Loss of life due to floods

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Abstract

This article gives an overview of the research on loss of life due to floods. The limited information regarding this topic is presented and evaluated. Analysis of global data for different flood types shows that the magnitude of mortality is related to the severity of the flood effects and the possibilities for warning and evacuation. Information from historical flood events gives a more detailed insight into the factors that determine mortality for an event, such as flood characteristics and the effectiveness of warning and evacuation. At the individual level, the occurrence of fatalities will be influenced by behaviour and individual vulnerability factors. Existing methods for the estimation of loss of life that have been developed for different types of floods in different regions are briefly discussed. A new method is presented for the estimation of loss of life due to floods of low-lying areas protected by flood defences. It can be used to analyse the consequences and risks of flooding and thereby provide a basis for risk evaluation and decision-making. The results of this research can contribute to the development of strategies to prevent and mitigate the loss of life due to floods.

Introduction

The impacts of floods on a global scale are enormous. Recent events confirm the catastrophic potential of floods. Hurricane Katrina caused catastrophic flooding in South East Louisiana and other states along the Gulfcoast of the United States in the year 2005. There were more than 1100 fatalities in the state of Louisiana and hundreds of these fatalities occurred in the flooded parts of the city of New Orleans. In 2007, cyclone Sidr engulfed and devastated coastal regions of Bangladesh, leading to the loss of probably thousands of lives. In general, flooding is one of the most significant types of natural disasters in terms of human impacts and economic losses (Jonkman, 2005; MunichRe, 2007). Owing to population growth and migration of population to coastal areas, a growth of the impacts of floods is expected. In addition, some publications expect an increase in the frequency of floods due to the effects of climate change (IPCC, 2007).

The consequences of a flood encompass multiple types of damage, such as environmental losses, economic damage and loss of life. An overview of different types of consequences is given in Table 1. The damage is divided into tangible and intangible damage, depending on whether or not the losses can be assessed in monetary values. Another distinction is made between the direct damage, caused by physical contact with floodwaters, and the indirect damage that occurs outside the flooded area (see e.g. Merz *et al.*, 2004).

Loss of life is considered to be the most important loss type in the public perception of disasters. It is also expected that loss of life is related to other types of consequences, as accidents with a large number of fatalities will generally cause large damage for other consequence types. However, the available information in the academic literature on loss of life due to floods is relatively limited. Existing literature sources focus on different aspects of the topic. Some studies investigate loss of life patterns on a global scale (Berz *et al.*, 2001; Jonkman, 2005) or discuss loss of life in the context of general public health impacts (Hajat *et al.*, 2003; Ahern *et al.*, 2005). Other studies focus on the analysis of the causes and circumstances of individual flood disaster deaths for specific regions or events (Coates, 1999; Jonkman and Kelman, 2005) or present methods for the estimation of loss of life (see also 'Existing methods for the estimation of loss of life due to floods').

This overview article gives an assessment of different types of information related to the loss of life due to floods. It includes analyses of the available information at different levels of aggregation (i.e. global, event and individual levels).

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Table 1 General classification of flood damage

	Tangible	Intangible
Direct	• Residences • Structure inventory • Vehicles • Agriculture • Infrastructure and other public facilities • Business interruption (inside flooded area) • Evacuation and rescue operations • Reconstruction of flood defences • Clean-up costs	• Fatalities • Injuries • Animals • Utilities and communication • Historical and cultural losses • Environmental losses
Indirect	• Damage for companies outside flooded area • Substitution of production outside flooded area • Temporary housing of evacuees	• Societal disruption • Damage to government

In addition, existing approaches for the estimation of loss of life and their applications are summarised. The relationships between these different types of information are addressed. This overview article is based on a PhD research at Delft University (Jonkman, 2007). The objectives of this research were to provide more insight into the loss of life caused by floods and to investigate the possibilities to improve the methods for loss of life estimation. The research was carried out in the context of a research programme on flood risks in the Netherlands (Rijkswaterstaat, 2006). Given the intended applications of this study to the Netherlands, most attention has been given to the consequences of flooding of low-lying areas protected by flood defences. However, relevant information from other flood types has been evaluated as well. The focus in this article is on the mortality during and directly after the flood event. Information on longer term impacts and follow-up consequences is for example found in Bennet (1970) and recent analyses of the longer term impacts of the flooding of New Orleans (Stephens *et al.*, 2007).

Information available regarding loss of life due to floods

In this section, available information is reviewed. Three aggregation levels are distinguished: global information, information from historical flood events and data regarding causes and circumstances of individuals.

Global perspectives of loss of life due to different flood types

Introduction

As floods can occur in different forms, sizes and at various locations with different vulnerabilities, their impacts will differ strongly. Although every flood can be considered a unique event with unique characteristics, patterns may be observed when a large number of floods are studied on a global scale. This provides an insight into (1) the magnitude of loss of life in floods on a global scale and (2) the mortality caused by flood events with respect to their type and location. In the context of this study (event), mortality has been defined as the number of fatalities divided by the number of exposed people in one event. Mortality values can be presented as fractions and percentages, i.e. 1% and 0.01%. In the following sections, information on loss of life due to inland floods and coastal floods is presented at a global level. Consequently, an overall comparison regarding mortality for different flood types is presented in the last subsection.

Inland floods

Information from the OFDA/CRED International Disaster Database[1] (EM-DAT, 2004) has been used to analyse the human impacts of inland flood events at a global scale (Jonkman, 2005). The database is expected to be a relatively complete information source for global disaster data. However, as the information in the database is collected from reports of governments, international organisations and press agencies, the quality and accuracy of the data strongly rely on the underlying sources (see also Jonkman, 2005, for a more extensive discussion of the quality of the database). It is noted that in the database, coastal floods are generally categorised as windstorms (see also 'Coastal floods'). Events categorised in EM-DAT as floods are generally inland floods and the statistical analysis presented in this section is limited to three types of inland (or freshwater) flood events: drainage floods, flash floods and river floods. Overall, information regarding 1883 flood events, which occurred between January 1975 and June 2002, has been considered. Over this period, the inland flood events in the database are reported to have killed 176 864 people and affected 2.27 billion people. Firstly, the data have been evaluated with respect to regional differences. Although the impacts differ in terms of absolute numbers of people killed, the average mortality by event is relatively constant over the continents. Secondly, the data have been analysed with respect to flood type. The impact of a flood will be strongly influenced by the

[1]EM-DAT contains data on international disasters and is maintained by the Centre for Research on the Epidemiology of Disasters in Brussels (CRED) in co-operation with US Office for Foreign Disaster Assistance (OFDA). A disaster is included in the database when at least one of the following four criteria is fulfilled: 10 or more people are killed, 100 or more people are affected, there is a declaration of a state of emergency or there is a call for international assistance.

