Kawata (2001)

Kawata (2001) compiled casualties due to historical tsunami disasters that have occurred in Japan, including the 1896 Great Sanriku Tsunami, the 1933 Showa Sanriku Tsunami, the 1944 To–Nankai Tsunami, the 1946 Nankai Tsunami and the 1993 Hokkaido Nansei– Oki Tsunami. Kawata attempted to determine an empirical relationship between the tsunami casualty rate and the observed or estimated tsunami height as shown in Figure 8. This empirical relationship suggested that tsunami casualties began to occur when the local tsunami height exceeds 2 metres. However, the exact casualty rate was not determined as a unique number for a particular value of tsunami height.

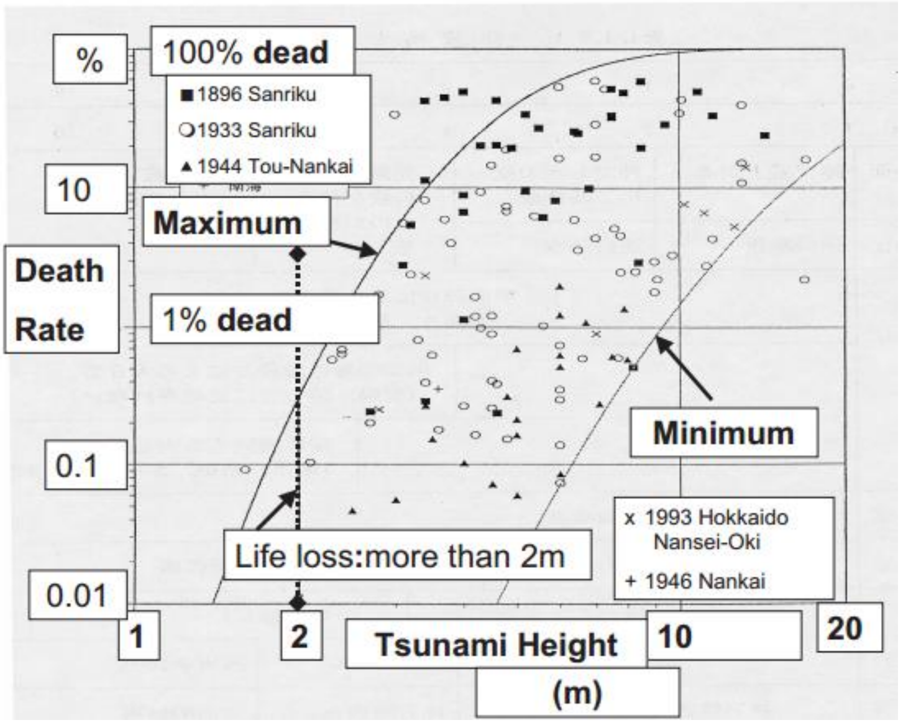

Figure 8: Relationship between Tsunami Height and Death Rate in Japan (after Kawata, 2001)

4.4.2 Sugimoto et al., (2003)

Sugimoto et al. (2003) proposed a method to calculate casualties from flooding by tsunami. The authors combined numerical simulations of inundation flow due to tsunami and an analysis of the evacuation process to estimate the loss of life. The number of tsunami victims was estimated by population in areas of maximum inundation. The number of deaths as a result of tsunami was estimated by the accumulated death toll of various areas in terms of time and space. The study took into account the consideration of the time necessary to begin to seek refuge after an earthquake, tsunami inundation depth on land, flow velocity and evacuation speed. A schematic of this method is shown in Figure 9.

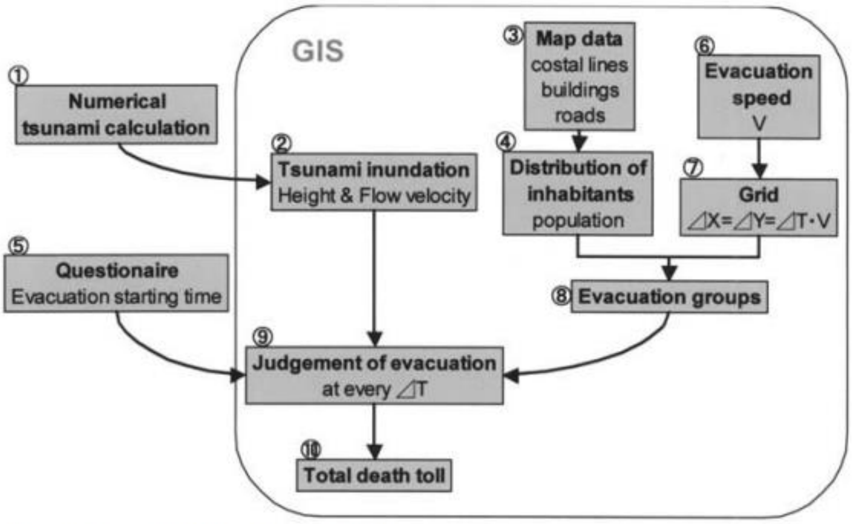

Figure 2. Flow chart of death toll prediction.

① Tsunami numerical calculation is done including inundation on land.

② Inundation heights and flow velocity data on land at constant time intervals; (ΔT), are imported as a tsunami data base.

