6TH INTERNATIONAL CONFERENCE
ON FLOOD MANAGEMENT
September 2014 - São Paulo - Brazil

A COMPARATIVE STUDY ON METHODS FOR LOSS OF LIFE ESTIMATION – APPLICATIONS TO CASE STUDIES IN THE UNITED STATES

S.N. Jonkman[1], B. Maaskant[1,2], B. Kolen[2], M. Zethof[2], W.P. Lehman[3], J.T. Needham[3]

1. *Delft University of Technology, Faculty of Civil Engineering and Geosciences, Department of Hydraulic Engineering, Delft, The Netherlands*
2. *HKV Consultants, Lelystad & Delft, the Netherlands*
3. *US Army Corps of Engineers, HEC, Davis, California, United States*

ABSTRACT: In the Netherlands, USA and other countries methods for the analysis of loss of life and evacuation associated with flooding are used in flood risk management. This paper compares the methods from the US and Netherlands in this field and considers both methodological principles as well as the outcomes for various case studies. Similarities and differences between the modeling approaches , input and output types and applications are discussed. As part of a comparison effort two case studies in the US have been selected: the Natomas Basin in California, and the Herbert Hoover Dike in Florida. These case studies are the first steps in a benchmark research on life loss models and recommendations for future improvement of the methods are provided.

Key Words: Loss of life, Consequences, Flood Risk Analysis, Evacuation, comparison effort.

1. INTRODUCTION AND BACKGROUND

Loss of life is one of the most important consequences of flood disasters. Historical events, such as the 1953 flooding in the Netherlands and the flooding of New Orleans due to hurricane Katrina, have demonstrated that the magnitude of life loss can be significant. Various methods have been developed in the Netherlands, US and other countries for various fields of application such as levee failure, dam breaching, and tsunamis – see section 2 and (Jonkman et al., 2008) for an overview. Although these methods provide first insights in the range of loss of life that could be expected, there are still a lot of questions related to the empirical foundation of these methods and their application for policy decisions.

This article focuses on a comparison of methods for the analysis of loss of life and EEM that are used in the Netherlands and the US. In recent years experts from both countries have exchanged knowledge and information on methods for loss of life due to levee and dam breaching. However, a case study in which various approaches for analyzing loss of life and EEM are rigorously compared has not yet been executed. Therefore, the objective of this study is to compare Dutch and American methods for the analysis of loss of life for a number of case studies in the US. This is referred to as the comparison effort in the remainder of this report. Overall, it is the aim of the research efforts in this project to contribute to the improvement of methods for loss of life estimation, risk assessment and emergency management, in the Netherlands, the US and other countries.

The scope of this paper is limited to methods developed in the Netherlands and methods developed by USACE (HEC FIA and Lifesim). However, the approach in the comparison effort has been chosen in such a way that other methods can be added to the analysis in a relatively easily in the future. The analyses and cases in this report mainly focus on larger-scale floods due to levee (or dike) failure. Other types of floods, such as dam breaching and flash floods, have not been directly considered as part of the case studies, but can be part of future investigation. The focus in this paper is on life loss. As part of the research project also US and Dutch methods for evacuation analysis were compared and reference is made to the research report (Jonkman et al., 2013) for further information on this aspect and a more comprehensive report of all findings.

2. REVIEW OF METHODS FOR LOSS OF LIFE ANALYSIS

2.1 General

Models for life loss estimation can be used for different purposes, such as the support of policy and engineering design decisions that are related to (acceptable) flood risk and to provide information to planners and emergency managers to improve and optimize their strategies. Examples of loss of life models are the empirical method developed for storm surge flooding in the Netherlands (Jonkman, 2007), the flood risks to people approach developed in the UK (Penning Rowsell et al., 2005), models developed for levee and dam breach flooding in the US (HEC FIA and Lifesim) and agent based models, such as BC Hydro's LSM, that give a detailed simulation of flooding and people movement and behaviour. More comprehensive overviews and discussions of the various methods are included in (Jonkman, 2007; Jonkman et al., 2008, di Mauro et et al., 2012).

A general characterization of various models is shown in **Figure 1** with respect to their level of detail and modeling principles. The level of detail (vertical axis) varies from the modeling of each individual's fate to an overall estimate for the whole event. On the horizontal axis the basic modeling principles are categorized. Mechanistic models are those that model the individual behaviour and the causes of death. Empirical models relate mortality in the exposed population to event characteristics.