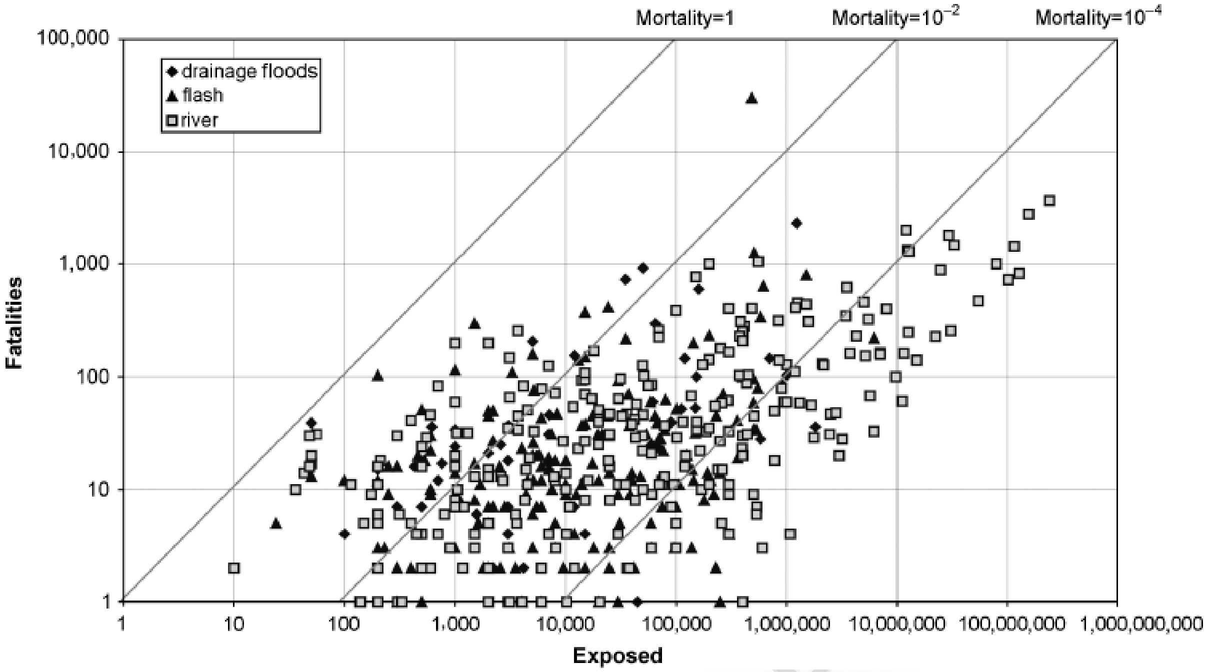


Figure 1 Number of fatalities and people exposed for floods with more than 0 fatalities by flood type.

Table 2 Average event mortality by event type

Event type	Number of events	Average event mortality
Drainage floods	70	5.3×10^{-4}
River floods	392	4.9×10^{-3}
Flash floods	234	3.6×10^{-2}

characteristics of the flood itself. On a general level, typical flood characteristics will differ between event types. For example, rapidly rising flash floods can cause more devastation than small-scale floods due to drainage floods. Figure 1 indicates the impacts by flood type, for the events with one or more fatalities. The total number of people exposed is shown on the *x*-axis and the number of fatalities on the *y*-axis (and both axes have a logarithmic scale). The lines in Figure 1 indicate different mortality levels.

Figure 1 shows that floods with large numbers of affected people are river floods, mainly occurring in Asia. Flash floods form a majority of the floods with lower numbers of exposed people. For the three flood types, the average event mortality is shown in Table 2. It shows that average mortality is highest for flash floods, as these are generally unexpected and rapidly evolving events, which severely affect smaller areas. River floods affect larger areas and more people, but result in relatively low values for numbers of fatalities and mortality per event. In general, they are more predictable and have less severe effects. Average mortality is low for drainage floods. More than half of the drainage events in the dataset causes one or zero fatalities. It is interesting to note that the average mortality approximately varies one order of magnitude (a factor 10) between event types.

A cross analysis of the combination of region and flood type shows that event mortality is relatively constant by flood type considered over the different continents. For example, flash floods result in the following average mortality values for the different regions: Africa (0.042), Americas (0.027), Asia (0.032) and Europe (0.056). These results do not indicate a relationship between mortality and the underlying determinants, such as socio-economic development of the region. The impacts in terms of absolute numbers killed differ by continent due to differences in the extent of the populations affected. These differences depend on the number of people present in the exposed areas and the local protection levels. The cross analysis shows that river floods in Asia are the most significant in terms of absolute impact, as they caused 40% of the deaths in the dataset considered and 96% of the total people affected.

Coastal floods

Coastal floods are generally caused by windstorms, including hurricanes, cyclones and typhoons. Strong winds and low atmospheric pressure cause set-up of water at the coast. Most of the fatalities due to these storms are caused by the

Table 3 Overview of coastal floods (sources: EM-DAT, 2004, and sources listed in Table 5)

Date	Location	Cause	Fatalities*	People exposed	Event mortality
1-2-1953	The Netherlands, southwest	Storm surge	1836	250 000	0.0073
1-2-1953	The United Kingdom, east coast	Storm surge	315	32 000	0.0098
26-9-1959	Japan, Ise Bay	Typhoon	5101	430 000	0.012
12-11-1970	Bangladesh	Tropical cyclone	300 000		
18-9-1974	Honduras	Tropical cyclone	8000		
12-11-1977	India, southern	Tropical cyclone	14 000	9 000 000	0.0016
25-5-1985	Bangladesh	Tropical cyclone	10 000	1 800 000	0.0056
30-4-1991	Bangladesh	Tropical cyclone	139 000	4 500 000	0.031
End of October 1998	Central America	Tropical cyclone	19 000		
29-10-1999	India, Orissa	Tropical cyclone	9800	12 600 000	0.008
29-8-2005	The United States: Louisiana and Mississippi	Hurricane (Katrina)	1118†	100 000‡	0.012
15-11-2007	Bangladesh	Tropical cyclone (Sidr)	More than 3000§		

*The reported numbers of fatalities may include considerable uncertainty, especially for the developing countries. For example, for the 1991 floods in Bangladesh the estimated death toll ranges between 67 000 and 139 000 (Chowdhury *et al.*, 1993), resulting in a mortality between 1.5% and 3.1%.
†Number of fatalities in Louisiana – most of these were due to flooding.
‡Number of people exposed to the flooding in New Orleans, assuming a population of approximately 500 000 in the flooded area and an 80% evacuation rate (see Jonkman, 2007 and Wolshon *et al.*, 2006).
§Estimate based on press sources, November 2007.