Figure 9: Flow Chart for Prediction of Death Toll due to Tsunami

4.4.3 Koshimura et al., (2006)

Koshimura et al. (2006) presented a method for estimating the number of casualties that may occur while people evacuate from an inundation zone when a tsunami has inundated an area. The method is based on a simple model of hydrodynamic forces as they affect the human body. The study suggests that the tsunami casualty occurrence is equal to the minimum hydrodynamic conditions that prohibit people's evacuation movement. This occurs when the hydrodynamic force due to the tsunami inundation flow affecting the human body exceeds the resistance force of an evacuee against the inundation flow. The authors present the following equation for tsunami casualty occurrence:

$$f(mg - w) \leq \alpha \int \frac{1}{2} \rho C_D U^2 dS + \int \rho C_M \frac{\delta u}{\delta t} dV$$

where:

mg	= the weight of the human body
w	= the buoyancy of the partially submerged human body
f	= the friction coefficient
ρ	= the density of the salt water
u	= the water velocity in the horizontal direction
C_D	= drag coefficient
C_M	= inertia coefficient
dS	= projected area perpendicular to the flow direction
dV	= volume element of the human body model
α	= stability coefficient

The method also uses a Tsunami casualty index (TCI) computed at each grid point of a numerical tsunami model to determine locations and times within the tsunami inundation zone where evacuation during the tsunami inundation is not possible and casualties are likely to occur. This is defined as:

$$TCI = \frac{Tc}{Ti}$$

where:

Tc	= the duration of the tsunami inundation flow during exposure
Ti	= total duration of the tsunami inundation flow that occurs within the area inundated by the tsunami

The authors suggest that the locations and times can be combined with information about population density to compute the potential number of casualties. Whilst the method presented is unlikely to reflect that true quantity of estimate of fatalities, the information derived from using the model may be useful in developing tsunami evacuation routes to avoid high risk locations.

4.4.4 CDMC (2003)

CDMC (2003) proposed a method for the estimation of loss of life due to tsunamis based on historical statistics of Japanese tsunamis. The authors present mortality as a function of tsunami wave height:

$$F_D = 0.0282 \times e^{0.2328 \times h_{ts}}$$

where

F_D	= mortality fraction
h_{ts}	= tsunami wave height (m)

5. Agent Based Modelling for Determining Flood Fatalities

Agent based models use a more deterministic (often semi empirical) approach to estimate loss of life. At their most sophisticated, these models combine the time varying flood inundation mapping of detailed numerical 2D flood models with a similarly detailed numerical representation of individuals (or sometimes groups of people) as they respond to the impending flood. The models consider the propagation of flood behaviour over the landscape and then consider human behaviour and decision making in response to the flood inundation. As well as representing human behaviour and decision making through use of complex probabilistic distributions (e.g. to represent individual choices to evacuate or not, timing response to evacuation warnings etc.) the models can include complex traffic modelling to provide detailed evaluation of the capacity of road networks to handle mass evacuation of flood affected communities.

The following section summarises the formulations of these models found in literature.

5.1 LIFEsim Model (McClelland, Bowles and Aboelata 2000 -2005)

McClelland and Bowles (2002), of Utah State University, undertook a comprehensive analysis of historical dam break cases and the factors determining loss of life for the U.S. Army Corps of Engineers (USACE) and the Australian National Committee on Large Dams (ANCOLD). Initial phases of the study involved characterising case histories of flood events and fatalities resulting from historic flood events. The authors presented results from different flood zones distinguished by the characteristics of the flood (depth, velocity) and the availability of shelter. They showed that fatalities observed in historical cases have often differed distinctly between flood zones. They divided zones into "Chance Zone", "Compromised Zone" and "Safe Zones" and found that in the most hazardous "Chance Zone", historical mortality rates ranged from FD = 0.5 to 1 with an average of 0.9. They used their analysis of historic events to develop a life-loss probability distribution function to develop a "LIFEsim" model. The LIFESim model is structured as a modular modelling system built around a database. Each module exchanges data with other modules through the database, which includes various geographic information system (GIS) layers and tables (Aboelata and Bowles, 2005). Internal modules comprise:

1) Dam Break / Flood Routing Module;
2) Loss of shelter, including prediction of building performance; (Loss-of-Shelter categories are assigned to each level in several types of buildings throughout the flooding area for which historical fatality-rate probability distributions were estimated by McClelland and Bowles (2002);
3) Warning and Evacuation; and
4) Loss of Life, which is based on scale-independent empirical relationships developed by McClelland and Bowles (2000). Updated probability distributions by Aboelata et al. (2003) for "Chance Zone", "Compromised Zone" and "Safe Zone" are displayed in Figure 10.

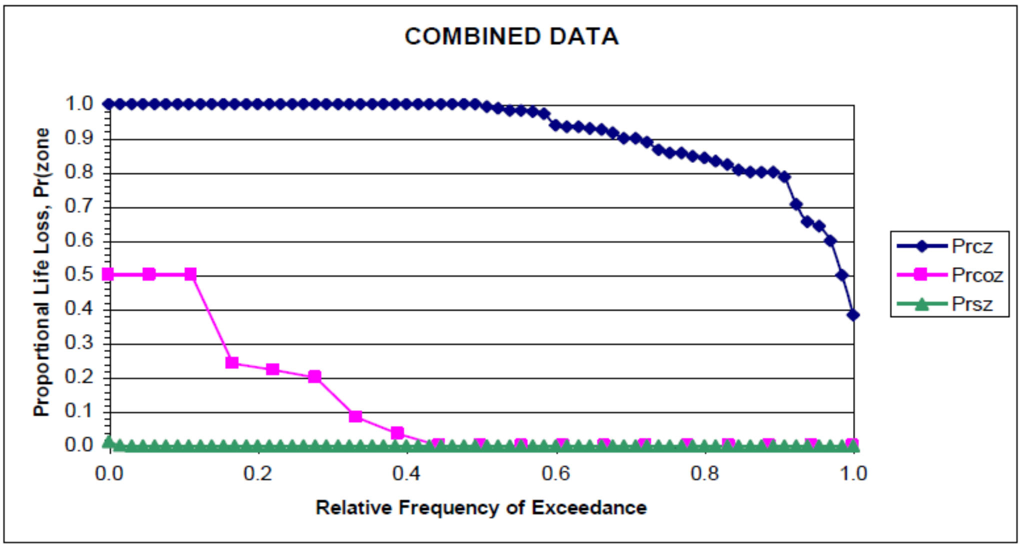

Figure 10: Probability Distribution (Aboelata et al., 2003)

The model is based on a GIS framework that can be used for both deterministic (scenario) and probabilistic (risk analysis) calculations. The LIFEsim model is applicable for estimating fatalities resulting from levee failure and dam break scenarios, as attributed to dam break formulations. Note that whilst the authors make every effort to provide the most holistic statistical interpretation of the historic data set, the model still includes subjective estimates and assumptions with significant justification through validation. Huang (2012) highlights that the great uncertainty associated with parameters in the LIFEsim model rendered it inapplicable to the study of changing rates of mortality over time.

