Risk Analysis, Vol. 29, No. 5, 2009 DOI: 10.1111/j.1539-6924.2008.01190.x

Loss of Life Caused by the Flooding of New Orleans After Hurricane Katrina: Analysis of the Relationship Between Flood Characteristics and Mortality

Sebastiaan N. Jonkman,[1,2,*] Bob Maaskant,[1,3] Ezra Boyd,[4] and Marc Lloyd Levitan[4]

In this article a preliminary analysis of the loss of life caused by Hurricane Katrina in the New Orleans metropolitan area is presented. The hurricane caused more than 1,100 fatalities in the state of Louisiana. A preliminary data set that gives information on the recovery locations and individual characteristics for 771 fatalities has been analyzed. One-third of the analyzed fatalities occurred outside the flooded areas or in hospitals and shelters in the flooded area. These fatalities were due to the adverse public health situation that developed after the floods. Two-thirds of the analyzed fatalities were most likely associated with the direct physical impacts of the flood and mostly caused by drowning. The majority of victims were elderly: nearly 60% of fatalities were over 65 years old. Similar to historical flood events, mortality rates were highest in areas near severe breaches and in areas with large water depths. An empirical relationship has been derived between the water depth and mortality and this has been compared with similar mortality functions proposed based on data for other flood events. The overall mortality among the exposed population for this event was approximately 1%, which is similar to findings for historical flood events. Despite the fact that the presented results are preliminary they give important insights into the determinants of loss of life and the relationship between mortality and flood characteristics.

KEY WORDS: Consequences; floods; Hurricane Katrina; loss of life; mortality; public health impacts

1. INTRODUCTION

Despite the enormous impacts of floods, there is relatively limited insight into the factors that determine the loss of life caused by flood events. A review of historical flood events showed that the number of fatalities due to 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.[1] In the literature several methods have been developed that can be used to assess the loss of life for flood events and to identify mitigation measures.[2,3] In general these methods consist of a quantitative relationship between the flood characteristics and the mortality in the flooded area. In this context mortality is defined as the number of fatalities divided by the number of people exposed. Mainly due to limitations in data collection and documentation, the existing methods and relationships have been derived based on events that occurred several decades ago, mainly in the 1950s and 1960s.

[1] Delft University, Faculty of Civil Engineering and Geosciences, Delft, The Netherlands.
[2] Royal Haskoning, Coastal and Rivers Division, Rotterdam, The Netherlands.
[3] HKV Consultants, Lelystad, The Netherlands.
[4] Louisiana State University, Hurricane Center, Baton Rouge, LA, USA.
*Address correspondence to Sebastiaan N. Jonkman, Delft University, Faculty of Civil Engineering and Geosciences, Stevinweg 1, 2628 CN, Delft, The Netherlands; tel: +316-1594-3962; s.n.jonkman@tudelft.nl.

In late August 2005, the New Orleans metropolitan area suffered the destructive power of Hurricane Katrina. Large parts of the city flooded. The objective of this article is to present the available data and provide an analysis of the relationship between flood characteristics and mortality for the flooded parts of New Orleans.

Empirical relationships are developed by relating the observed spatial distribution of mortality to simulated flood characteristics. Analysis of this tragic event enables the analysis of the influence of different flood and event characteristics on mortality for such a recent event. Findings can be compared to existing studies and methods that have been derived for flooding of similar types of areas, i.e., low-lying areas protected by flood defenses.

The focus in this article is on the mortality during and directly after the flood event in the flooded areas of the city of New Orleans and the consequences for other areas are not treated in detail. A more comprehensive presentation of the available data regarding the fatalities and their causes and circumstances is found in Reference 4. Stephens *et al.*[5] provide an analysis of the longer term impacts of the event. Data regarding loss of life for states other than Louisiana that were affected by Katrina is not discussed in detail here. MMWR (Reference 6, pp. 239–242) provides a review of mortality for the states of Florida (14 fatalities) and Alabama (15 fatalities). It is estimated in press reports that more than 230 fatalities occurred in the state of Mississippi, but no official list of victims is available.

This study focuses on loss of life. Several sources provide comprehensive discussions of other types of consequences, such as economic losses,[7–11] physical and mental health impacts,[6,12–14] and pollution from industrial and household chemicals that mixed with floodwaters.[15–17] A general analysis of different types of consequences is given in the report of the Interagency Performance Evaluation Taskforce.[10]

The outline of this article is as follows. After a general description of relevant events and processes during Hurricane Katrina (Section 2), Section 3 reports the results of flood simulations that give insight into the flood characteristics. Section 4 provides an overview of the available information regarding Katrina-related fatalities. Characteristics and circumstances of Katrina-related fatalities are described in Section 5. The relationship between flood characteristics and mortality is analyzed in Section 6. Section 7 provides a discussion of various issues, such as a comparison with existing loss of life models and the uncertainties in the data. Concluding remarks and recommendations are given in Section 8.

Fig. 1. Location of the city of New Orleans.

2. GENERAL INFORMATION REGARDING HURRICANE KATRINA

This section gives a general description of Hurricane Katrina, mainly focusing on the New Orleans area and issues most relevant for analysis of loss of life. Several other studies give a more comprehensive description of the characteristics of Hurricane Katrina,[18] and the performance of the flood protection system.[19–21]

2.1. General Situation and Past Studies

New Orleans is situated in the delta of the Mississippi River (Fig. 1). The city and its surrounding suburbs make up a metropolitan area that is largely below sea level and entirely surrounded by levees (synonyms: flood defenses or dikes). Therefore, the area has a so-called polder,[1] bowl, or bathtub character. As a consequence of its geographical situation, the area is vulnerable to flooding from

[1] Polder: relatively low-lying area protected from flooding by flood defenses, such as dikes/levees. Drainage systems are needed to discharge rainwater from the polder and to prevent rise of the groundwater table.

hurricanes, high discharges of the Mississippi River, and heavy rains.

The possibility of a major storm surge flood disaster in New Orleans was already known long before Hurricane Katrina formed. In the 20th century the city experienced floods after hurricanes in 1915, 1947, and 1965 (Hurricane Betsy). During Betsy, an estimated 13,000 people were rescued from floodwaters and approximately 40 drowned in floodwaters. Numerous publications have reported the threats associated with hurricanes. In June 2002, the *Times-Picayune* newspaper published a five-part series entitled "Washing Away." This series of articles claims that as many as 200,000 residents of the area would not be able to evacuate and that "between 25,000 and 100,000 people would die."[22] One year before Hurricane Katrina, a joint federal, state, and local planning exercise looked at a fictitious Hurricane Pam scenario: a slow moving Category 3 hurricane passes just west of New Orleans with a 20 ft (approximately 6.5 m) storm surge that overtops levees and inundates the entire city. In this scenario, search and rescue (S&R) crews would have to conduct over 22,000 boat and helicopter missions, 1.1 million people would experience long-term displacement, nearly 400,000 suffer injury or illness, and over 60,000 people would perish.[23]

2.2. General Characteristics of Hurricane Katrina

Hurricane Katrina formed as a tropical storm in the Atlantic Ocean southeast of Florida. On August 25, 2005 Katrina made landfall near Miami, Florida, as a Category 1 hurricane on the Saffir-Simpson scale. In Florida it resulted in 14 fatalities.[6] The storm weakened slightly as it crossed Florida and entered the Gulf of Mexico on August 26 as a tropical storm. Katrina quickly regained hurricane status and it began to take aim for southeast Louisiana (see Fig. 2). Between August 26 and 28 the storm initially strengthened to a Category 5, peaking at 1:00 pm August 28 with maximum sustained wind speeds of 175 mph (280 km/h) and wind gusts up to almost 220 mph (350 km/h). Before making its second landfall near Buras, Louisiana, it weakened to a Category 3 status with sustained winds of 125 mph (200 km/h).

2.3. Preparation: Evacuation, Shelter in Place

In the days before landfall, computer models predicted possible flooding of New Orleans. The first evacuation orders came early Saturday morning (August 27) for the outlying coastal areas, such as Plaquemines and St. Bernard parish.[2] Utilizing lessons learned one year earlier from Hurricane Ivan, state and local officials initiated the staged hurricane evacuation plan officially on Saturday. The next morning, shortly after Katrina was upgraded to Category 5 strength, Mayor Nagin issued a mandatory evacuation order for New Orleans. By the time storm conditions reached New Orleans, 430,000 vehicles had fled the metropolitan region using primary roads[24,25] with an estimated additional 10,000–30,000 using secondary roads. Based on these traffic counts, Wolshon[24,26] estimates that 1.1 million people, or 80% to 90% of the population at risk in southeast Louisiana, evacuated the area before the storm.

Source: Wikipedia; map from NASA; hurricane track from the U.S. National Hurricane Center.
Fig. 2. Track of Hurricane Katrina.

In addition to the evacuation of the general population, Hurricane Katrina forced the nursing homes and hospitals in the region to quickly make hard decisions about who to evacuate and in what way. These challenges presented no easy solutions, as both evacuation and sheltering-in-place presented risks to nursing home and hospital patients. Among the nursing homes in the area at risk, 21 homes evacuated before the storm and 36 did not.[27] Local authorities set up various shelters in the city. In St. Bernard parish, two schools were offered as shelters. In Orleans parish, the Superdome was set up as a shelter. Boyd[28] estimates that of the 72,000 people who remained in the city after the evacuation an estimated 26,000 individuals sheltered in the Superdome[29] but

[2] Parish: administrative subdivision that is used in Louisiana. Note that the parish name does not always correspond to the name of the flooded "bowl." For example, Orleans parish covers the Orleans bowl, Orleans East bowl, and a small part of the St. Bernard bowl.