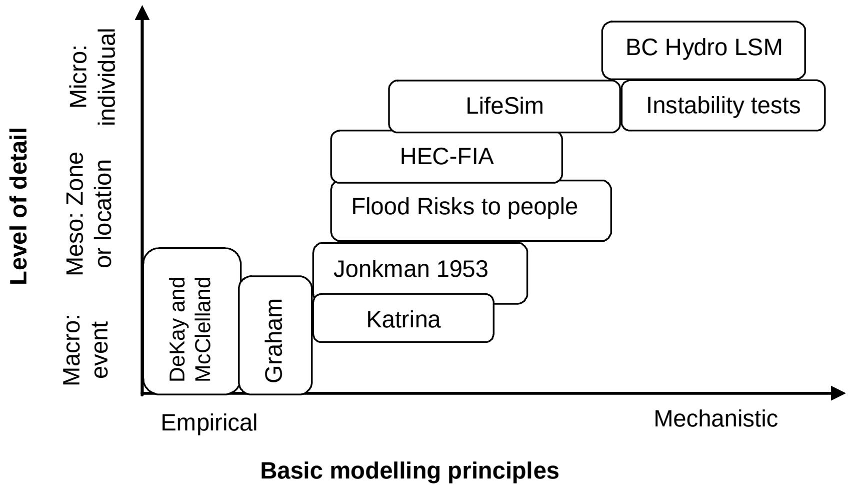


Figure 1: Comparison of loss of life models (based on Johnstone *et al*., 2005).

Estimation of the loss of life requires insight in a number of variables and elements that can be clarified based on the formula below (Jonkman, 2007):

$$N = F_d(1 - F_E)N_{PAR} \qquad (1)$$

Where:

N – loss of life estimate; F_d – mortality fraction; F_E – evacuation fraction (also evacuation effectiveness), N_{PAR} – number of people at risk.

Thus, analysis of life loss requires insight in three main factors. Firstly, there is the number of people potentially at risk (N_{PAR}), which can be derived from population densities and sometimes data that distinguishes presence of people as a function of the time of the day or season. Secondly, the effectiveness of evacuation and shelter strategies need to be defined to determine how many people will be exposed to the flood. This can be done by various approaches, including traffic models at different levels of detail (See Kolen, 2013 for an overview). An accurate estimate for the evacuation effectiveness fraction (F_E) is essential. For example, note that changing the value of FE from 0.95 to 0.9 will double the life loss estimate. Thirdly, there is the estimation of the mortality fraction $F_{D.}$ It is the ratio between the number of people killed and the number of people exposed in the floodzone,

The mortality is generally expressed as a function of flood characteristics, such as depth, flow velocity and rise rate, and outputs of hydrodynamic flood simulations are generally used to estimate these parameters. In some models mortality is also related to structural building performance in flood loads or is made dependent on the state in which people are present (e.g. in a building, car or in the water by foot).

2.2 Comparison of Dutch and US methods

In this paper methods developed in the Netherlands and US are compared in more detail. A detailed comparison is presented in the research report (Jonkman et al., 2013) and in the overview table in the appendix of this paper.

The first model concerned has been developed (Jonkman, 2007) based on data from the 1953 storm surge disaster in the Netherlands (1853 fatalities), UK (315 fatalities). Mortality functions have been derived for various zones that are dependent on water depth and rise rate. In the latest version of the model (see fig. 2 and 3), the mortality functions are interpolated between the low-rise situation (w<0,5 m/hr) and a high rise zone situation (w>4m/hr). A similar and related model concept has been derived based on data on the loss of life in New Orleans after hurricane Katrina in the year 2005 (Jonkman et al., 2009). A breach zone with a high mortality rate is distinguished if $dv>5m^2/s$ and an empirical relationship between F_d and water depth has been empirically derived for other areas. This latter function is now used as part of the levee screening tool in the United States.

In the United States two models (HEC FIA and Lifesim) are used for planning purposes and levee (risk) screening. HEC-FIA is a single event geospatially based model that calculates life loss and economic losses. HEC-FIA attempts to model the full progression of the flood wave with as little data as necessary, and the response of individuals to warnings and the flood wave. From the hydraulic inputs HEC-FIA looks at how well the structures and individuals survive based on their ending location and exposure to the hazard. The population is distributed over three states (cleared, evacuating and not mobilized) and for each state predefined mortality distribution are assigned. The model is static with respect to modelling people's behavior and movement in a flood. Lifesim is similar to HEC FIA but models the evacuation and movement of people during the flood situation in a dynamic way, whereas HEC FIA is static.