5.2 HECFIA (USACE, 2012)

http://www.hec.usace.army.mil/software/hec-fia/

HECFIA (Hydrologic Engineering Centre-Flood Impact Analysis) is a general framework for estimating the consequences of flood inundation. The model is a spatially distributed dynamic simulation model that can be used to estimate flood damages to structures and contents, losses to agriculture and estimate loss of life. It can take advantage of time varying spatial outputs from hydrodynamic flood models. When used to estimate loss of life, the system uses a GIS interface to relate spatial property and infrastructure data and flood inundation data to estimate a PAR and then applies a simplified LIFEsim (Aboelata et al., 2003) approach to estimate flood fatalities.

The system requires a digital elevation model (DEM), an impact area polygon, gridded information regarding inundation depths and velocities, a structure (building) inventory, flood wave arrival times, warning dissemination information, mobilisation information and a safe zone boundary. Estimates of loss of life are determined by first assigning the PAR to three evacuation outcome categories:

- Cleared: the people who are able to evacuate safely.
- Caught: the people who are caught by flood waters while evacuating. This population is assigned to the chance flood lethality zone.
- Not mobilised: the people who do not evacuate the structure they are in.

The system then assigns the PAR who have not mobilised into to three flood lethality zones:

- Chance zones: applicable when the flood depth or DV will destroy the shelter provided by buildings.
- Compromised zones: applicable when flood depth or DV is likely to partially damage a building.
- Safe zones: where flood depths and DVs are less than the compromised zone thresholds.

Distributions of fatality rates for each flood lethality zone are based on McClelland and Bowles (2002). The average of each distribution is 0.91, 0.12 and 0.0002 for the chance, compromised and safe zones respectively.

5.3 British Columbia Hydro/ HR Wallingford Life Safety Model (Assaf and Hartford 2002, Johnstone et al*.,* (2005)

http://www.lifesafetymodel.net/

The 'Life Safety Model' developed by British Columbia Hydro (Johnstone et al., 2005) moves away from general empirical models adopting a more deterministic approach. The Life Safety Model presents an approach to simulate 'receptors' on the floodplain, which can be either individuals or groups of people such as family groups who respond and act together, based on their interaction with a flood wave. The model operates within a geographic information system (GIS) platform to compute the interaction of an object in the flood based on the physical properties of the flood wave (velocity and depth). In this model the object's (i.e. the person at risk, buildings, vehicles etc.) damage and loss functions are defined using stability/vulnerability relationships and thresholds, and coupled with 2-dimensional hydrodynamic flood properties to determine if the object can withstand the flood (Sakamoto, 2011). In the model, the objects with damage and loss functions include:

1. The population at risk;
2. The buildings in which the population may reside or take refuge;
3. The vehicles in which the population may evacuate; and
4. The roads upon which the population travel when evacuating.

In this model an individual's fate is modelled mechanistically, i.e. individual fatalities are accounted for at an individual level when the building in which the person stays is destroyed, or when a person walking outside is overwhelmed by water, or when a person fleeing in a vehicle is overwhelmed by water. The model's fundamental physics are based on mathematical models of "human toppling" defining the stability of people in water as described e.g. in Lind et al., (2004) or damage to buildings in floods by Clausen and Clark (1990) and the stability of vehicles in water. The physical interaction of this model is described in detail by Johnstone et al*.,* (2005).

The advantage of the model is that it has an agent based simulator which allows the model to represent a myriad of probable scenarios, which could result from a flood event. The system allows unknown variables such as the effectiveness of the warning, traffic network capacity and changing population size and demographics to be tested and the model can be applied to a range of flood events across a risk profile. The system is also able to simulate a range of flood types including fluvial floods, coastal events and floods generated by tsunamis ((Hartford et al., 1997)). Calculations can account for diurnal and seasonal human behaviour resulting in different values for loss of life based on the time of occurrence of the flood event, e.g. at different times of the year, different days of the week, different times of day. Due to a lack of detailed information, many assumptions in the model are necessarily based on expert judgement and are to a limited extent supported by research results.

HR Wallingford has been working with the Life Safety model since 2006 and is now the developer of the model (having signed an agreement with BC Hydro in 2012).

http://www.hrwallingford.com/software/life-safety-model-lsm

The BC Hydro LSM model and the LIFESim modelling systems are the first serious efforts to dynamically and spatially simulate evacuation during flood events.

These models are computationally intensive due to the detail included in the model analysis. Agent based models also require comprehensive and detailed datasets in order to simulate the response of individuals and the community to floods. Input data required includes:

- Topography;
- Detailed flood data;
- Cadastral and building use data;
- Census data;
- Behavioural information on various members of the community, e.g. workers, students, etc.;
- Traffic network information;
- Evacuation planning;
- Level of warning; and
- Warning response.

6. Australian Applications of Loss of Life Models

The literature review conducted for this study noted a limited number of applications of loss of life models to estimate flood fatalities in an Australian context.