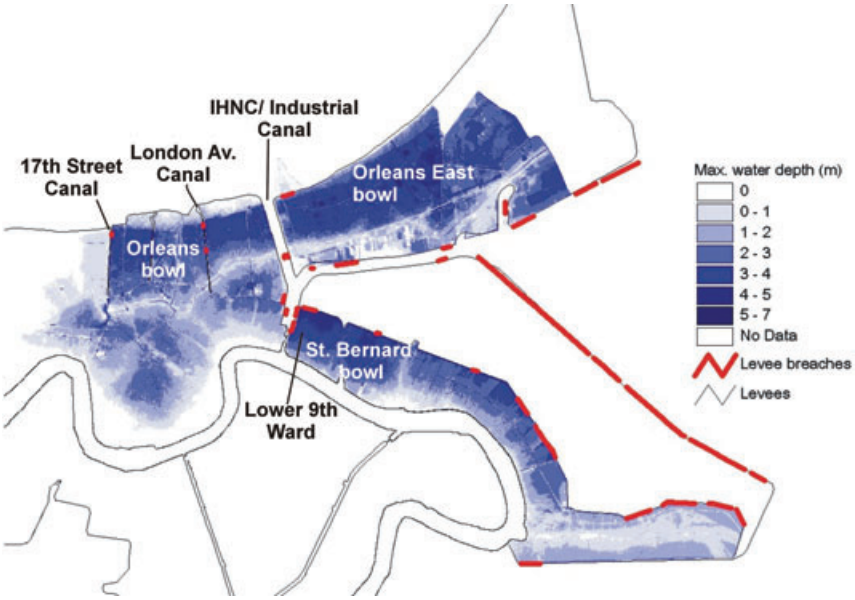

Fig. 3. Overview of flooded area, levee breach locations, and maximum water depths. (Breach locations are based on field observations and data of the LSU Hurricane Center. Water depth for the Orleans and St. Bernard bowls is based on flood simulations (see Section 3), water depth for New Orleans East is based on data provided by LSU Hurricane Center.)

in later estimates a number of 10,000 to 15,000 is used. Initially, the Superdome served its purpose as a shelter of late resort well. The problems that developed later mainly resulted from the heat and humidity, lack of supplies and delays in the post-storm evacuation, and the difficult conditions.

2.4. Impacts: Levee Breaches and Flooding

During its final landfall on August 29, Katrina's storm surge caused massive flooding and devastation along a 170-mile (approximately 270 km) stretch of the U.S. Gulf Coast. The entire coastline of the state Mississippi suffered massive destruction due to surge flooding. The storm surge also caused massive overtopping and breaching of levees around New Orleans. The flooded area of the city basically consists of three bowls: the central part of the city (Orleans), New Orleans East, and St. Bernard; see Fig. 3. The first flooding of residential areas in greater New Orleans occurred almost two hours before the storm's landfall. Between 4:30 am and 5:00 am water was already rising in the Industrial Canal.[3] The waters flowed into the Orleans bowl to the west, and into the New Orleans East bowl on the east side of the Industrial Canal. Later that morning more catastrophic breaching occurred along the southern arm of the Industrial Canal. Two major breaches in the floodwalls resulted in a rapidly rising and fast moving flood of the St. Bernard bowl, with catastrophic consequences.

Especially the neighborhood of Lower 9th Ward, which was closest to the breach, was most severely affected. In the Orleans bowl the levees in the 17th Street and London Avenue drainage canals failed, leading to floods in a large part of the central area. The New Orleans East bowl flooded more gradually due to a number of smaller breaches and overtopping cases. An area of approximately 260 km^2 of the city flooded, at some locations more than 4 m deep. Fig. 3 gives an overview of the flooded area and the locations of the levee breaches. It took over 40 days to dewater the city.

2.5. Aftermath: Search and Rescue Operations

The flooding of large parts of metropolitan New Orleans necessitated a massive urban search and rescue effort that involved numerous local, state, federal, and private organizations. Individuals in peril had to be rescued from roofs and attics. Patients, staff, and family members had to be evacuated as hospitals and nursing homes flooded. In the five days that followed Hurricane Katrina, rescue workers completed an estimated 62,000 water, roof, and attic rescues by either boat or helicopter. Over 100 helicopters and 600 boats were utilized.[30] Reflecting their first priority to protect the lives of those trapped by the flood, search and rescue (S&R) teams initially transported people from attics and floodwaters to higher ground, such as elevated highways and

[3] The official name of the Industrial Canal is the Inner Harbor Navigation Channel (IHNC).

bridges. Following this immediate rescue, available ground transportation was used to bring people to the Superdome, the Convention Center, and the I-10 Cloverleaf.[31] The sheltering population at these locations continued to grow in the days that followed the hurricane. As the days passed before relief arrived, hunger, thirst, and desperation took hold. Finally, on Thursday, September 1, three days after Hurricane Katrina made landfall, buses began evacuating people from the Superdome. The evacuation of the Convention Center began the next day. When the poststorm evacuation of New Orleans finished on September 4, an estimated 78,000 displaced persons had been relocated to shelters set up across the nation.[32] In the first phase that covered approximately 10 days, search and rescue operations focused on saving the living. After that the sad task of recovering the deceased began.

3. SIMULATION OF FLOOD CHARACTERISTICS

3.1. Background

Several organizations, including the Federal Emergency Management Agency (FEMA) and the Louisiana State University (LSU) Hurricane Center, have made floodmaps that provide insight into the water depths in the flooded parts of New Orleans. These maps have been made by combining terrain elevation data, information regarding the extent of the flooded area, and the water levels.[33] The size of the flooded area can be derived from aerial photography or satellite imagery. Water levels in the flooded area can be identified based on watermarks on buildings; see Fig. 4 for an example. However, due to effects of the tide and pumping, multiple watermarks are visible and a uniform interpretation is often difficult.

For an analysis of flood fatalities, other flood characteristics than water depth will be relevant as well. These include flow velocity, rise rate, and arrival time of floodwater. These characteristics have not been observed in the field during the flood event. However, there might be some indirect and mostly qualitative evidence, such as eyewitness accounts that describe flood conditions, and damage patterns that indicate the severity of local flow conditions (e.g., damage to buildings due to flow velocity). To gain more insight into these flood characteristics, simulations have been made for two of the New Orleans bowls (Orleans and St. Bernard). The results of these simulations have been used to analyze the relationship between the flood characteristics and mortality in Section 6. In addition, the simulations could be useful for visualization and communication of the course of flooding.

Fig. 4. Water marks on a building near the breach in the 17th Street Canal.

3.2. Approach for the Flood Simulations

The flood simulations of overland flow have been made by means of a two-dimensional hydraulic model, SOBEK-1D2D, developed by WL|Delft Hydraulics. De Bruijn[34] and Maaskant[35] give further background information. The following points summarize the approach used for the flood simulations:

(1) For terrain height a digital elevation model was made using data from U.S. Geological Survey (USGS).
(2) Levee heights and breach locations are based on information provided by the LSU Hurricane Center. This information is based on field observations.
(3) In the flood simulation a terrain model has been used with a rectangular raster with grid cells of 28 m × 28 m.
(4) A uniform terrain roughness has been assumed in the simulation with a manning value of 0.3 m. This value is representative for rural terrain. The effect of single objects such as buildings on the roughness is not directly assessed, but it is assumed to be included in the average roughness.
(5) Only inflow through the main breaches has been considered. Overtopping of levees, the effects of rainfall, drainage canals, and pumping have not been considered.

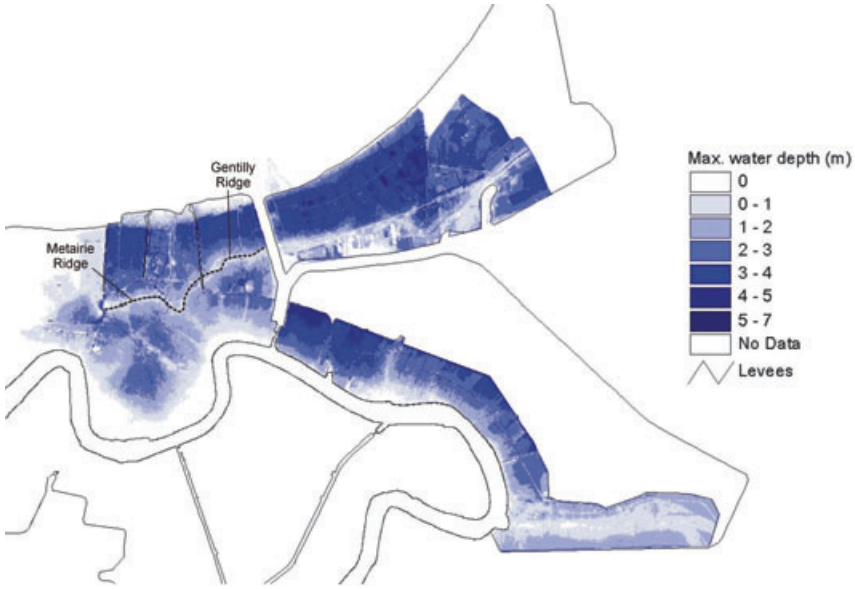

Fig. 5. Maximum water depth. (For the Orleans and St. Bernard bowls it is obtained from simulations. Water depth for the Orleans East bowl is based on the flood depth map provided by the LSU Hurricane Center.)

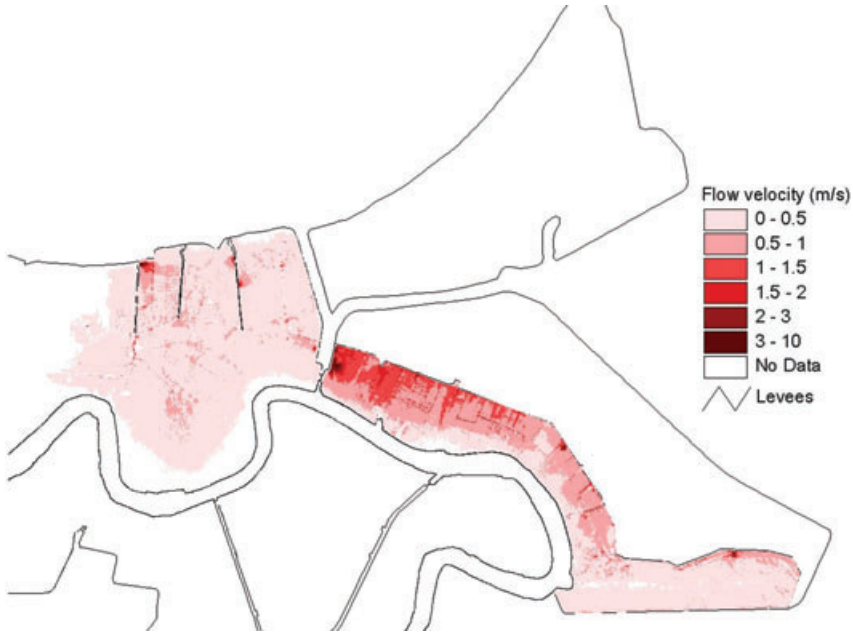

Fig. 6. Maximum flow velocity for the Orleans and St. Bernard bowls.