The mortality functions used in the various models are compared graphically below. The HEC-FIA functions have been shown for a single story residence. Two figures are shown for two domains of water depth. In the Dutch method no effect of the rise rate is included up to water depths of 2.1m and one mortality function is used. For higher water depths various functions are used depending on the rise rate.

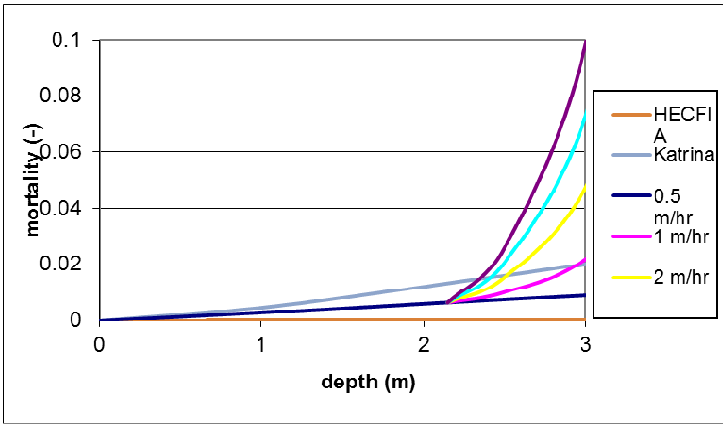


Figure 2: Comparison of the 1953 interpolated method, Katrina functions and HEC FIA for a single story residence (0-3 meter).

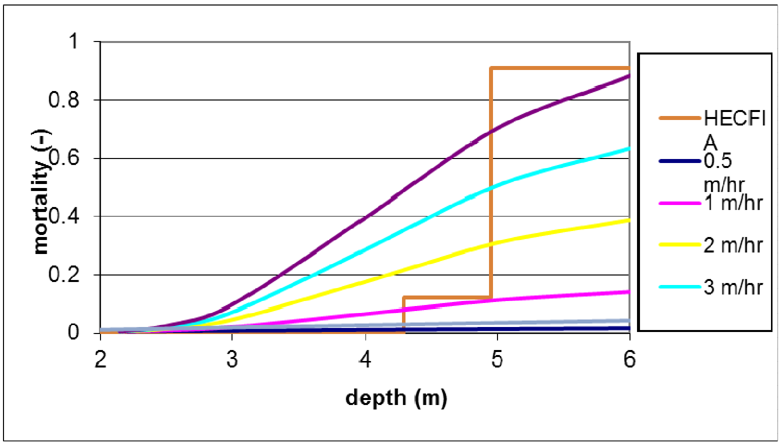


Figure 3: Comparison of the 1953 interpolated method, Katrina functions and HEC FIA for a single story residence (2-6 meters).

For water depths up to 2m the Katrina method gives the highest mortality rate prediction, higher than the interpolated 1953 and HEC FIA method. HEC FIA estimates a mortality fraction of 0.0002 up to depths of 4.3m (13 ft) for people in a one story building. This is lower than the mortality fractions from the interpolated 1953 and Katrina functions. It is not a fully valid comparison since the 1953 and Katrina functions will be applied to all the people present in the area, whereas the low mortality rate in HEC FIA will only be applied to people in a building. In HEC FIA mortality functions and criteria can also be defined for other states, For example people can be computed to be caught while evacuating, putting them in a "state" with no shelter from the flood, resulting in a higher mortality rate. For a given set of hydraulic conditions, the distribution over buildings and states determine mortality.

The comparison of methods and mortality functions show that there are several differences between the models in terms of model framework, their empirical basis and the functional relationships that are applied. Therefore, it is firstly important to understand how the differences in outcomes between different models emerge. This can be done by applying them to hypothetical cases and flood scenarios as is demonstrated in section 3 of this report.

3. CASE STUDIES AND COMPARISON EFFORT

In order to compare the outcomes and behavior of the models two case studies located in the United States have been considered: the Natomas Basin (CA) and Herbert Hoover Dike (Fl). A more comprehensive overview of outcomes of the various cases is included in the technical report (Jonkman et al., 2014). As HEC FIA and Lifesim give the same results for cases without evacuation we compare three methods: the mortality functions for 1953, Katrina and HEC FIA.

3.1 Natomas Basin results

The Natomas Basin is a low-lying area of approximately 222 km^2 that is situated in Sacramento-San Joaquin Delta in California. This area is surrounded by 69 km of levees, which reduce the likelihood of flooding at the western boundary from the hazard of Sacramento River and at the southern boundary from the American River. The levee system of Natomas Basin is designed to meet the 200-year flood protection level.