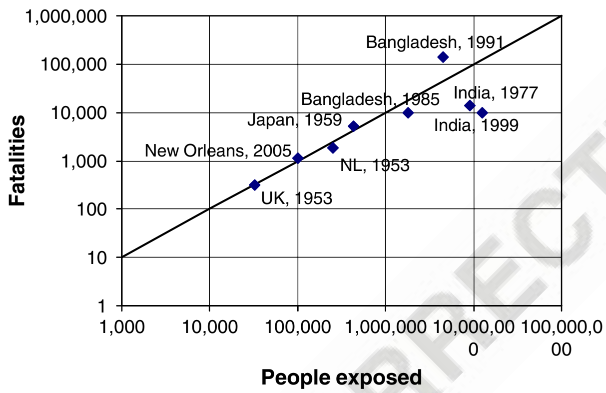


Figure 2 Number of fatalities and people exposed for coastal floods from Table 3. Events are also indicated in the figure.

flood effects (Rappaport, 2000). In the EM-DAT database, coastal floods are generally categorised as windstorms. Therefore, some available statistics regarding the impacts of some large coastal floods in the 20th century have been separately collected from EM-DAT and other sources and these are summarised in Table 3.

Although this dataset only includes a small sample of coastal floods, the total number of fatalities far exceeds the accumulated number of fatalities for inland floods. Coastal floods are capable of causing large numbers of fatalities, as they are often characterised by severe flood effects (large depths and velocities) when low-lying coastal areas are flooded. In addition, they have often occurred unexpectedly without substantial warning. This allowed little or no time for warning and preventive evacuation and resulted in large exposed populations. Especially developing countries such as Bangladesh have been severely affected by coastal floods. It is noted that temporal trends might be reflected in the data, as improvements are made on a global scale in the prediction of storms and typhoons and warning and evacuation of the population (Schultz *et al.*, 2005).

Figure 2 shows the number of fatalities versus the number of exposed people for the events from Table 3. Results show that the average event mortality for the considered events is in the order of magnitude of about 1% (average mortality $F_D = 0.0097$). For the events in the Netherlands, United Kingdom and Japan, the deviation from the observed mortality is $< 40\%$. Also, the findings for the New Orleans flood event are consistent with the 1% average. Based on these results, the 1% mortality value can be used as a first rule of thumb to estimate the number of fatalities for large-scale coastal flood events.

Discussion

Differences in average event mortality for different flood types can be related to (1) the severity of flood impacts and (2) the possibility of warning and evacuation. Table 4 schematically shows typical event characteristics and average event mortalities for different event types. Comparison of the event types shows that those with the most severe physical effects, and limited possibilities for evacuation, result in the highest (average) mortality. Examples are tsunamis, dam breaks and flash floods. Recent investigations of the human impacts of the Indian Ocean tsunami of the year 2004 (Guha-Sapir *et al.*, 2006; Nishikiori *et al.*, 2006; Rofi *et al.*, 2006; Doocy *et al.*, 2007) showed that mortality at different locations was in the order of magnitude of 10%. These high mortality values could be related to the unexpected occurrence of the event and the deadly flood effects associated with the tsunami wave. The consequences of dam break can be catastrophic and depending on the level of warning and the severity of the flood wave, the event mortality can range between 1% (less severe dam breaks) and 30–100% (severe dam breaks without warning) (Graham, 1999). The average mortality for coastal floods is approximately 1% and lower mortality values are generally obtained for river floods and drainage floods (see the previous sections).

The extent of consequences is also related to the type of area that is affected. The consequences of flooding can be particularly large when low-lying areas protected by flood defences are flooded. In these areas, land level is below (high) water levels. In case of a breach in the flood defences, extensive areas will be flooded up to large flood depths. These low-lying areas are mainly found in delta areas, such as the Netherlands. It is expected that the consequences of floods in such delta areas will be larger than those in nondelta areas (e.g. upper catchment of a river), both in absolute (fatalities, damage, exposed population) and relative (mortality, damage fraction) terms. The difference between the flooding potential of delta and nondelta areas is schematically illustrated in Figure 3.

Overall, the averages presented in Table 4 provide very general indications of the order of magnitude of the overall event mortality. Such general indicators could provide a rough but useful first estimate for mortality for an event type. However, the variation in event mortality remains large due to variations in circumstances between events. To estimate mortality and loss of life more accurately for one event, case-specific circumstances (flood characteristics, possibility of warning and evacuation) have to be taken into account and this will be discussed in the next section.

Historical flood events and the determinants of loss of life

To analyse the determinants of loss of life, documentation of historical flood events has been collected and analysed. It was found that the availability of documentation of historical flood events is limited. One reason could be that other activities (e.g. rescue, reconstruction) have a higher priority than data collection shortly after a flood disaster.

Available information for some historical flood events has been analysed; see Table 5 for an overview and Jonkman, 2007, for further details.

Despite differences with respect to their temporal and geographical situation, the major factors that have determined the loss of life in these historical flood events seem to be similar. Based on the available information and previous analyses (e.g. Tsuchiya and Yasuda, 1980; Bern *et al.*, 1993; McClelland and Bowles, 2002; Ramsbottom *et al.*, 2003), the main determinants of loss of life 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 (the Netherlands and United Kingdom 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, the 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 polders, will be most at risk.
- The combination of larger water depths and rapid rise of waters is especially hazardous. In these cases, people have

Table 4 Order of magnitude of average event mortality for different flood types

Flood type	Severity of impacts	Evacuation	Mortality (order of magnitude)
Tsunamis	Severe	Difficult	
Dam breaks			0.1
Flash floods			
Coastal floods			0.01
River floods			10^{-3}
Drainage floods	Less severe	Possible	10^{-4}

Table 5 Overview of flood events and literature sources for which the determinants of loss of life have been analysed

Date	Affected area	Loss of life	Source	Contains information on
1-2-1953	Southwest of The Netherlands	1835	Waarts (1992); Duiser (1989); Slager (1992)	Loss of life by municipality and relationship with flood characteristics, such as depth, rise rate and velocity
1-2-1953	The United Kingdom, east coast	315	Kelman (2003); Pollard (1978)	Effects of warning, building vulnerability, age of the population
26-9-1959	Ise Bay, Japan	5101	Tsuchiya and Yasuda (1980); JWF (2005)	Relationship between mortality and water depth and warning
30-4-1991	Bangladesh	139 000	Chowdhury *et al*. (1993); Bern *et al*. (1993)	Role of warning, shelter and collapse of buildings and individual vulnerabilities (age, gender)
24-9-2002	Japan, Shiranui Town	12	Kato (2002)	Role of water depth, warning and collapse of building