(6) Breach widths are based on descriptions by IPET[20] and Seed *et al.*[21,22] Based on these reports the growth rate of the breach has been estimated. Inflow discharges through breaches are determined based on the outside water levels reported in[36] and estimates of the development of the breach profile over time.

(7) Simulations have been made for the Orleans[34] and St. Bernard[35] bowls. No simulations are available for New Orleans East.

(8) To reduce the calculation time for the St. Bernard bowl, only flooding of the residential area is simulated; the wetlands between the 40-Arpent levee and Lake Borgne have not been taken into account.

Given the above assumptions and limitations regarding the input data it is important to realize that these simulations give a first-order insight into flood conditions in the affected area, but are not detailed or exact approximations of the flood flow conditions.

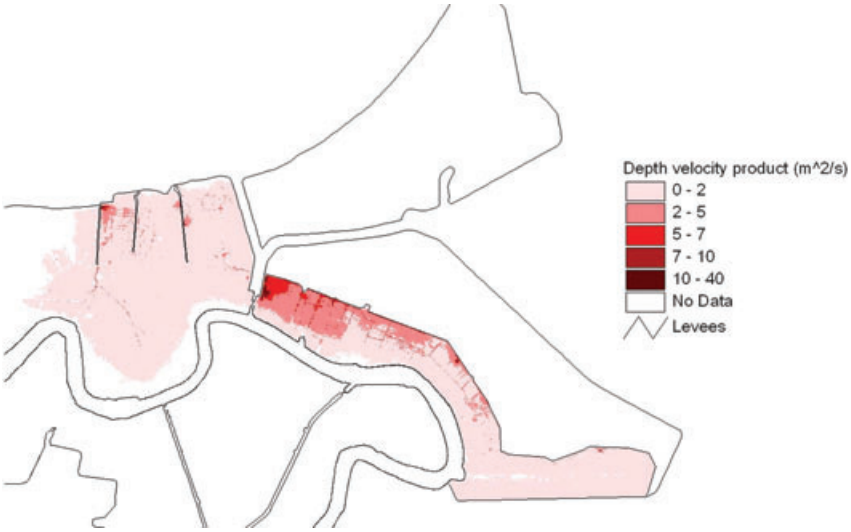

Fig. 7. Product of maximum water depth and maximum flow velocity (hv) for the Orleans and St. Bernard bowls. (These results are conservative as maximum values of depth and velocity need not have occurred simultaneously, i.e., $h_{\max} v_{\max} > (hv)_{\max}$.)

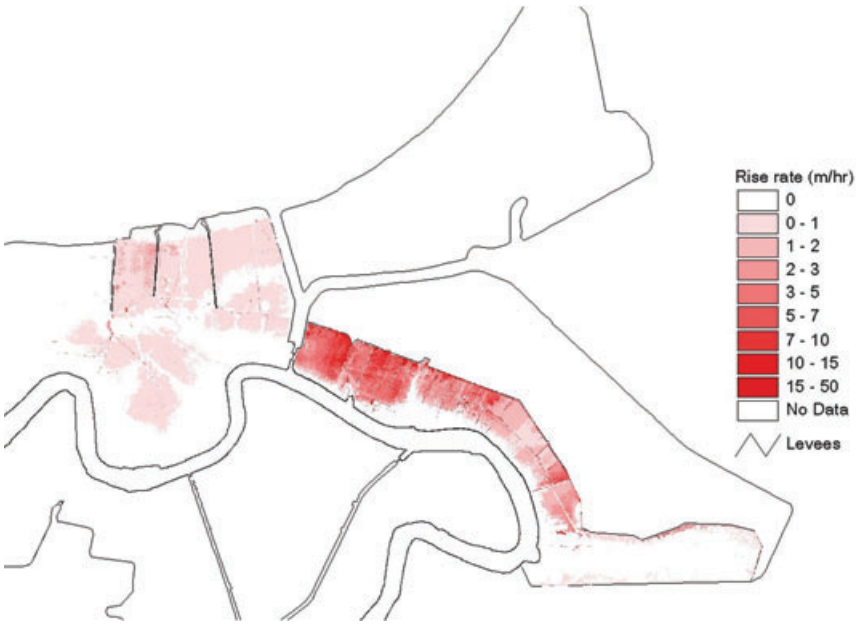

Fig. 8. Rise rate for the Orleans and St. Bernard bowls over the first 1.5 m of water depth.

3.3. Simulation Results

Information on the water depth, flow velocity, rise rate, and arrival time is obtained as output from the simulations. Figures 5 to 9 show the simulated water depth, flow velocity, the product of depth and velocity, rise rate, and arrival time of the water for the Orleans and St. Bernard bowls.

The simulations show that the most severe conditions occurred in the St. Bernard bowl. Very high flow velocities (3–10 m/s) occurred near the catastrophic breaches in the levees along the Industrial Canal. These effects caused destruction in the Lower 9th Ward. Water depths in St. Bernard reached 3 to 4 meters in the deepest parts and rise rates were high (>5 m/hr) for most of the area.

The Orleans bowl also suffered large water depths. In some locations (especially in the Lakefront area) the water depth was more than 5 meters. However, the flow velocities and rise rates were lower than in St. Bernard. Based on the simulations it is estimated that in the Orleans bowl only very near the breaches were the flow velocities high (larger than 1 m/s to 2 m/s). For most of the area rise rates were relatively small. The highest rise rates in this area (1 to 2 m/hr) occurred in the northern part. Most

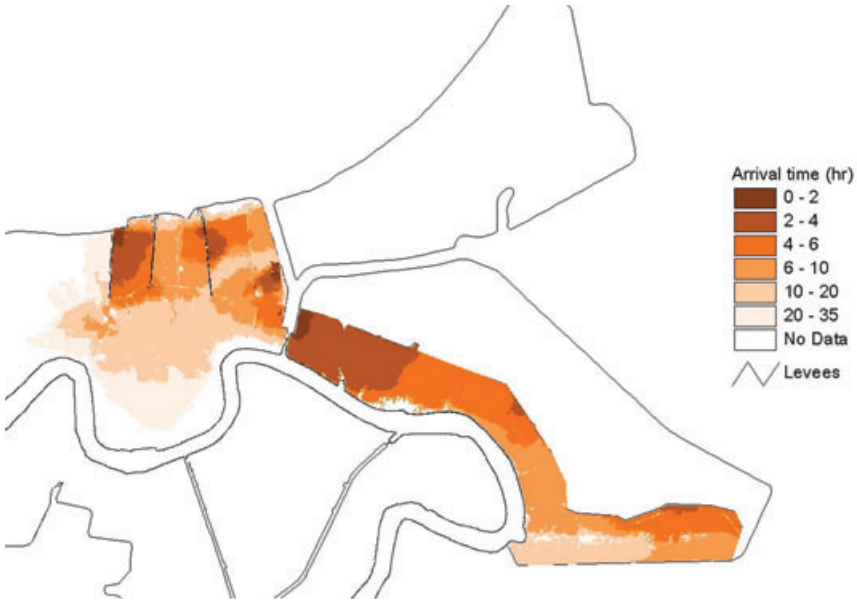

Fig. 9. Arrival time of the water for the Orleans and St. Bernard bowls after the initial breaches.

of the Orleans bowl flooded within a day. In the middle of the Orleans bowl there are the Gentilly and Metairie ridges that blocked the flow from north to south for some period.

The results of the simulations have been verified with available information regarding flood characteristics.[33,35] Comparison with the flood depth maps provided by LSU Hurricane Center shows that the flood depth is approximated well for the Orleans bowl (the difference for 90% of the grid cells was smaller than 0.3 m).[34] Somewhat larger differences between the simulated depths and the LSU flood maps were found for the St. Bernard bowl. For the southeastern part of the bowl the difference exceeded 1m.[35] Calculated arrival times of the water flow are compared with eyewitness descriptions from Reference 36 and these show good agreement (on average 20 minutes difference) for the St. Bernard bowl.[35] For the Orleans bowl the agreement between simulations and eyewitnesses differs between locations,[34] ranging from no almost no deviation in arrival time for locations near the breaches in the London Avenue Canal to several hours for locations in the southern part of the Orleans bowl. Differences between observations and simulations could be caused by the fact that overtopping of levees and effects of rainfall were not considered in the simulations. In addition, important assumptions that influence the flooding course in the simulations concern the starting time of breaching and the hydraulic roughness of the area.

4. DATA REGARDING KATRINA-RELATED FATALITIES

4.1. General

In the period after Katrina, deceased victims (fatalities) were recovered in a search process that involved governmental and private organizations. The buildings that were searched by rescue teams were marked by a sign that indicated the date and outcomes of the search operation; see Fig. 10. For each victim who was recovered there exists a "receipt of remains." This form includes basic information such as the date, time, and location of recovery, along with the agency that recovered and the agency that transported the remains. It also includes some basic comments about the scene and sometimes lists a presumptive identification of the victim.

The Department of Health and Hospitals (DHH) of the state of Louisiana coordinated the data collection. This agency also provides the official figures on dead and missing on their "Katrina Missing" website.[4] As of August 2, 2006 this site listed 1,464 deceased victims and it is noted that the cases of an additional 135 missing have been turned over to law enforcement. Of the confirmed dead, 1,118 victims perished within Louisiana, while 346 victims perished outside of the state of Louisiana. Statistics regarding ethnicity, age, and gender have been made

[4] http://www.dhh.louisiana.gov/offices/page.asp?ID=192&Detail=5248, accessed July 2008.