The area is relatively flat with an elevation ranging approximately between 3 to 12 meter above mean sea level, where it should be noticed that the surface elevation of the adjacent land to the levee is lower than the water surface level of the Sacramento and American River. Figure 4 (left) gives a geographical overview of Natomas Basin. The population density varies over the Natomas Basin. The northern part of this area (Sutter Counties) is not densely populated at all, but the southern part (Northern Sacramento) is very densely populated. In the year 2010, over 100,000 residents were living in this area. The population in this area is rapidly urbanizing, since in 2000 only approximately 40,000 people were living in Natomas Basin.

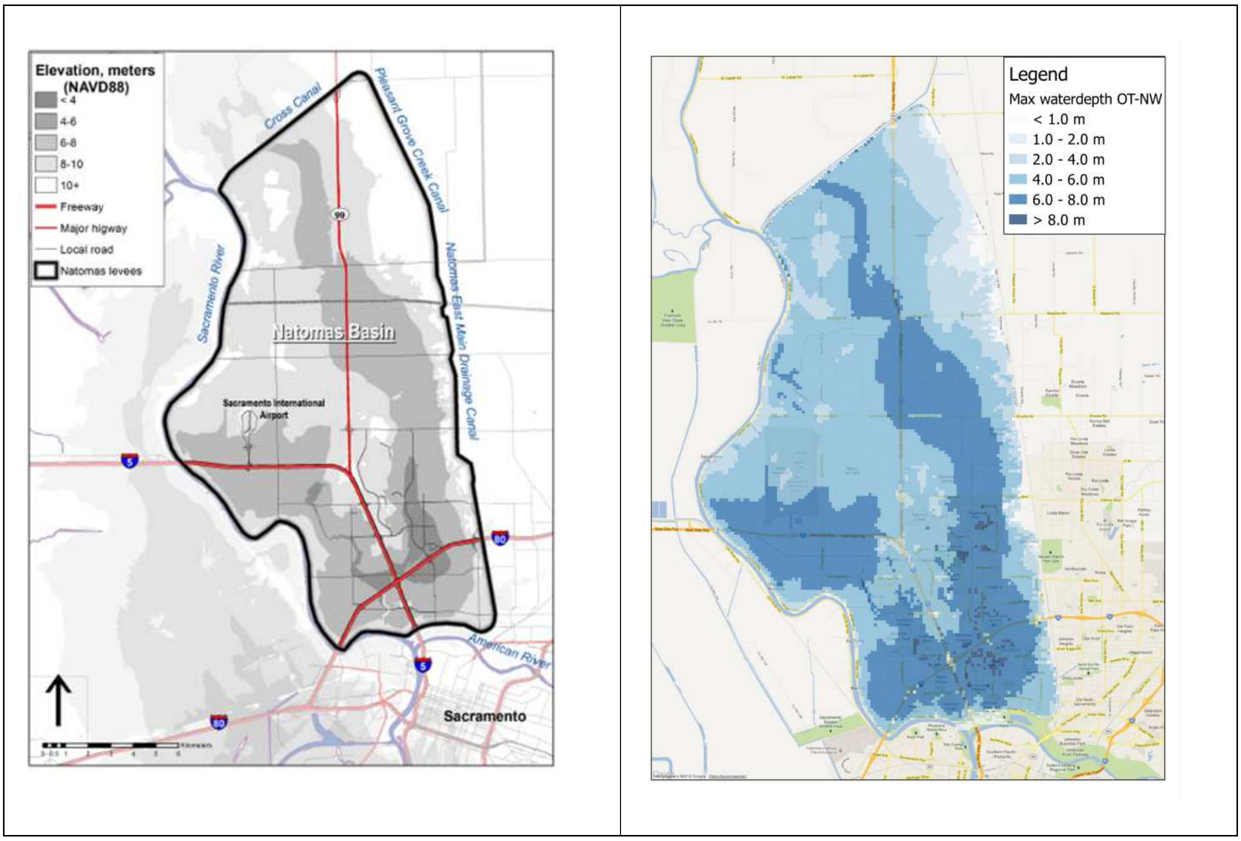
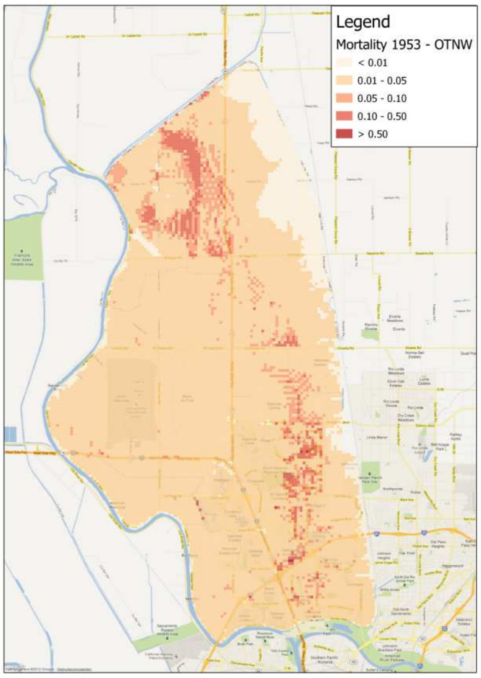