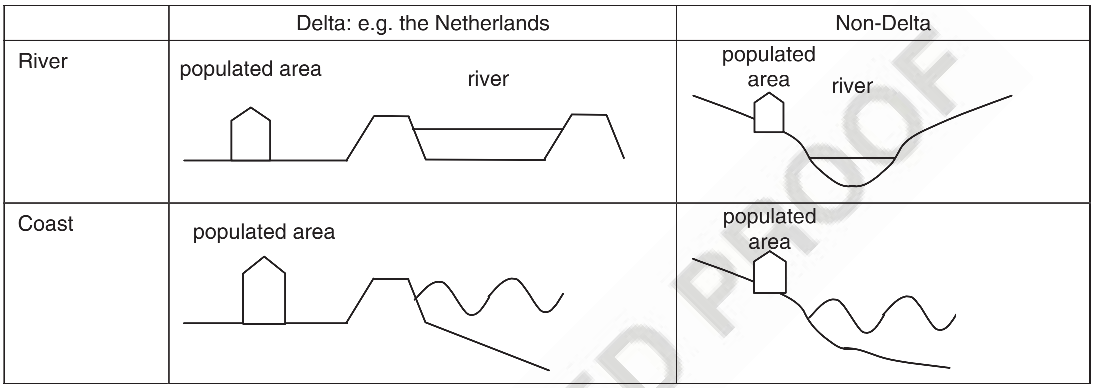


Figure 3 Schematic difference between delta and nondelta areas with respect to topography and potentially flooded areas.

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 (the Netherlands and United Kingdom 1953, Japan 1959), many fatalities occurred behind dike breaches and collapsed sea walls, as flow velocities in these zones are 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.

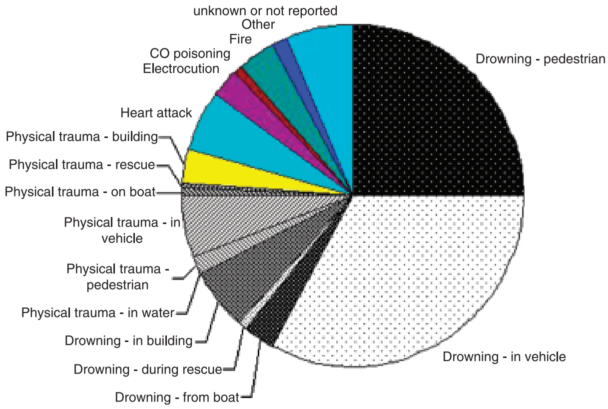
The above factors are important determinants of the loss of life. Local variations in the above factors may lead to differences between mortality fractions for different locations within one flood event. Especially unfavourable combinations of the above factors will contribute to high mortality. For example in the 1953 floods in the Netherlands, mortality was highest at locations where (a) no flood warnings were given, (b) the waters rose rapidly to larger water depths and (c) where the quality of buildings was poor.

Causes and circumstances of individual flood disaster deaths

This section discusses the loss of life at the individual level. Past work analysed the causes and circumstances of flood fatalities for specific regions (Coates, 1999, for Australia) and flood types (French *et al*., 1983; Mooney, 1983, for flash floods in the United States). A study (Jonkman and Kelman, 2005) has been carried out to analyse the causes and circumstances of flood disaster deaths for relatively small-scale floods in Europe and the United States. Thirteen flood events from Europe and the United States were included, mainly considering inland (river) flood events. Each case study is relatively recent (within the past 20 years) and involved relatively few deaths (< 50). The events resulted in 247 reported flood fatalities. The individual-by-individual data were aggregated for analysis. Results with respect to causes of death are presented in Figure 4. In the categorisation, a distinction is made between three main categories (drowning, physical trauma, other causes) and several subcategories that give further information on the detailed causes and circumstances.

Approximately two-thirds of the fatalities occurred through drowning and within this category, vehicle-related drownings occurred most frequently. Thus, a substantial number of flood fatalities were not related to drowning, but to physical trauma (11.7% of the fatalities) and other causes, such as heart attacks during evacuation and return (5.7%), deaths during clean-up due to electrocution (2.8%) and deaths from fires following the floods (3.6%).

The influence of individual vulnerability factors has been investigated. Approximately 70% of the reported fatalities



Category		%
Drowning	As a pedestrian	25.1%
	In a vehicle	32.8%
	From a boat	2.8%
	During rescue	0.8%
	In a building	6.1%
Physical Trauma	In water	0.0%
	As a pedestrian	1.6%
	In a vehicle	5.7%
	On a boat	0.8%
	During rescue	0.4%
	In a building	3.2%
Other	Heart attack	5.7%
	Electrocution	2.8%
	CO poisoning	0.8%
	Fire	3.6%
	Other	1.2%
	unknown or not reported	6.5%

Figure 4 Distribution of the causes and circumstances of death for the 13 considered events (247 fatalities), based on Jonkman and Kelman (2005).

are male. Likely causes are the high involvement of males in driving, the high proportion of males in the emergency and supporting services and males' risk-taking behaviour. A substantial proportion of the flood-related deaths is believed to be attributable to unnecessary risk-taking behaviour (see also Coates, 1999; WHO, 2002). Overall, the way people respond to floods is an important factor in the associated morbidity and mortality (French and Holt, 1989).

The above findings are expected to be specific for the type of floods studied, i.e. smaller scale floods in Europe and the United States. High-fatality events with more severe flood impacts, such as storm surges, hurricanes and tsunamis, exhibit different patterns with respect to individual vulnerabilities. For example, the storm surge flooding in the Netherlands in 1953 and the flooding of New Orleans in 2005 resulted in similar patterns with respect to overall flood mortality. In both cases, many of the fatalities were elderly[2] and both events resulted in a nearly equal distribution of fatalities over the genders. Two epidemiological studies (Bern *et al*., 1993; Chowdhury *et al*., 1993) analysed flood mortality after the cyclone in Bangladesh in 1991. The analyses showed that death rates were substantially higher for females than for males and that children and older women were most vulnerable. Several analyses (Guha-Sapir *et al*., 2006; Rofi *et al*., 2006) of mortality due to the Indian Ocean tsunami in the year 2004 have been conducted. Results showed that the risk of death was greatest in the youngest and oldest age groups, and among females. Overall, patterns regarding individual vulnerabilities seem to be dependent on the type of flooding and the characteristics of the population and area that are affected.