Fig. 10. Signs on a home indicating the outcomes of a search operation.

public for 853 of the Louisiana fatalities identified at the St. Gabriel and Carville morgues.

4.2. Description of the Data Set of Recovery Locations

The LSU Hurricane Center established a collaborative effort with the DHH and the Medical Examiner's Office of the state of Louisiana. As part of this collaboration, DHH provided the LSU Hurricane Center with data on the recovery locations for the deceased victims.[4] The latest data set, obtained on September 14, 2006, lists 771 fatalities with recovery locations in the state of Louisiana. This corresponds to 69% of the victims recovered within the state. The recovery locations have been geocoded, i.e., the locations have been identified on a map and entered into a GIS layer.

The obtained data set of recovery locations is based on the information from the receipts of remains. However, a number of these forms lack complete information, limiting the ability to map all the recovery locations. The data set used in this article has been supplied by the LSU Hurricane Center and it includes the following information: date of recovery, recovery location (geographical coordinates, state, parish), type of facility in which the body was found, and information regarding the organizations that performed recovery and transportation. Each entry in the data set describes the recovery of one victim. In some cases, multiple victims are recovered from one location. The recovery locations data set has been used for further analysis of the spatial distribution of the recoveries (see Section 5.3) and the relationship between flood characteristics and mortality (Section 6).

4.3. Brief Discussion of the Data Set

Several issues are associated with the interpretation and analysis of the data:

(1) At the time of the analysis the total list of deceased victims was still incomplete; 135 people are missing and in the period after Katrina remains of people have been found sporadically in collapsed buildings and more remote areas, such as the marshes.
(2) A broad operational definition has been used for a Katrina-related fatality. It concerns anyone from the affected areas that died between August 28 and October 1, 2005 for which the circumstances of death can be linked to Hurricane Katrina.
(3) The recovery location of a body does not necessarily equal the location of death. Bodies could have been moved by the flood flow or by other people before final recovery. This is most relevant for recoveries in open, public locations. However, analysis of the recovery locations (see below) shows that most fatalities were recovered in buildings. A limited number of bodies have been recovered along the edge of the flood zone, possibly indicating that they were moved by the flood. Despite these uncertainties, it is assumed that the recovery location is identical to the location of the fatality in the analysis that follows.

Given these issues it is emphasized that the data sets used in this study are preliminary and not fully complete. Nevertheless it is expected that the data sets give a representative impression of loss of life caused by Hurricane Katrina. First, the majority of recoveries has been completed and the final number of fatalities is not expected to grow substantially. Second, the data set includes the majority of recoveries inside the flooded areas and it is therefore expected that it gives a good insight into the spatial distribution of fatalities and the mortality in these areas. Overall, the recovery data include more than two-thirds of the officially reported number of fatalities in the state Louisiana.

5. CHARACTERISTICS AND CIRCUMSTANCES OF KATRINA-RELATED FATALITIES

5.1. Individual Characteristics of Fatalities

Based on the data set of deceased victims, the characteristics of Katrina-related fatalities, such as age, gender, and race, are discussed. Data are available for 853 Katrina-related fatalities. Information regarding other potentially important factors, such as medical cause of death, activity, and behavior during the hurricane impact, was not available.

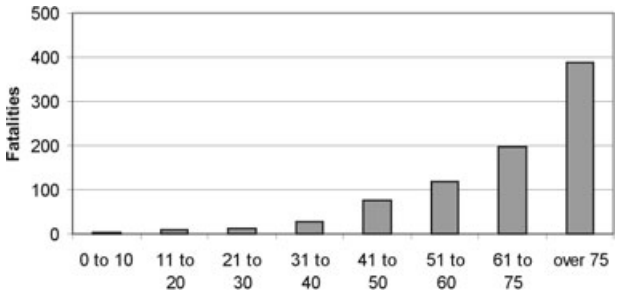

Fig. 11. Age distribution of 829 fatalities.

5.1.1. Age

The age distribution of fatalities is given for 829 fatalities and is presented in Fig. 11. Age is unknown for 24 fatalities. The majority of victims were elderly. Out of 829 victims of whom age is known, less than 1% were children and just over 15% were under 51. Older people comprise the majority of the deceased: nearly 85% are older than 51 years, nearly 60% are over 65, and almost half are older than 75 years of age. Population statistics for Orleans and St. Bernard parish[5] show that of the pre-Katrina population about 25% were older than 50, 12% older than 65, and 6% older than 75.

A possible explanation of the vulnerability of the elderly is the following. Members of this population group are the most likely to need assistance to evacuate before the storm and are the least capable to survive the physical hazards of the flood (e.g., by moving to higher floors or shelters) and the delays before being rescued and the deterioration of basic public health services both inside and outside flooded area. Another factor that could have contributed to the large number of older fatalities in residential areas is that elderly might be less able or willing to evacuate before a hurricane. A past survey[37] indicated that there is a slight decline in the evacuation rate with age. However, only very limited information is available for evacuation rates among different age groups for Katrina.

5.1.2. Gender

The available data do not indicate that gender played a dominant role in Katrina-related mortality in Louisiana. For the 853 victims for which gender is known, 432 (50.6%) are male and 421 (49.3%) are female. A general comparison with the gender distribution of the affected population (47.1% males; 52.9% females) shows that males are slightly overrepresented in the fatality data set. In a simple statistical analysis the hypothesis has been tested that the fatality data set is a random sample from the total population in the affected area by means of Pearson's χ^2 test (see the Appendix). A significance level of 5% has been chosen. The assessment shows that the probability of obtaining a result at least as extreme as the one that was actually observed, given that the null hypothesis is true, equals $p = 0.039$ and the null hypothesis can be rejected.

5.1.3. Race

Of 818 fatalities for which race is listed, 451 (55%) are African American and 334 (40%) are Caucasian (white). Of the others, 18 (2%) victims are listed as Hispanic, 6 (1%) are listed as Asian Pacific, 4 (<1%) are listed as Native American, and 5 (<1%) are listed as other. The race of 35 victims was unknown. In general terms this distribution is similar to the racial distribution of the affected population (see the Appendix). The observed percentage of African-American fatalities (55%) is smaller than the percentage of this group in the overall affected population (59%) and these results do not directly support claims that African Americans were more likely to become fatalities.[38] In a preliminary and simple statistical analysis the null hypothesis has been tested that the fatality data set is a random sample from the total population of the affected area for the percentage of African Americans. Analysis with Pearson's χ^2 test (see the Appendix) shows that the probability of obtaining a result at least as extreme as the one that was actually observed, given that the null

[5] Data source: Greater New Orleans Community Data Center, http://www.gnocdc.org/, accessed July 2007.

hypothesis is true, equals $p = 0.013$. A significance level of 5% has been chosen and the null hypothesis can be rejected. However, given the large spatial variation in the race distribution of the population in the New Orleans area, a more detailed statistical analysis of the relationship between mortality and population characteristics at the neighborhood level is recommended.

5.1.4. Discussion

The above outcomes concerning the causes and circumstances of fatalities can be compared with earlier findings. Jonkman and Kelman[39] showed that, for small-scale river floods in Europe and the United States, males are highly vulnerable to dying in floods and that unnecessary risk-taking behavior contributes significantly to mortality. In addition, that study did not indicate that elderly were more vulnerable. The individual characteristics of Katrina-related fatalities are different and likely characteristic of large-scale and more unexpected flooding. During such events survival chances will be related to individual endurance, which is generally less for elderly. In that respect the outcomes for Katrina are comparable with characteristics of the fatalities for the 1953 flood in the Netherlands. This event also exhibited a higher vulnerability of elderly and an almost an equal distribution of fatalities over the genders.[1]

5.2. Type of Recovery Locations

The data set of recovery locations provides information regarding the type of location where the body was recovered for 746 victims; see Table I. The majority of victims (53%) were recovered from individual residences. Fieldwork shows that many of the residential recovery locations were single-story homes that were either not elevated or elevated less than three feet. Medical locations, such as hospitals and medical centers, comprise 147 (20%) of the recovery locations and nursing homes make up 76 (10%) of the recovery locations. 54 (7%) victims were recovered from open street locations. Twenty-six (3%) victims were recovered from public shelters, 18 from the Convention Center, and 8 from the Superdome. These latter two facilities served as shelters of last resort for tens of thousands of people before, during, and after the storm. Twenty (3%) victims were recovered from commercial and public buildings, such as churches and schools.

Table I. Recovered Victims from the Data Set of Recovery Locations by Location Type

Location Type	Fatalities	
Residence	404	54%
Medical	147	20%
Nursing home	76	10%
Open/street	54	7%
Morgue/coroner's office/funeral home	39	5%
Public shelter	26	3%
Public building	20	3%
Total	746	

5.3. Spatial Distribution of Recoveries

The majority of victims were recovered from parishes that suffered the direct flood impacts of Katrina, such as Orleans and St. Bernard parishes. In addition, a substantial number of fatalities occurred in parishes that did not suffer the direct impact of Katrina. In total, 147 fatalities were recovered outside the flooded area.

Fig. 12 gives an overview of the spatial distribution of recoveries in and near the flooded parts of New Orleans. A distinction is made between two categories of fatalities:

(1) Recoveries from residential locations such as residences, nursing homes, street locations, and public buildings. In these facilities fatalities can often be directly related to the flood effects.
(2) Recoveries from medical locations, shelters, and morgues/funeral homes. These recovery locations indicate that these fatalities were not directly related to the impacts of floodwaters. For example, while the Superdome was inside the flood zone, the raised sections of this facility protected those sheltering from floodwaters. Similarly, for hospitals in the flooded areas the ground floors were evacuated as part of storm preparations.

A similar map was published in the *Times-Picayune* newspaper under the title "Where they were found."[6] Although many of the recovery locations shown in that article correspond to the map here, it differs for a substantial number of recovery locations.