Figure 4: Left: Geographical overview Natomas Basin with the elevation heights in meter above mean sea level ([Jonkman et al., 2012]); Right: Flood depths for a breach in the Northwest corner of the area.

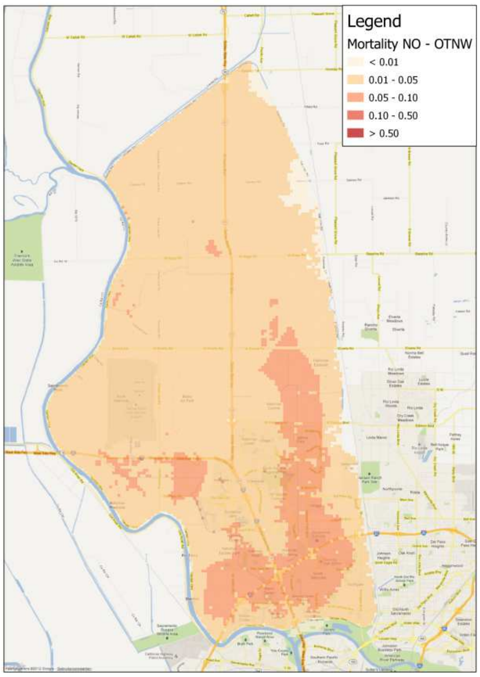
In this case study the loss of life is determined for two flood scenarios that describe high-water flood failure scenarios with overtopping and a resulting breach. The first scenario is a breach in the northwest of the area along the Sacramento River. The second case is a breach along the American river in the south of the area. In this paper we will focus on the NW breach, see flood map in fig. 4 – right. The largest water depths occur in the southern part of Natomas Basin, with mainly water depths between 6 to 8 meters. The rate of rise (not shown here) is max 1.0 m/hr for the largest part of Natomas Basin. The rate of rise amounts over 1.0 m/hr to 2.0 m/hr in the area close to the breach. In the densely populated area in the South there are only a couple of single cells where the rate of rise is larger than 1.0 m/hr.

Figure 5 and Table 1 compare the mortality and life loss estimates for the three models. Table 1 also includes the results for the southern breach in the Natomas Basin.

1953 model



Katrina model



HEC FIA (due to the model structure mortality can only be shown for areas

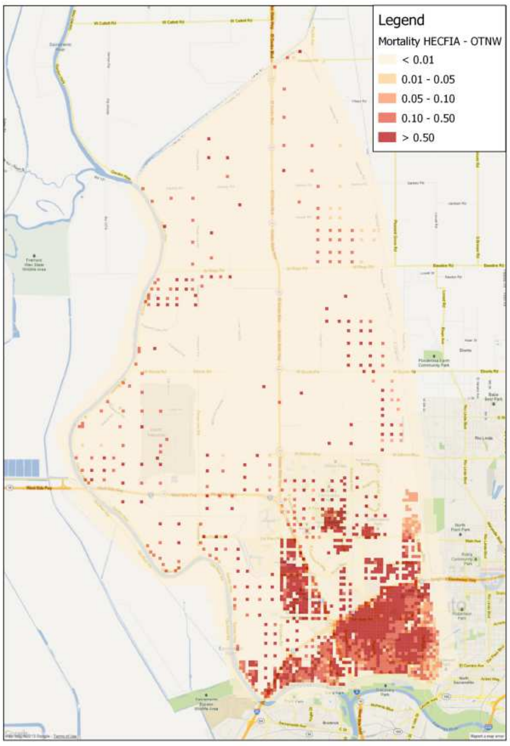


Figure 5: Loss of life and mortality estimates for the 1953, Katrina and HEC FIA models – for the Natomas Basin case study, breach in the Northwest of the area