Discussion

In the preceding sections, different aggregation levels of information regarding loss of life due to floods have been reviewed. Three types of information are available: (1) global data; (2) information for historical flood events; and (3) information on the causes and circumstances of individual flood disaster deaths. In the context of this research, it is an important question as to how these types of information can be used to develop a method to estimate loss of life. Indicators derived from global statistics provide a useful but rough estimate of the order of magnitude of mortality that could be expected for one event. However, these statistics do not provide a sufficient basis for a case-specific estimation of loss of life, as the reported variations in these statistics are considerable. At the other end of the spectrum, it is found that the occurrence of individual fatalities is mainly dependent on individual circumstances and behaviour. In order to give a reliable estimation of loss of life, event-specific conditions have to be taken into account, such as flood characteristics, warning and evacuation. It is therefore chosen to develop a method for the estimation of loss of life based on information from historical flood events and the main determinants that resulted from the evaluation of these events.

Methods for the estimation of loss of life due to floods

Existing methods for the estimation of loss of life due to floods

In the literature, several methods have been developed to provide a quantitative estimate of the loss of life caused by flood events. An accurate estimate of loss of life is important

[2]Of the fatalities in New Orleans after hurricane Katrina, nearly 85% was over 51 years old (while that age group formed 25% of the population). Of the fatalities due to the 1953 flood event in the Netherlands, 34% was over 51 years old (while that age group formed 22% of the population).

in order to be able to determine the consequence and risk levels and to analyse risk reduction strategies. A comprehensive literature study of existing methods for the estimation of loss of life has been performed. Here a brief summary is provided and a more complete overview can be found in Jonkman (2007) and Jonkman *et al.* (2008).

Methods have been developed for different types of floods in different regions, for example for coastal floods due to storm surges and hurricanes/typhoons in Japan (Tsuchiya and Kawata, 1981) and the United States (Boyd *et al.*, 2005). In the Netherlands, several methods have been proposed for the estimation of loss of life for both coastal and river floods that could flood large low-lying areas due to dike breaches. Most methods are directly or indirectly based on data on the fatalities caused by the 1953 flood disaster in the Netherlands (see e.g. Waarts, 1992). Based on Japanese data for river floods, Zhai *et al.* (2006) derived a relationship between the number of inundated houses and the loss of life. Penning-Rowsell *et al.* (2005) developed an approach for assessing the flood risks to people. It has been applied to various riverine areas in the United Kingdom. Following the catastrophic flooding of New Orleans after hurricane Katrina in the year 2005, a model for the estimation of loss of life for (future) floods of New Orleans has been derived (IPET, 2007).

Also, methods have been developed for other flood types. Examples are the models proposed for dam break floods (DeKay and McClelland, 1993; Graham, 1999; Hartford and Baecher, 2004; Johnstone *et al.*, 2005) and tsunamis (Sugimoto *et al.*, 2003; Koshimura *et al.*, 2006).

Although flood fatalities can occur due to various other causes such as physical trauma, heart attack and drowning in cars (see 'Causes and circumstances of individual flood disaster deaths'), loss of human stability and consequent drowning are a high personal hazard. Therefore, several authors have investigated the issue of human (in)stability in flowing water. The likeliness of instability is generally related to a critical depth–velocity product (with unit m^2/s) that indicates the combination of depth and velocity that would lead to a person's instability. Such criteria can be used for the creation of flood hazard or flood risk maps. Abt *et al.* (1989) and Karvonen *et al.* (2000) (the latter in the European research project Rescdam) conducted experimental tests to determine the conditions that lead to instability. Recently, a limited number of new experiments have been undertaken by the Flood Hazard Research Centre (Jonkman and Penning-Rowsell, 2008). Figure 5 shows the combinations of depth and velocity that resulted in instability in the experiments. Overall, instability occurs for depth–velocity products (hv) between 0.6 and 2 m^2/s. The tests by Abt *et al.* resulted in an average critical depth–velocity product of $hv = 1.35\ m^2/s$. Differences in the reported test results can be related to test circumstances (configuration, bottom friction) and personal characteristics (weight, height, clothing).

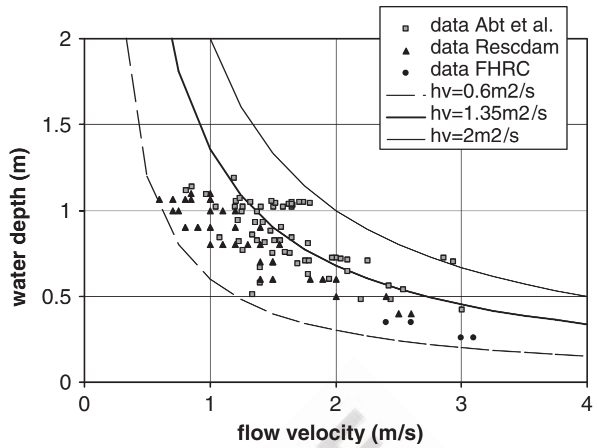


Figure 5 Depth–velocity combinations that resulted in instability for the available experimental series (Abt *et al.*, 1989; Karvonen *et al.*, 2000; Jonkman and Penning-Rowsell, 2008).

All the reviewed models include some kind of function that relates mortality to the flood characteristics. Depending on the flood type and the type of area, different variables will be most significant in predicting loss of life. For example, for large dam break floods warning time is very important, as people exposed to the flood wave will have limited survival chances. For floods of low-lying areas, factors such as the possibilities for evacuation, water depth and flow velocity will be most important (see 'Historical flood events and the determinants of loss of life'). An evaluation showed that many of the existing methods do not take into account all the most relevant determinants of loss of life and that they are often, to a limited extent, based on empirical data of historical flood events (Jonkman, 2007). Given these limitations, a new method for the estimation of loss of life has been developed.

A new method for the estimation of loss of life due to floods

A new method has been proposed for the estimation of loss of life due to floods. It is applicable to low-lying areas protected by flood defences and specifically focuses on large-scale flooding due to breaching of flood defences. Low-lying areas protected by flood defences can be found in river deltas in different parts of the world, for example in the United States (Mississippi River), China (Yangtze River) and the Netherlands (Rhine River). The proposed method takes into account most of the main determinants of loss of life (see 'Historical flood events and the determinants of loss of life'), such as the flood characteristics and the possibilities for evacuation. A summary of the main characteristics of the method is given here; further details can be found in Jonkman (2007) and Jonkman *et al.* (2008).