[6] http://www.nola.com/katrina/pdf/katrina_dead_122005.pdf, accessed July 2008.

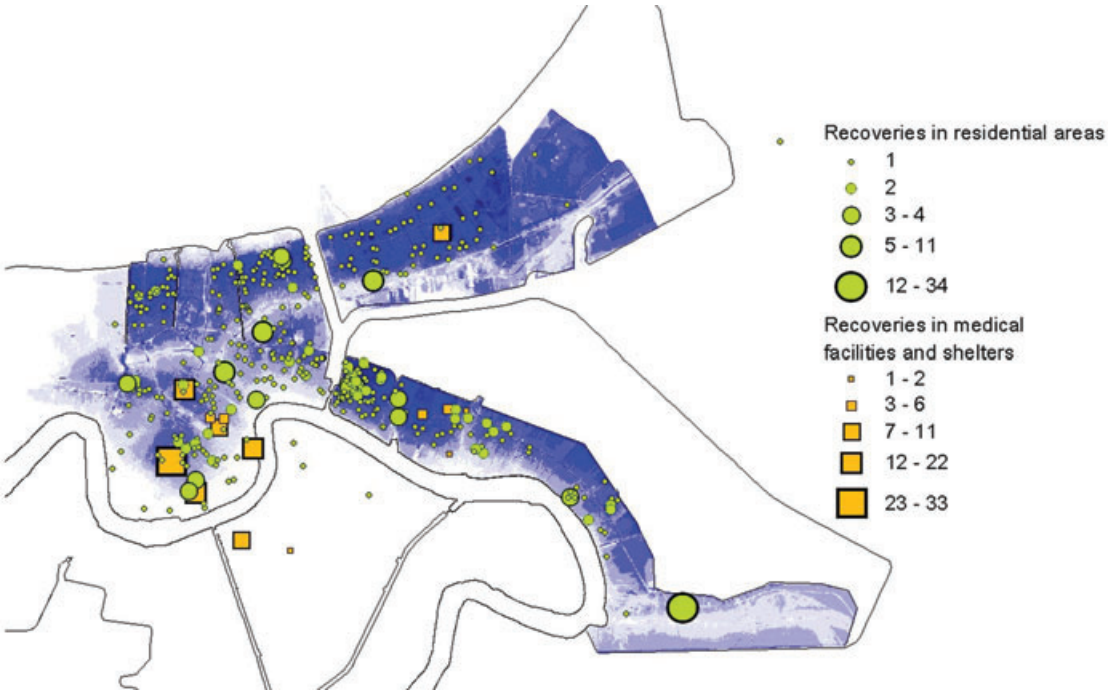

Fig. 12. Recovery locations and flooded area.

5.4. Discussion of Circumstances of Katrina-Related Fatalities

A first discussion of the causes and circumstances of different groups of fatalities is presented below that is based on the available information that has been described in the previous sections. As no data were available for a substantial number of fatalities in the state of Louisiana (31%) the findings and discussions are preliminary and not necessarily fully representative for all fatalities in Louisiana.

Of the 771 recovered fatalities, 147 (19%) occurred outside the flooded area in Louisiana. Most of these fatalities were evacuees and their occurrence is likely related to the adverse public health situation that affected those who evacuated as a result of Hurricane Katrina. Likely death causes include lack of necessary medical services, chronic conditions, stress-induced heart attacks or strokes, violence, and suicide.[13]

In total, 624 of the 771 recovered fatalities (81%) occurred inside the flooded area. Of these, 106 were recovered from locations such as public shelters and hospitals that indicate that these fatalities were not directly related to the impacts of floodwaters. Most of these fatalities, about 90, occurred in hospitals. For these groups of fatalities death causes are likely similar to those who died outside the flooded area, i.e., lack of necessary medical services, chronic conditions, stress-induced heart attacks or strokes, or violence. Several sources document the critical public health conditions that developed in medical facilities.[40–42]

This leaves 518 recovered fatalities (67% of the total recoveries) that most likely resulted from direct exposure to the physical impacts of the flood. Typical death causes for people exposed to the floodwaters include drowning (in a building or in the street) or physical trauma due to impacts from debris and/or building collapse.[39] Many of these fatalities occurred in areas near large breaches in the Lower 9th Ward in the St. Bernard bowl and in areas where large water depths occurred. Available data indicate that a substantial number of victims (more than 20) were recovered from residences inside the flooded areas from attics or floors that were not flooded. This suggests that these people died due to adverse conditions associated with extended exposure in the flooded area in the days after Katrina. Typical death causes could include dehydration/heat stroke, heart attack/stroke, or other causes associated with lack of sustaining medical supplies. Initially thought to be a major threat to those remaining in the flooded area, disease and toxic contamination do not appear to explain many of the deaths.

Analysis of individual characteristics of victims showed that the majority of victims were elderly (see Section 5.1). The specific vulnerability of this group is sadly illustrated by the large numbers of fatalities in nursing homes in flooded area, where 65 fatalities occurred in total. Thirty-one victims were recovered from St. Rita's nursing home in the southeastern part of the St. Bernard bowl.

6. ANALYSIS OF THE RELATIONSHIP BETWEEN FLOOD CHARACTERISTICS AND MORTALITY

6.1. General Approach

6.1.1. Past Work and Approach

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.[1] Mortality is defined as the number of fatalities divided by the number of people exposed to the flooding in that area. It has been observed from historical disasters that mortality rates are the highest near breaches and in areas with a large water depth, a high rise rate, and a large number of buildings collapsed. By analyzing empirical information from historical floods, such as the floods in the Netherlands in 1953, mortality functions have been developed that are particularly applicable to floods of low-lying areas that are protected by flood defenses.[1,2] These functions relate the mortality among the exposed population to the flood characteristics for different zones in the flooded area. Analysis showed that different zones can be distinguished in an area that floods due to breaching of flood defenses. In a zone near a breach flow velocities are high, leading to the collapse of buildings and instability of people standing in the flow. Another zone is characterized by rapidly rising waters and people in this zone may have difficulties in reaching shelters or higher grounds. Third, a remaining zone is distinguished in which the flooding is more slow-onset. In the breach zone the flow velocity is the most important factor. In the other two zones the water depth and the rise rate were found to be the most important factors. An example of the mortality function is shown in Fig. 13.

The existing empirical relationships are based on historical flood events that mainly occurred several decades ago, such as the coastal flooding in the Netherlands in 1953. As the consequences of the flooding of New Orleans were relatively well-documented these data provide additional insight into the relationship between flood characteristics and mortality. In the following sections this relationship is further analyzed based on observed and simulated data for the Hurricane Katrina flood event.

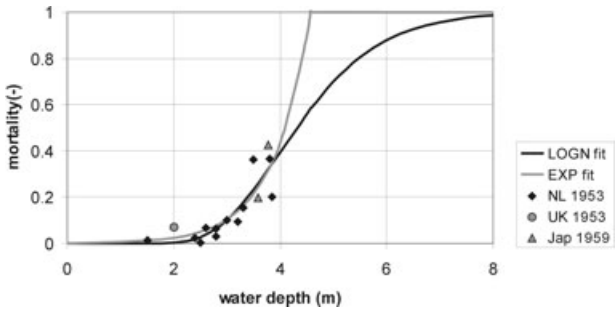

Fig. 13. Mortality function for the zone with rapidly rising waters.[1]

6.1.2. Input Data and Assumptions

General approach. It is analyzed whether a statistical relationship between mortality and flood characteristics (a so-called mortality function) can be derived based on the empirical data for New Orleans. Several types of distribution functions have been tested (exponential, lognormal, normal, etc.) and the functions have been derived by means of a least square fit. The correlation coefficient R^2 is used to express the strength of the relationship between the observed mortality and the predicted mortality with the derived function. In the analysis the study area is divided into different locations of similar flood characteristics. For each location average mortality is determined and an average value for the flood depth is estimated. Existing spatial subdivisions of the city (e.g., tracts, neighborhoods, blockgroups) have been examined. If the spatial unit is too small the number of locations will be large relative to the number of fatalities. Then there will be many locations without fatalities and the randomness in the occurrence of fatalities will become important. If the chosen spatial unit is too large then it is no longer correct to assume constant flood conditions in one spatial unit because spatial variations become too large. As a practical choice for balancing the number of locations and the level of detail the neighborhood level has been chosen in the analysis; see Fig. 14 for the subdivision. Application of the previously described approach requires insight into the flood characteristics, the

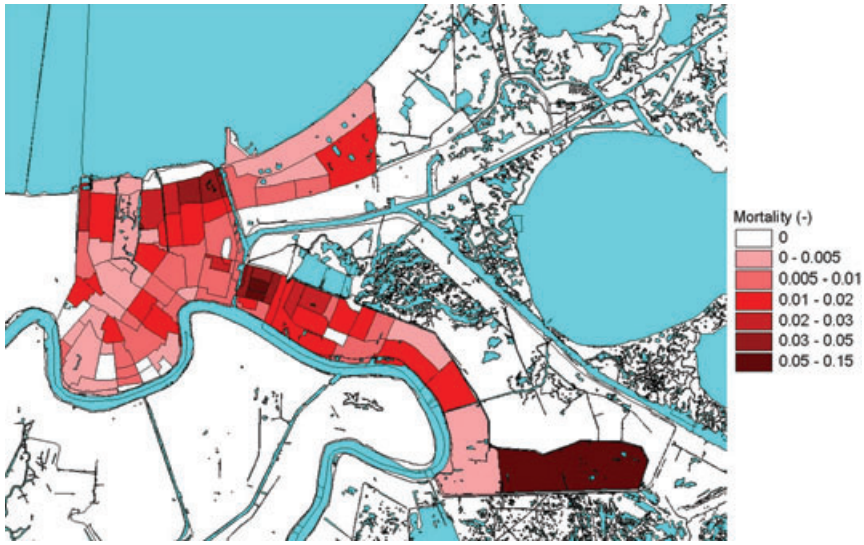

Fig. 14. Mortality by neighborhood. (A high mortality occurred in the neighborhood in the southeast because 30 fatalities occurred in one nursing home.)

number of fatalities, and the number of people exposed. For these three factors the most important sources of input data and assumptions are described below.