	Sacramento River – North West		*American River – South Side*	
	Absolute value	Average mortality	Absolute value	Average mortality
Interpolated 1953 method	909	0.025	1811	0.045
New Orleans method	2815	0.08	1100	0.028
HEC-FIA and Lifesim	18412	0.46	4226	0.11

Table 1: Overview loss of life for all four methods

For this case the main findings can be summarized as follows:

- The life loss depends on the breach location and flood characteristics. The life loss ranges from 900 (interpolated 1953), 2800 (Katrina) and 18,000 (HEC FIA) for a breach in the northwest of the area. The interpolated 1953 method is sensitive for the rise rate, whereas does not affect the Katrina function.
- For the large water depths in the south of the area (>5m) HEC FIA results in very high mortality rates (90%) and life loss. These are higher than the mortality rates obtained with the Dutch models which are in the range of 2 – 8%.
- A breach in the southern part of the basin still results in large water depths in the populated areas (3 – 5m). HEC FIA leads to larger mortality rates and life loss totals than the two Dutch methods, but differences are less than for the more extreme Northwestern breach.

It is noted that these calculations are based on the reference year of 2000. Since then, the population has grown from about 40,000 people (year 2000) to almost 100,000 people in the current situation. Depending on the scenario, the life loss has increased by a factor 2.5 to 3. It is expected that required evacuation times will also increase with population growth.

It is clear that the models give very different outcomes when no evacuation is assumed due to differences in life loss modelling principles and functions. In addition, evacuation effectiveness would have to be considered. A comparison of the outcomes of various evacuation modelling approaches used in the Netherlands and US for the Natomas Basin case study is included in the research report (Jonkman et al., 2013). A main difference is that the evacuation tools in the Netherlands take into account only preventive evacuation (i.e. before a breach), whereas HEC FIA considers mainly evacuation of people after breaching up to flood depths of 0,5m.

3.2 Herbert Hoover Dike

Another case that was considered was the Herbert Hoover dike area. It is situated south of Lake Okeechobee and is an area that is mainly used for agricultural activities. The residential areas in the area are the city of Clewiston and Belle Glade. The effects of a break of the dike with a 30 ft (10m) lake level affecting near the town of Clewiston is shown in figure *. This scenario leads to more moderate flood conditions than those in the Natomas Basin. Typical water depths for this breach are between 1 and 4m, flow velocities are relatively small (1 m/s) and so are rise rates (<0.01m/hr). The population of Clewiston is somewhat over 6,000 people. In this case the three methods give predictions that are in the same range: 120 fatalities for the 1953 model, 240 fatalities for the Katrina model and 300 fatalities for the HEC FIA model. The differences between the model are much smaller than for the more severe Natomas Basin case (see section 3.1). This illustrates that different models “behave” differently in various flood characteristics.