Lang (2009) reviewed ten methods for estimating loss of life due to dam failure and noted that dam owners in Australia had commonly applied the method of Graham (1999) in dam safety risk analysis as it was the method recommended by the Australian Committee on Large Dams (ANCOLD, 2003). Lang (2009) notes that *'Despite its limitations, the Graham (1999) model is simple to use and understand, and has been used extensively in practice. Uptake of more recently developed empirical models is expected to be minimal in Australia, for reasons including public availability and queries regarding their applicability outside the jurisdictions they were developed for.'* Lang (2009) also noted that more sophisticated, '*dynamic simulation'* (agent based) models were likely to be the next step in consequence analysis of dam failure, as these models were better able to *'…simulate the influence of warning and evacuation assumptions on life safety consequences. These additional capabilities will be especially important where the effectiveness of non-structural dam safety upgrades (e.g. improved warning systems or evacuation routes) need to be assessed.'* Lang (2009) noted that the major drawbacks for dynamic simulation models are their limited availability, implementation complexity and that their uptake would be *'…unlikely unless a benchmarking study shows costs involved in its application is offset by the benefits of more robust estimates of life loss.'*

Lang et al. (2011) compared four different loss of life models by applying them to two dams in south-eastern Australia. Three empirical methods Graham (1988), Graham (1999), RESCDAM (Reiter 2001) and one dynamic simulation method HECFIA were applied. The paper concluded that the Graham (1999) and HECFIA methods were suitable for estimating loss of life for dam failures and provided similar estimates for loss of life for this case, but obtained quite different estimates for loss of life for natural floods. In particular, the paper noted that ANCOLD (2003) does not recommend Graham (1999) for estimating flood fatalities for natural flood events and used the alternative method of Hill et al. (2007) to estimate fatalities for this case. The RESDAM (Reiter 2001) method was not recommended.

ANCOLD (ANCOLD, 2013) held a series of training short-courses in 2013 outlining preferred methods for estimating dam failure consequences. Loss of life estimation methods for dam failures presented on this course demonstrated on the method of Graham (1999) and dynamic modelling using HECFIA. In particular, HECFIA was applied to the information available for the Grantham 2011 flood. The HECFIA results (see Table 7) demonstrated that this software system was able to successfully reproduce the Grantham flood fatality rates.

Table 7: Grantham Flood Fatality Rates Estimated using HECFIA (after ANCOLD, 2013)

Location	HEC-FIA	Loss of Life
Grantham	14.4	12
Placid Hills	1.7	1
Helidon	1.6	0
Helidon Spa	0.7	0
Tenthill Creek area	0.8	0
Withcott	0.7	2
Gatton	0.3	0
Total	20.2	19

Molino et al., (2014) describes an application of the LSM model to the township of Windsor north west of Sydney. The application used comprehensive available information provided by NSW SES on the population distribution through the township (property by property), traffic network and evacuation route data, flood warning, departure and travel assumptions to model emergency evacuation of the township. While the paper successfully demonstrated the functionality and capability of the software to model an evacuation, it did not extend to using the LSM software to estimate loss of life. The full functionality of this aspect of the software could not be demonstrated due to the lack of a suitable 2D flood inundation dataset to apply to the LSM model.

Meneses et al. (2015) applied the RCEM (USBR, 2014) method to five Australian dams and compared the results from this method to the estimates using Graham (1999) and HECFIA. Meneses et al. concluded that RCEM should supersede the Graham (1999) method as recommended by the USBR. This conclusion was based on similar outcomes from the local study compared to international benchmarking.

Meneses et al. also concluded that '*HEC-FIA can also be applied where PLL estimates are likely to be influenced by PAR evacuation constraints, and / or where dam owners are considering the efficacy of non-structural improvements (e.g. improved warning times).'*

7. Discussion

There is good, general knowledge in the accessed literature on the causes of loss of life in flood. However, a simple, reliable, generic relationship for the quantification of flood fatalities is not readily available. The referenced studies have greatly improved the understanding of flood-caused loss of life mechanisms and might aid development of plans for flood disaster reduction. The loss of life estimates from each method can be considered indicative only.

The methods presented in this report have been developed for different types of floods in different geographic regions. Applications that have received significant attention and research are dam breaks in USA and Canada, coastal storm surges in Japan, floods and storm surge in the Netherlands and tsunami in Japan and Indonesia.

Ultimately, each of the reviewed empirical methods include a function, which relates mortality to flood characteristics. Many of these functions have been validated for individual flood events where loss of life has occurred. Several methods are noted as being specific to dam failure flooding and are not recommended for natural river flooding. None of the many methods reviewed have proved to be scalable over a range of flood sizes and intensities (hazard levels). Nor have methods developed in one region proved readily portable to other geographic areas. Social and cultural differences in the attitude and approach to evacuation also make porting international methods to Australian conditions problematic.

Each of the empirical functions depends on variables describing the flood type, which are highly variable from flood to flood and area to area. However, the empirical functions are typically related to flood behaviour parameters that are available as outputs from a contemporary flood study. These parameters include:

- Flood inundation extent;
- Flood depth (D), flow distribution, flow velocity(v), flood hazard (v* D);
- Flood timing including:
    - Time to arrive (overtop);
    - Time to peak;
    - Rate of rise;
    - Inundation duration.

Each method also requires an estimate of the population at risk, which would typically be able to be estimated from property counts and readily available population data from the Australian Bureau of Statistics.

Human behavioural responses to flood and evacuation including social and cultural differences between regions also contribute to the community response to each flood event and are significant in predicting loss of life in any particular event. A common limitation of the existing empirical approaches is that they could not explain the long-term change of flood fatality or mortality with changing socio-economic conditions.

An important finding of many of the papers reviewed is that the proportion of fatalities compared to the population at risk, while highly variable depending on a broad range of parameters (see Section 3) is often a very small proportion of the total population at risk. CDMC (2003) found that even in the most violent of inundation events, such as a tsunami, that mortality rates were in the order of 15% to 20% of the population at risk.

While some methods acknowledge that portions of the population such as the very young and the elderly may be more vulnerable during floods, attempts to specifically account for varying demographics are not typically represented in the methods. Note also that none of the empirical methods specifically account for the mode or location of fatalities. While the methods acknowledge the various ways that people may perish in flood waters, the methods do not generally distinguish between a person who dies in a house, in a vehicle, on foot etc. rather the methods make broad fatality estimates based on the PAR.

Agent based and dynamic models provide a detailed assessment of a community flood response and a deterministic method for estimating loss of life during flood. However, these models are data and computationally intensive and highly parameterised, with little means for calibration/validation of the model parameters. As such, they are a relatively expensive alternative to empirical approaches and without a means for calibration, potentially no less reliable. These types of models do have the distinct advantage of being able to clearly represent, assess and contrast various floodplain risk mitigation scenarios. Where the cost, complexity or consequences of flood mitigation options warrant the time and expense, agent based or dynamic models can be used to visualise and estimate the incremental reduction in fatality estimates pre and post the flood mitigation option.