To estimate the loss of life caused by a flood event three general steps have to be taken into account:

(1) Analysis of flood characteristics, such as water depth, rise rate and flow velocity;

(2) Estimation of the number of people exposed (including the effects of warning, evacuation and shelter); and

(3) Assessment of the mortality among those exposed to the flood.

Step 1: First a so-called flood scenario has to be defined. The term flood scenario refers to one breach or a set of multiple breaches in the dike ring and the resulting pattern of flooding, including the flood characteristics. The most relevant flood characteristics for loss of life estimation include water depth, rise rate, flow velocity and arrival time of the water (see also 'Historical flood events and the determinants of loss of life') and these can be simulated by means of a two-dimensional hydrodynamic simulation model. In the simulation it is important to account for the roughness and geometry of the flooded area. Certain line elements, such as local dikes, roads, railways and natural heights, might create barriers that can significantly influence the flood flow and the area affected, thereby dividing the area into smaller compartments. Analysis of the flood scenario requires an insight into the hydraulic boundary conditions that lead to flooding, the locations of the breaches and their timing and extent and the topography of the threatened area. The results of the flood simulation can be used as input for the estimation of the number of people exposed (step 2) and the flood mortality (step 3).

Step 2: An estimate of the number of people exposed can be obtained by accounting for the number of inhabitants in the flooded area and the reduction of the population due to evacuation and shelter. The number of inhabitants can be obtained from census data, but for some applications population dynamics[3] needs to be taken into account to estimate the number of people exposed. Evacuation is defined in this study as 'the movement of people from a (potentially) exposed area to a safe location outside that area before they come into contact with physical effects'. In general, the possibilities for successful evacuation will depend on the time available until the breaching of flood defences and the arrival of the floodwater in an area and the time required for evacuation. In the Netherlands and elsewhere, several models have been developed to simulate the course of an evacuation (see e.g. van Zuilekom *et al*., 2005). These models simulate the traffic flow and also account for delays of the evacuation due to decision-making, warning and response. As input, such models need information on the available road and exit capacity, on the spatial distribution of the population and on the moment of departure of different groups in the population. By combining these different sources of information, an estimate can be made of the fraction of the population that is able to evacuate.

[3]An example of population dynamics that could affect the size of a population in an area is the fact that a part of the population could work outside of the flooded area. Also, the dependence of the population on the time of the day could be taken into account.

Step 3: The mortality among the exposed population is defined as the number of fatalities divided by the number of exposed people. It can be estimated by means of so-called mortality functions that specify the relationship between the flood characteristics (such as water depth) and mortality. Based on an analysis of mortality patterns for historical floods, three typical hazard zones are proposed for flooding due to breaching of a flood defence (see Figure 6). The breach zone is characterised by high flow velocities, which can lead to the collapse of buildings and instability of people in the flood flow. In the zone with rapidly rising waters, it will be difficult to reach shelter on higher grounds or higher floors of buildings. A rapid rise rate of the water is particularly hazardous in combination with larger water depths. A location is assumed to be in the zone with rapidly rising water if the rise rate exceeds 0.5 m/h. The flood conditions in the remaining zone are a slower onset of flooding, which offers better possibilities to find shelter. Within the three zones, locations could be distinguished that have different values for the flood characteristics, such as the flood depth – see the numbers in Figure 6 for an example of the different locations.

Based on historical information from several historical floods (such as the floods in the Netherlands in 1953 and in Japan in 1959), mortality functions have been developed for the hazard zones. Figures 7 and 8 show the mortality functions for the zone with rapidly rising water and the remaining zone. The two mortality functions explicitly include the effects of water depth. The numerical value of the rise determines which of the two functions has to be used. For the breach zone, insufficient data were available and a damage criterion has been proposed that estimates the level of mortality as a function of the combination of water depth and flow velocity. The function for the zone with rapidly rising water gives a good fit with the observed data and shows that mortality increases rapidly when the water

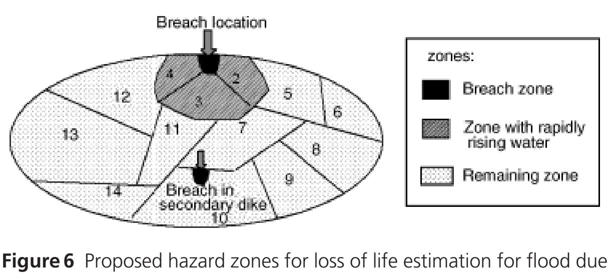


Figure 6 Proposed hazard zones for loss of life estimation for flood due to breaching of flood defences (Jonkman, 2007).

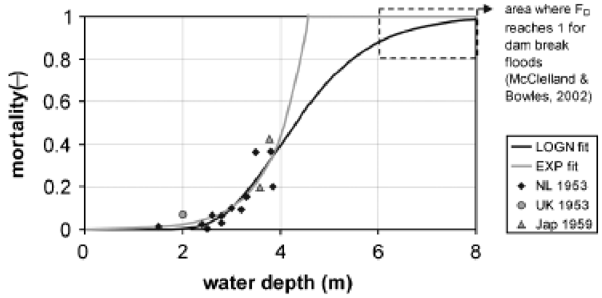


Figure 7 Mortality function for the zone with rapidly rising water (Jonkman, 2007).

depth increases. One uncertainty is the course of the function for larger water depths, as no direct empirical data are available to calibrate the trendline for these conditions. The best-fit trendline for the remaining zone is less adequate. For these observations, the effects of warning and other factors could be relevant (see also Jonkman, 2007, for further discussion).

As a first-order validation, the outcomes of the proposed method have been compared with information from some historical floods. This showed that it gives an accurate approximation of the number of fatalities observed during historical flood events. The outcomes of the proposed method are sensitive to the chosen flood scenario and the rise rate of the floodwater. As the number of fatalities is dependent on the flood scenarios [i.e. on the location of the breach(es) and the course of flooding], it is important to define a representative set of different flood scenarios, for example in the context of a risk assessment.

The trends in the above mortality functions show some relationship with the findings regarding the average event mortality for different flood types (see 'Information available regarding loss of life due to floods'). Average event mortality values for coastal floods (1%) and river floods (0.5%) correspond to the order of magnitude of mortality that follows from the mortality function for the remaining zone where mortality is generally between 0 and 0.01 for typical flood water depths (between 0 and 4 m). Global statistics show that mortality becomes larger if the water becomes deep and rises rapidly, e.g. for flash floods and dam breaks. An added value of the proposed method is that it provides an insight into the factors that influence mortality at a local level. Yet, more data analysis and further investigations of the influence of different factors are recommended to improve the empirical foundation of the mortality functions.