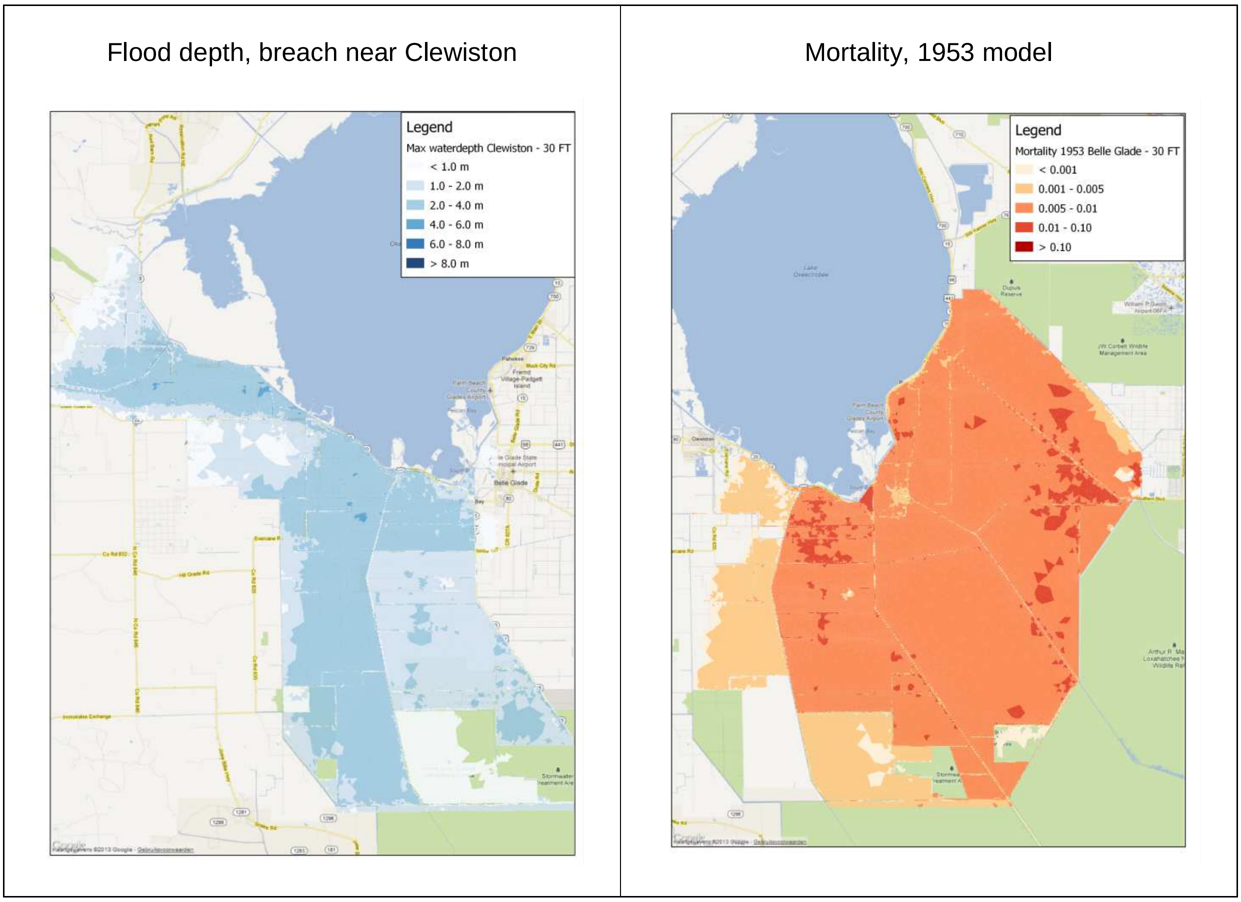


Figure 6: Breach in the Herbert Hoover dike near Clewiston: flood depth (left) and mortality with the 1953 model (right).

4. CLOSING REMARKS

There are several differences in the methods for loss of life estimation used and developed in the Netherlands and the HEC FIA and Lifesim methods applied in the US. Both approaches use relationships between the mortality and flood conditions (esp. water depth). Whereas continuous functions are used in the Netherlands, a stepwise function is used in the US. The mortality rates in the stepwise function are lower than the Dutch functions for lower water depths (<4m), but much higher for higher water depths. If scenarios with high water depths are considered (e.g. in Natomas) HEC FIA gives higher estimates than the other models. Overall, if no evacuation is assumed HEC FIA is much more sensitive to differences water depths. Within the Dutch method the functions are applied to all people exposed in a flooded area (irrespective of their state). For a given set of hydraulic conditions, the mortality function determines mortality. In the US method mortality is related to a large extent to the type of state or structure in which people are present (i.e. in a house, or on the road). The two case studies gave further insight in differences between model behaviour and functioning under different scenarios. However, since both scenarios are hypothetical it cannot be said which model gives the best prediction. It is therefore highly recommended to “test” or validate the various models for actual floods that have occurred in the (recent) past. A general issue in loss of life and evacuation modelling is the lack of historical calibration data. However, there are some important datasets. For example, the New Orleans / Katrina loss of life dataset (Jonkman et al., 2009) could be highly relevant for such a comparison. Another recent event with significant life loss was the flooding on the West coast of France due to storm Xynthia in the year 2010

(Vinet et al., 2012). This led to about 60 fatalities due to surge and flood effects. A recent validation effort (di Mauro and de Bruijn, 2012) focused on the Canvey Island case study. This island was flooded during the 1953 surge on the North Sea and about 60 fatalities occurred on the island. It could further investigated how important factors that are currently not included in the life models, e.g. water temperature, could be further included. Further research on such cases could also support the development of guidelines for which models can be used for certain flood types and conditions. Overall, further international cooperation between various model developers and users is highly recommended, also to utilize the scarce data on life loss. Links to other fields and communities, such as dam safety, could be strengthened to exchange information, case histories and best practices.