8. A Simplified Approach to Estimating Loss of Flood

Investigation of the methods for estimating flood fatalities in available literature showed that most methods followed a generic framework. This framework is illustrated diagrammatically in Figure 11.

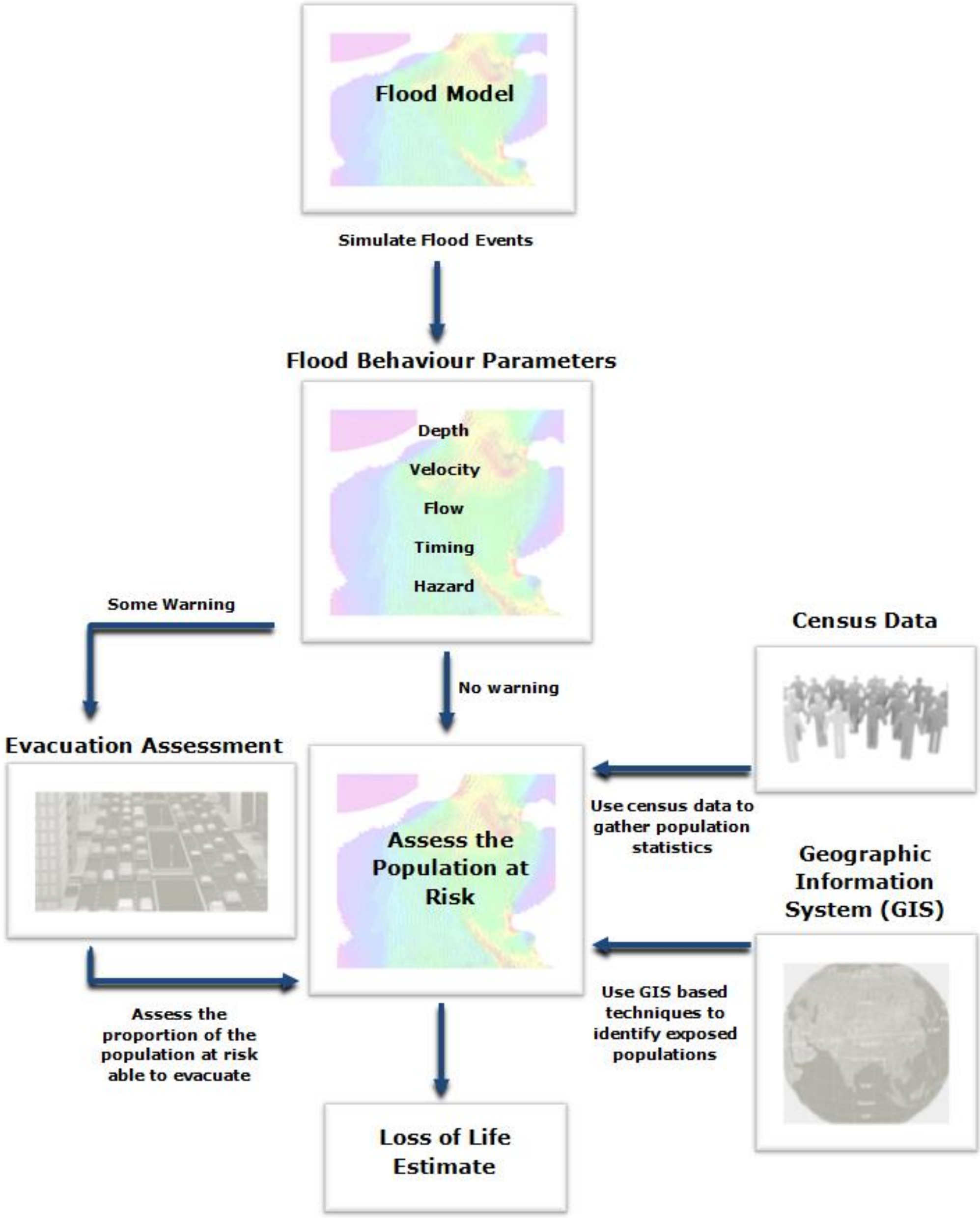

Figure 11: Generic Method for Estimating Flood Fatalities

In many cases, this framework could be cost effectively applied in a floodplain management study using datasets typically available from a flood study developed using the approaches recommended in Handbook 7 (AEMI, 2014). The generic framework for estimating the loss of life during a flood is as follows:

1. Undertake a flood study of the subject floodplain to determine design flood behaviour;

2. Interpret flood hazard for the floodplain using the methods outlined in Handbook 7 (AEMI, 2014) *Technical Flood Risk Management Guideline: Flood Hazard*

3. Use Handbook 7 (AEMI, 2014) *Technical Flood Risk Management Guideline: Flood Emergency Response Classification of the Floodplain* and census data to estimate the PAR of exposure during the flood. Where information on emergency and evacuation planning is available, this might be used to adjust the PAR.

4. Use a method based on these two sets of data developed in Steps 2) and 3) above to determine a loss of life estimate by applying a mortality function(s) to the population at risk.

The mortality function can be determined from one of the empirical methods described in this report. Careful consideration of the following factors is required when choosing the mortality function methodology:

a) Flood behaviour parameters (depth, velocity, timing etc.);
b) Exposure of the population (ability to evacuate, shelter-in-place, nature of housing); and
c) Population characteristics (age, health, amount of flood education, mobility etc.).

Where flood evacuation is a critical element of estimating the PAR of flood exposure, more detailed traffic modelling of the evacuation process or agent based modelling might be warranted.

8.1 Benchmarking Methods to Australian Flood Fatality Data

Since many of the methods for estimating loss of life reviewed for this study are based on methods developed internationally on overseas data sets, an assessment of the applicability of the methods to a local test case was considered warranted. While the test case presented below is by no means conclusive, and benchmarking against additional floodplains is needed, the test case is a useful guide as to which methods might be applicable in an Australian context.