Applications

The proposed method can be applied to provide quantitative estimates of loss of life caused by floods in the context of safety evaluations, either in deterministic (scenario) or in probabilistic (risk) calculations. Both types of applications are demonstrated below based on recent risk assessment studies in the Netherlands (see e.g. Rijkswaterstaat, 2006).

Results are presented for flood scenarios of South Holland. This is one of the largest flood-prone areas in the Netherlands. The area has 3.6 million inhabitants and it is also the most densely populated area in the country and includes major cities such as Amsterdam, Rotterdam and Den Haag. Flooding of this area can occur due to breaches at various locations both along the coast and along the river. The consequences for various flood scenarios have been assessed by means of the method described in 'A new method for the estimation of loss of life due to floods'. As an example, the output for a more severe coastal flood scenario with breaches at two locations (Den Haag and Ter Heijde) is considered. In this case, an area of approximately 230 km^2 could be flooded with more than 700 000 inhabitants. It is expected that the possibilities for evacuation of this area are limited because the time available for evacuation (approximately 1 day) is insufficient for a large-scale evacuation of this densely populated area. Eventually, it is

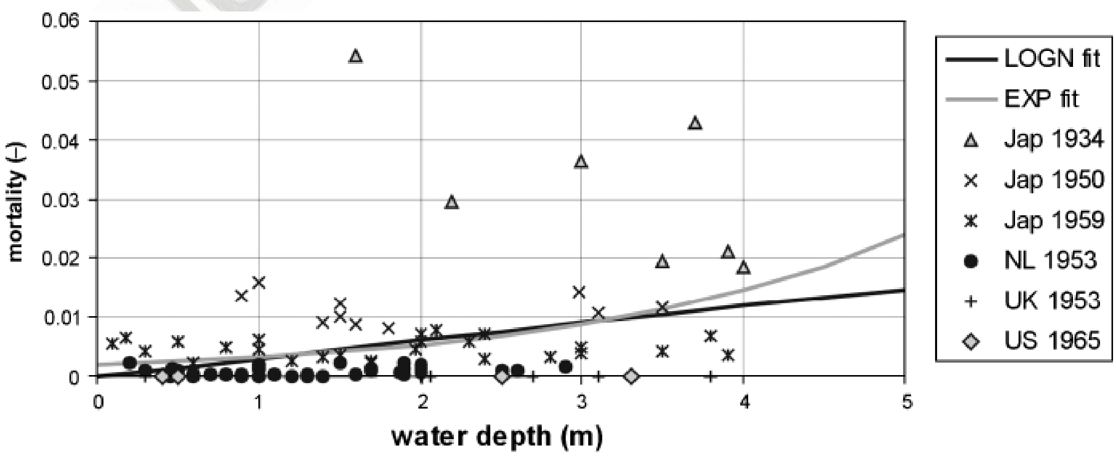


Figure 8 Mortality function for the remaining zone (Jonkman, 2007).

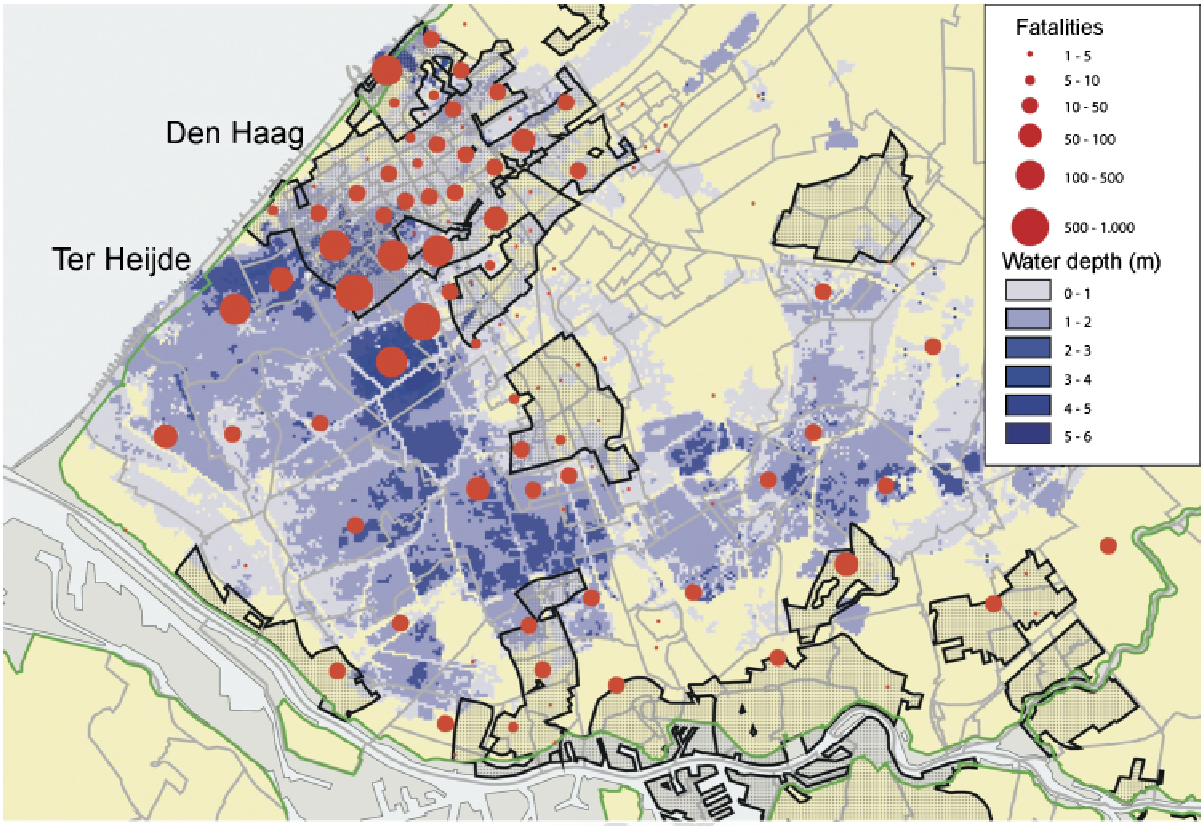


Figure 9 Fatalities by neighbourhood and flooded area for the scenario with breaches at Den Haag and Ter Heijde (Jonkman, 2007).

calculated that this flood scenario could lead to more than 3000 fatalities. Figure 9 shows the flooded area and the spatial distribution of the number of fatalities estimated with the method described in 'A new method for the estimation of loss of life due to floods'.