Flood characteristics. The influence of the factors water depth, rise rate, flow velocity, and arrival time of the water has been analyzed, as these are expected to be important determinants of loss of life.[1] The results from the flood simulations have been used to determine values for flood characteristics at different locations. The influence of other potentially relevant factors, such as the effects of waves, the local level of warning, etc., has not been examined due to lack of data. In the analysis only the Orleans and St. Bernard bowls were considered as no results of flood simulations were available for the New Orleans East bowl.

Fatalities. The analysis only includes the fatalities in the flooded area that are expected to be directly associated with the flood conditions,[7] i.e., the recoveries in residential locations (see also Section 5.3). Fatalities in medical locations and shelters are not included in the analysis because these are generally not directly related to the physical flood impacts. Information regarding the New Orleans fatalities is based on the GIS data set that indicates the spatial distribution of recovery locations (Section 5.3). It is noted that the recovery data set does not include all the fatalities reported in the state of Louisiana. Although most of the missing data concern fatalities from parishes outside of the flooded area, the reported mortality fractions could still be underestimates of the eventual mortality fractions in the flood zone.

The exposed population. The population that is exposed to the floodwaters (N_{EXP}) can be found by subtracting the evacuated (F_E) and sheltering (F_S) fractions of the population from the original population at risk (N_{PAR}):

$$N_{\mathrm{EXP}} = N_{\mathrm{PAR}}(1 - F_E - F_S).$$

The population at risk (N_{PAR}) is defined as the original population in the area prior to Hurricane Katrina. In a first-order and general analysis the evacuation and shelter fractions are assumed constant for the whole exposed area. In reality there likely were differences in evacuation rates between neighborhoods, but the limited data that are available regarding the Katrina evacuation do not provide sufficient information on evacuation rates at a neighborhood level. Overall, the presented estimates are crude, but necessary given the limited amount of data.

Data from the U.S. Census 2000 have been used to determine the population at risk. Due to the effects of evacuation and shelter the number

[7] A limited number of fatalities in the flooded area might be caused by wind effects. However, it is expected that the number of wind fatalities will be limited as (a) most people found shelter during the passage of the storm; (b) storms in the past with comparable strength and no flooding have caused much fewer fatalities. For example, Hurricane Betsy (1965) and Hurricane Frederic (1979) occurred in the same area and were of similar strength (Category 3). The numbers of fatalities for these storms are considerably smaller than for Katrina. Betsy caused 76 fatalities (of which a substantial part were due to local flooding) and Frederic caused five fatalities (Reference 53; pp. 1–28).

Table II. Overview of Number of Inhabitants, Exposed, and Fatalities for the Three Flooded Bowls

Bowl	Inhabitants (flooded area)	Exposed	Recovered No. of Fatalities*	Mortality
Orleans	255,860	25,590	260	1.02%
St. Bernard	85,420	8,540	190	2.22%
New Orleans East	96,290	9,620	68	0.71%
Total	437,570	43,750	518	1.18%

*This column includes the number of recovered people in residential locations. Fatalities in special facilities, such as hospitals and shelters, are not included as these are expected not to be related to flood characteristics.

of exposed population was reduced before the hurricane. Based on the analysis of traffic counts it is estimated that 80–90% of the "at risk" population in southeast Louisiana evacuated the area before the storm.[24,26] In this study we assume an evacuation rate of 80% for New Orleans (a number that was also stated by the mayor of New Orleans, Ray Nagin). In addition, based on available descriptions, it is assumed that another 10% found shelter in special facilities, such as the Superdome and Convention Center.[8] This results in an estimate of the exposed population in the flooded area of approximately 10% of the inhabitants, corresponding to approximately 44,000 people exposed (see Table II).

6.2. Results

6.2.1. Mortality by Bowl and Neighborhood

Table II summarizes the number of exposed, fatalities, and mortality rates for the three bowls of New Orleans. For all three bowls the average mortality fractions are in the order of magnitude of 1%. Differences in mortality between these bowls are likely related to the severity of the flood impacts, as is discussed later.

A general overview of mortality rates by neighborhood is shown in Fig. 14. The flooding of the Orleans bowl was caused by breaches along the Industrial Canal in the east and the 17th Street and London Avenue canals in the north. These resulted in the flooding of large parts of the central city. The largest water depths and mortality rates are found for the deeper parts of the bowl, mainly in the north near Lake Pontchartrain. The relatively high mortality in the St. Bernard Bowl (2.2% on average for the whole area) is mainly due to the severe flood conditions and the large number of fatalities near the breaches. In the St. Bernard bowl the highest mortality values (5–7%) occurred in the neighborhood Lower 9th Ward next to the two large breaches in the Industrial Canal levees. The quantitative relationship between mortality and flood characteristics is discussed further in the next sections.

6.2.2. Relationship Between Water Depth and Mortality

The relationship between mortality and flood characteristics has been analyzed. Assessments have been made for the following flood characteristics: water depth, rise rate, velocity, and arrival time of the water after breaching. Only for water depth (see below) and flow velocity (see next section) do there appeared to be significant relationships. Fig. 15 shows the relationship between average water depth by neighborhood and mortality. A distinction has been made between observations in the Orleans bowl and the St. Bernard bowl. The observations for the Lower 9th Ward neighborhood in the St. Bernard bowl have not been included in this analysis as the effects of flow velocity played an important role in this area, see also Fig. 6 and Section 6.2.3 for further discussion. It is noted that the New Orleans East bowl was not included in the analysis as no simulations of flood characteristics were available. The figure shows that mortality increases with the water depth. Fig. 15 displays the best fit trendlines for the Orleans and St. Bernard bowls and the best fit trendline for the combined data set with observations from the two bowls. The following relationship between water depth and

[8] Boyd[27] estimates that 72,000 people remained in the city after evacuation. This corresponds to approximately 18% of the initial population of the flooded areas. He also mentions that 26,000 people (6.3% of the population in flooded areas) found shelter in the Superdome.[29] The estimate of a shelter percentage of 10% results when additional populations in other shelters are also included. It is noted that a later report issued by the Louisiana National Guard estimates the sheltered population in the Superdome to be in 10,000–12,000 range. As such, the above numbers have to be considered as preliminary.

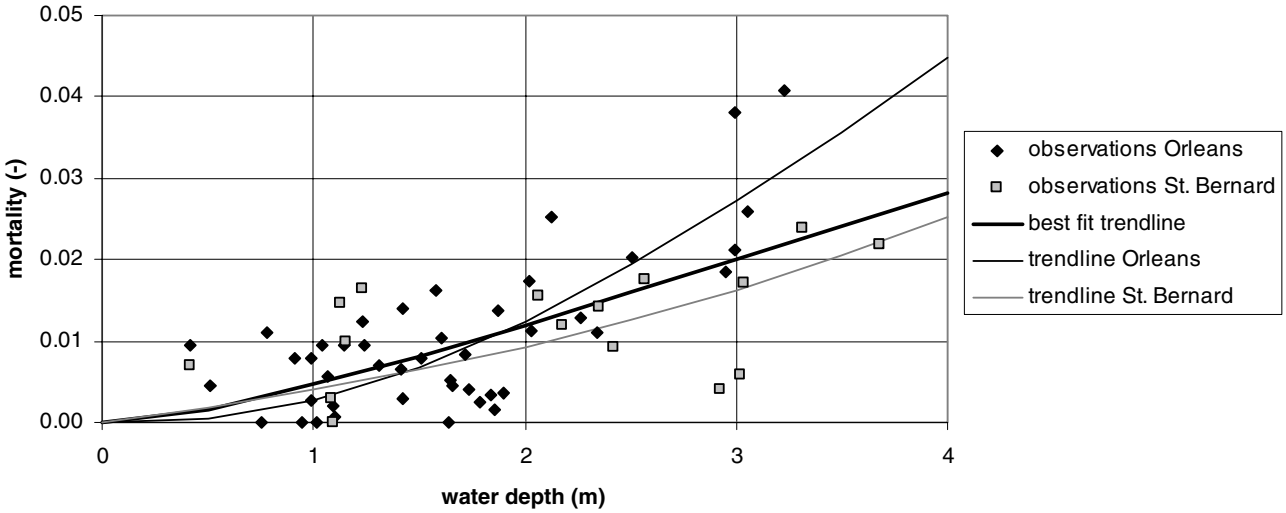

Fig. 15. Relationship between water depth and mortality for the Orleans and St. Bernard bowls.

mortality is found for the combined data set:

$$F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right)$$
$$\mu_N = 5.20 \ \sigma_N = 2.00$$

where $F_D(h)$ is the mortality fraction as a function of water depth h; h the water depth (m); μ_N, σ_N are the average and standard deviation for the log-normal distribution (m); Φ_N the cumulative normal distribution.

The correlation between observations and predictions with the function is $R^2 = 0.42$, which is moderate. The best fit function is described with a log-normal distribution. It is interesting to note that this type of function is also applied in other fields to describe the relationship between dose and (human) response, for example, for lethality due to exposure to toxic substances.[43]

The derived mortality function can be used to provide a point estimate of mortality for a given water level. Although a clear trend can be observed from the data set, there is considerable uncertainty associated with this mortality function due to the variation in the observations. The model uncertainties in the mortality function have been determined for the 95% confidence interval (results not shown in the figure). These bandwidths have been derived by statistical analysis of the available observations, while assuming that all fitted curves should lead to a mortality of zero for a flood depth of zero meter. Within the 95% confidence interval the mortality varies approximately plus or minus 50% from the central point estimate. Thereby the uncertainty in the mortality and loss of life predictions can be quantified.

6.2.3. *Mortality in the Breach Zone: Lower 9th Ward*

In total, 184 fatalities in the data set were recovered in the St. Bernard bowl. Many of these fatalities (73) occurred in the neighborhood of the Lower 9th Ward. This neighborhood is located next to the two large breaches in the Industrial Canal levees. Various eyewitness accounts tell how the floodwater entered this neighborhood through the breaches with great force and how it caused death and destruction in the areas near the breaches. This observation is further confirmed by the large number of homes destroyed and the patterns in residential damage in this area.