8.1.1 Grantham Flood

In January 2011, unusual climatic conditions resulted in extreme weather over much of Queensland. In particular, extreme rainfall over Toowoomba and the upper Lockyer Valley caused catastrophic flash flooding, which had resulted in the deaths of 19 people. Although the loss of life and damage to property was widespread, the community of Grantham suffered most from these events with twelve (12) local residents either confirmed deceased or still missing (OOSC, 2012).

Detailed flood modelling was completed for the Lockyer Creek floodplain at Grantham as part of the Grantham Floods Commission of Inquiry (Grantham Floods Commission of Inquiry, 2015). These flood models were extensively calibrated to peak flood levels and eyewitness testimony for the January 2011 event. This flood event was assessed to have a 0.25% annual exceedance probability (AEP) (Grantham Floods Commission of Inquiry, 2015) which is in the extreme range beyond the typically adopted flood planning event. Information on the response of the community before, during and immediately after the event is described in detail in the Commissioner’s report. This report along with other publically available information has been used to derive a loss of life estimate for the event and to provide a local estimate of flood mortality.

8.1.2 Background Information

A GIS based method was adopted to determine the total population and risk based on a count of residential properties on the inundated floodplain as shown in Figure 12. The population at risk was determined by multiplying the property count by the number of people per household sourced from the 2011 census data for Grantham (Australian Bureau of Statistics (ABS), 2011). These values are summarised in Table 8.

Table 8: Grantham Floodplain Parameters

Parameter	Value	Comments
Number of Houses in the Floodway	92	Computed using GIS using floodway extent (see tab for example)
Number of Houses in High Hazard Zone (v x d > 2)	78	
Average Number of People Per House	2.6	Sourced from the Australian Bureau of Statistics Grantham (Australian Bureau of Statistics (ABS), 2011).
Total Population at Risk	239	
Total Population at Risk in High Hazard Zone	203	
Maximum Flood Depth (m)	2	Estimated - but expected to be available from flood study
Warning Time (mins)	0	Assumed no official warning
Rate of Rise of Water (m/hour)	0.5	Assumed Value

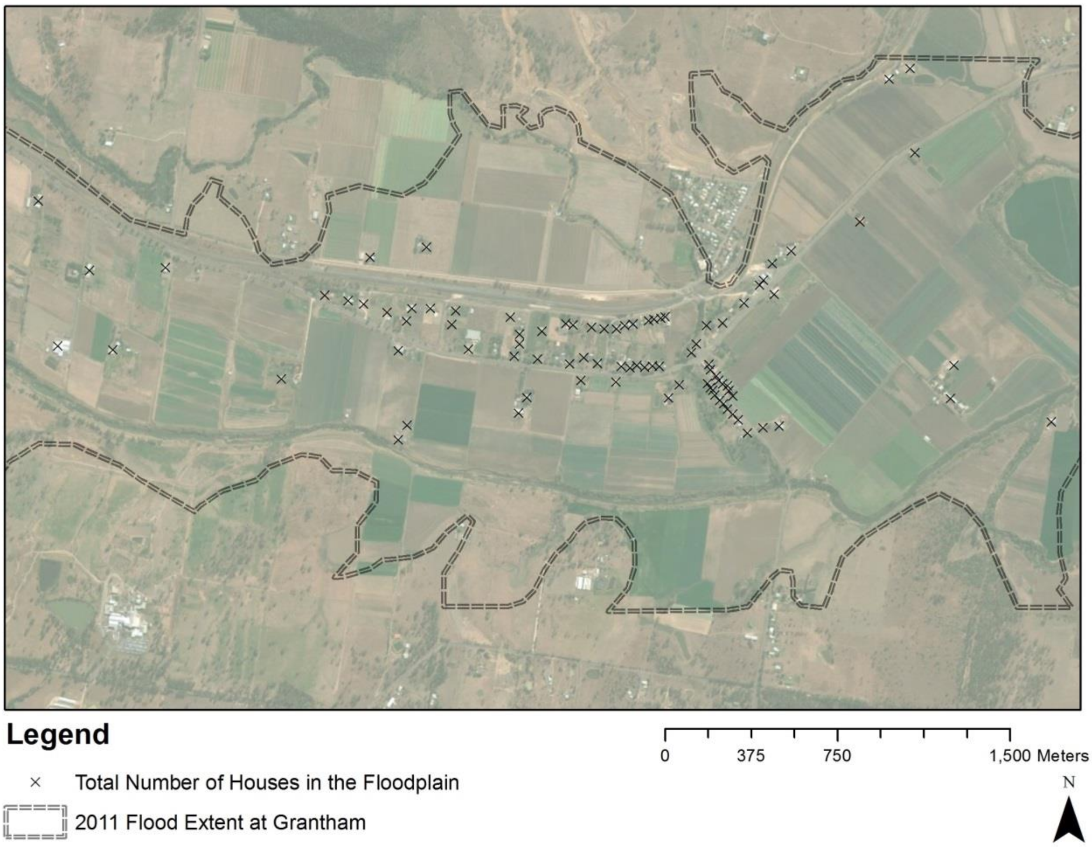

Figure 12: Properties in Floodway

8.1.3 Comparison of Fatalities in Grantham with Methods Reported in Literature

The available flood behaviour and population at risk data was used to estimate the total number of fatalities using selected methods presented in Section 4. The fatalities predicted by each of these methods is summarised in Table 9.