The above method for loss of life estimation can also be used in the context of flood risk assessment. In that case, the probabilities and consequences for different flood scenarios that could affect the area have to be taken into account. In the Netherlands and other countries, methods have been developed for the estimation of the failure probabilities and risk levels of flood defence systems (see e.g. Hall *et al.*, 2005; Apel *et al.*, 2006). In Rijkswaterstaat (2006), an estimate of the flooding probability of South Holland of 3.94×10^{-4} per year or approximately once in 2500 years was given. The flood risks to people can be presented in different ways. The probabilities and consequences of different flood scenarios can be presented in a table or graphically in a so-called FN curve. It shows the probability of exceedance in 1 year of a certain number of fatalities due to a flood event and both axes are generally displayed in logarithmic scale. The FN curve is used to display and limit the risks in different sectors and countries (Jonkman *et al.*, 2003). Figure 10 displays the FN curve for South Holland.

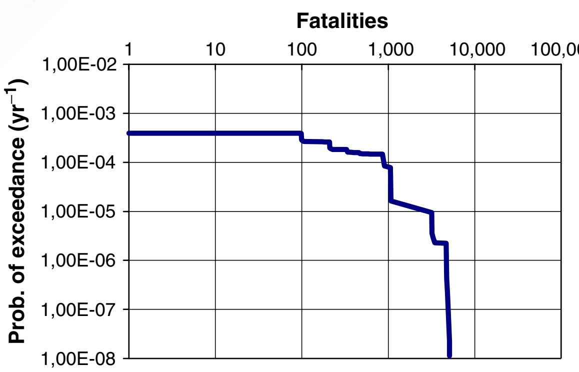


Figure 10 FN curve for flooding of South Holland (Jonkman, 2007).

Based on the probabilities and fatality numbers for the scenarios, the expected number of fatalities can be determined. This yields $E(N) = 0.21$ fat/year. The standard deviation equals $\sigma(N) = 16.1$ fat/year. For this type of small probability–large consequence event, the expected number of fatalities per year is generally relatively small. However, the number of fatalities in one single event can be large, resulting in a large standard deviation of the number of fatalities. In addition, the individual risk can be assessed and this is the probability of being killed due to an accident at a certain location. For South Holland, the individual risk for most locations is smaller than 10^{-6} per year, while a higher risk value in the order of magnitude 10^{-5} per year is found for two locations with a low elevation.

These analyses have several applications. Information on single flood scenarios and their consequences can be used to improve the preparation of emergency operations and develop effective evacuation plans. As the model includes the most relevant factors that determine loss of life, it also offers the possibility to take into account other measures that reduce consequence and risk levels, such as land-use planning, the improvement of warning and evacuation plans and the use of shelters.

The results from risk analyses can be used as input for risk evaluation and decision-making. The calculated risk level outcomes can be compared with existing risk limits that are proposed in the literature (see e.g. Vrijling *et al*., 1998). In the Netherlands, risk limits for the risks to people are used in several domains (e.g. for the chemical sector and airport safety). It is currently being investigated whether such limits are also applicable to flood safety. As input for decision-making, the risks of flooding can also be compared with other risk fields, e.g. with the chemical sector.

If it is decided that the flood risks are unacceptable, various measures can be considered. The level of risk reduction due to different measures has to be evaluated. The cost efficiency of measures can be specifically related to the reduction of loss of life by means of the evaluation of the cost of saving and extra statistical life (CSX) or life year (CSXY) (Tengs *et al*., 1995).

Concluding remarks

The limited information regarding loss of life in historical floods has been evaluated. Analysis of global data on natural disasters shows that the impacts of floods on a global scale are enormous. Comparison of data for different types of floods showed that the average event mortality values are related to the severity of the effects and the possibilities for warning and evacuation. Large-scale coastal and river floods that affect low-lying areas protected by flood defences can cause many fatalities. Based on available event statistics, it has been shown that a first-order estimate of loss of life due to coastal flood events can be obtained by assuming that 1% of the exposed population will not survive. This rule of thumb gives a good approximation of the overall number of fatalities for some historical events, e.g. the floods in the Netherlands in 1953 and the flooding of New Orleans after hurricane Katrina in 2005.

By analysing historical flood events, the insight into the factors that influence loss of life caused by floods has been improved. The number of fatalities caused by a flood event is determined by the characteristics of the flood (depth, velocity, rise rate), the possibilities for warning, evacuation and shelter and the loss of shelter due to the collapse of buildings. At the individual level, the occurrence of fatalities will be influenced by behaviour and individual vulnerability factors such as age and gender.

The existing models for loss of life estimation used in different regions and for different types of floods (e.g. for dam breaks, coastal floods, tsunamis) have been reviewed. A new method has been proposed for the estimation of loss of life caused by the flooding of low-lying areas protected by flood defences. An estimate of loss of life due to a flood event can be given based on (1) information regarding the flood characteristics; (2) an analysis of the exposed population and evacuation; and (3) an estimate of the mortality among the exposed population. By analysing empirical information from historical floods, such as the floods in the Netherlands in 1953, mortality functions have been developed. These relate the mortality among the exposed population to the flood characteristics for different zones in the flooded area. This method can be used to evaluate the consequences of (hypothetical) flood scenarios. By combining with information on the probability of flood events, the risks to people can be quantified. These results provide a basis for the evaluation and decision-making regarding flood protection levels. It is noted that for a full evaluation, other consequence types (e.g. economic damage and social impacts) also need to be taken into account in the decision-making.

Better data collection at various levels (global, event, individual) would be required to improve the insight into loss of life due to floods. Especially for developing countries for which the consequences of flooding are most severe, the amount of available data is limited. The studied data on the consequences of floods are the by-product of the enormous human suffering due to events that we strive to avoid. However, the data that are available could contribute to prevention and mitigation of such disasters in the future. Standardised collection and reporting of the available data for historical flood disasters is recommended (see also WHO, 2002; Hajat *et al*., 2003; Jonkman and Kelman, 2005). Q4

One relatively well-documented event that could provide valuable additional insights concerns the flooding of New Orleans due to hurricane Katrina. Based on available information, several topics could be further investigated such as the relationship between flood characteristics and mortality, the characteristics of individual fatalities and underlying vulnerability factors and the longer term impacts of such a major disaster.

The above recommendations outline the need for further improvement of the knowledge of loss of life due to floods. However, it is even more important to transfer the findings of the existing research into policy and practice to reduce the loss of life due to flood events. Global data provide an insight into the risk levels of various regions and this type of information could be used for the prioritisation of risk reduction strategies. Based on quantitative methods, the consequence reduction of specific measures can be predicted. An insight into individual vulnerability factors provides a basis for the formulation of education strategies to prevent flood fatalities. At the individual level, education, awareness and warning appear to be key to preventing flood mortality.

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