The relationship between flood characteristics and mortality has been analyzed further for the St. Bernard bowl. The large number of fatalities near the breaches in the Lower 9th Ward appears to be related to the large number of collapsed buildings in the area and the consequent loss of shelter. Areas with high levels of building damage are characterized by large values of the product of water depth and flow velocity; see Fig. 16. Past work shows that water depth-flow velocity is strongly related to the extent of building damage[44,45] and loss of human stability in flood flows.[46] Most of the collapsed buildings and fatalities were found in the area where $hv > 5$ m^2/s. Observations in the field show that the area with

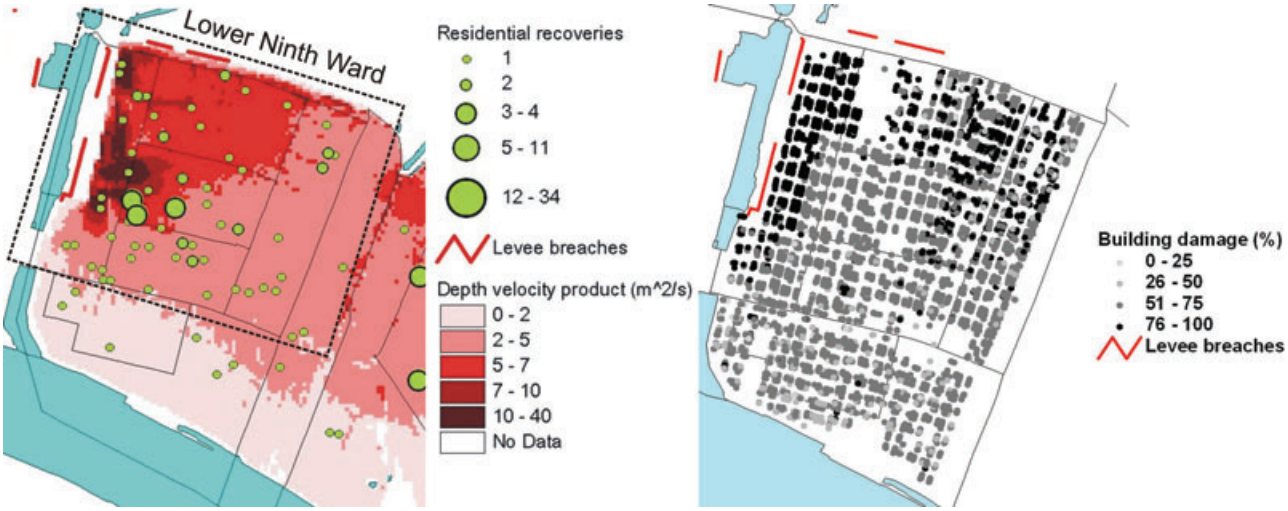

Fig. 16. Spatial distribution of the recovered fatalities and the depth-velocity product for the Lower 9th Ward (left) and building damage levels (Right—*Source*: http://www.unifiedneworleansplan.com/home2/section/24, accessed December 2006. Damage levels determined in post-Katrina damage assessments conducted by the city of New Orleans and FEMA.)

large-scale structural damage to houses covers almost the whole Lower 9th Ward. Average mortality for this neighborhood was $F_D = 0.053$ (or 5.3%) and the mortality varied between $F_D = 0.033$ and $F_D = 0.07$ for the locations within this neighborhood.

In the Orleans bowl higher flow velocities only occurred locally very near the breaches; see also Fig. 6. Comparison with the building damage and visual observations in the field shows that hardly any buildings collapsed near these breaches in Orleans along the 17th Street and London Avenue Canals. Comparison with the data set of recovery locations shows that no fatalities were found in the zones near breaches. Based on these observations it is expected that the flow velocity did not have a substantial influence on mortality in the Orleans bowl.

6.2.4. *Summary of Mortality Functions*

The derived mortality functions for the flooding of New Orleans are summarized in Fig. 17. Following the general approach for loss of life estimation that has been developed in earlier work (see Section 6.1) different zones are distinguished. The findings for Lower 9th Ward are considered representative for the breach zone and the mortality function that has been derived for the other areas is applied to the so-called remaining zone.

When this approach is applied to the analyzed locations in the Orleans and St. Bernard bowls the estimated number of fatalities is 395, while the actual observed number for the considered locations is 404. There is a good correlation ($R^2 = 0.74$) between observed and calculated mortality fractions by location.

The proposed mortality functions are applicable to calculate mortality associated with the physical impacts of the flood. The occurrence of fatalities associated with the adverse public health situation is not included in the proposed functions. This group of fatalities proved to be substantial, covering approximately one-third of the total number of recovered (see also Section 5.4).

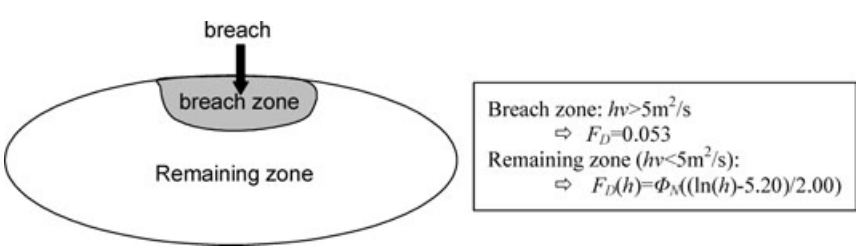

Fig. 17. Mortality functions and zones derived based on data for the flooding of New Orleans.

7. DISCUSSION

In this section a number of issues are discussed. These include a comparison of the findings with existing methods for loss of life estimation (Section 7.1). Consequently, the development of loss of life patterns over time is discussed (Section 7.2). Section 7.3 discusses the main uncertainties and the status of the results.

7.1. Comparison with Existing Methods for Loss of Life Estimation

The first general finding relates to overall mortality fraction for the whole event. Based on available event statistics it has been shown that a first-order estimate of loss of life due to historical coastal flood events can be obtained by assuming that 1% of the exposed population will not survive.[1] The average mortality associated with the flooding of New Orleans (1.2%) is thereby similar to the average event mortalities due to flood disasters in history. The mortality fractions for the three bowls (see Table II) are also in this order of magnitude.

In general it is found that, similar to the historical flood events, the mortality rates were the highest in areas near breaches and in areas with large water depths. The findings of the above analysis are compared to the mortality functions that have been derived mainly based on the data for the 1953 flood in the Netherlands (see Section 6.1). In this Dutch method it was found that the mortality would become substantially higher if a certain threshold value of the rise was exceeded. Fig. 18 shows the mortality observations for New Orleans plotted against the values of the rise rate. For the New Orleans data set there does not appear to be a relationship between

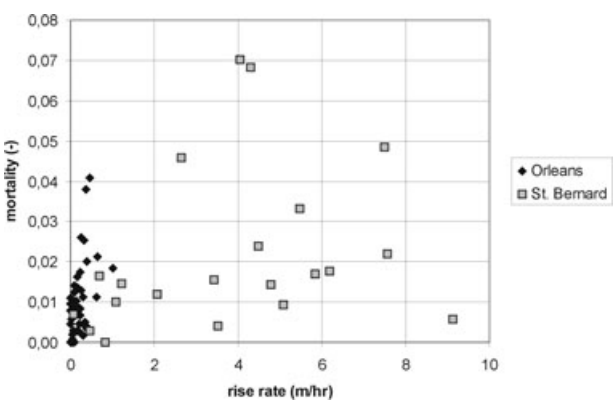

Fig. 18. Relationship between rise rate and mortality for the Orleans and St. Bernard bowls.

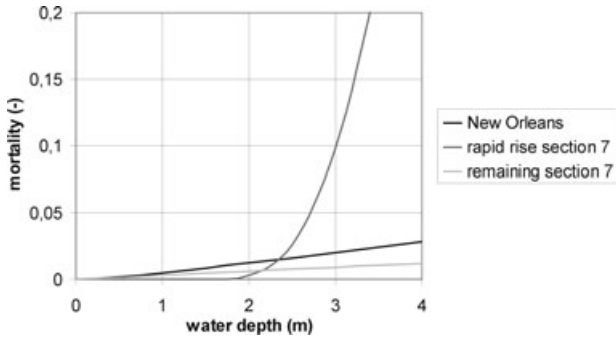

Fig. 19. Mortality function for New Orleans and mortality functions for the Dutch method.

the mortality and the value of the rise rate. The factors depth and velocity appeared to be most relevant for this event.

The derived mortality functions for new Orleans are compared with those derived for the Dutch 1953 floods (see Fig. 19). For water depths below 2.5 m the function for New Orleans gives a somewhat higher mortality fraction than the Dutch functions. The derived function for New Orleans is in between the earlier proposed functions for larger water depths ($h > 2.5$ m). The uncertainty margins for the Dutch mortality function are approximately plus or minus 50% within the 95% confidence interval[1] and thereby similar to the bandwidth for the mortality function for New Orleans (see Section 6.2.2). It is interesting to note that the Dutch method has been applied after the New Orleans flood disaster to give a hindcast of the observed number of fatalities. The total number of fatalities that is predicted for the New Orleans flood with the Dutch method was within a factor of 2 with the (preliminary) number of observed recoveries in the flooded area. This is a relatively good result. Other estimates in the period shortly after the disaster gave numbers that ranged up to 72,000 fatalities.[47] It is also interesting to mention that both methods (New Orleans and Dutch) give very similar outcomes when they are applied to (hypothetical) flood scenarios for an area in the Netherlands.[35] For most of these scenarios the New Orleans method resulted in a somewhat higher estimate of loss of life (on average 15%) than the Dutch method.