This paper focused on life loss. An important and related topic concerns evacuation and emergency management (EEM). The magnitude of life loss is directly influenced by the effectiveness of EEM. One particular challenge in this field is to improve estimates of and insights in evacuation effectiveness, based on empirical data and the joint research efforts of social scientists and more engineering related research.

5. REFERENCES

di Mauro M, de Bruijn K.M., Meloni M. (2012) Quantitative methods for estimating flood fatalities: towards the introduction of loss-of-life estimation in the assessment of flood risk. Natural Hazards 63, 1083 – 1113.

Johnstone W.M., Sakamoto D., Assaf H., Bourban S. (2005) Architecture, Modelling framework and validation of BC Hydro's Virtual Reality Life Safety Model, in: Vrijling et al. (eds.) Proceedings of the International Symposium on Stochastic Hydraulics, May 23, 24 2005, Nijmegen, the Netherlands

Jonkman S.N. (2007) Loss of life estimation in flood risk assessment. Theory and applications. PhD thesis Delft University (354 pag.)

Jonkman S.N., Hiel L.A., Bea R.G., Foster H., Tsioulou A., Arroyo P., Stallard T., Harris L. (2012) Integrated Risk Assessment for the Natomas Basin (CA) Analysis of Loss of Life and Emergency Management for Floods. *ASCE Natural Hazards Review,* Volume 13, Issue 4 (November 2012), pp. 297 - 309.

Jonkman S.N., Maaskant B., Kolen B., Zethof M., Lehman W. (2013) Loss of life, evacuation and emergency management – comparison and application to case studies in the USA. Final draft Research Report Delft University of Technology.

Jonkman S.N., Vrijling J.K., Vrouwenvelder A.C.W.M. (2008) Methods for the estimation of loss of life due to floods: A literature review and a proposal for a new method, *Natural Hazards, Vol.46/3, pp. 353-389*

Penning-Rowsell E., Floyd P., Ramsbottom D., Surendran S. (2005) Estimating injury and loss of life in floods: A deterministic framework, Natural Hazards Vol. 36 No. 1-2 pp. 43-64

Vinet F., Lumbroso D., Defossez S., Boissier L. (2012) A comparative analysis of the loss of life during two recent floods in France: the sea surge caused by the storm Xynthia and the flash flood in Var. Natural Hazards April 2012, Volume 61, Issue 3, pp 1179-1201

6. APPENDIX: COMPARISON OF LOSS OF LIFE METHODS

	1953, and 1953 interpolated	**Katrina**	**HEC FIA**	**Lifesim**
Application: flood types	Levee breaching, river, coastal	Levee breaching, river, coastal	levee breaching, dam failure	levee breaching, dam failure
Application	Regional and national risk assessment	Regional and national risk assessment	Planning purposes	Planning &More detailed analysis
Implemented	HISSSM standard tool in the NL	used in levee screening tool in the US	HEC-FIA	Lifesim
Inputs				
Population data	Inhabitants	Inhabitants	Day or night population	Day or night population
Main hydraulic Input data*	d, v, w	d, v	d, v, w, t	d, v , w, t
Building vulnerability / shelter	- (building indirectly in breach zone)	- (indirectly in breach zone)	Degree of shelter included	Degree of shelter included
Shelter	Can be included as a separate fraction	Can be included as a separate fraction	Degree of shelter is included	Degree of shelter is included
Evacuation concept	Evacuation before flood considered, given as input fraction	Evacuation before flood considered, given as input fraction	Includes warning and evacuation routine before and during a flood.	Includes warning and evacuation routine, incl. road network before and during a flood
Scale of input data	Larger-scale (dike ring) population distribution	Larger-scale (dike ring) population distribution	Individual structure level	Individual structures
Model concept				
Type of modelling	Static, empirical	Static, empirical	Static, based on distribution of people over zones	Dynamic
Empirical basis	1953 Netherlands UK, 1959 flood in Japan	2005, Katrina New Orleans	Derived from Lifesim	Various dam break floods
Method: zones and states	four zones: breach, rapid rise, transition, remaining	Two zones: Breach, other	3 states: cleared, evacuating and not mobilizes, with 3 criteria: safe, compromised, chance	Dynamic model Three states: safe, compromised, chance
Mortality rate calculation	Continuous functions	Continuous functions	Step-wise functions	Step-wise functions
Main reference(s)	Jonkman, 2007 Maaskant et al., 2009	Jonkman et al., 2009	USACE, 2011a	McClelland and Bowles, 1999, 2002; Aboelata, 2003

*d – flood depth, v – flow velocity; w – rise rate; t – arrival time