Table 9: Fatalities Predicted by Literature at Grantham

Method	Loss of Life Estimate	Comments
Stanford/FEMA Model	38	
Institute for Water Resources (1986)	48	
United States Bureau of Reclamation (Brown and Graham, 1988; U.S. Bureau of Reclamation, 1986, 1989)	120	No warning
	21	Some warning
	1	Warning > 1.50 Hours
DeKay and McClelland (Bureau of Reclamation, 1991, 1993)	40	Assuming high force flood event
Graham (1999, 2010)	2.4 - 19.1	Assuming medium flood severity flood, vague understanding and < 60 min warning (See Table 6)
	10	As above with recommended mortality value of 0.04
Duiser (1989) and Waarts (1992)	1.6	
Dutch Ministry of Transport (HKV 2000-2005)	0	
Asselman and Jonkman (2003)	6	
Jonkman (2009)	4	
RCEM (USBR, 2014)	0 - 4	Assuming little or no warning

The results presented in Table 9 show a wide range of flood fatality estimates from a minimum estimate of zero (0) using the Dutch Ministry of Transport (HKV 2000-2005) to 120 for United States Bureau of Reclamation method with no warning. While it is not generally recommended for natural flood events, the dam failure based method presented by the USBR (Graham, 1999) provides the closest loss of life estimate to the reported number of fatalities at Grantham for the January 2011 flood. In the absence of a more comprehensive assessment of Australian based data sets, this method might be used as a first pass estimate for determining a loss of life estimate.

8.1.4 Mortality factor for Grantham

In addition to considering methods presented in literature, an assessment of an empirical mortality factor for Grantham was made using readily available information. This mortality rate was assessed by first determining the population at risk based on the number of houses within the high hazard flood zone, as shown in Figure 14. This method was considered relevant as most of the people who perished in the flood at Grantham were in or nearby their homes that were exposed to high flood hazard thresholds as presented in Figure 13.

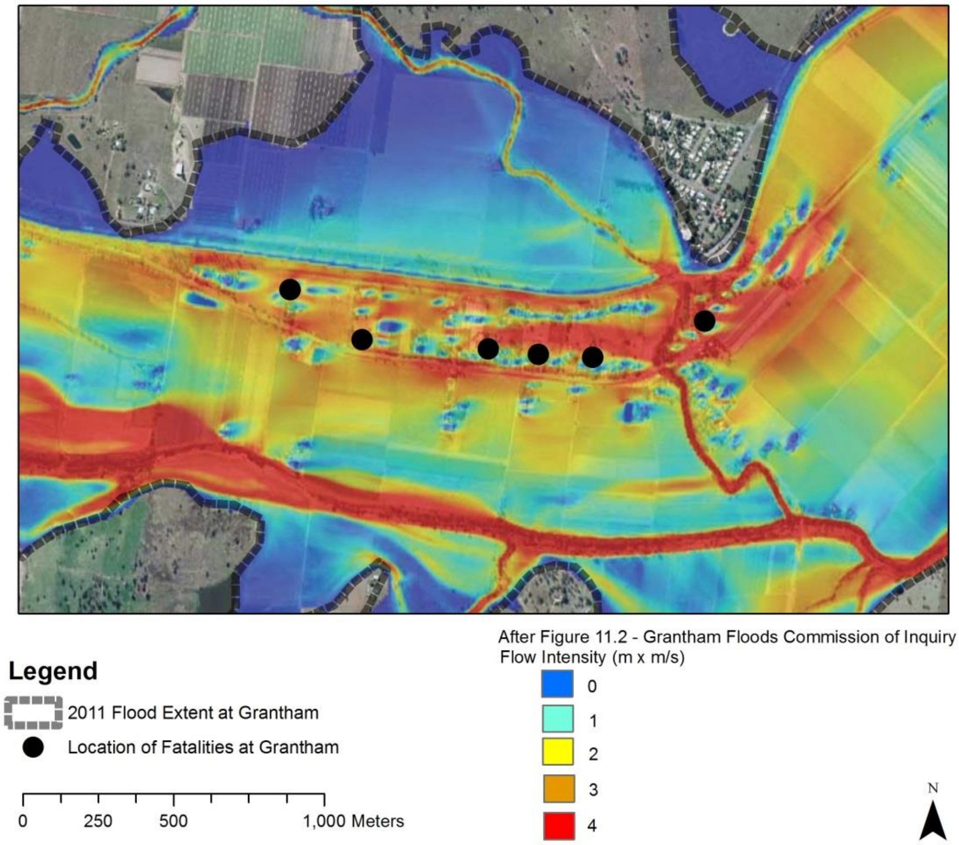

Figure 13: Location of Fatalities at Grantham

A previous review of flood hazard (Smith et al., 2014) showed that structural damage to residential property is anticipated when buildings are exposed to flood hazards (v x D) greater than 1 (H5 Threshold). RESCDAM (2001) states that velocities of greater than 2 m/s will likely result in either partial or total damage for masonry, concrete and brick buildings and on the basis of information presented in Smith et al. (2014) most residential property is unlikely to withstand flood hazard (v x D) values higher than 2. Modelling of the 2011 floods in Lockyer Valley, suggests that v x d products of more than 2.5 m^2/s were experienced in much of the Grantham town area with some areas above 5 m^2/s as shown in Figure 14. Attempts at self-evacuation by vehicle including large trucks also proved fatal in these conditions (Grantham Floods Commission of Inquiry, 2015).