7.2. Discussion Regarding the Effects of Changes in Time on the Loss of Life Caused by Floods

The Dutch method has been mainly derived based on events that occurred in the 1950s, while

the New Orleans flood occurred in 2005. Certain circumstances that affect flood mortality could have changed over time. Some argue that these changes will have mainly reduced the loss of life caused by flood events.[48] Potentially positive developments include improvements of prediction, transportation, building quality, communication and possibilities of warning of those in the flood zone, emergency response, and rescue. However, there are also developments that could have a negative influence, e.g., the dependence of modern societies on technical systems, such as electricity and communication and the fact that people are less used to withstand harsh natural conditions. The New Orleans flood event gave some insight into the potential relevance of such factors.

The event showed the limitations of evacuation and emergency response. A majority of the population (80–90%) evacuated before the floods and this probably saved thousands of lives. However, the consequences for the people who stayed and were exposed to the floods were still disastrous. In addition, a severe crisis situation developed among evacuees and the people in hospitals and shelters. The situation after the flooding illustrated the difficulties in organizing a fast and effective rescue action.[32]

In many respects the New Orleans flood is very comparable to historical large-scale flood events. Similar to historical events the mortality fractions in New Orleans were the highest in areas near breaches and in areas with large water depths. The overall mortality fraction among those exposed for the New Orleans flood is approximately 1.2%. This is comparable to the average event mortalities observed for historical events, such as the floods in 1953 in the Netherlands (0.7%) and the floods in 1959 in Japan (1.2%).[1] In addition, the New Orleans flood disaster was also characterized by some circumstances that were more favorable than during historical floods. For example, most people were warned of the hurricane and the water temperature was higher than during historical disasters and this reduced the risk of hypothermia.

Overall, the available data for New Orleans do not support the claim that mortality among those exposed during a contemporary flood event is lower than during historical events. Based on analysis of dam break flood events from the 19th and 20th centuries, McClelland and Bowles[49] come to a similar conclusion and mention that mortality patterns are consistent across the centuries.

7.3. Status of the Results

This section concerns a brief discussion of the status of the analyses that have been reported in the previous sections. It is important to stress that the results are preliminary for a number of reasons.

First, the applied mortality data are still incomplete and cover approximately 70% of all fatalities. In addition, the analysis of mortality functions is limited to the Orleans and St. Bernard bowls. The Orleans East bowl is excluded from the analysis because no results of flood simulations were available for this bowl.

Second, various crude assumptions have been made in the analysis of the number of people exposed. For all the considered areas it has been assumed that 10% of the original population was exposed. However, spatial differences in evacuation rates and exposed populations could have an effect on the resulting mortality values. It is recommended to investigate the spatial distribution of evacuation and shelter rates for the flooded areas of New Orleans.[50]

Third, results of the flood simulations have been used to estimate flood characteristics. Limitations in these simulations could influence the outcomes. Examples of limitations are the capabilities to model breaches or neglecting of the effects of rainfall.[34,35] Also the fact that flood characteristics (e.g., depth and rise rate) have been averaged out per neighborhood could affect the outcomes because variations between flood characteristics within one neighborhood could exist.

Given the above issues, the detailed results regarding the influence of flood characteristics on mortality have to be considered as indicative and preliminary. Despite the limitations, the reported results give important insight into the relationship between flood characteristics and mortality.

8. CONCLUDING REMARKS

The flooding of New Orleans due to Hurricane Katrina showed the catastrophic consequences of large-scale floods. A preliminary data set that gives information on the recovery locations for 771 fatalities has been analyzed and this resulted in the following conclusions:

(1) Two-thirds of the analyzed fatalities were most likely associated with the direct physical impacts of the flood and mostly caused by drowning. One-third of the analyzed fatalities

occurred outside the flooded areas or in hospitals and shelters in the flooded area due to causes such as strokes, heart attacks, and lack of medical services. These fatalities were due to the adverse public health situation that developed after the floods. Overall, the elderly were the most vulnerable. Nearly 60% of fatalities were over 65 years and 85% of fatalities were over 51 years.

(2) Similar to historical flood events, mortality rates were highest in areas near breaches and in areas with large water depths. The highest mortality fractions were observed near the severe breaches in Lower 9th Ward. An earlier proposed approach, in which mortality functions for different zones in a flooded area are distinguished, is also applicable to New Orleans. A relationship has been found between the water depth and mortality. One difference with earlier findings is that the data for New Orleans do not show an influence of the rise rate of the water on mortality.

(3) The available data for New Orleans do not support the claim that mortality during a contemporary flood event is lower than during historical events. The overall mortality among the exposed population for this event was approximately 1%, which is similar to findings for historical flood events.

The derived mortality functions can be used to provide quantitative estimates of loss of life for different flood scenarios, either in deterministic (scenario) or probabilistic (risk) calculations. By combination with information on the probability of flood scenarios the risk to life can be quantified with different risk measures. The individual risk indicates the probability of death for a person at a certain location in the area. The societal risk expresses the probability of a disaster with many fatalities. These results can be used as input for decision making about the acceptable level of flood risk.[51] Risk assessment will also be used for decision support in the development of plans for future protection of New Orleans against flooding.[52] The approach for loss of life estimation that has been described in Section 6.1.1 of this article includes the most relevant factors that determine loss of life. With the method the effectiveness of measures to reduce the consequences of flooding, such as evacuation, shelter, compartment dikes, and land-use planning can be evaluated. The outcomes obtained with the method are also applicable to compile flood risk maps that indicate most hazardous areas and these results can also be used for risk communication and the preparation of emergency management strategies.

The presented results and analyses are preliminary. The analyzed mortality data are incomplete (they cover 69% of all fatalities in the state of Louisiana) and first estimates have been used for the estimation of the size of the population exposed. It is recommended to collect more accurate data regarding fatalities, the exposed population, and the flood characteristics. Important factors that deserve further investigation are the influence of the collapse of buildings and the effects of rise rate on mortality. Based on more complete analyses, an improved method for loss of life estimation may be derived from the New Orleans data in the future. Further cross-analysis of individual characteristics, death causes, and spatial patterns in fatality rates is recommended to gain more insight into the causes of death in different affected regions. Information regarding social factors (income, poverty, ethnicity) could be added in the analysis to gain more insight into the effects of social vulnerability factors.

ACKNOWLEDGMENTS

Dr. Karin de Bruijn (Deltares) is gratefully acknowledged for her work on the flood simulations. We thank Dr. Pieter van Gelder (Delft University) for his advice regarding the statistical analyses. In addition, we acknowledge Dr. Louis Cataldie and Frances Kosak of the Louisiana State Medical Examiner's Office for their efforts to compile and help us interpret the dataset regarding fatalities due to Hurricane Katrina's impact in Louisiana.

APPENDIX: STATISTICAL ANALYSIS FOR RACE AND GENDER

In this simple and preliminary analysis the outcomes for gender and race for the fatality data set are compared with the characteristics of the overall population.

Data for the affected population were obtained from the Greater New Orleans Community Data Center for the pre-Katrina population. These data were derived from the U.S. Census of the year 2000. Data were used for Orleans and St. Bernard parishes as these correspond to the flooded areas and both sub data sets were combined to create one total data set (see Table A1). It is assumed that this total joint data set corresponds to the overall population. In this simple analysis it is also assumed that the gender and

Table A1. Overview of Population Statistics for Gender and Racial Diversity for the Affected Area

	Affected Area			
	Orleans Parish	St. Bernard Parish	Total	Fatality Data Set
Population/number	484,647	67,229	551,876	853
Male	46.9%	48.3%	47.1%	50.6%
Female	53.1%	51.7%	52.9%	49.4%
Racial and ethnic diversity				
Population/number	484,647	67,229	551,876	818
African American	66.6%	7.6%	59.4%	55.1%
White	26.6%	84.3%	33.6%	40.8%
Hispanic	3.1%	5.1%	3.3%	2.2%
Asian Pacific	2.3%	1.3%	2.2%	0.7%
Native American	0.2%	0.5%	0.2%	0.5%
Other	1.2%	1.2%	1.2%	0.6%

Source: U.S. Census Bureau. *Census 2000 Full-Count Characteristics (SF1)*. From a compilation by the Greater New Orleans Community Data Center; http://www.gnocdc.org/prekatrinasite.html, accessed November, 2008, and the fatality data set.

race distribution are spatially homogeneous; see also the short discussion at the end of this appendix.

Hypothesis and Statistical Test Method

In a simple statistical analysis the null hypothesis has been tested that the fatality data set is a random sample from the total population in the affected area. In that case it is likely that the race and gender distribution of the fatality data set corresponds to the total population. The hypothesis has been tested by means of Pearson's χ^2 test with one degree of freedom. A significance level of 5% has been used and the hypothesis is rejected if the observed χ^2 value is larger than the critical χ^2 value that corresponds with the chosen significance level. This critical value equals $\chi^2 = 3.8$.

Gender

For the 853 victims for which gender is known in the fatality data set, 432 (50.6%) are male and 421 (49.3%) are female. The expected number of male and female fatalities can be determined based on the percentages for the population in the affected area (see Table A2).

This results in the following value $\chi^2 = 4.23$.

The assessment shows that the probability of obtaining a result at least as extreme as the one that was actually observed, given that the null hypothesis is true, equals $p = 0.039$ and the null hypothesis can be rejected.

Race

Of 818 fatalities for which race is listed, 451 (55%) are African American and 367 (35%) were non African American. The expected number of African American and non African American fatalities can be determined based on the percentages for the population in the affected area (see Table A3).

This results in the following value $\chi^2 = 6.21$.

The assessment shows that the probability of obtaining a result at least as extreme as the one that was actually observed, given that the null hypothesis is true, equals $p = 0.013$ and the null hypothesis can be rejected.

Closing Remark

It is noted that the spatial variation in the ethnic distribution in the New Orleans area is large. Therefore, the presented results are no more than preliminary and first-order estimates. Given the high spatial variation of the race distribution of the

Table A2.

	Male	Female	Total
Observed	432	421	853
Expected	402	451	853

Table A3.

	African American	Non African American	Total
Observed	451	367	818
Expected	486	332	818

population in the New Orleans area, a more detailed statistical analysis of the relationship between mortality and population characteristics at the neighborhood level is recommended.

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