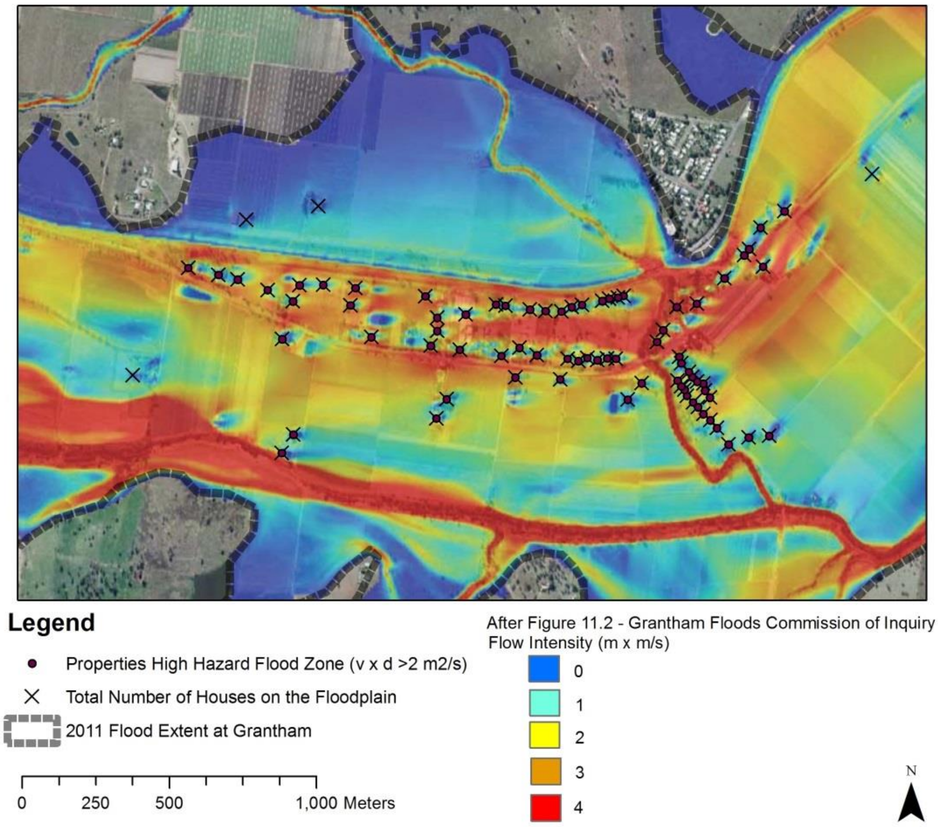

Figure 14: Properties H5 Hazard in Grantham

Hazard classifications to define a population at risk were determined using the AEM Handbook 7 flood hazard vulnerability curves (AEMI, 2014) as shown in Figure 15. A flood hazard threshold H5 was adopted to classify areas of the floodplain where the population of risk was derived.

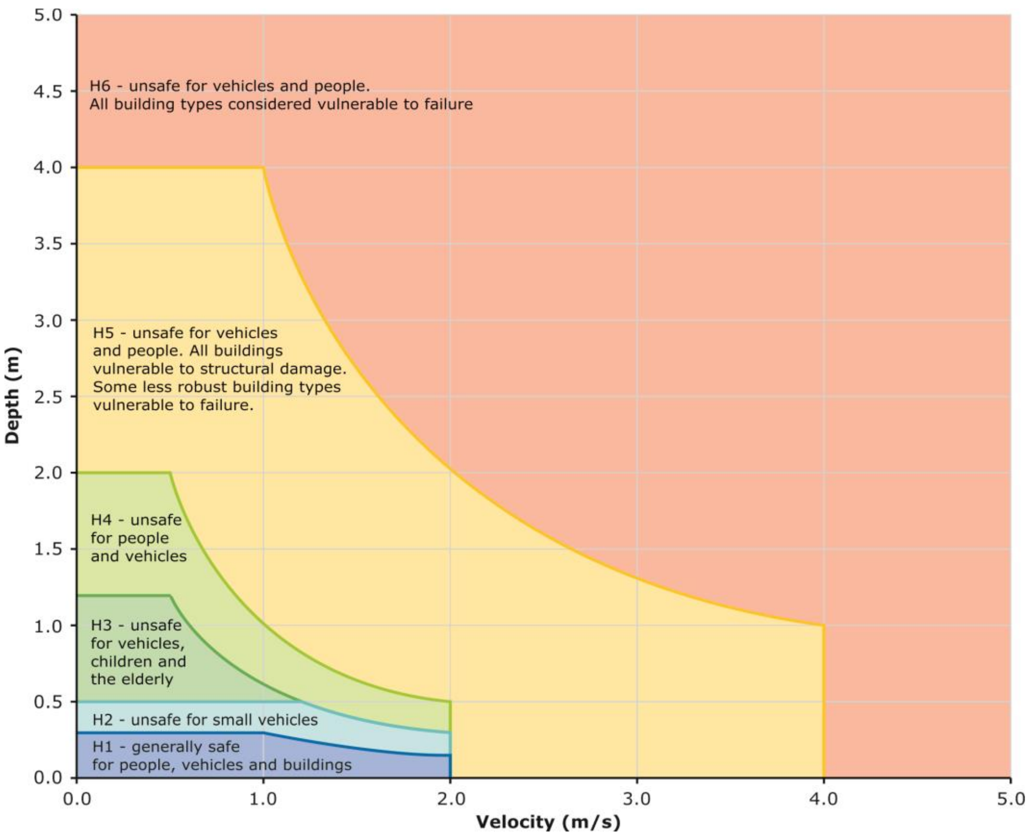

Figure 15: Flood Hazard Curves (after AEMI, 2014)

The mortality factor was calculated as follows.

$$F_G = \frac{N_{total}}{PAP_H}$$

$$for\ PAP_H \text{ in } h \times v > 2$$

where

F_G	= mortality fraction of the inhabitants at Grantham
N_{total}	= total number of fatalities reported at Grantham
PAP_H	= population at Risk in the high hazard flood zone
h	= water depth (m)
v	= flow velocity (m^2/s)

On this basis the flood mortality rate for Grantham for the January 2011 flood event was determined to be 0.06.

$$F_G = \frac{12}{203} = 0.06$$

9. Conclusions

This study has identified a range of methods for estimating loss of life during floods. While there is extensive general knowledge in the accessed literature on the causes of loss of life in flood conditions, a simple, reliable, generic relationship for the quantification of flood fatalities that could be readily applied as a cost effective additional metric for quantifying flood hazard and consequences is not readily available.

While the referenced studies have greatly improved the understanding of flood-caused loss of life mechanisms and might aid development of plans for flood disaster reduction, the loss of life estimates from each method can be considered indicative only. Many of the methods rely on subjective choices by the practitioner. As such, this study has not identified any of the referenced methods as being more consistent or reliable for estimating flood fatalities. Floodplain management practitioners are encouraged to review the range of presented methods, their assumptions, data requirements, computational overheads and detail of outputs in order to determine which method is most suitable for their specific needs.

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